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Published in:
High Voltage

DOI:
10.1049/hve2.12405

E-pub ahead of print: 25/01/2024

Please cite the original version:
A new technique for fault diagnosis in transformer insulating oil based on infrared spectroscopy measurements

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Abstract
Condition monitoring of the insulating system within power transformers has a massive importance according to the electrical utilities. Dissolved gas analysis (DGA) is frequently used for this purpose. However, DGA lacks the necessary level of accuracy to identify all equipment faults, particularly in their initial stages of degradation. Also, it does not have the capability for real-time monitoring and relies on manual sampling and laboratory testing, causing potential delays in fault identification. Additionally, the interpretation of DGA data necessitates specialised expertise, which may pose difficulties for smaller entities that have limited access to resources. Therefore, the contribution of this research is to use infrared spectroscopy measurements as a new effective technique substituting the DGA method for fault diagnosis in insulating oil. The inception faults that were considered in this study were the electrical fault (discharges of high energy) and the thermal fault (300°C < Temperature < 700°C). Regarding that, two test cells were crafted especially for serving the simulation processes inside the laboratory for both types of inception faults. Subsequently, six samples of pure paraffinic mineral oil were taken to be degraded in the laboratory. Following that, all of them besides another sample that were not subjected to any kind of faults were taken to be examined by Fourier transform infrared (FTIR) spectroscopy to obtain an overview of the oil's behaviour in each fault case. After that, the FTIR analysis was initially verified utilising the DGA method. Then, for further affirmation, the dielectric dissipation factor (DDF) for all samples was measured. In the final analysis, the verification tests provide experimental evidence about the outperformance of this new optical technique in detecting the transformer's inception faults in addition to proving its potential for being a superior alternative to the well-known traditional diagnostic techniques.

1 | INTRODUCTION

Without a shred of doubt, power transformers are the main equipment within power transmission as well as distribution networks since they serve as a vital link in a long chain of other equipment that provides electrical energy to customers. Accordingly, it is very important to ensure the optimum operation of power transformers [1]. In fact, the insulating system of power transformers is frequently exposed to fault occurrences due to various causes, and each cause has its impact on the transformer's condition. Therefore, the condition monitoring of a power transformer's insulating system has massive importance according to the electrical utilities. This is due to the huge information the insulation's state provides about the troubles that already exist within the transformer. Thus, as early as these problems are well detected, the transformer's probability of being suddenly brought out of service decreases in a significant way. Actually, there are several diagnostic techniques by which the transformer's condition can be evaluated [2, 3]. Up to the present time, the most popular diagnostic technique utilised worldwide for detecting the transformer's inception faults is the dissolved gas analysis.

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(DGA). This technique is capable of predicting the type of inception fault that occurred based on the concentrations of certain fault gases dissolved in the oil. The concentrations of such gases are measured via a device called gas chromatography (GC), and then the analysis is conducted utilising one or more of the methods that lie under the umbrella of the DGA technique. Generally, there are several traditional DGA methods such as the Doernenburg ratio, Duval triangles, key gas, the international electrotechnical commission (IEC) ratio, Duval pentagons, and Roger's ratio [4–6]. However, the accuracy of the mentioned DGA methods is somewhat low compared to the other diagnostic techniques. Fortunately, after the implementation of the internet of things (IoT), artificial intelligence (AI), and machine learning (ML) in such traditional DGA methods, diagnostic accuracy was much improved [7–10]. Despite the high dependence on the DGA technique in detecting transformer inception faults, it has many drawbacks. Actually, it is a destructive expensive technique that requires an experienced operator to conduct the measurements; also, it is time-consuming since the GC device takes a large amount of measuring time [11, 12]. Further, it is not an eco-friendly technique by the way as it utilises toxic organic solvents besides other resources. These disadvantages have forced immediately the researchers to find other alternatives to be utilised in monitoring the condition of power transformers. Lately, optical spectroscopy techniques have attracted most of the attention towards efficient monitoring of the insulating system quality within power transformers. Since such techniques are non-destructive, easy to be conducted, cost-effective, and eco-friendly besides having high accuracy in material characterisation [13, 14].

In this regard, the authors in Ref. [15] have tried to predict the type of fault via the Duval triangle method based on the intensities of the dissolved gases absorbance peaks utilising the Fourier transform infrared (FTIR) spectroscopy. Furthermore, in Ref. [16], the transformer oil’s quality was evaluated based on its molecular structure with the aid of FTIR spectroscopy. Also, the spectrum of such optical techniques can be correlated with the output of some traditional diagnostic techniques such as total acid number (TAN) and dielectric dissipation factor (DDF) as in Refs. [17, 18]. Moreover, ultraviolet-visible (UV-Vis) spectroscopy was utilised in detecting the transformer oil quality based on the by-products formed within the oil due to thermal ageing [19]. However, in Ref. [20], the transformer health index was calculated based on the number of ageing by-products that were formed within each oil sample utilising UV-Vis spectroscopy. Concerning Raman spectroscopy, it was utilised also in determining the thermal ageing stage of oil-paper insulation [21]. Last but not least, the role of optical spectroscopy techniques in detecting transformer inception faults was introduced by our research group in Ref. [22]. The FTIR spectra of mineral oil samples that have been electrically as well as thermally degraded were utilised in the discrimination between those types of inception faults. However, this investigation has some drawbacks that have been fulfilled in this current work. These drawbacks are as follows: the oil’s spectral behaviour for each fault type was not studied comprehensively since only one case of degradation severity was considered for each fault type. Also, the FTIR analysis was confirmed with only one diagnostic technique.

According to the plentiful survey mentioned above and the authors’ knowledge, no one in the previous works has deeply discussed the capability of monitoring the transformer inception faults based on the oil insulation’s spectrum utilising any of the various optical spectroscopy techniques. In this regard, the new proposed investigation has covered the lack in this research area by utilising the FTIR spectroscopy technique to comprehensively study the effects of various types of transformer inception faults on the transformer oil’s spectral behaviour. Therefore, the contribution of this paper is as follows:

- Degrading six samples of pure paraffinic mineral oil electrically and thermally inside the laboratory utilising special test setups.
- Examining all of the degraded samples besides a reference sample by FTIR spectroscopy according to the ASTM E1252-98 standard in order to study the oil’s spectral behaviour in each fault type [23].
- Confirming the FTIR analysis initially through the DGA method utilising a GC according to the ASTM D3612-02 standard [24]. Thereafter, for further verification, the DDF for all of the oil samples was estimated with an LCR metre according to the IEC 60,247 standard [25].
- Checking the reliability of this new optical technique in discriminating between transformer inception faults besides being an alternative to the well-known traditional diagnostic methods.

2 | SAMPLES PREPARATION AND EXPERIMENTAL PROCEDURES

For ensuring the applicability of the FTIR spectroscopy for being an alternative to the well-known conventional diagnostic techniques, six samples each of which was 400 mL of pure mineral oil (Shell Diala S2 ZU-1 Dried) were degraded in the laboratory utilising experimental setups that were crafted especially for conducting the following types of faults. For more details, three of the samples named S3, S4, and S5 were degraded electrically through different numbers of repeated high-voltage impulses (discharges with high energy). On the other hand, the rest of the samples named S5, S6, and S7 were subjected to various periods of thermal overheating (300°C C < Temperature < 700°C) to be degraded thermally.

