Assessment of Dielectric Paper Degradation through Mechanical Characterisation

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Abstract

Power transformers life is limited fundamentally by the insulation paper state, which can be analysed through different techniques such as furanic compound concentration, dissolved gases, methanol concentration, Fourier transform infrared spectroscopy, X-ray diffraction, scanning electron microscope, refractive index of cellulose fibres, degree of polymerisation or tensile strength. The two last techniques provide the best way to evaluate mechanical resistance of insulation paper. This chapter describes briefly the most remarkable studies about post-mortem assessment and thermal ageing tests in which mechanical properties are some of the characteristics evaluated to determine paper degradation. This work also gathers the main relationships developed until now to relate different by-products generated during transformer operation with loss of paper mechanical properties. Finally, this chapter defines the future approaches, which could be used to study paper degradation.

Keywords: dielectric paper, insulation oil, tensile strength, post-mortem, thermal ageing test

1. Introduction

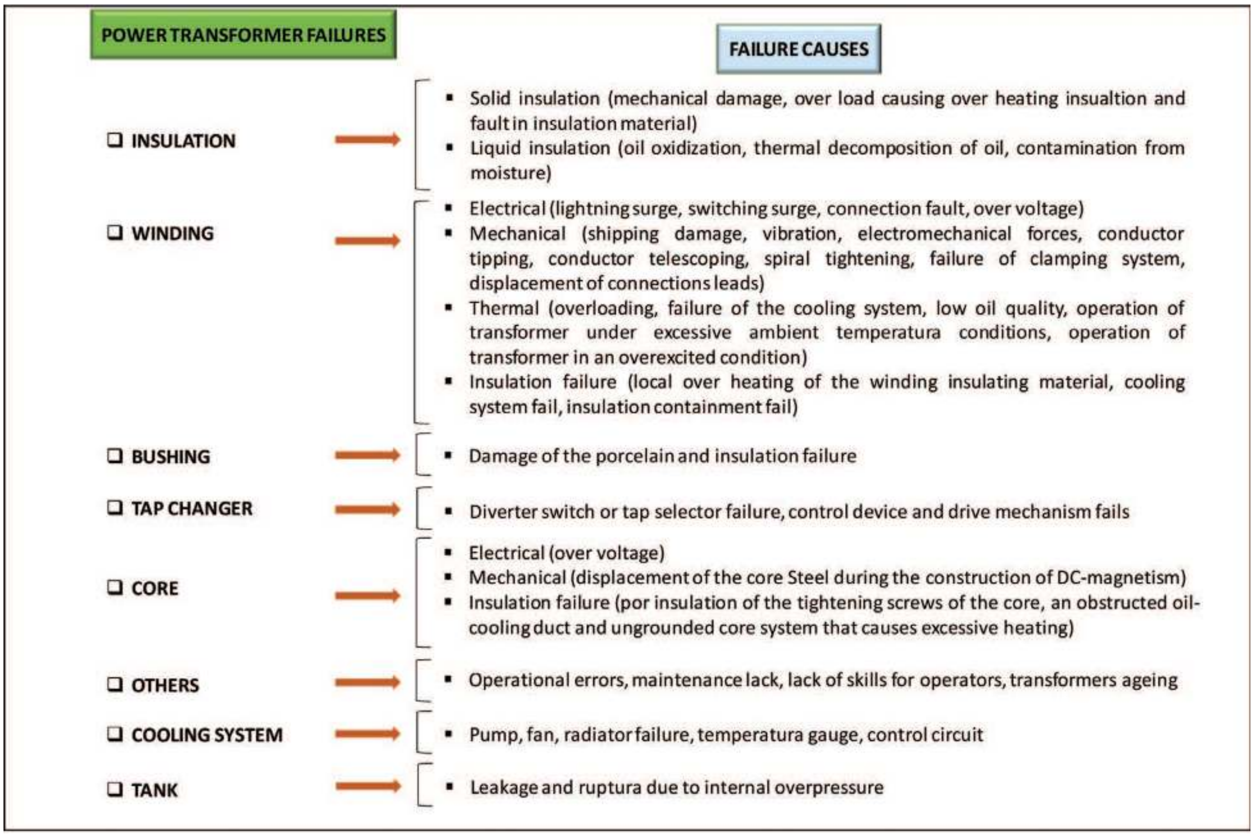
Since the nineteenth century, the use of alternating current (AC) against direct current (DC) was imposed. The machine used for increasing or reducing of AC voltage is the transformer, which has allowed the development of the power market, making possible the electricity transport over long distances thanks the reduction of Joule losses during high-voltage (HV) transport. Electrical insulation and cooling systems are critical parts of electric power transformers during their operation [1].

Transformer losses generate heat, which produces an increase in temperature and an efficiency decrease. Once a power transformer starts its operation, heat begins to be produced, which origins a progressive increase of the temperature. This increase continues until permanent regime conditions are reached. The temperature rise above the service conditions results in an accelerated degradation of the insulating materials. Additionally, insulation systems of oil-filled transformers are subjected to repeated lightning impulses, which brings potential risk to the insulation system, being the liquid/solid interface the weak link. Assessment of insulation condition can be obtained by partial discharge (PD) monitoring [2]. For instance, some authors [3–8] have analysed the effect of oil and pressboard ageing (electrical and/or thermal) on the characteristic of PD from inception to flashover, surface discharge inception voltage (SDIV) variation, creepage discharge inception voltage (CDIV) or creepage discharge flashover voltage (CDFV) of oil/solid insulation specimens with different ageing degrees. Other authors have studied the effect of polarity on the accumulation of charges at the oil-solid interface [9], the accumulative effect of repeated lightning impulses and its damage mechanism [10], the electrical deterioration caused by PD under long-term AC voltage [11] or the performance of alternative liquids in comparison with mineral oil [12].

On the other hand, thermal ageing of insulation system in power transformers can favour the initiation of short-circuit forces, which can end up in a permanent deformation or failure [13].

The type of cooling system in power transformers depends on different factors, mainly associated with the machine power. The two main groups in which this kind of systems can be divided are: dry and liquid cooling. For small transformers (100–50,000 kVA) [14], the external surface of the transformer is sufficient to evacuate by convection and/or radiation the generated heat to the environment. In such cases, the transformer is air-cooled, being called dry transformer. These transformers depend on air to enter at the bottom, flow upward over the core and coil surfaces and exit through the openings near to the top. In medium-large powers, the cooling system is generally of liquid type, so that the core and the windings are immersed in oil and contained in a steel tank. This kind of transformers is named oil-filled and in them, the oil absorbs the heat generated, transports it and dissipates it to the environment through an exchange boundary. In some cases, this boundary is the outer surface of the tank, often flapped, which evacuates heat by natural convection and radiation. As the power of the transformer increases, external radiators are added to increase the exchange surface as well as fans to force the convection. In high-power transformers, the cooling of the oil can be also carried out by means of an oil–water exchanger.

In power systems, most of power transformers are oil-filled [15], and their insulation system is mainly composed of cellulose [16]. The oil provides electrical insulation together with cellulosic materials, as well as cooling. Once a transformer starts its operation, the insulation system degrades over time through different physical–chemical mechanisms. In the case of oil, it is quite simple to maintain it in suitable conditions, and it is even feasible to replace if it would be required. However, this is not possible with solid insulation because this cover wires which constitute the windings of the transformer. Under a practical point of view, replacing the solid



☐ INSULATION
- Solid insulation (mechanical damage, over load causing over heating insualtion and fault in insulation material)
- Liquid insulation (oil oxidization, thermal decomposition of oil, contamination from moisture)

☐ WINDING
- Electrical (lightning surge, switching surge, connection fault, over voltage)
- Mechanical (shipping damage, vibration, electromechanical forces, conductor tipping, conductor telescoping, spiral tightening, failure of clamping system, displacement of connections leads)
- Thermal (overloading, failure of the cooling system, low oil quality, operation of transformer under excessive ambient temperatura conditions, operation of transformer in an overexcited condition)
- Insulation failure (local over heating of the winding insulating material, cooling system fail, insulation containment fail)

☐ BUSHING
- Damage of the porcelain and insulation failure

☐ TAP CHANGER
- Diverter switch or tap selector failure, control device and drive mechanism fails

☐ CORE
- Electrical (over voltage)
- Mechanical (displacement of the core Steel during the construction of DC-magnetism)
- Insulation failure (por insulation of the tightening screws of the core, an obstructed oil-cooling duct and ungrounded core system that causes excessive heating)

☐ OTHERS
- Operational errors, maintenance lack, lack of skills for operators, transformers ageing

☐ COOLING SYSTEM
- Pump, fan, radiator failure, temperatura gauge, control circuit

☐ TANK
- Leakage and ruptura due to internal overpressure

Figure 1. Transformer failures and their causes.

insulation would imply re-manufacturing the transformer almost completely, which is not practical. Consequently, it can be concluded that the life of a power transformer is limited fundamentally by the insulation paper state, which highlights the enormous importance of knowing its behaviour and its degradation rate over time.

Not only solid insulation components suffer continuous ageing, but also the dielectric oil. During transformers operation, the insulation system degrades generating a wide range of by-products such as furanic compounds, water, CO_2, CO, low and high molecular weight acids, and so on [16].

