ASSESSING THE AGEING OF TRANSFORMER INSULATION SYSTEM USING DIFFERENT AGEING INDICATORS

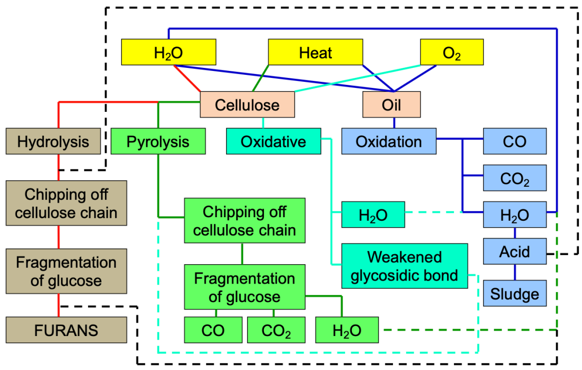
Insulation systems are critical components that ensure the efficient and reliable operation of power transformers. Assessing the ageing of these insulation systems are essential for maintaining their performance and preventing failures. Various ageing indicators can be used to evaluate the condition of transformer insulation systems, providing valuable insights into their health and helping to extend their operational life.

INTRODUCTION

Transformers are key assets in electrical power systems, and their reliability is crucial for uninterrupted power supply. The insulation system within a transformer plays a pivotal role in its performance, acting as a barrier to electrical, thermal, and mechanical stresses. Over time, the insulation system ages due to various factors, including thermal, electrical, and environmental conditions. Assessing the ageing of transformer insulation systems is vital to ensure their longevity and reliability. This article explores different ageing indicators used to evaluate the condition of transformer insulation systems.

TRANSFORMER INSULATION DEGRADATION PROCESS

The degradation process of transformer insulation system a complex process influenced by various factors, including thermal, electrical, chemical, and mechanical stresses. This ageing phenomena will determine the lifetime of the transformer and mainly caused by three basic factors; heat, oxygen and moisture.

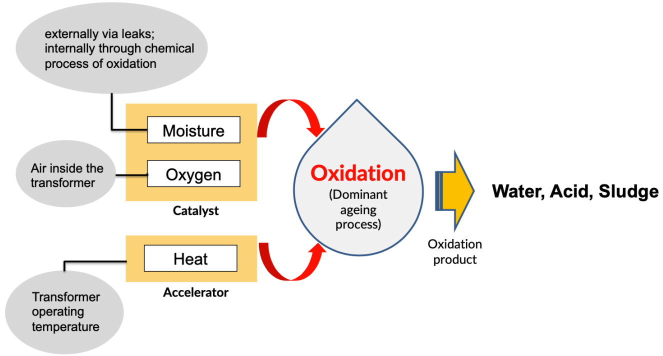


Depolymerisation under the effect of temperature is accelerated in the presence of moisture, oxygen and acids.

It is widely accepted that the main impact upon insulation longevity and depolymerisation of cellulose paper is heat or temperature. This process is further accelerated in the presence of moisture, oxygen and acids. A closer look on the impact of moisture, it has a serious role in premature ageing of insulation system including increases the risk of bubbling in the insulation and risk of partial discharge.

Degradation of Oil Insulation

Oxidation is the main cause of transformer oil degradation. It occurs when the oil reacts with oxygen, moisture and heat which leading to the formation of acids, sludge, and other polar compounds. Moisture acts as a catalyst for the ageing process. It can come from the environment



Ageing mechanism of oil insulation

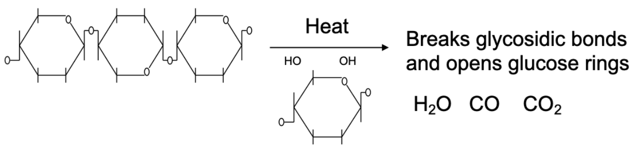
or be generated within the transformer due to the breakdown of cellulose insulation. The degradation process will be accelerated with an increasing of temperature. The ageing by-product produced can deteriorate the oil's insulating properties and cooling efficiency. Acids can damage the paper and copper windings, while sludge can clog cooling ducts.

Degradation of Paper Insulation

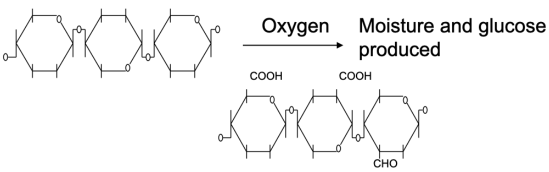
Insulation paper typically made from cellulose, is a critical component of a transformer's insulation system. Over time, this paper degrades or ages due to various factors, which can significantly impact the transformer's performance and lifespan. The degradation of paper insulation is not uniform and follows thermal and moisture gradients.

High operating temperatures accelerate the degradation of cellulose paper. The heat causes the cellulose molecules to break down, reducing the paper's mechanical strength and insulating properties. The ageing by-product from thermal degradation may include glucose molecules, moisture, carbon monoxide and carbon dioxide.