2.1 | Electrical degradation

According to the IEC and the institute of electrical and electronics engineers (IEEE) standards, the electrical faults that commonly happen within power transformers were classified into three classes depending on the energy level of the electrical discharges [5, 26]. For more details, the classes under the
umbrella of electrical fault type starting from the one with the lowest energy level until reaching the one with the highest energy level are partial discharge, discharges of low energy \((D_1)\), and discharges of high energy \((D_2)\), respectively. Therefore, to comprehensively study the impact of electrical fault on mineral oil's behaviour, the worst electrical fault type which is \(D_2\) was conducted in the laboratory via the test platform shown in Figure 1 according to IEC 60060-1 [27].

### 2.1.1 Test cell specifications

It is clear from the scheme of the electrical fault experimental setup depicted in Figure 1 that the test cell is composed of only two parts. The first part (upper part) is a PA6 Nylon cover consisting of a needle high-voltage electrode made from steel with a 0.01 mm tip radius and a 1.5 mm diameter. Besides, a conical funnel with a 20° slope angle is already carved in the cover and connected to a syringe of 100 mL via an air-bleeding pipe with a three-way valve. The second part (lower part) is a PA6 Nylon foundation where at its centre, there is a brass circular plate electrode with a 20 mm diameter earthed through an earthing system of 0.5 \(\Omega\). Also, upon the foundation the body of the test cell in which the oil is placed exists. It is a transparent Perspex vessel of 100 mm inner diameter, 5 mm thickness, 70 mm height, and a total capacity of 550 mL. Also, there are two O-Rings for preventing the evolved gases from escaping out of the vessel and the external gases from entering. Note that the clearance and creepage distances were taken into consideration during the design phase for minimising the risk of flashover [16, 28].

### 2.1.2 Experiment procedure

For simulating the electrical fault of class \(D_2\), firstly, the test cell was cleaned very well; then, 400 mL of pure mineral oil was poured slowly into the Perspex vessel. Following that, the test cell was well-sealed with bolts and nuts. After the test cell was sealed completely, the degradation was performed through the impulse voltage test system shown in Figure 1. The oil within the test cell was subjected to repeated high-voltage impulses of positive polarity through a needle-to-plate electrode configuration of 1 mm gap distance keeping a time interval of 30 s between impulses. Then, by reaching the end of the degradation process, the plunger of the syringe was pressed gently to guarantee that most of the formed gases were dissolved into the oil. Furthermore, the impulse voltage applied during this accelerated impulsive degradation was a standard lightning impulse of 70 kV peak value as well as a front time and tail time of 1.2 and 50 \(\mu\)s, respectively, according to the IEC 60,060-1 [27].

Anyway, the three samples \(S_2\), \(S_3\), and \(S_4\) that were utilised in this kind of degradation were subjected to different numbers of repeated electrical impulses. The samples have been degraded by 30, 45, and 90 impulses to study the behaviour of mineral oil comprehensively when subjected to this kind of fault. In addition, the waveforms of all impulses in each electrical fault condition were monitored carefully during the test utilising the Tektronix DPO 7104C Digital Phosphor Oscilloscope of 10X attenuation based on the measuring system that will be described in the next sentences for ensuring that the specifications of the high-voltage impulse were nearly constant during the deterioration process for all oil samples. For more details, the measuring system that was utilised in this work was calibrated to achieve the measuring requirements in the IEC 60,060-2 and is composed of the following components. Firstly, an impulse voltage divider (high voltage capacitor) with a 255 voltage dividing ratio is connected directly in parallel with the test cell as shown in Figure 1 to reduce the peak of the impulse wave from 70 kV to about 275 V. Secondly, a coaxial cable (transmission system) which is connected to the divider's low voltage arm for transferring the output signal to an attenuator of 10X attenuation further reduces the peak level from 275 V to about 28 V before entering the oscilloscope to prevent overloading the oscilloscope's input circuitry. Note that the coaxial cable, the attenuator, and the oscilloscope's input each of them have a surge impedance of 50 \(\Omega\) to provide approximately a zero-reflection coefficient (proper impedance matching throughout the system) and prevent the measured wave from reflection that can lead to signal distortion, standing waves, and inefficient power transfer. Subsequently, for ensuring that the entire waveform is visible and well-scaled on the screen without any distortion or clipping, the oscilloscope was properly configured by setting up the voltage and time per division to 10 V and 2 \(\mu\)s, respectively [29].

![Figure 1](image)

**Figure 1** Scheme of the electrical fault experimental setup.

### 2.2 Thermal degradation

Thermal faults refer to the faults that frequently happen within power transformers whose hotspot temperature can lead to the thermal decomposition of the insulation materials or metals. Indeed, they were classified into three categories based on the temperature level of the faults according to the IEC and IEEE standards [5, 26]. These categories, which are \(T_1\), \(T_2\), and \(T_3\), have temperature levels as follows: below 300°C, from 300°C to 700°C, and above 700°C, respectively. In this investigation, the immersed heating method which is widely used for
generating thermal faults in the laboratory was employed to conduct the $T_2$ thermal fault with the aid of the experimental setup depicted in Figure 2 for studying the thermal fault effect on the mineral oil's behaviour. Actually, the basis for choosing the $T_2$ thermal fault among the three types of transformer thermal faults is as follows. Firstly, the $T_2$ thermal fault is widely adopted in the literature instead of the $T_1$ and $T_3$ thermal faults. Regarding the $T_1$ thermal fault, it was widely adopted in the literature as its effect on the oil's molecular structure is very low, and since the main goal of this work is to study the thermal effect on the mineral oil's molecular structure behaviour, the $T_1$ thermal fault will not be suitable with our research goal. Concerning the $T_3$ thermal fault, it is difficult in the laboratory to go beyond the $T_2$ thermal fault level by the immersed heating method. The underlying reason behind that returns to the pool boiling phenomenon that limits the temperature of the immersed heating element as reported in Refs. [28, 30, 31].

In general, pool boiling is defined as boiling from a heated surface submerged in a large volume of stationary liquid. Subsequently, the immersed heating technique resembles a pool boiling process. Theoretically, the pool boiling process passes through four stages which are natural convection, nucleate boiling, transition boiling, and film boiling, respectively. However, practically, the temperature range within the transition boiling stage will be missed as illustrated with the aid of Figure 3. For more details, the natural convection starts when the input power is below approximately 290 W or the surface heat flux is below 25 W/cm$^2$, where the heating element's temperature is below the mineral oil's boiling temperature which is about 290°C. In this stage, the heat energy is dissipated by the oil's light natural convection and as the input power increases the heating element's temperature also increases in a nearly linear way. Once the input power reaches above 290 W, the nucleate boiling stage is initialised where the heating element's temperature becomes greater than the oil's boiling temperature. Certainly, this difference in temperatures is sufficient to initialise vapour nucleation. Therefore, the heat energy is dissipated via vapourisation and strong oil convection. Since vapourisation normally absorbs large amounts of heat energy, as the input power increases, the surface heat flux increases but with a minimal increase in the heating element's surface temperature. Thus, the heating element's temperature in the nucleate boiling region remains almost constant 'saturated' even with input power largely rising and has an upper limit temperature at the critical surface heat flux point known as the Nukiyama temperature. This temperature is 330°C (always about 40°C higher than the liquid's boiling point). Hence, the temperature in the nucleate boiling region approximately remains between 320°C and 330°C. Following this stage, the liquid should be in the transition boiling stage; however, in a practical situation if the input power to the heater is individually controlled, the heating process will follow the first and second stages and once the Nukiyama temperature is reached. Where the input power approaches 1200 W or surface heat flux of 102 W/cm$^2$, any small increment of the input power causes a sudden jump to the heating element's surface temperature to the film boiling region, and the transition boiling region is missed.