These by-products can influence the normal operation of the transformers causing a raise of failure probability. Therefore, it is important to determine the ageing state of the transformers through the monitoring of the condition of their electrical insulation. The state of degradation of the oil can be determined through various parameters such as interfacial tension, oxidation stability, acidity, dissolved gases analysis (DGA), breakdown voltage, dissipation factor, and so on [16, 17]. In the case of insulation paper, the study of its degradation can be done through the determination of the degree of polymerisation (DP) or through the tensile index. The purpose of these two procedures is to determine the mechanical strength of the paper. While the first method does a representative strength measure, the second one determines the true measurement [18]. However, both tests can only be carried out through scrapping transformers, since in both cases it is necessary to take a sample of the solid component, which requires drain the oil.

The knowledge of the oil and paper ageing processes through the measure of the real state of degradation of the machine is essential to predict the failure of a transformer in service [19, 20], which can be due to different causes as was gathered by Murugan and Ramasamy [21], **Figure 1**.

The main aim of this chapter is to describe the opportunities offered by the variables obtained through stress–strain curve in post-mortem studies as well as accelerated thermal ageing tests carried out in laboratory, describing some of its advantages and challenges. This chapter is structured as follows: Section 2 explains some of the most used methods to evaluate paper ageing. Section 3 exposes the main post-mortem studies carried out until now, as well as the methods and a mathematical model based on DP and tensile index used to analyse paper degradation. The following section describes accelerated thermal ageing tests in which mechanical properties have been used to determine paper degradation. Additionally, this section describes a mathematical model defined by the authors of this chapter, which can be used to determine the paper ageing through mechanical properties, obtained from tensile test. Finally, the conclusions are presented.

2. Paper degradation assessment

The study of paper ageing in power transformers is critical to maximise the operation period, and it can be carried out through different methods, some of the most used are:

2.1. Furanic compounds concentration

This is a non-intrusive technique, which can be used to estimate the ageing of the dielectric paper. It has been concluded by different authors [22–32] that there is a relation between furanic compounds and degree of polymerisation. This relation has been defined through mathematical models such as gathered in **Table 1**.

These models are empirical, obtained through experimental data, so when they are applied to a 2-FAL concentration of for example 0.25 ppm, the value of DP ranges from 764.45 to 535.45 Therefore, there is a huge difference between the results.

These compounds can be determined through high performance liquid chromatography (HPLC) or extraction with methanol [32, 33]. The first step of the furanic compounds measure is to extract them from the oil, which can be done through solid–liquid extraction or liquid–liquid extraction. After that, it is analysed by the HPLC in which it is eluted in the specified column and detected through an ultra violet (UV) detector [18].

A varied range of factors could affect the analysis of furanic compounds: high moisture (furfuryl alcohol, FA), overheating or normal ageing (2-furfuraldehyde, 2FAL), high temperature (5metyl-2furfural, 5MEF).

Mathematical model		Reference
$DP = 325 \cdot \left(\frac{19}{13} - \log_{10}(2FAL)\right); 100 \leq DP \leq 900$	(1)	[22]
$DP = \frac{1}{0.0035} \cdot \left(1.51 - \log_{10}(2FAL)\right); 150 \leq DP \leq 1000$	(2)	[23]
$DP = \frac{1850}{2.3+2FAL'}; 150 \leq DP \leq 600$	(3)	[24]
$DP = \frac{1}{-0.0035} \cdot \left(\log_{10}(2FAL \cdot 0.88) - 4.51\right)$	(4)	[25, 26]
$DP = \frac{800}{[0.186 \cdot 2FAL]+1}$	(5)	[27]
$DP = 356.1 - 343.8 \cdot \log_{10}[TotalFurans]$	(6)	[28]
$DP = \frac{1.4-\log_{10}(2FAL)}{0.003}; 200 \leq DP_{av} \leq 800$	(7)	[29]
$DP = \frac{2.6-\log_{10}(2FAL)}{0.0049};$	(8)	[30]
$DP = 402.47 - 220.87 \cdot \log_{10}\left(C_{fur}\right)$	(9)	[30]
$DP = -121 \cdot \ln\left(C_{fur}\right) + 458$	(10)	[31]
$DP = 405.25 - 347.22 \cdot \log_{10}(2FAL)$	(11)	[32]

DP: degree of polymerisation of the cellulosic paper in the windings of a transformer.
2FAL: mg of furfural/kg of oil.
DPav: average degree of polymerisation of the cellulosic paper in the windings of a scrapped transformer.
Total furans: mg of total concentration of furans/kg of oil.
Cfur: mg of total concentration of furans/kg of oil.

Table 1. Furans and DP correlations.

2.2. Dissolved gas analysis

It is a technique used to identify faults during transformer operation. This analysis can be also utilised to describe the paper ageing through CO and CO_2 dissolved in the oil. Different works have showed that there is a relationship between the concentration of these gases and the DP ($CO_2/CO \leq 7.4$, $DP > 600$; $7.4 < CO_2/CO < 8.0$, $400 < DP < 600$; $8 \leq CO_2/CO < 8.7$, $250 < DP < 400$; $CO_2/CO \geq 8.7$, $DP < 250$) [34, 35]. The gases, which can be extracted from the oil using different methods [18], are detected using the gas chromatography technique whose operating principle is like HPLC.

2.3. Methanol concentration

The determination of the amount of this alcohol can be used to monitor the depolymerisation of the paper under normal operating conditions of the transformer. Methanol offers a faster indication of the early stages of paper degradation than furans [18]. This volatile product can be measured through a gas chromatograph equipped with a mass selective detector in the electron impact mode [36].

2.4. Fourier transform infrared spectroscopy

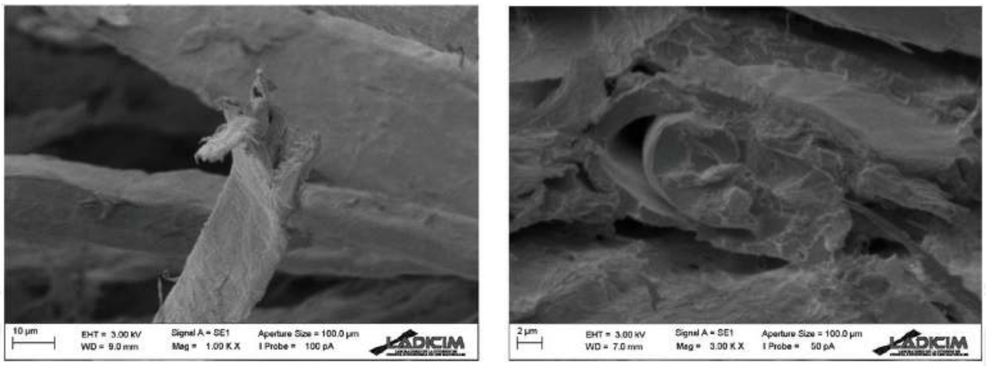
Infrared spectroscopy is a technique used for materials analysis, which uses the infrared region of the electromagnetic (EM) spectrum [37]. It is based on the specific vibration frequencies, which have the chemical bonds of the substances. These frequencies correspond to the energy levels of the molecule and depend on the shape of the potential energy surface of the molecule, the molecular geometry, the atomic mass and the vibrational coupling. If a sample receives light with the same energy from that vibration and the molecules suffer a change in their bipolar moment during vibration, then this will appear in the infrared spectrum. To make measurements on a sample, a monochrome ray of infrared light is passed through the sample, and some of this radiation is absorbed by the sample and some of it is transmitted. By repeating this operation in a range of wavelengths, an infrared spectrum can be obtained. This spectrum represents the molecular absorption and transmission, generating a fingerprint of a sample with absorption peaks, which correspond to the frequencies of vibrations between the bonds of the atoms that constitute the material. The size of the peaks in the spectrum is a direct indication of the amount of material [37, 38]. This technique provides precise information about functional groups (O-H, CH, C=O, C-O) changes [37, 38].

2.5. X-ray diffraction

This is a rapid analytical technique based on the dispersion of the X-ray beam by matter and on the constructive interference of waves that are in phase and that are dispersed in certain directions of space. X-rays are generated in a cathode ray tube by heating a filament to produce electrons, which are accelerated toward the sample applying a voltage. When the electrons have sufficient energy to dislodge inner shell electrons of the target material, characteristic X-ray spectrum is obtained which allows the identification of crystalline phases qualitatively and quantitatively. The crystal structure and crystallinity are the key properties of the crystalline polymer material for deciding its electrical performance. By analysing the length, width, height and diffraction angle, crystal structure identification and chemical phase analysis could be implemented. Therefore, X-RD analysis is very helpful in the investigation of the crystal structure of the cellulose fibres in the transformer paper [39].

2.6. Scanning electron microscope

Scanning electron microscope (SEM) can obtain the electronic image of sample’s surface to show its microstructure [40]. The SEM is capable of producing high-resolution images of a sample surface (**Figure 2**). A heated electron emission produces an electron beam, which is focused by one or two condenser lenses to a fine focal spot. The beam passes through a pair of scanning coils in the objective lens, which deflect the beam both horizontally and vertically. Consequently, the beam scans in a raster fashion over a rectangular area of the sample surface [39]. It allows knowing in detail the state of the surface of a material, which can provide important information about the microstructure, impurities, degree and origin of alteration of the material.



New Kraft paper (2% initial moisture)

Kraft paper aged in mineral oil at 130°C for 1083 hours

Figure 2. SEM result of Kraft paper.

2.7. Refractive index of cellulose fibres

The refractive index (RI) of cellulose fibres can be determined using the dispersion staining method (DSM) whose principle is as follows: when cellulose fibres are immersed in liquid, white light will be dispersed at the boundary of the two substances. At this point, there is a spectrum that does not refract (it passes straight through). This particular spectrum has the condition: “RI of cellulose fibre = RI of immersion-liquid.” When this particular spectrum is intercepted by an optical mask and condenses the spectra that are not intercepted, the cellulose fibre appears to be coloured. It is possible to know the RI of cellulose fibres at a particular spectrum by observing dispersion colour through DSM [41].

2.8. Degree of polymerisation

The degree of polymerisation can be defined as the average number of glucose rings in each cellulose chain and it is dimensionless [19]. These chains of cellulose break up during transformer operation by exposure to oxygen, moisture and heat, which produce a decrease of mechanical strength of paper. This weakening end up in transformer fail and it is commonly accepted that this failure occurs when DP = 150 to 200 [34].

The DP of dielectric paper can be measured using an Ubbelohde viscometer tube [42]. The first step of the procedure is to measure the viscosity of paper, deionised water and cupriethylene-diamine (Cuen) mixture and the next step is to calculate the specific viscosity. Once the specific viscosity has been obtained the DP can be estimated.

2.9. Stress: strain curve

The paper strength is due to fibre strength and inter-fibre bonding strength [18]. Tensile strength (TS) can be described by stress and strain curve (**Figure 3**), which is obtained through tensile test.

This test is used to determine the behaviour of a material when a specimen is clamped in an axial loading frame (**Figure 4**). The data obtained from this test (load and displacement) are used to determine stress and strain using the original specimen cross-sectional area A_0 (m2) and length L_0 (mm).

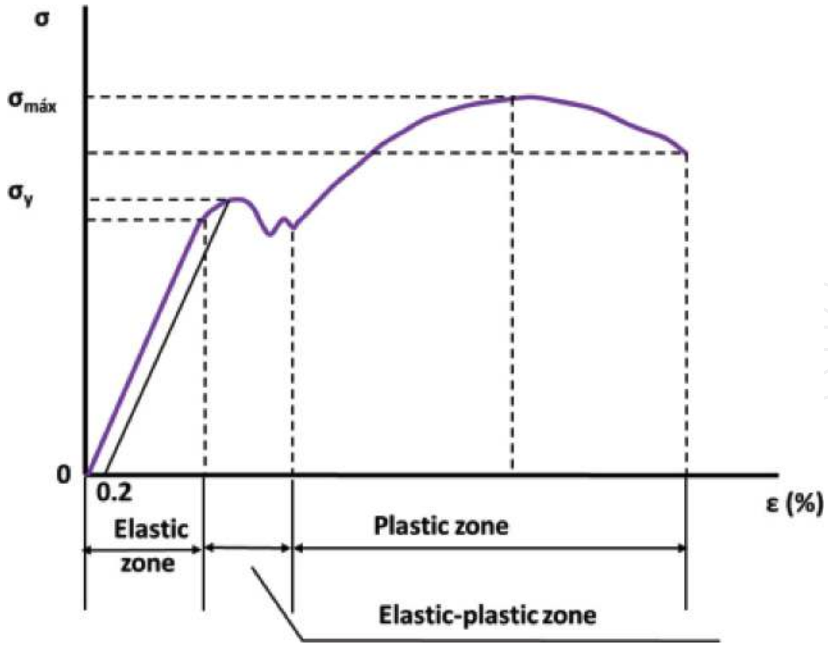


Figure 3. Stress–strain curve.

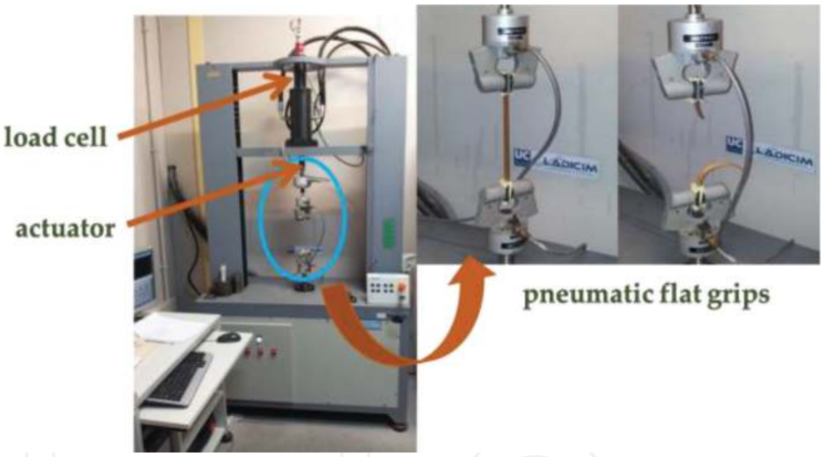


Figure 4. An universal servo hydraulic test machine (model ME-405-1, SERVOSIS) with an axial load cell of ±1 kN capacity, an actuator of ±50 mm of dynamic stroke and equipped with pneumatic flat grips.

Stress (σ) is the internal load applied to a specific surface; it is usually expressed in Pa or MPa when the value is high.

$$\sigma = \frac{F}{A_0} = \frac{F}{b \cdot a} \tag{1}$$

where σ is the stress (Pa); F is the load (N); A_0 is the original specimen cross-sectional area (m^2); a is the original width of the specimen (m) and b is de original thickness of the specimen (m).

Strain (ε) is the change in the size or shape of a specimen due to internal stress produced by one or more loads applied to it or by thermal expansion.

$$\varepsilon = \frac{l - l_0}{l_0} \tag{2}$$

At the beginning of stress–strain curve (**Figure 3**), many materials follow Hooke's law, so that stress is proportional to strain being the modulus of elasticity or Young's modulus (Y, Pa) the constant of proportionality. As strain increases, many materials end up deviating from this linear proportionality, the point in which this happens is named the proportional limit. This behaviour is associated with plastic strain. This plasticity requires molecular mobility and not all materials have it. The microstructural rearrangements associated with plastic strain are usually not reversed when the load is removed, so the proportional limit is often the same as or close to the materials' elastic limit, which is the stress needed to produce a permanent residual strain on a specimen once this is unloaded. A parameter related with this behaviour is the yield stress (σ_y, Pa), which is the stress required to generate plastic strain in a specimen and it is often considered to be the stress needed to generate a permanent strain of 0.2%. In the stress–strain curve appears a point of Maximum Tensile Strength (σ_{max}, Pa), beyond this point the material appears to strain soften. The area under the stress–strain curve up to a given value of strain is the total mechanical energy per unit volume consumed by the material to get that strain [43]. An additional parameter, which can be obtained through stress–strain curve, is the tensile index.

$$TI = \frac{F/_a}{G} \tag{3}$$

where TI is the tensile index (kN m^{-1} kg^{-1}); F is the load (kN); a is the original width of the specimen (m) and G is the grammage (kg m^{-2}).

Dielectric papers used in the isolation system of oil-filled transformers have different values of the mechanical properties (**Table 2**).

As dielectric paper ages, the risk of transformer failure will rise. According to the study carried out by Murugan and Ramasamy [21], approximately 41% of the faults produced in a fleet of transformers (196 transformers ranging from 33 to 400 kV and from 5 to 315 MVA) were due to failures in the insulation system. Thus, it is critical to monitor the condition of the insulating

Property		**Grade K presspaper**	**Grade 3 presspaper**	**Grade K diamond dotted presspaper**	**Grade 3 diamond dotted presspaper**	**PSP 3050**
Typical thickness (mm)		> 0.2	> 0.2	> 0.2	> 0.2	0.7
σ_{max} (MPa)	MD	110	91	110	91	≥ 70
	XD	50	40	39	40	≥ 50
ε (%)	MD	2.4	2.8	2.4	2.8	≥ 6
	XD	7.6	7.8	7.5	7.8	≥ 8

MD: machine direction of paper; and XD: cross direction of paper.

Table 2. Typical mechanical properties of dielectric papers.

solid, which can be carried out through techniques based on paper ageing by-products (furanic compounds, methanol, dissolved gases…), DP or stress–strain curve. The last technique is the best way to analyse paper degradation [18]. However, the implementation of the two last techniques is only possible through post-mortem studies (scrapping transformers). Another possibility to paper assessment is through correlations based on thermal ageing tests carried out in laboratory. The following sections describe the possibilities that stress–strain offer in order to obtain useful information not only in post-mortem studies, but also in accelerated thermal ageing tests.

However, the implementation of the two last techniques is impossible during transformer operation because it is not possible obtain paper samples from in-service transformers and the only opportunity is through post-mortem studies (scrapping transformers). Another possibility to paper assessment is through correlations based on thermal ageing tests carried out in laboratory. The following sections describe the possibilities that stress–strain offer in order to obtain useful information not only in post-mortem studies, but also in accelerated thermal ageing tests.

3. Post-mortem studies

Although power transformers are tested machines whose life-span pass 20 years even in many cases 40 years [44, 45], their failure diagnostics are becoming increasingly important due to the high cost of these devices.

The aim of power transformers post-mortem studies is to understand the failure mechanisms, so it is essential to collect information about the fault, sequence of events previous the fault, protective operation and protective devices performance. This information requires to be collected immediately after the failure occurs, to reproduce it accurately. Therefore, if there is no an efficient diagnostic methodology included in maintenance program, test results will not be useful to prevent future failures. There are cases in which failures do not manifest in a protective device operation, so routine monitoring can help to detect abnormal operation conditions. Though end-of-life assessments can provide useful information, they are not always conclusive enough to make the decision about the appropriate time to remove a transformer from service. This is the reason why the availability of the history of test results from a power transformer may help to have a better evaluation about the most suitable moment to replace this kind of machines [46].