Consequently, the transition boiling's temperature range is missed in the immersed heating process. Within the film boiling stage, the heating element is covered by a stable vapour film through which the heat energy is transferred by radiation heat transfer. Accordingly, the heating element's surface temperature would significantly increase at a temperature normally higher than 1000°C as the input power (surface heat flux) increases. Note that based on many previous investigations, this extremely high temperature may lead to inhomogeneous temperature distribution along the heating element, and the hot-spot temperature may reach the burnout temperature. In this way, 330°C (Nukiyama temperature) is the highest stable temperature that can be achieved by the immersed heating element in mineral oils which is located within the temperature range of the so-called $T_2$ thermal fault (300–700°C). While the

**FIGURE 2** Scheme of the thermal fault experimental setup.

**FIGURE 3** Heating element’s temperature-input power relationship (Pool boiling curve).
temperature range between the Nukiyama temperature (330°C) and the burnout temperature (normally higher than 1000°C) could not be reached, hence the T3 thermal fault cannot be generated in the laboratory. In other words, heating beyond 1200 W is less controllable as compared to the situation below 1200 W. In this regard, the experimental setup was utilised to generate specifically the T2 thermal fault.

2.2.1 | Test cell specifications

It is obvious from the scheme of the thermal fault experimental setup depicted in Figure 2 that the test cell is composed of two parts. The first part which is the upper cap is a PA6 nylon lid consisting of the following: the power supply connections and copper clamps that hold a heating element in a 70-turn coil shape (the coil size is 5 mm in diameter, 70 mm in length, and made from Kanthal A-1 resistive wire of 0.6 mm diameter). Moreover, there was a terminal for the thermometer, a type K thermocouple with a temperature range from -200°C to 1260°C, and a reverse funnel shape of 20° slope angle, which is already excavated in the cap itself and connected to a syringe of 100 mL via an air bleeding pipe with a three-way valve. The second part (lower part) consists of the following: a PA6 nylon foundation upon a transparent Perspex vessel of 100 mm inner diameter, 5 mm thickness, 70 mm height, and a total capacity of 550 mL. Also, there are two O-Rings for preventing the evolved gases from escaping out of the vessel and the outside gases from entering. The O-Rings are placed as follows: one of them is attached to the downside of the top cap to block the gap between the cap and the vessel, whereas the other one is attached to the downside of the vessel to block the gap between the vessel and the nylon foundation [28, 32].

2.2.2 | Experiment procedure

In the beginning, the vessel was well cleaned, then 400 mL of pure mineral oil was poured slowly into the test cell. Subsequently, the test cell was well sealed by bolts and nuts. After that, the test was conducted to generate the T2 thermal fault as seen in Figure 2. Firstly, the thermal fault was generated by injecting controlled input power into the heating element during the heating period ranging from 295 to 305 W. It has been found that this range of power lets the heating element reach the onset of the saturation region in the input power-heating element temperature relationship shown in Figure 3 [30]. The previously mentioned range of power has been attained by approximately adjusting the voltage of a 50-Hz single-phase variable AC power supply (autotransformer) in the range from 41.6 to 42.25 V which has let a passage of current through the heating element nearly from 7.11 to 7.23 A, respectively. Secondly, for keeping the vessel at a safe temperature away from its melting point since the oil was in direct contact with the vessel’s inner walls, a thermometer was utilised to monitor the surface temperature of the oil sample under test. So, when the oil temperature approached 110°C, the power supply was disconnected until the oil was cooled down to room temperature (nearly 25°C), and then the heating could be restarted.

This was repeated until the total time of heating reaches the designated thermal fault duration. Note that after each heating period, the test cell was placed in cold water keeping its upper part above the water level beside a fan directed towards it to decrease the cooling period as much as possible. Moreover, after each cooling period and before the start of the next heating period, the plunger of the syringe was compressed gently to ensure that most of the formed gases were dissolved into the oil. Regarding the above condition, the designated heating period for each oil sample was subdivided into small heating periods. For more details, in each small heating period, the heating element was powered for about 3 min followed by a 30-min cooling period. In this investigation, the three oil samples S5, S6, and S7 were subjected to localised overheating of 40, 60, and 90 min total heating durations, respectively, to comprehensively study the behaviour of mineral oil when subjected to this fault type, and bearing in mind that the previously mentioned heating durations were achieved after 14, 20, and 30 cycles of heating and cooling, respectively.

3 | CHARACTERISATION OF OIL SAMPLES

After the degradation processes of the oil samples whose conditions are summarised in Table 1, test specimens were extracted from the test cells via a 100 mL glass gas-tight syringe according to the ASTM D3613-98 after the test cells remained undisturbed for about 16 h. This was done to allow for complete mixing and obtain a homogeneous sample besides allowing the fault gases in the system to reach a quasi-equilibrium state [33]. For more details, the procedure considered in taking the test specimens will be illustrated in the next sentences. First of all, the upper cover of the test cell was opened and then the syringe was positioned in the middle of the Perspex vessel to ensure that the test specimen obtained is representative of the bulk from which it was taken. Following

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Fault type</th>
<th>Number of impulses/Heating duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Normal case</td>
<td>Not degraded</td>
</tr>
<tr>
<td>S2</td>
<td>Electrical fault</td>
<td>30 impulses</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td>45 impulses</td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td>90 impulses</td>
</tr>
<tr>
<td>S5</td>
<td>Thermal fault</td>
<td>40 min. Heating</td>
</tr>
<tr>
<td>S6</td>
<td></td>
<td>60 min. Heating</td>
</tr>
<tr>
<td>S7</td>
<td></td>
<td>90 min. Heating</td>
</tr>
</tbody>
</table>
that, the piston was pushed back slowly to pull out only 10 mL of oil to avoid air bubbles being formed.

Subsequently, the syringe was kept vertical and then the piston was carefully depressed to eject any air bubbles present within the oil. Indeed, the previous steps were repeated until the syringe was filled to its full capacity. Afterwards, the syringe was sealed with a Luer lock fitting to minimise its exposure to the atmosphere and protect the test specimen from environmental contaminants. Actually, for each oil degradation condition, there were two oil specimens preserved in separate syringes, one syringe was kept for the DGA test, while the other one was utilised to fill glass test tubes fitted with screw caps to be utilised in the FTIR and DDF tests. Thereafter, all the test specimens were properly labelled and stored in a cardboard box to be protected from sunlight to avoid photodegradation.