There are some examples of post-mortem studies that have used the DP as technique to determine the paper ageing. For instance, Koch et al. [17] through a research project in which worked together the IEH Karlsruhe, power stations, utilities and a manufacturer. One of its aims was the definition of a correlation between DP and furanes in the oil, the other aim was to obtain data about the ageing process of transformers populations. This project carried out the post-mortem analysis of two generator transformers. The result tests showed that the lowest DP value occurs at about 75% of the winding length and not at the top in the LV and the HV windings. This allowed to conclude that the hot spot temperature does not occur at the top of the winding. Additionally, these authors obtained that there is a good correlation between DP and the content of furanes in the oil and that the CO_2/CO ratio can be used to detect the degree of carbonisation of the insulation paper. Martins et al. [47] also evaluated the condition of a single power transformer, specifically a 63-MVA, 150/63/10-kV, shell-type unit to make a decision regarding its transfer to a new substation. They measured the DP from selected points in the transformer connections insulation to get a paper-ageing diagnostic and compare it with the predicted diagnostic based on the previous oil analysis [dissolved gas analysis (DGA), colour, appearance, breakdown voltage, water content, acidity, dielectric dissipation factor, sediment and sludge, interfacial tension, flash point and furanic compounds]. Their evaluation showed that the calculation of DP using correlations based on 2-FAL require care because DP values depend on variables such as temperature, oxygen, water content, oil type and degradation oil. These authors also estimated DP values using the calculated thermal profiles. However, their results concluded that loading data included the daily peaks are insufficient to obtain an accurate temperature distribution. Finally, they concluded that more post-mortem studies with detailed operational data would improve the knowledge of the correlation between 2-FAL in oil and the DP of insulating paper. DP was also used to estimate paper ageing in the post-mortem assessment carried out by other authors [28, 48]. Leibfried et al. [28] proposed a systematical method for taking paper samples from scrapped power transformers and a methodology for the evaluation of DP values suggesting a grouping into different types of transformers, at least in Germany, which the operation mode and consequently the ageing rate inside transformers is substantially different. Using the data obtained in their study, Leibried et al. derived a formula to estimate average DP through the 2-FAL concentration, although they obtained that this equation does not provide 100% reliable evaluation of transformer condition. In the case of Jalbert and Lessard [48], insulating paper from six power transformers (open-breathing core-type power transformers built in 1958, initially cooled with OFWF systems and since 1990s modified to OFAF cooling systems) as well as representative oil samples needed to evaluate the oil quality and its content of chemical markers (furans and alcohols) were tested. These authors concluded that it is critical to obtain a complete DP profile of the transformer in order to apply any model. They also focused on the need to establish concentration thresholds to define more accurately the insulation paper condition. The experimental results of these post-mortem assessments give a variation of DP values ranged from less than 5% to more than 40%, which indicates the results variability of this technique.

It was not until 2014, that post-mortem studies were carried out considering not only DP, but also tensile index, despite the fact that some authors like Emsley et al. [49] have developed an expression, which correlated DP and tensile strength with temperature and time. The approach applied by Carcedo et al. [50] showed a case study, which used, the model proposed by Emsley et al. to predict the values of tensile index and degree of polymerisation [49], in an alternative way for post-mortem assessment. These authors estimated temperature distributions considering the machine life-span and the DP and TI values of new and aged Kraft paper. Carcedo et al. [50] took paper samples from a failed distribution transformer (three-phase transformer with a rated power of 800 kVA at 50 Hz and manufactured in 1986 with an ONAN cooling system) to measure DP and TI. Later, the temperature distributions were obtained based on DP and TI test results and Emsley et al. model [49]:

$$DP_t = \frac{k_2 \cdot DP_0 \cdot e^{k_2 t}}{e^{k_2 t} \cdot (DP_0 \cdot k_{1_0} + k_2) - DP_0 \cdot k_{1_0}} \tag{4}$$

$$TI_t - TI_0 = K_1 \cdot e^{-k_2 t} + K_2 \cdot \ln\left(e^{k_2 t} - K_3\right) - K_4 \tag{5}$$

$$k_{1_0} = A_{1_0} \cdot e^{\frac{-E_{a10}}{R^* T}} \tag{6}$$

$$k_2 = A_2 \cdot e^{\frac{-E_{a2}}{R^* T}} \tag{7}$$

$$K_1 = \frac{k_2 \cdot k_{1_0}}{k_2} \tag{8}$$

$$K_2 = k_4 \cdot K' \tag{9}$$

$$K_3 = k_{1_0} \cdot K' \tag{10}$$

$$K_4 = K_2 \cdot (\ln(1 - K_3)) + K_1 \tag{11}$$

$$K' = \frac{DP_0}{DP_0 \cdot k_{1_0} + k_2} \tag{12}$$

where DP_t is the insulation DP value at time t; DP_0 is the initial insulation DP value; t is the time (s); k_{10} is the initial rate at which bonds break; k_2 is the rate at which k_{10} changes; TI_t is the insulation tensile strength index value at time t; TI_0 is the initial insulation tensile strength index value; k_{10}, k_2, k_3 and k_4 constants can be obtained assuming that Arrhenius equation is valid from normal temperature of power transformers up to the temperatures used in ageing experiments:

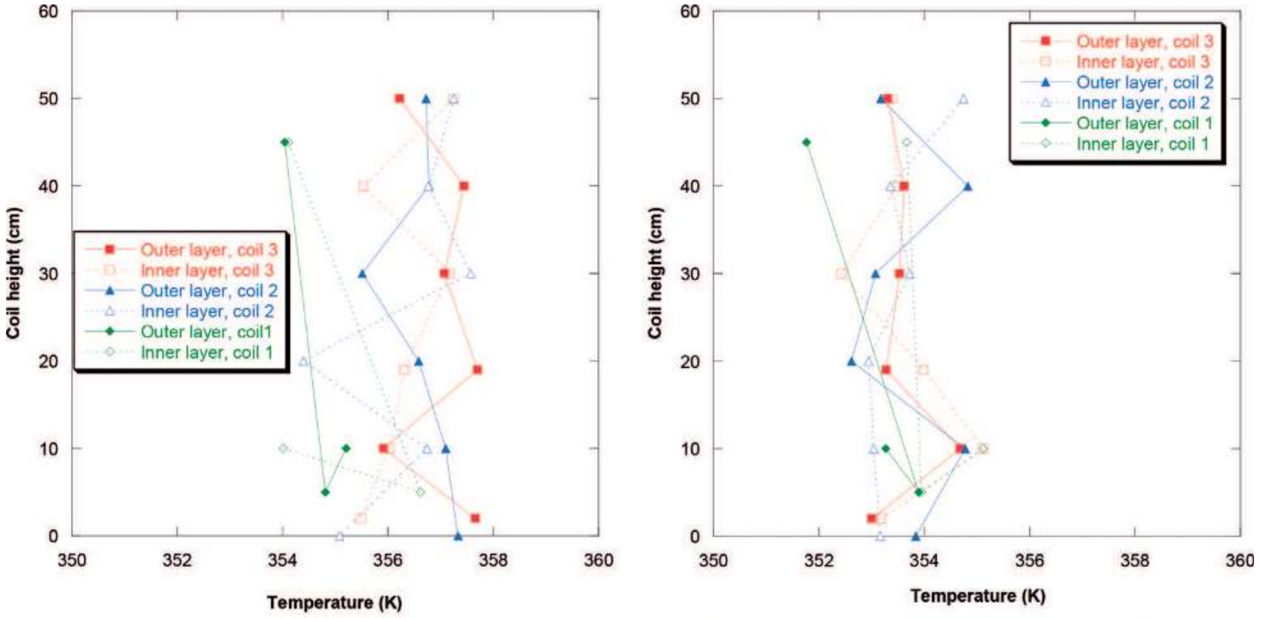
$$k = A \cdot e^{\frac{-E_a}{RT}} \tag{13}$$

where k is a rate constant; A is the pre-exponential factor (s^{-}1); E_a is the activation energy (J mol^{-}1); R is the molar gas constant (8.314 JK^{-}1 mol^{-}1) and T is the temperature (K).

Finally, these temperature distributions obtained by Carcedo et al. [50] and represented by authors of this chapter (**Figure 5**) were compared in order to show the suitability of tensile analysis for post-mortem studies. These authors concluded that the maximum difference for the same point was less than 3.3 K; therefore, both methods were suitable for post-mortem evaluations, being the TI more reliable and repeatable indicator.

Azis et al. also used stress–strain curve to investigate the mechanical strength of paper from 10 scrapped power transformers [51]. These authors not only used TI to carried out the transformers assessment, but also the low molecular weight acid (LMA). They concluded that there is a relationship between LMA in oil and TI of paper, which tends to be generic for both laboratory tests and in-service ageing data.

In the paper written by Müllerová et al. [52], was described the methodology followed to create and utilise as a making decision tool a database which gathers data about the condition of the insulation system of a group of 24 transformers (1 transformer of 330 MVA, 400/121 kV;



Temperatures using DP test results

Temperatures using TI test results

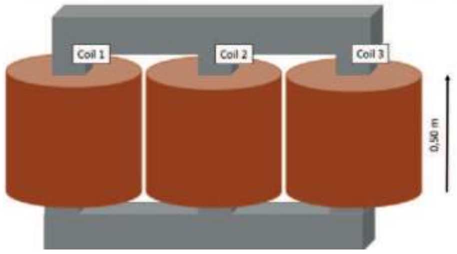


Figure 5. Temperature distribution using different test results.

3 transformers of 254 MVA, 420/13.8 kV; 3 transformers of 250 MVA, 400/121 kV; 15 transformers of 250 MVA, 420/15.75 kV; 1 transformer of 200 MVA, 231/121 kV; 1 transformer of 200 MVA, 230/121 kV). These machines were studied through post-mortem analysis carried out for several years. The study of these devices analysed the values of DP, tensile strength, as well as, information from running history of the transformers (DGA and 2-FAL). They observed that transformers with similar level of ageing are defined rather by manufacturer and construction than by the loading regime, which has less influence. Moreover, they found that the correlation of DP and tensile strength corresponds with specific transformers groups. Nevertheless, there are some transformers whose DP values range far less in comparison with tensile strength, which might indicate a higher accuracy of this variable to distinguish paper degradation. On the other hand, the DGA tests showed that they are essential for ageing evaluation because they can provide information about running problems (ineffective cooling, leaking, higher gases development).

Even though the number of post-mortem studies has increased during the last years, there is not enough data to develop an accurate end-of-life failure model [53]. For this reason, it is essential to go on with the study of scrapped transformers to obtain more information about the most representative variables of the transformer ageing. Initially, the state of insulating solid was measured through DP; however, later assessments have demonstrated that in some cases the tensile or index strength can be more sensitive to differentiate the level of paper ageing.

4. Accelerated thermal ageing in laboratory

Currently, most of oil-filled power transformers use as dielectric liquid, mineral oil, which is obtained from the middle range of petroleum-derived distillates. This fluid has shown suitable thermal and dielectric properties to carry out its functions as cooling and insulation. Nevertheless, it possess two important drawbacks, the first one is its low flash point and the second one is its low biodegradability, which can represent a high risk if spills or leaks would take place. This situation has led to the development of alternative transformer oils such as silicones, synthetic and natural esters. In particular, vegetal oils have drawn most attention and research [54].

During last two decades, the study of transformer oil-based nanofluids has become of great interest due to their prospective properties as cooling and dielectric liquids [55]. For example, Li et al. [56] prepared a nanofluid dispersing Fe_3O_4 nanoparticles in a vegetal oil and using oleic acid as surfactant. These authors compared the behaviour of this nanofluid with the pure oil measuring power frequency breakdown voltage and relative permittivity. The breakdown voltage of nanofluids has also been measured by Thabet et al. [57], nevertheless, in that work the insulation liquid was based on mineral oil and different nanoparticles (ZnO, MgO, Al_2O_3, TiO_2, SiO_2, $LiTaO_3$, Fe_3O_4, graphite), as well as multi-nanoparticles collections, which were combination of two of the nanoparticles studied previously. These dielectric properties and other such as dissipation factor, dielectric constant or electrical resistivity have been studied by many authors [58, 59], analysing the effect of different nanoparticles ($CaCu_3Ti_4O_{12}$, TiO_2, Al_2O_3). The streamers in transformer oils under lightning impulse voltage have been observed, too by authors such as et al. [60, 61], Cavallini et al. [62], Sima et al. [63] and Liu et al. [64] or simulated as Velasco et al. [65]. The last ones not only evaluated dielectric properties, but also thermal conductivity of nanofluids obtained through the dispersion of AlN nanoparticles. The effect of nanoparticles on heat transfer characteristics was also studied by Guan et al. [64] and Morega et al. [66]. The last ones additionally evaluated the specific magnetisation of other nanofluid to open new venues in optimising conventional electrotechnic constructions or to design novel devices [67]. Creeping discharge and flashover characteristics of the oil/pressboard interface under AC and impulse voltages was studied by Lv et al. for a nanofluid based on TiO_2 nanoparticles [68], obtaining an increase of the shallow trap density and a lower shallow trap energy level of oil-impregnated pressboard which can improve the creeping flashover strength of oil/pressboard interface.

When it is desired, the replacement of one usual component of the insulation system, as in the case of alternative dielectric oils, it is important to study the stability of the new system and compare it with the system widely used in power transformers (mineral oil/Kraft paper). For this reason, many accelerated thermal ageing studies have been carried out in the laboratory.

The first laboratory tests of accelerated thermal ageing focused on the behaviour of paper in mineral oil. For instance, Shroff and Stannett [69] aged Kraft paper and thermal upgraded paper in mineral oil at four temperatures. The results of their study showed that there is a direct relationship between the DP and the moisture in paper and the concentration of furanic compounds. These authors also proposed as paper end-of-life criteria a DP = 200 and a tensile strength equal to 50% of its original value. Other authors such as Yoshida et al. [70] also implemented ageing tests using mineral oil as dielectric liquid at different temperatures (120, 140 and 160°C). In this case, they analysed the behaviour of Kraft and pressboard paper, obtaining as main conclusions the existence of a relationship between the concentration of CO/CO_2 and the evolution of the DP and the tensile strength. On the other hand, Hill et al. [71] studied the tensile strength of the paper, the DP and the concentration of furans in ageing tests of Kraft paper in mineral oil at different temperatures, obtaining as a result the existence of a relationship between furans, DP and tensile strength. In addition, these authors proposed a paper degradation model based on the tensile strength. Emsley et al. [49, 72, 73] also proposed a degradation model, although this was based on the relationship between tensile strength and DP for Kraft paper and cotton paper aged in mineral oil. Since last decade, ageing studies have begun to take into account alternative oils. For example, Mcshane et al. [74–77] evaluated DP, tensile strength, moisture in oil and paper, as well as furan content when Kraft and thermal upgraded paper were aged in a mineral oil and in a natural ester. The results of their tests showed that the degradation rate experienced by the paper during thermal ageing at different temperatures was lower in the natural ester. These authors proposed the protective mechanisms developed by the ester that might explain the minor degradation suffered by the paper in the alternative oil. Other authors such as Shim et al. [78] also obtained greater thermal stability in the natural ester compared to mineral oil by the measure of the tensile strength for Kraft and diamond dotted paper. Similar results were presented by Azis [18], who analysed paper degradation using tensile strength, breakdown voltage, dynamic viscosity, acidity and concentration of low and high molecular weight acids in the oil. The measure of the concentration of low molecular weight acids (LMA) allowed observing that these tend to remain in the natural ester, which might explain the best behaviour of the Kraft paper during the ageing, in addition to the hydrolytic protection made by the oil. The behaviour of thermal upgraded and Kraft paper in mineral oil and in natural ester was also evaluated by Abdelmalik et al. [79], who studied the tensile and dielectric strength of the paper. Their results also showed that oils based on natural esters protect better against the degradation than mineral oil. Saruhashi et al. [80] studied for aramid paper tensile index, as well as breakdown voltage, acidity, colour and kinematic viscosity of the oil. In their study, they carry out ageing tests at two temperatures in three different oils (silicone, natural ester and synthetic ester). They found a slight variation of the tensile index in the three oils. The degradation of Kraft paper aged in a natural ester was also evaluated through the tensile strength by Widyanugraha et al. [35], who also measured the gases generated during ageing at two different temperatures. The tensile strength suffered initially a decrease and subsequently an increase during thermal ageing. It was assumed that this behaviour was due to the transesterification process. The tensile strength of the paper, besides other characteristic properties of the oil degradation, was analysed by Madavan and Balaraman [81], who obtained that the paper aged in oils based on natural esters had a lower degradation compared to Kraft paper immersed in mineral oil. In recent years, different authors have tried to find additional methods to study paper degradation when this is aged thermally in laboratory. For example, Arroyo et al. [16, 82, 83] related the paper's tensile index with an indirect measure of its degradation, such as the concentration of methanol and ethanol in the oil. They also proposed three degradation models for Kraft and thermal upgraded paper. Each model was based on a different property (tensile index, DP, methanol and ethanol concentration in oil). The proposed models were obtained from the ageing data of the paper in mineral oil at three temperatures. Finally, they evaluated the influence that the concentration of stabilisation additives can have on the thermal stability of thermal upgraded paper. The results showed that the higher this concentration is, the better the paper stability, although it changes whereas the degradation of the paper takes place. Another alternative model based on a damage parameter D to predict the remaining life of Kraft paper has been defined by the authors of this chapter. This parameter can be based on any mechanical property (strength, Young's modulus, yield stress, energy consumed, strain under ultimate strength, etc.) obtained of the tensile test (Annex). This damage parameter can be used to evaluate additional mechanical properties which have not been used previously in a new proposed mathematical model based on temperature and time. The damage parameter D is defined as:

$$D = 1 - \frac{\mathrm{Pr}operty_i}{\mathrm{Pr}operty_0} \tag{14}$$

where $\mathrm{Property}_\mathrm{i}$ is the value of a macroscopic property (strength, yield stress…) in any situation of time (t) and temperature (T) and $\mathrm{Property}_0$ is the value of the same property of the original paper not subject to ageing. It can be observed that the damage parameter D can only take values between 1 and 0. The value 1 represents an insulation paper which has lost all its mechanical resistance whereas the value 0 corresponds to new insulation solid.

The evolution of D with t for different ageing conditions can be obtained through the mathematical model:

$$D = D_{\max} \cdot \left(1 - \exp(-a \cdot t)\right) \tag{15}$$

where the parameter a is a rate constant that indicates the effect of oil temperature in which the paper is aged, on the increase of the damage, D, suffered by paper along the time; $\mathrm{D}_{\max}$ is the maximum value reached experimentally by the damage; t is the time (h). The parameter a can be expressed by means of Arrhenius equation as a function of the ageing temperature.

Finally, the analysed Property can be expressed as a function of the time and the temperature:

$$\mathrm{Pr}operty_i = \mathrm{Pr}operty_0 \cdot \left(1 - D_{\max}\left(1 - \exp(-a \cdot t)\right)\right) \tag{16}$$

This mathematical model, which determines the damage suffered by paper aged in an oil, is a simplified macroscopic model that takes into account the general damage experienced by the paper.