In this way, the specimens were ready to be examined as soon as possible via the following diagnostic techniques. Firstly, the chemical structure of the oil specimen was characterised via FTIR spectroscopy according to ASTM E1252-98 [23]. This characterisation was conducted to observe the changes that occurred in the chemical structure of each oil sample to find a methodology that helps in discriminating between transformer inception faults via this optical method. Then, to initially confirm the FTIR spectroscopy analysis, the samples were analysed through the DGA method utilising a GC according to ASTM D3612-02 [24]. Secondly, for further verification, the DDF test was performed according to IEC 60,247 for each oil sample [25].

3.1 | FTIR spectroscopy technique

FTIR spectroscopy is a non-destructive optical instrument mainly utilised for particular purposes such as measuring the basic properties of a molecule, quantitative analysis of known species within the material, compound identification, and finally, structural elucidation [34]. This optical technique depends on measuring the Infrared (IR) radiation transmitted or absorbed by a certain material, which is mainly due to the vibrational and rotational absorption bands of its molecules, as a function of wavelength (λ) or its reciprocal which is termed as wavenumber (ν). Furthermore, the plot resulting from such a measurement is so called the FTIR spectrum, and it is commonly presented with the Transmittance (T) of the IR radiation on the ordinate and the wavenumber on the abscissa. T is the ratio between the radiant power transmitted by a certain sample (I) and the total radiant power incident on it (I₀) as clear from Equation (1) [35].

\[
T = \frac{I}{I_0} \quad (1)
\]

For more supplementary information, IR radiation is electromagnetic radiation in the range of wavelengths (wavenumbers) from approximately 0.78 μm (12,800 cm⁻¹) to 1000 μm (10 cm⁻¹). However, this range of wavelengths can be divided into three main subregions which are as follows: the near-IR (NIR) region, the mid-IR (MIR) region, and the far-IR (FIR) region. In order to conduct the FTIR qualitative measurements for comprehensively studying the spectral behaviour of the oil samples in the MIR range (from 2.5 μm (4000 cm⁻¹) to 50 μm (200 cm⁻¹)) and comparing them together, a constant volume of 20 μL was taken from each sample [36]. Then, the characterisation process was carried out via the Agilent Cary 630 FTIR with its diamond attenuated total reflectance (ATR) according to the ASTM E1252-98 standard [23]. The reason behind choosing the MIR range specifically among the three main subregions was as follows. Most of the molecules at room temperature are in the vibrational ground state, and the transition from this vibrational state to the next vibrational state is known as the fundamental transition (mode). The fundamental transition is of great importance for IR spectroscopy since it is the highest in intensity. In fact, such a transition within the molecules of mineral oils is always monitored in the MIR range [37].

3.1.1 | Principle of operation

As illustrated in Figure 4a, FTIR spectroscopy is composed of four main parts which are a source of polychromatic IR radiation, a spectral analyser (Interferometer), a sample compartment, and lastly, a radiation detector. Indeed, the IR source commonly used is the Globar whose typical operating temperature is about 300 K [37]. The IR beam incoming from the source is immediately collimated and then directed towards the interferometer. This Michelson’s interferometer consists of three main parts, the first part is a beam splitter which is placed at an angle of 45° and acts as a partially reflecting mirror, it splits the whole IR radiation into two equal beams, one half is transmitted to the movable mirror and the second half is transmitted to the fixed mirror. After that, the two beams are reflected to the splitter again where they are recombined and

![FTIR spectrophotometer](image-url)
directed towards the sample compartment. Subsequently, portions from certain wavelength components in the whole IR radiation are absorbed by the sample's molecules, and the rest of the radiation is transmitted and directed towards the detector [38]. The methodology through which the final spectrum is obtained from the detector will be discussed more deeply.

Firstly, when the two beams are reflected from the mirrors and recombined again at the splitter, a phase difference is observed between them, since the paths they travelled are not of the same length. However, the main reason for this phase difference is the movable mirror movement. If the movable mirror's distance from the splitter is equal to that of the fixed mirror, the two beams will be in a phase resulting in constructive interference, and the light power signal detected at the detector will be of its maximum value. On the other hand, if the movable mirror is displaced by $\lambda/4$ consequently the phase difference becomes $\lambda/2$, and destructive interference between the two beams will result and the light power signal detected will be of its minimum value. But in fact, the movable mirror is always in continuous motion, forming at the detector an oscillating light power signal (Interferogram) for each wavelength component within the whole IR radiation [14, 35]. For more information, the interferogram is a plot of the light power intensity versus the optical path difference between the two mirrors which is known as retardation. Finally, the detector receives the overall interferogram which is due to the combination of all of the interferograms (cosine waves) produced from each wavelength component. Then, the overall interferogram is converted into an electrical signal, and by computing the Fourier transform of such signal, the FTIR spectrum is simply generated [39].

3.1.2 | Experiment procedure

The characterisation has been performed as follows: firstly, a volume of 20 μL from the oil sample was placed in the ATR accessory as obvious in Figure 4b. Next to that, the IR beam was allowed to travel in the crystal which is a transparent medium of a higher refractive index than that of the oil sample until it struck the interface between the crystal and the oil medium at an angle greater than the critical angle. At that moment, attenuated total reflectance occurred, and the IR beam was reflected internally into the crystal (denser medium). Despite the internal reflection being total, an electromagnetic wave called an evanescent wave penetrated the oil medium at the point where the IR beam contacts the interface and was partially absorbed by the oil sample. Finally, the reflected beam carried the absorption information of the sample and was collected at the detector for obtaining the FTIR spectrum of the oil under test.

3.2 | Dissolved gas analysis method

For confirming the reliability of FTIR spectroscopy results, the mineral oil samples each of 100 mL were examined via the GC analyser according to method C (Headspace Sampling) in the ASTM D3612-02 standard. The process of determining the concentrations of dissolved gases was performed via the headspace GC (DANI GC1000 DPC Digital Gas Chromatograph along with the DANI HSS 86.50 static headspace sampler). For more details, only the concentrations of the hydrocarbon gases were considered for each oil sample, while the concentration of the Hydrogen gas (H₂) which is an air gas was neglected for more accurate analysis as it may have a misleading impact on the whole study [24].

3.3 | Dielectric dissipation factor test

The tan-delta (tan $\delta$) or the dielectric dissipation factor (DDF) is an important electrical dimensionless ratio through which the condition of the dielectric material can be determined. Basically, the dielectric loss of the insulation is the power dissipated via the insulating medium once it is subjected to an alternating voltage. Good dielectrics usually have a very low DDF. On the other hand, a high DDF may indicate that there are problems in the insulation's structure. Anyway, the DDF test in this investigation was performed on all of the faulted oil samples according to the IEC 60,247 besides the equipment's user guides utilising the test setup which is composed of the Agilent E4980A precision LCR metre along with the Agilent 16,452A liquid test fixture [25, 40].

While taking measurements, approximately 3.4 mL from the oil sample was injected into the liquid test fixture. Then, the LCR metre was set to the parallel circuit mode. This is to measure the parallel equivalent capacitance ($C_P$) in (F) besides measuring the parallel equivalent resistance ($R_P$) in (Ω) for the oil dielectric. After selecting the circuit mode, the test was performed for each oil sample in the frequency ($f$) range from 20 Hz to 2 MHz to study the oil dielectric's behaviour comprehensively. Finally, for each oil sample, the DDF values (represented by $D_{DDF}$ in the formula) corresponding to the whole range of frequency were simply calculated with the aid of Equation (2) [25].

$$D_{DDF} = \frac{1}{2 \times \pi \times f \times R_P \times C_P} \quad (2)$$

4 | RESULTS AND DISCUSSIONS

4.1 | FTIR spectroscopy

4.1.1 | Mineral oil composition

In general, the mineral oil's molecule is mainly composed of three main hydrocarbon compounds with around 25 carbon atoms per molecule as illustrated in Figure 5 [41, 42]. The first one is the paraffinic compound, which is an open-chain aliphatic saturated hydrocarbon compound whose carbon atoms are bonded together through (C–C) sigma bonds (a type
of single covalent bond) in straight or branched lines. Secondly, the naphthenic compound, which is a cyclic aliphatic saturated hydrocarbon compound whose carbon atoms are linked together for forming a ring where within each ring, 5, 6, or 7 carbon atoms are attached through C–C sigma bonds.

Finally, there is the aromatic compound, which is a cyclic aromatic unsaturated hydrocarbon compound whose carbon atoms are bonded together as benzene rings where within each ring 6 carbon atoms are attached through double covalent bonds (C≡C). One is a sigma bond which is formed from localised electrons that are shared between only the two carbon atoms of the bond (presented as a solid line). The other one is a pi bond (a type of single covalent bond weaker than the sigma type) which is created due to the 6 delocalised pi electrons shared between all of the carbon atoms, and they are roaming freely within a doughnut shape (drawn as a dashed line) [36].

4.1.2 Molecular structure of the utilised mineral oil

According to the FTIR spectrum of the reference sample that is apparent in Figure 6a, six important peaks were observed along the whole range of wavenumber from 4000 cm\(^{-1}\) to 400 cm\(^{-1}\). Such peaks whose details are summarised in Table 2 were sufficient for the molecular structure characterisation. In general, four of them are located in the vicinity of the functional group region (from 4000 cm\(^{-1}\) to 1400 cm\(^{-1}\)), and the rest are located in the fingerprint region (from 1400 cm\(^{-1}\) to 600 cm\(^{-1}\)) [37, 38]. The first peak (at 3175 cm\(^{-1}\)) is mainly due to the stretching mode of the sigma bonds between the carbon and hydrogen atoms (C–H) within the aromatic compound. Furthermore, the second peak (at 2924 cm\(^{-1}\)) represents the stretching mode of the C–H sigma bonds in both the methyl (CH\(_3\)) and methylene (CH\(_2\)) groups within the aliphatic compound.

In fact, this peak represents the total concentration of C–H bonds within the aliphatic compounds generally without specifying the percentage of each of the methyl and methylene groups from this concentration [38]. So, the judgement on the oil type cannot depend on this peak only. Subsequently, the third peak (at 1607 cm\(^{-1}\)) is due to the stretching mode of the C≡C bonds within the aromatic compound that appears at a very weak intensity as the previous aromatic peak. The reason for that is during the refining process, the aromatic and polyaromatic contents are reduced to nearly 5% to enhance the stability and dielectric properties of the oil as most of these compounds are detrimental [43]. The fourth peak (at 1457 cm\(^{-1}\)) is mainly due to the bonding mode of the C–H sigma bonds in the CH\(_2\) groups within the aliphatic compound. Similarly, the judgement on the oil type cannot be based on this peak only, since both paraffinic and naphthenic compounds have CH\(_2\) groups in their structure [14, 36].

Anyway, by entering the fingerprint region, the scene became more clear. The fifth peak noticed (at 1377 cm\(^{-1}\)) is mainly due to the bonding mode of the C–H sigma bonds in the CH\(_3\) groups within the aliphatic compound. Based on the

FIGURE 5 The typical molecule of mineral oil.

FIGURE 6 FTIR spectral behaviour in the range of 4000 cm\(^{-1}\)–400 cm\(^{-1}\): (a) No-fault case, (b) Electrical fault cases, and (c) Thermal fault cases.
intensity of this peak, which is nearly half the intensity of the previously mentioned peak, a decision was taken that the utilised mineral oil is paraffinic since the CH\textsubscript{3} groups are only found in the paraffinic compounds. Bearing in mind that, if the concentration of the naphthenic compounds is greater, the intensity of this peak will not be found or found with very weak intensity. The last peak which is an important peak (at 724 cm\textsuperscript{-1}) represents the bending mode of the C–H sigma bonds within the CH\textsubscript{2} groups within a long open chain aliphatic compound \[36, 38\]. Certainly, the decision that was taken was confirmed by this peak.

4.1.3 | Spectral response due to electrical and thermal faults

The spectra of all electrical fault cases along with the no-fault case are depicted in Figure 6b. It is obvious from the spectra that there is a noticeable significant random reduction in the aliphatic peaks (not completely compatible with the degradation sequence), which means a reduction in the aliphatic bonds (aliphatic compounds decreased) within the oil molecules. Concerning the two aromatic peaks that appeared at wave-numbers 3175 cm\textsuperscript{-1} and 1607 cm\textsuperscript{-1}, respectively, there is a continuous decrement in the peaks (completely compatible with the degradation sequence) until they completely disappeared in \(S_4\) \[14\].

Regarding the degradation via the thermal fault, the spectra of the samples together with the no-fault case are presented in Figure 6c. It is apparent from the spectra that there is a random slight reduction in the aliphatic peaks (not completely compatible with the deterioration sequence). Subsequently, the aromatic peaks shown at the wave-numbers 3175 cm\textsuperscript{-1} and 1607 cm\textsuperscript{-1}, there is a visible peak increment at the wave-number 1607 cm\textsuperscript{-1} (inversely matches with the degradation sequence). For the peaks at the wave-number 3175 cm\textsuperscript{-1}, there is also an increment in the peaks (inversely quasi-compatible with the deterioration sequence) \[36\].

4.1.4 | Analysis interpretation

First of all, it is obvious from the above spectra that the reduction in most of the aliphatic peaks is not completely matching with the progression by which the oil samples were degraded in both fault types. Similarly, the same situation occurred with aromatic peaks located at the wavenumber 3175 cm\textsuperscript{-1} in case of the thermal fault. Indeed, this is because in some cases where a molecule contains multiple normal vibration modes, some of these modes may occur at the same wavenumber which is known as degenerate modes. Accordingly, the transmittance intensities of the individual peaks corresponding to the stretching and bending modes of the bonds within the different functional groups in a certain oil specimen under test are varied randomly from another specimen of the same volume taken from the same oil sample (same degradation condition). For example, if two oil specimens of the same volume are taken from the same oil sample (same degradation condition), they may not have identical spectra, but certainly, the overall intensity of aliphatic (or aromatic) peaks of both specimens will be the same \[37\].

Hence, the variation of the intensities is not a problem anymore, since this variation cannot alter the total concentration of bonds already existing within the oil sample under characterisation \[23\]. Moreover, it is not accurate to compare the changes that occurred in the molecular structure of the oil based on the alteration that happened to the intensity of certain individual peaks. As such, a change does not represent the actual change that occurred in the molecular structure of the oil and is not a condition to be compatible with the gradual increase in the degradation severity. Otherwise, for an equitable comparison, the overall alteration that happened in all of the individual peaks (for each sample’s spectrum) must be considered in the comparison instead. Based on that, the overall alteration that occurred in the aliphatic, as well as the aromatic peaks, was considered in this investigation for studying the alteration that happened in the molecular structure of the oil due to degradation.