On the other hand, Pei et al. [40] tried to relate the degradation suffered by pressboard aged at 130°C in mineral oil, through the tensile strength, with the microscopic appearance of its surface, using for this analysis the scanning electron microscope (SEM). The results of his study showed that the pressboard degradation is accompanied by changes in the superficial structure.

All these works have found that the thermal degradation of the paper can be evaluated using mechanical parameters such as tensile strength or TI. However, until now, other parameters obtained from the tensile test have not been considered, such as Young's modulus, strain, elastic limit, and so on, which might offer a more accurate view of the loss of mechanical strength by the paper. On the other hand, the use of SEM for materials aged in mineral oil seems to provide additional information on the relationship between the shape of cellulose fibres and their mechanical strength. Regarding the behaviour of cellulosic material in alternative oils, although several ageing studies have been carried out, degradation models based on mechanical properties have not been proposed. These mathematical models will allow to estimate the remaining life of dielectric papers as a function of temperature and time. The development of these degradation models requires analyse which mechanical properties can offer a better description of the loss of mechanical resistance. Additionally, the utilisation of SEM can help to detect when the behaviour of the solid insulation becomes fragile increasing the failure probability.

5. Conclusions

There are several techniques that can be used to evaluate insulation paper degradation; however, the two most used in post-mortem analysis have been the degree of polymerisation (DP) and tensile strength. One of these post-mortem studies obtained as conclusions that the experimental results give a variation of DP values ranged from less than 5% to more than 40%, which indicates the results variability of this technique. On the other hand, all these end-of-life studies have shown the necessity of complement DP profile of the transformer with chemical markers such as furans, methanol, dissolved gases, and so on. Because of these by-products derived from paper and oil degradation can detect running problems (ineffective cooling, leaking, higher gases development), which might be useful to prevent future failures.

Data obtained from post-mortem analysis should be complemented with tests carried out in the laboratory. These tests have provided useful correlations between oil markers and paper degradation in a short period of time and make possible establish comparisons between mineral and alternative oils in accelerated thermal ageing tests. The measure of paper mechanical strength has been limited until now at the estimation of tensile strength and tensile index, in spite of the fact that additional parameters (Young's modulus, yield stress, energy consumed, etc.) obtained in the tensile test can provide more accurate analysis of the loss of mechanical properties. For instance, the energy consumed might be more convenient to follow the changes of mechanical properties of insulation paper since in its definition the other two parameters (strength and strain) are used. Data obtained from stress–strain curve should be complemented with the information provided by techniques as SEM, which could detect behaviour changes in the paper related with type of failure. This could be carried out using texture analysis, which might provide information about thermal degradation of paper using the information provided by the statistical variation of pixels grey level intensities in an image.

The results obtained from PD measurements have shown that solid ageing has little influence; nonetheless, oil ageing has great influence on PD characteristics over liquid/solid interface.

Additionally, it has been observed by different authors that thermal ageing has significant impacts on surface morphology of insulation solid, which influences the developing process of PD. Therefore, it is necessary to analyse the effect of increasing the ageing time on the reduction in partial discharge magnitude for application in on-field practical tests. This analysis needs to take into account not only mineral oil, but also new insulating oils (natural and synthetic esters) which have proved to be a viable substitute. Moreover, there is an incomplete understanding of the oil/solid interface yet, as well as a lack of standardisation in PD measurements for diagnostic purposes of the HV components in which insulating liquids are employed.

Finally, the use of nanoparticles in power transformers has opened new ways in optimising their design because different studies have obtained an enhancement in dielectric properties (breakdown strength, partial discharge inception voltage, creeping flashover strength of oil-impregnated papers…) and thermal conductivity without significant change in the viscosity.

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A. Annex

Having the data of Force (kN) and Displacement (mm), the following sequence of MATLAB, allows to obtain the different mechanical parameters of the material, which will be used in the mathematical model based on damage parameter defined by the authors of this chapter.

1-Define the constants: Initial length, Gramage, A_0, a…

2-Load from a file with the results of Force (kN), Position (mm).

3-Matlab performs the calculations, represents the stress–strain graph and shows a summary table with the mechanical parameters.

```
clc

clear.

% Define constants.

a0 = 3;g = 0.15783222;a = 0.015;l = 180;

nm = 4;

% Open files Data.

fileID = fopen(‘data.txt’);
```

```
D = textscan(fileID,’%f %f’);

fclose(fileID);

% Preparate Data.

F_data = D{1};

pos_data = D{2};

F = zeros((length(F_data)-1)/nm,1);

pos = zeros((length(F_data)-1)/nm,1);

for i = 1:((length(F_data)-1)/nm).

F(i) = 0.25*(F_data(nm*(i-1) + 2) + F_data(nm*(i-1) + 3) + F_data(nm*(i-1) + 4) + F_data(nm*(i-1) + 5));

pos(i) = 0.25*(pos_data(nm*(i-1) + 2) + pos_data(nm*(i-1) + 3) + pos_data(nm*(i-1) + 4) + pos_data(nm*(i-1) + 5));

end

pos0 = pos_data(1);

eps = (pos-pos0)./l;

sigma = F./a0;

% Calculate.

n = 0;

while true.

n = n + 1;

pdte1 = (sigma(n + 1)-sigma(n))/(eps(n + 1)-eps(n));

pdte2 = (sigma(n + 2)-sigma(n + 1))/(eps(n + 2)-eps(n + 1));

pdte3 = (sigma(n + 3)-sigma(n + 2))/(eps(n + 3)-eps(n + 2));

if (abs((pdte1-pdte2)/pdte1) < 3e-2) && (abs((pdte2-pdte3)/pdte1) < 3e-2).

pdte = pdte1;

break.

end

if n + 3==length(sigma).

break.

end
```

```
end
rect1 = pdte.*eps;
sigmar = sigma(length(sigma));
epsd = eps(length(sigma));
rect2 = pdte.*(eps-0.002);
sigmay = 0;
for i = 1:length(sigma).
if abs((sigma(i)-rect2(i))/sigma(i)) < 1e-2.
sigmay = sigma(i);
i_corte = i;
break.
end
end
Am = 0;
tem = zeros(length(sigma)-1,1);
for i = 1:length(sigma)-1.
tem(i) = (sigma(i + 1) + sigma(i))*0.5*(eps(i + 1)-eps(i));
Am = Am+tem(i);
end
ts = max(F)/a/g/1000;
% Screen size.
ss = get(0,'screensize’);
width = ss(3);
height = ss(4);
% Graphic.
f = figure;
vert = ss(4)/1.5;
horz = ss(3)/1.5;
set(f,'Position’,[(width/2)-horz/2, (height/2)-vert/2, horz, vert]);
plot(eps,sigma,'b’).
```

```
hold on.
axis([0 epsd 0 max(sigma)]).
plot(eps,rect1,'–r').
plot(eps,rect2,'–m').
plot([eps(1) eps(i_corte)],[sigmay sigmay],':k').
plot([eps(i_corte) eps(i_corte)],[0 sigmay],':k').
% Resumen Data.
dat = {pdte,sigmay,sigmar,epsd,Am,ts};
t = uitable(f);
t.ColumnName = {'Elasticity Modulus','Elastic limit','Maximun Tension','Deformation under maximum tension','Absorbed Energy','Tensile Index'};
t.Data = dat;
t.Position = [vert/2 vert-50 t.Extent(3) t.Extent(4)];
```

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References

[1] Karsai K, Kerényi D, Kiss LL. Large Power Transformers. Amsterdam; New York: Elsevier; New York, NY, U.S.A.: Distribution for the U.S.A. and Canada, Elsevier Science Pub. Co., 1987. Studies in electrical and electronic engineering, 25. 614 p. ISBN: 0444995110 9780444995117 0444417133 9780444417138

[2] Siada AA. Power Transformer Condition Monitoring and Diagnosis. Chapter 2: Power Transformer Condition Monitoring and Diagnosis: concepts and Challeges. Albarracin R, Robles G, Ardila-Rey JA, Cavallini A, Passaglia Pagination R: c. 300pp. 2018. ISBN: 978-1-78561-254-1

[3] Li J, Si W, Yao X, Li Y. Partial discharge characteristics over differently aged oil/pressboard interfaces. IEEE Transactions on Dielectrics and Electrical Insulation. 2009;**16**(6):1640-1647. DOI: 10.1109/TDEI.2009.5361584

[4] Dai J, Wang ZD, Jarman P. Creepage discharge on insulation barriers in aged power transformers. IEEE Transactions on Dielectrics and Electrical Insulation. 2010;**17**:1327-1335. DOI: 10.1109/TDEI.2010.5539705

[5] Xu J, Wang W, Li C, Wang X, Zhou B, Li Y, Wang T, Experimental research on the evolution of creepage discharge in aged pressboard. Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP). 2011;484-488. DOI: 10.1109/CEIDP.2011.6232700

[6] Sarathi R, Yadav KS, Swarna M. Understanding the surface discharge characteristics of thermally aged copper sulphide diffused oil impregnated pressboard material. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**:2513-2521. DOI: 10.1109/TDEI.2015.004905

[7] Niasar MG, Taylor N, Janus P, Wang X, Edin H, Kiiza RC. Partial discharges in a cavity embedded in oil-impregnated paper: Effect of electrical and thermal aging. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**:1071-1079. DOI: 10.1109/TDEI.2015.7076808

[8] Yadav KS, Sarathi R. Understanding the dielectric properties of pressboard material thermally aged in dibenzyl disulphide (DBDS) included transformer oil. IEEE Transactions on Dielectrics and Electrical Insulation. 2017;**24**:647-655. DOI: 10.1109/TDEI.2016.006083

[9] Qi B, Zhao X, Li C, Wu H,Transient electric field characteristics in oil-pressboard composite insulation under voltage polarity reversal. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**(4):2148-2155. DOI: 10.1109/TDEI.2015.004347

[10] Sima W, Sun P, Yang Q, Yuan T, Lu C, Yang M. Study on the accumulative effect of repeated lightning impulses on insulation characteristics of transformer oil impregnated paper. IEEE Transactions on Dielectrics and Electrical Insulation. 2014;**21**:1933-1941. DOI: 10.1109/TDEI.2014.004298

[11] Cui Y, Zhu L, Ji S, Cao P, Zhang F. Partial discharge development in needle-plane configuration of oil-paper insulation under AC voltage. IEEE Transactions on Dielectrics and Electrical Insulation. 2017;**24**:2469-2476. DOI: 10.1109/TDEI.2017.006270

[12] Azcarraga CG, Cavallini A, Piovan U, A comparison of the voltage withstand properties of ester and mineral oils. IEEE Electrical Insulation Magazine. 2014;**30**(5):6-14. DOI: 10.1109/MEI.2014.6882595

[13] Geißler DH, Short-Circuit Withstand Capability of Power Transformers

[14] Siemens, Power Engineering Guide Edition 7.0

[15] VITO, LOT 2: Distribution and power transformers Tasks 1–7. 2011

[16] Arroyo OH, Fofana I, Jalbert J, Ryadi M. Relationships between methanol marker and mechanical performance of electrical insulation papers for power transformers under

accelerated thermal aging. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**(6):3625-3632. DOI: 10.1109/TDEI.2015.005386

[17] Koch M, Tenbohlen S, Giselbrecht D, Homagk C, Leibfried T. Onsite, online and post mortem insulation diagnostics at power transformers. CIGRE 2007. Brugge, Belgium, 2007

[18] Azis N. Ageing assessment of insulation paper with consideration of in service ageing and natural ester application [Thesis] UK: The University of Manchester; 2012

[19] Zhang GJ, Wei JL, Dong M, Mu HB, Li HJ, Zhang YB, Li YM, Yan Z. Lifetime monitoring and estimation strategy for large power transformer. In: International Conference on Condition Monitoring and Diagnosis; 21–24 April 2008; Beijing, China. p. 1-6

[20] Morais DR, Bencz E, Rolim JG Condition assessment of power transformers through the integration of historical and on-line data in a multi-agent system. Journal of Control, Automation and Electrical Systems. 2014;**25**:93-102. DOI: 10.1007/s40313-013-0069-3

[21] Murugan R, Ramasamy R. Failure analysis of power transformer for effective maintenance planning in electric utilities. Engineering Failure Analysis. 2015;**55**:182-192. DOI: 10.1016/j.engfailanal.2015.06.002

[22] Heisler A, Banzer A. Zustandsbeurteilung von Transformatoren mit Furfurol-Bestimmung. Das Magazin für die Energiewirtschaft. 2003:58-59

[23] Chendong X. Monitoring paper insulation ageing by measuring furfural contents in oil. In: EPRI, 7th Int. Symp. High Voltage Eng.; 26–30 August; Dresden, Germany; 1991:139-142

[24] De Pablo A. Interpretation of Furanic Compounds Analysis—Degradation Models. In: CIGRE WG D1.01.03. 1997; Paris. France

[25] Stebbins RD, Myers DS, Shkolnik AB. Furanic compounds in dielectric liquid samples: Review and update of diagnostic interpretation and estimation of insualtion ageing. In: Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials; 1–5 June 2003. p. 921-926

[26] Shkolnik AB, Rasor RT, Myers SD. Statistical insights into furan interpretation using a large dielectric fluid testing database. In: Transmission and Distribution Conference and Exposition (T&D) IEEE PES; 7–10; Orlando. 2012. p. 1-8

[27] Mtetwa NS. Accuracy of furan analysis in estimating the degree of polymerization in power transformers [thesis]. M. Sc. (Eng.) University of the Witwatersrand; 2008

[28] Leibfried T, Jaya M, Majer N, Schafer M, Stach M, Voss S. Postmortem investigation of power transformers—profile of degree of polymerization and correlation with furan concentration in the oil. IEEE Transactions on Power Delivery. 2013;**28**(2):886-893. DOI: 10.1109/TPWRD.2013.2245152

[29] Lütke H, Höhleim I, Kachler AJ. Transformer aging research on furanic compounds dissolved in insulating oil. In: CIGRE; París, Francia; 2002. p. 15-302

[30] Dong M, Yan Z, Zhang GJ. Comprehensive diagnostic and aging assessment method of solid insulation in transformer. In: Annual report conference on electrical insulation and dielectric phenomena, Albuquerque USA; 2003. 19-22 p. 137-140

[31] Li E, Song B. Transformer health status evaluation model based on multi-feature factors. In: International Conference on Power System Technology (POWERCON 2014); 20–22 October 2014; Chengdu, China. p. 1417-1422

[32] Lin C, Bide Z, Yuchun Y. The aging diagnosis of solid insulation for oil-immersed power transformers and its remaining life prediction. In: Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific; 28-31 march 2010; Chengdu; China. 2010. p. 1-3

[33] Levchik S, Scheirs J, Camino G, Tumiatti W, Avidano M. Depolymerization processes in the thermal degradation of cellulosic paper insulation in electrical transformers. Polymer Degradation and Stability. 1998;**61**:507-511. DOI: 10.1016/S0141-3910(97)00249-8

[34] Teymouri A, Vahidi B. CO_2/CO concentration ratio: A complementary method for determining the degree of polymerization of power transformer paper insulation. IEEE Electrical Insulation Magazine. 2017;**33**(1):24-30. DOI: 10.1109/MEI.2017.7804313

[35] Widyanugraha T, Rachmad R. Wendhy, Suwarno. DGA and tensile strength test on accelerated thermal aging of ester oil and Kraft paper. In: 5th International Conference on Electrical Engineering and Informatics; August. Vol. 2015. Indonesia: Bali; 2015. pp. 177-180

[36] Schaut A, Autru S, Eeckhoudt S. Applicability of methanol as new marker for paper degradation in power transformers. IEEE Transactions on Dielectrics and Electrical Insulation. 2011;**18**(2):533-540. DOI: 10.1109/TDEI.2011.5739459

[37] Thermo Nicolet Corporation. Introduction to Fourier Transform Infrared Spectrometry, [Internet]. 2001. Available from: https://www.niu.edu/analyticallab/_pdf/ftir/FTIRintro.pdf

[38] Abi Munajad A, Subroto C, Suwarno. Fourier transform infrared spectroscopy (FTIR) analysis of transformer insulation paper in natural ester. In: International Conference on High Voltage Engineering and Power Systems (ICHVEPS); 2-5 October 2017; Sanur, Indonesia. p. 446-450

[39] Liao R, Tang C, Yang L. Stanislaw G. Thermal aging micro-scale analysis of power transformer pressboard. IEEE Transactions on Dielectrics and Electrical Insulation. 2008; **15**(5):1281-1287. DOI: 10.1109/TDEI.2008.4656235

[40] Pei C, Shengchang J, Lingyu Z, Yanjie C, Shihua Z, Yun L, Huisheng Y, Ping P. The effect of thermal aging on surface structure and mechanical strength of oil-impregnated pressboard. International Conference on Condition Monitoring and Diagnosis (CMD); 25–28 September 2016; Xi'an; China. 2016:1000-1003

[41] Yoshida M, Uchida K, Kato M, Konishi Y. New diagnosis method of aging degradation for insulating paper in power transformers by measuring the refractive index of cellulose fibers. In: 2012 IEEE International Conference on Condition Monitoring and Diagnosis (CMD) International Conference; 23–27 September 2012; Bali, Indonesia; p. 56-59

[42] IEC 60450:2004 Measurement of the average viscometric degree of polymerization of new and aged electrical papers

[43] Roylance D. Stress-strain curves. Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139. 2001. Available froom: https://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/MIT3_11F99_ss.pdf

[44] Martin D, Marks J, Saha T. Survey of Australian power transformer failures and retirements. IEEE Electrical Insulation Magazine. 2017;**33**(5):16-22. DOI: 10.1109/MEI.2017.8014387

[45] Sanchez J, Banovic M. A general overview of power transformer diagnosis. Transformers Magazine. 2013:22-26

[46] Binder W. Trends in power transformer failure analysis. Transformers Magazine. 2014;**1**(1): 30-33

[47] Martins MA, Fialho M, Martins J, Soares M, Castro MC, Lopes R, Campelo H. Power transformer end-of-life assessment—Pracana case study. IEEE Electrical Insulation Magazine. 2011; **27**(6):15-26. DOI: 10.1109/MEI.2011.6059980

[48] Jalbert J, Lessard MC. Cellulose chemical markers relationship with insulating paper post-mortem investigations. IEEE Transactions on Dielectrics and Electrical Insulation. 2015; **22**(6):3350-3354. DOI: 10.1109/TDEI.2015.005295

[49] Emsley M, Heywood RJ, Ali M, Xiao X. Degradation of cellulosic insulation in power transformers. Part4: Effects of ageing on the tensile strength of paper. IEEE Proceedings - Science Measurement and Technology. 2000;**147**(6):285-290. DOI: 10.1049/ip-smt:20000644