Fortunately, it is observed, after utilising this methodology, that the overall alteration in both fault types is completely compatible with the gradual increase in degradation degree. For more details about this methodology, the total transmittance intensity of all individual peaks representing the aliphatic C–H bonds within each oil sample was taken as an indication of the concentration of the aliphatic compounds presented. In the same way, the total transmittance intensity of all individual peaks representing the aromatic C–H bonds and the aromatic C═C bonds within each oil sample was taken as an indication of the concentration of the aromatic compounds found.

<table>
<thead>
<tr>
<th>Wavenumber (cm\textsuperscript{-1})</th>
<th>Functional group</th>
<th>Vibration mode</th>
<th>Relative intensity</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>3175</td>
<td>≡CH</td>
<td>C–H stretching</td>
<td>Weak</td>
<td>Aromatics</td>
</tr>
<tr>
<td>2924</td>
<td>C–H</td>
<td>C–H stretching</td>
<td>Strong</td>
<td>Aliphatics</td>
</tr>
<tr>
<td>1607</td>
<td>C═C</td>
<td>C═C stretching</td>
<td>Weak</td>
<td>Aromatics</td>
</tr>
<tr>
<td>1457</td>
<td>CH\textsubscript{2}</td>
<td>C–H bending (scissoring)</td>
<td>Medium</td>
<td>Aliphatics</td>
</tr>
<tr>
<td>1377</td>
<td>CH\textsubscript{3}</td>
<td>C–H bending (wagging)</td>
<td>Medium</td>
<td>Aliphatics (Alkanes)</td>
</tr>
<tr>
<td>724</td>
<td>CH\textsubscript{2}</td>
<td>C–H bending (rocking)</td>
<td>Weak</td>
<td>Aliphatics (Alkanes)</td>
</tr>
</tbody>
</table>
Furthermore, additional analysis was performed based on the same concept in which the total area under all of the individual peaks representing the aliphatic C–H bonds within each oil sample was taken as an indication of the concentration of the aliphatic compounds. Also, the total area under all of the individual peaks representing the aromatic C–H bonds and the aromatic C=C bonds within each oil sample was taken as an indication of the concentration of the aromatic compounds found. This analysis was conducted to validate the reliability of analysing the variation that occurred in the FTIR spectra by comparing the overall alteration that happened in all of the peaks instead of comparing the alteration that occurred in certain individual peaks. Note that the total transmittance of aliphatic peaks as well as aromatic peaks besides the total area under such peaks is presented in Table 3.

### Analysis via total intensity method

By just looking at Figure 7, which illustrates the influence of each fault type on the total transmittance intensities of the aliphatic as well as the aromatic compounds, it can be noticed from the bar graph shown in Figure 7a that the total transmittances of the aliphatics in the electrical fault cases have much higher values than that of thermal fault cases, which means that there is a higher reduction in the aliphatic compounds within the oil samples that were subjected to electrical deterioration. Secondly, the rate by which the total transmittance increases is high concerning the cases of the electrical fault type which is clear from Figures 7b,c. It is obvious from those figures that the aliphatic compounds are reduced at a much higher rate in the case of electrical degradation, by approximately 2.4 from the rate of reduction in the case of the thermal fault. In fact, this returns to the high temperature of the electrical degradation which is greater than 1000°C [5, 22].

This temperature was responsible for generating much heat energy that was capable of breaking a large amount of the C–C bonds (90.2 kcal/mol) and C–H bonds (101.1 kcal/mol), resulting in a significant reduction in the aliphatic compounds with a very high rate.

Conversely, the low temperature of the thermal fault type (approximately 320°C) was responsible for generating lower heat energy which was only capable of breaking a small amount of the C–C bonds (mostly within paraffinic compounds) and very few quantities of the C–H bonds that result in a moderate reduction in the aliphatic compounds with a very low rate [36, 44]. Furthermore, the bar graph in Figure 7d represents the alteration that happened in the aromatic compounds with values that provide valuable information that can be utilised in differentiating between the two kinds of faults. Concerning the electrical degradation, there is a reduction that occurred in the aromatic compounds (total transmittance increased above the normal case). On the contrary, the aromatic compounds were increased in the case of thermal degradation (total transmittance decreased below the normal case).

Also, Figures 7e,f show the rates of increment, as well as the decrement in the total transmittance. The reason behind the opposite alteration that occurred in the aromatic compounds will be clarified in depth next. Concerning the degradation via electrical impulses, the bond breakage that was responsible for the reduction in the aromatic compounds occurred in two stages. First, the flow of the electrical arc (electrons of high energy) established an interruption to the continuous pathways of the overlapping p-orbitals within the aromatic ring. This interruption made the 6 pi electrons unable to delocalise over the entire conjugate system and became localised electrons. Consequently, the aromatic ring converted from a stable resonance hybrid structure with 6 C=C bonds of the same length between the carbon atoms to an unstable contributing resonance structure with only 3 C=C bonds (due to the localised pi electrons) and 3 C–C bonds. At this stage, the probability of the ring being thermally decomposed became higher than before. Secondly, the high heat energy generated during the fault was sufficient to break most of the ring’s C=C bonds (90.2 kcal/mol), C–H bonds (110.7 kcal/mol), and some of the ring’s C=C bonds (174.5 kcal/mol).

This results in a high decrement in the aromatic compounds until they completely disappear [4, 36].

For the samples degraded by overheating, the low heat energy generated during the fault has a very low probability of breaking the bonds of the stable aromatic ring which are the C=C bonds (174.5 kcal/mol) and the C–H bonds (110.7 kcal/mol). Instead, each carbon atom within most of the cyclohexanes (naphthenic ring with 6 carbon atoms) breaks down

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Total transmittance of peaks (a.u.)</th>
<th>Total area under peaks (a.u.)</th>
<th>Total concentration (ppm)</th>
<th>DDF (at 50 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aliphatics</td>
<td>Aromatics</td>
<td>Aliphatics</td>
<td>Aromatics</td>
</tr>
<tr>
<td>S1</td>
<td>2.1528708</td>
<td>1.980181</td>
<td>133.037858</td>
<td>0.475889782</td>
</tr>
<tr>
<td>S2</td>
<td>2.687951</td>
<td>1.984868</td>
<td>67.4726097</td>
<td>0.374375825</td>
</tr>
<tr>
<td>S3</td>
<td>2.847887</td>
<td>1.99317</td>
<td>64.63545354</td>
<td>0.162991021</td>
</tr>
<tr>
<td>S4</td>
<td>3.204721</td>
<td>1.995007</td>
<td>28.22514177</td>
<td>0.145798879</td>
</tr>
<tr>
<td>S5</td>
<td>2.403468</td>
<td>1.977135</td>
<td>106.8145382</td>
<td>0.642862595</td>
</tr>
<tr>
<td>S6</td>
<td>2.474257</td>
<td>1.968355</td>
<td>98.48623247</td>
<td>0.911948033</td>
</tr>
<tr>
<td>S7</td>
<td>2.578586</td>
<td>1.963025</td>
<td>90.15792671</td>
<td>0.97346403</td>
</tr>
</tbody>
</table>
one of its two aliphatic C–H bonds. Consequently, additional weak pi bonds were formed between the naphthenic carbon atoms that were already joined together with strong sigma bonds. This results in the formation of aromatic rings that are more stable utilising only 49.8 kcal/moL [36, 45]. In this way, an increment occurred in the aromatic compounds but in very few quantities, since there were only small quantities of the naphthenic compounds within the utilised mineral oil. For more details, Figures 8a,b show the impacts of the electrical fault on the mineral oil molecule. Similarly, the thermal overheating impacts on the mineral oil molecule can be seen in Figures 8c,d.

Analysis via total area method

Figure 9 illustrates the influence of each fault type on the total area under the transmittance peaks of the aliphatic as well as the aromatic compounds. It can be noticed from the bar graph shown in Figure 9a that the total aliphatic areas of the electrical fault cases have much lower values than that of the thermal fault cases, which means a higher reduction in the aliphatic compounds. Secondly, the rate by which the total area decreases is high concerning the cases of electrical fault which is clear from Figures 9b,c. It is obvious from those figures that the aliphatic compounds are reduced at a much higher rate in the case of electrical deterioration by a factor of approximately 2.3 from the rate of reduction in the case of the thermal fault.

This reduction factor is nearly equal to that obtained by the previous analysis. Moreover, it is clear from the bar graph presented in Figure 9d, which provides the alteration that happened in the aromatic compounds, that there is a reduction in the aromatic compounds (total area decreased below the normal case) concerning the electrical fault cases. On the other hand, the aromatic compounds have increased in the cases of thermal fault (total area increases above the normal case). Also, Figures 9e,f show the rates of the decrement, as well as the increment in the total area. Fortunately, the opposite behaviour

![Figure 7](image1.jpg)

**Figure 7** Influence of each fault type on aliphatic as well as aromatic compounds based on total transmittance intensity (Noting that "r" refers to the linear correlation coefficient): (a) Total transmittance of aliphatic peaks, (b) Electrical degradation and total transmittance of aliphatic peaks, (c) Thermal degradation and total transmittance of aliphatic peaks, (d) Total transmittance of aromatic peaks, (e) Electrical degradation and total transmittance of aromatic peaks, and (f) Thermal degradation and total transmittance of aromatic peaks.

![Figure 8](image2.jpg)

**Figure 8** Effect of fault's temperature on mineral oil's molecule structure: (a) Large amounts of heat energy generated during electrical degradation, (b) High reduction in the aliphatic and aromatic bonds, (c) Moderate heat energy produced during thermal degradation, and (d) Small reduction in aliphatic bonds and new benzene ring formed.
noticed for the aromatic compounds is the same behaviour observed in the previous analysis. Thus, the same trend is obtained by both methodologies, and this initially validates the reliability of analysing the variation that occurred in the FTIR spectra by comparing the overall variation that happened in all of the individual peaks. To check the accuracy of both methods and to what extent they are compatible with the gradual increase in fault severity, the linear correlation coefficient ($r$, absolute value) was evaluated for both methodologies. As illustrated in Table 4, the two methods have high linear correlation coefficients, but the total intensity method has a little bit higher values for both fault types. Therefore, both methods are applicable in analysing the variation that occurred in the FTIR spectra; however, it is recommended to use the total intensity method because it is higher in accuracy.

4.2 Validation of FTIR analysis

Without shed doubt, the alteration that occurred in the aliphatic, as well as the aromatic compounds within the mineral oil molecule, must be balanced by an opposite variation in the by-products formed due to the propagation reactions of the free radicals generated during the pyrolysis and oxidation processes [4, 22, 44–46]. So, in the next sections, the alteration in the fault by-products in all their forms (gases, liquids, and solids) was studied to confirm the reliability of the above-performed analysis on the outcomes obtained from FTIR spectroscopy characterisation.

4.2.1 Dissolved gas analysis stage

The first stage in the affirmation process is to study the variation that happened in the gaseous by-products [47]. In this regard, the total concentrations of hydrocarbon gases dissolved in each oil sample presented in Table 3 were compared. Figure 10 illustrates the effect of each fault type on the production behaviour of gaseous by-products. It can be observed from Figure 10a that there is a huge difference between the amounts of hydrocarbon gases generated in each fault type. As obvious, the total amount of hydrocarbon gases in S$_2$ (least electrical fault case in severity) is 23 times that in S$_7$ (extreme thermal fault case). Also, it is clear from Figures 10b,c that the rate by which the gases were created due to electrical arcing is about 142 times the rate by which gases were generated due to local overheating. In fact, the underlying reason behind such a

FIGURE 9 Influence of each fault type on aliphatic as well as aromatic compounds based on total area under transmittance peaks (Noting that ‘r’ refers to the linear correlation coefficient): (a) Total area under aliphatic peaks, (b) Electrical degradation and total area under aliphatic peaks, (c) Thermal degradation and total area under aliphatic peaks, (d) Total area under aromatic peaks, (e) Electrical degradation and total area under aromatic peaks, and (f) Thermal degradation and total area under aromatic peaks.

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Total transmittance of peaks</th>
<th>Total area under peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aliphatics</td>
<td>Aromatics</td>
</tr>
<tr>
<td>Electrical fault</td>
<td>97.2729%</td>
<td>91.4572%</td>
</tr>
<tr>
<td>Thermal fault</td>
<td>98.603%</td>
<td>95.5235%</td>
</tr>
</tbody>
</table>
hugely differences in the total amount of hydrocarbon gases is definitely the severe thermal decomposition (pyrolysis) to which the oil samples were subjected during the electrical degradation. There was a cleavage of C=C and C–H bonds in large quantities within the aliphatic and aromatic compounds besides the moderate cleavage of the C=C bonds within the aromatic compounds. This is due to the significant heat energy that has been generated along with the role of electrons’ flow described previously. Consequently, this results in the formation of free alkyl radicals in large quantities via hydrogen abstraction and radical decomposition propagation reactions. Afterwards, some of these radicals were involved in termination reactions in which they react with each other and with hydrocarbon radicals to generate huge quantities of hydrocarbon fault gases such as methane (CH$_4$), ethane (C$_2$H$_6$), ethylene (C=C=C=C), and acetylene (C$_2$H$_2$) [1, 22, 46].

In opposition, during the thermal fault cases, low heat energy has been generated that results in a small amount of C–C and C–H bonds cleavage (mostly within paraffinic compounds) besides a few cleavages of the C–H bonds within all of the aliphatic compounds and approximately no C=C bonds breakage within the aromatic compounds. Consequently, this results in the formation of a small number of free alkyl radicals where a few of them were involved in termination reactions to form a small amount of the hydrocarbon fault gases. In the final analysis, the alteration in the GC results is compatible with the alteration in the aliphatic and aromatic compounds illustrated through the FTIR analysis. In this way, the reliability of the FTIR analysis was tentatively confirmed [4, 44, 45].