[50] Carcedo J, Fernández I, Ortiz A, Carrascal IA, Delgado F, Ortiz F, Arroyo A. Post-mortem estimation of temperature distribution on a power transformer: Physicochemical and mechanical approaches. Applied Thermal Engineering. 2014;**70**(1):935-943. DOI: 10.1016/j.applthermaleng.2014.06.003

[51] Azis N, Liu Q, Wang ZD. Ageing assessment of transformer paper insulation through post mortem analysis. IEEE Transactions on Dielectrics and Electrical Insulation. 2014;**21**(2): 845-853. DOI: 10.1109/TDEI.2013.004118

[52] Müllerová E, Hrůza J, Velek J, Ullman I, Stříska F. Life cycle management of power transformers: Results and discussion of case studies. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**(4):2379-2389. DOI: 10.1109/TDEI.2015.005025

[53] Awadallah SKE, Milanović JV, Jarman PN. Quantification of uncertainty in end-of-life failure models of power transformers for transmission systems reliability studies. IEEE Transactions on Power Systems. 2016;**31**(5):4047-4056. DOI: 10.1109/TPWRS.2015.2497969

[54] Mahanta DK, Laskar S. Electrical insulating liquid: A review. Journal of Advanced Dielectrics. 2017;**7**(4):1-9. DOI: 10.1142/S2010135X17300018

[55] Primo VA, García B, Albarracín R. Improvement of transformer liquid insulation using nanodielectric fluids; a review. Electrical Insulation Magazine. 2018 in press

[56] Li J, Zhang Z, Zou P, Grzybowski S, Zahn M. Preparation of a vegetable oil-based nanofluid and investigation of its breakdown and dielectric properties. IEEE Electrical Insulation Magazine. 2012;**28**(5):43-50. DOI: 10.1109/MEI.2012.6268441

[57] Thabet A, Allam M, Shaaban SA. Investigation on enhancing breakdown voltages of transformer oil nanofluids using multi-nanoparticles technique. IET Generation, Transmission & Distribution. 2018;**12**(5):1171-1176. DOI: 10.1049/iet-gtd.2017.1183

[58] Arun Ram Prasath RT, Roy NK, Mahato SN, Thomas P. Mineral oil based high permittivity CaCu3Ti4O12 (CCTO) nanofluids for power transformer application. IEEE Transactions on Dielectrics and Electrical Insulation. 2017;**24**(4):2344-2353. DOI: 10.1109/TDEI.2017.006096

[59] Emara MM, Mansour DA, Azmy AM. Mitigating the impact of aging byproducts in transformer oil using TiO2 nanofillers. IEEE Transactions on Dielectrics and Electrical Insulation. 2017;**24**(6):3471-3480. DOI: 10.1109/TDEI.2017.006586

[60] Lv Y, Ge Y, Du Q, Sun Q, Shan B, Huang M, Li C, Qi B, Yuan J. Fractal analysis of positive streamer patterns in transformer oil-based TiO2 nanofluid. IEEE Transactions on Plasma Science. 2017;**45**(7):1704-1709. DOI: 10.1109/TPS.2017.2705167

[61] Lv Y, Ge Y, Li C, Wang Q, Zhou Y, Qi B, Yi K, Chen X, Yuan J. Effect of TiO2 nanoparticles on streamer propagation in transformer oil under lightning impulse voltage. IEEE Transactions on Dielectrics and Electrical Insulation. 2016;**23**(4):2110-2115. DOI: 10.1109/TDEI.2016.005730

[62] Cavallini A, Karthik R, Negri F. The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**(5):2592-2600. DOI: 10.1109/TDEI.2015.005016

[63] Sima W, Shi J, Yang Q, Huang S, Cao X. Effects of conductivity and permittivity of nanoparticle on transformer oil insulation performance: Experiment and theory. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;**22**(1):380-390. DOI: 10.1109/TDEI.2014.004277

[64] Liu D, Zhou Y, Yang Y, Zhang L, Jin F. Characterization of high performance AIN nanoparticle-based transformer oil nanofluids. IEEE Transactions on Dielectrics and Electrical Insulation. 2016;**23**(5):2757-2767. DOI: 10.1109/TDEI.2016.7736835

[65] Velasco J, Frascella R, Albarracín R, Burgos JC, Dong M, Ren M, Yang L. Comparison of positive streamers in liquid dielectrics with and without nanoparticles simulated with finite-element software. Energies. 2018;**11**(2):361. DOI: 10.3390/en11020361

[66] Pîslaru–Dănescu L, Morega AM, Morega M, Stoica V, Marinică OM, Nouraş F, Păduraru N, Borbáth I, Borbáth T. Prototyping a ferrofluid-cooled transformer. IEEE Transactions on Industry Applications. 2013;**49**(3):1289-1298. DOI: 10.1109/TIA.2013.2252872

[67] Pîslaru-Dănescu L, Morega AM, Telipan G, Morega M, Dumitru JB, Marinescu V. Magnetic nanofluid applications in electrical engineering. IEEE Transactions on Magnetics. 2013;**49**(11):5489-5497. DOI: 10.1109/TMAG.2013.2271607

[68] Lv YZ, Zhou Y, Li CR, Ma KB, Wang Q, Wang W, Zhang SN, Jin ZY. Nanoparticle effects on creeping flashover characteristics of oil/pressboard interface. IEEE Transactions on Dielectrics and Electrical Insulation. 2014;**21**(2):556-562. DOI: 10.1109/TDEI.2013.004151

[69] Shroff DH, Stannett AW. A review of paper aging in power transformers. IEEE Proceedings on Generation, Transmission and Distribution. 1985;**132**(6):312-319. DOI: 10.1049/ip-c:19850052

[70] Yoshida H, Ishioka Y, Suzuki T, Yanari T, Teranishi T. Degradation of insulating materials of transformers. IEEE Transactions on Electrical Insulation. 1987;**22**(6):795-800. DOI: 10.11 09/TEI.1987.298942

[71] Hill DJT, Le TT, Darveniza M, Saha T. A study of degradation of cellulosic insulation materials in a power transformer part 2: Tensile strength of cellulose insulation paper. Polymer Degradation and Stability. 1995;**49**(3):429-435. DOI: 10.1016/0141-3910(95)00100-Z

[72] Emsley AM, Heywood RJ, Ali M, Eley CM. On the kinetics of degradation of cellulose. Cellulose. 1997;**4**(1):1-5. DOI: 10.1023/A:1018408515574

[73] Gasser HP, Huser J, Krause C, Dahinden EAM. Determining the ageing parameters of cellulosic insulation in a transformer. In: High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467). Vol. 23-27. August; London, UK: IEEE; 2002. pp. 1-5

[74] Mcshane CP, Rapp KJ, Corkran JL, Gauger GA, Luksich J. Aging of paper insulation in natural ester dielectric fluid. In: Transmission and Distribution Conference and Exposition, 2001 IEEE/PES; 2–2 November. Vol. 2001. Atlanta GA, USA: IEEE; 2002. pp. 675-679

[75] Rapp KJ, Luksich J. Reaction rates of paper aged in natural ester dielectric fluid. In: Conference on Electrical Insulation and Dielectric Phenomena, 2001 Annual Report. Vol. 14-17. Canada: October;.Kitchener, Ontario; 2001. pp. 209-212

[76] Mcshane CP, Rapp KJ, Corkran JL, Gauger GA, Luksich J. Aging of Kraft paper in natural ester dielectric fluid. In: IEEE 14th International Conference on Dielectric Liquids, 2002. ICDL 2002. Proceedings of 2002. Vol. 12-21. Austria: July; Graz; 2002. pp. 173-177

[77] Mcshane CP, Corkran JL, Rapp KJ, Luksich J. Aging of paper insulation retrofilled with natural ester dielectric fluid. In: Conference on Electrical Insulation and Dielectric Phenomena, 2003 Annual Report. Vol. 19-22. USA: October; Albuquerque; 2004. pp. 124-127

[78] Shim MS, Jung JI, An JS, Choi SH, Seo YJ, Huh CS. Tensile strength of electrical insulating paper in natural ester and mineral oil. In: 4th International Conference of Power Engineering and Optimization (peoco2010). Vol. 23-26. Malaysia: June; Shah Alam; 2010. pp. 563-565

[79] Abdelmalik AA, Fothergill JC, Dodd SJ. Aging of Kraft paper insulation in natural ester dielectric fluid. In: IEEE International Conference on Solid Dielectrics (ICSD 2013); 30 June – 4 July; Bologna, Italy: IEEE 2013. p. 541-544

[80] Saruhashi D, Bin X, Zhiyuan I, Yanabu S. Thermal degradation phenomena of flame resistance insulating paper and oils. IEEE Transactions on Dielectrics and Electrical Insulation. 2013;**20**(1):122-127. DOI: 10.1109/TDEI.2013.6451349

[81] Madavan R, Balaraman S. Failure analysis of transformer liquid - solid insulation system under selective environmental conditions using weibull statistics method. Engineering Failure Analysis. 2016;**65**:26-38. DOI: 10.1016/j.engfailanal.2016.03.017

[82] Arroyo OH, Jalbert J, Fofana I, Ryadi M. Temperature dependence of methanol and the tensile strength of insulation paper: Kinetics of the changes of mechanical properties during ageing. Cellulose. 2017;**24**(2):1031-1039. DOI: 10.1007/s10570-016-1123-7

[83] Arroyo OH, Fofana I, Jalbert J, Rodriguez E, Rodriguez IB, Ryadi M. Assessing changes in thermally upgraded papers with different nitrogen contents under accelerated aging. IEEE Transactions on Dielectrics and Electrical Insulation. 2017;**24**(3):1829-1839. DOI: 10.1109/TDEI.2017.006449