4.2.2 | Dielectric dissipation factor stage

In the second stage of the verification process, the main concern is to carefully study the alteration that took place in the liquid as well as the solid by-products. In fact, as the amounts of these by-products increase within the oil insulation, the power loss (DDF) increases. Generally, the DDF values can be taken as an indication of the by-product quantities formed in each oil sample [48, 49].

Anyhow, it is clear from Figure 11a that the insulating material seems to be stable throughout the whole range even after the electrical fault. However, at the frequency of 50 Hz, there is a slight increment which is completely compatible with the sequence of the degradation’s severity. Similarly, it is obvious from Figure 11b that the insulating material seems to be stable over the whole range of frequency even after the thermal fault. Also, a slight increment was noticed at 50 Hz that is fully matching with the sequence of thermal degradation. For the variation to be comprehensively studied, the DDF values of all of the oil samples at the frequency of 50 Hz (illustrated in Table 3) were compared together as clear in the bar graph depicted in Figure 11c. It can be observed that the electrical fault cases have slightly higher values of DDF than the thermal fault cases.

Additionally, the increment rate in the DDF values due to the electrical fault is not much greater than that of the thermal fault as apparent in Figures 11d,e. Indeed, what made the generation rates of the fault by-products to be very close to each other can be explained as follows. Concerning the solid by-products, they were generated on a very large scale in the electrical fault cases as compared to the cases of the thermal fault as obvious in Figure 12. The huge difference is due to the significant number of free alkyl radicals formed due to the thermal decomposition of the aliphatic as well as aromatic compounds within mineral oil in case of electrical degradation. Some of those radicals react with oxygen through oxidation reactions to produce peroxy radicals. After that, the peroxy radicals and the free alkyl radicals combine forming stable compounds (solid by-products). These products are mainly carboxylic acids (formed on a wide scale) and some other products such as ketones and aldehydes that gave the oil its dark colour. In contrast, for thermal overheating, the decomposition was very low and confined to the aliphatic compounds only resulting in a much lower number of free alkyl radicals being formed. This is the reason behind the pale yellow colour of the oil sample since only a few solid by-products were formed [43, 44].

Concerning the liquid by-products, they have been generated in small quantities in both fault types. However, aromatic compounds that already exist in the oil’s molecular structure have a great impact on the DDF of the liquid dielectric. In fact, the DDF of an oil sample is directly proportional to the concentration of the aromatic compounds within it [50]. Considering the electrical fault cases, there is a reduction in the
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2 Hz–2 (20 and 50 factor (at (a)

**FIGURE 11** Dielectric dissipation factor: (a) Electrical fault (20 Hz–2 MHz), (b) Thermal fault (20 Hz–2 MHz), (c) All samples (at 50 Hz), (d) Its relationship with electrical degradation (at 50 Hz), and (e) Its relationship with thermal degradation (at 50 Hz).

![S1 S7 S4](image)

**FIGURE 12** Oil’s colour gets darker as the concentration of the ageing by-products increases within it: (a) No-fault case (transparent), (b) Extreme condition of thermal fault (pale yellow), and (c) Extreme condition of electrical fault (light brown).

aromatic compounds. On the other hand, there is an increment in the aromatic compounds considering the thermal fault cases. This opposite variation in the aromatic compounds is the reason behind the unexpected DDF values measured in the thermal fault cases which are quietly close to the values of the electrical fault cases. In the final analysis, the alteration in the DDF results is compatible with the alteration in the aliphatic as well as the aromatic compounds explained via the FTIR analysis. In this way, the reliability of the FTIR study in this work was well confirmed [43].

It is obvious that FTIR spectroscopy is superior over the traditional techniques such as DGA and LCR tests in detecting the small variations that happened to the oil after its subjection to light electrical and thermal faults. Actually, this returns to the high sensitivity of the FTIR characterisation process which is always performed on the microscopic scale that includes the studying of individual molecules and providing detailed information about the local properties and interactions within the sample. Therefore, FTIR spectroscopy could be successful in the discrimination process between the electrical and thermal faults with a high accuracy that could not be obtained with conventional diagnostic techniques.

### 4.3 Key findings

After the reliability of the FTIR spectroscopy analysis was confirmed, the authors came up with a great methodology that is summarised in the flowchart shown in Figure 13. Through
this methodology, the discrimination between the transformer inception faults via FTIR spectroscopy became a fact. First of all, before a power transformer becomes in service, a sample from its oil insulation should be characterised by FTIR spectroscopy as a reference; then, the total transmittances of the aliphatics and aromatics should be calculated and recorded. After that, at different time intervals, oil samples should be taken, characterised and their total transmittances recorded. From such historical data, the inception fault type can simply be predicted by plotting these data in a bar graph. If the total transmittance of the aliphatics is highly increased, this may point out that there is an electrical fault, otherwise the fault type may be a thermal fault.

In the previous stage, the fault type is initially determined, and to confirm such a decision, the following step should have proceeded. If the total transmittance of the aromatics is decreased, the decision will go to the thermal fault or else an electrical fault will be predicted. In this way, the inception fault type within a power transformer can be determined precisely in an easy procedure and low cost unlike the traditional techniques utilised. From the authors’ point of view, the proposed methodology may be more effective if online monitoring on the site is considered instead of offline monitoring [14].

5 | CONCLUSIONS AND FUTURE WORK

In this contribution, the electrical, as well as thermal faults that frequently happen in the oil-immersed transformers, was conducted in the laboratory on pure paraffinic mineral oil samples utilising special test cells. Next, the faulty samples besides a reference sample were taken to be characterised with FTIR spectroscopy. Subsequently, their spectral behaviour was comprehensively analysed and then verified via two well-known traditional diagnostic techniques which are the DGA method and the DDF test. After the FTIR analysis had been confirmed, it was concluded that

- It is more accurate to compare the FTIR spectra of the faulty samples based on the total alteration that happened in all of the individual aliphatic peaks (or in all of the individual aromatic peaks) instead of comparing certain individual peaks.
- The FTIR spectra of the faulty samples can be analysed by either comparing the total transmittance intensity of the peaks or comparing the total area under peaks, but it was found that the comparison based on the total transmittance intensity is more accurate.
- The aliphatic compounds are reduced at a much higher rate in the case of electrical degradation by approximately 2.4 from the rate of reduction in the case of the thermal fault.
- The aromatic compounds are reduced in the electrical fault case, unlike the thermal fault case in which aromatic compounds are increased (opposite behaviour).
- The detection process of light inception faults can be conducted via FTIR spectroscopy with great accuracy based on the alteration in the aliphatic as well as the aromatic compounds that happened in a specific oil sample. Also, it can be a superior alternative to the well-known traditional diagnostic techniques.

In future work, the reliability of other spectroscopy techniques such as PL spectroscopy and UV-Vis spectroscopy in discriminating between transformer inception faults will be considered. Besides making some important modifications in the setups utilised in conducting the inception faults to be suitable for performing online monitoring via FTIR spectroscopy.

ACKNOWLEDGEMENTS

The authors thank the Science, Technology & Innovation Funding Authority (STIFA), Egypt, under a grant (31292) for their support.

CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Darwish, M.M.F., et al.: A new technique for fault diagnosis in transformer insulating oil based on infrared spectroscopy measurements. High Voltage. 1–17 (2024). https://doi.org/10.1049/hve2.12405