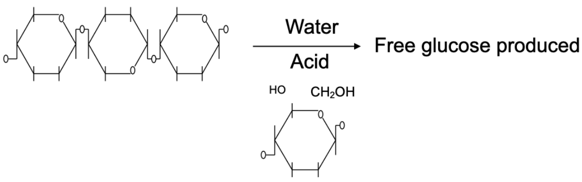
Moisture reduces the dielectric strength of the paper, making it less effective as an insulator and accelerating the ageing process. The presence of oxygen leading to the formation of acids and other degradation products and further degrade the paper and reduce its insulating properties.



Thermal degradation



Oxidative degradation



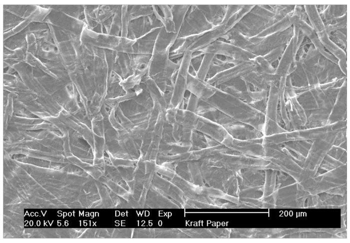
Hydrolytic degradation

TRANSFORMER AGEING INDICATORS

Paper and oil in transformers deteriorate under combined stress of oxygen, moisture and heat during the operating of transformers. Hence, aging of transformer oil and paper is needs to be examined through consistent methods. There are several ageing indicators can be used to assess the health and remaining life of the transformer. Some of the ageing markers are explained as follows.

Degree of Polymerisation (DP)

The Degree of Polymerisation (DP) is a crucial indicator of the condition of the paper insulation in power transformers. It refers to the number of repeating glucose units in the cellulose molecule of the paper insulation. Higher DP values indicate longer cellulose chains and stronger paper. Conversely, lower DP values mean shorter chains and weaker paper, which can compromise the transformer's insulation system. New paper typically has a DP value between 1200 and 1500. As the paper ages and degrades, the DP value decreases.



New insulating paper

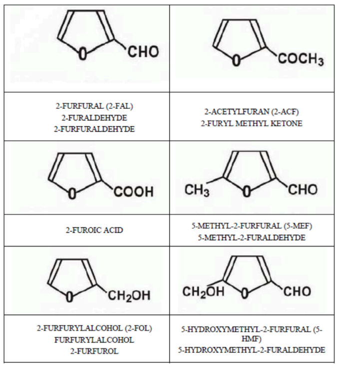

Degraded paper insulation

The life of a transformer is often considered to be the life of its paper insulation. When the DP value drops to around 200, the paper is generally considered to have reached the end of its useful life. At this point, the paper has lost significant mechanical strength and is at a higher risk of failure. The DP measurement is invasive as it involves taking actual paper sample and not always feasible for in-service transformers. Therefore, indirect ageing markers are more preferable and practical to assess the condition of paper insulation system.

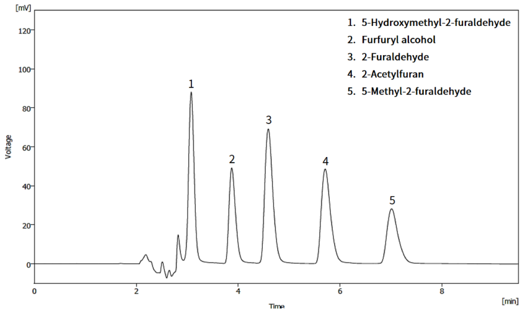
Furans Compound

Furanic compounds are chemical by-products formed from the thermal degradation of cellulose, which is a primary component of the paper insulation used in transformers. The presence and concentration of furanic compounds serve as indicators of the condition of the paper insulation. As the paper degrades, these compounds dissolve into the oil and unusual increases can signal significant insulation degradation.

Six furanic compounds, namely 2-furfural (2-FAL), 2-acetylfuran (2-ACF), 2-furoic acid, 5 methyl-2-furfural (5-MEF), 2-furfurylalcohol (2-FOL) and 5-hydroxymethyl-2-furfural (5-HMF) were identified as potential paper ageing indicators. Of these furanic compounds, 2-FAL is used more than the others due to its greater stability in oil and availability at higher concentrations than the others in transformers.



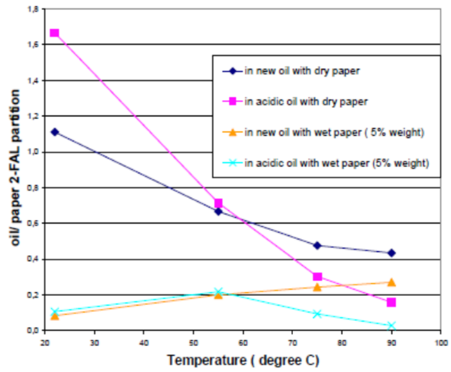
Chemical structures of furanic compounds



Furanic compound chromatogram - liquid/liquid extraction

The analysis of furanic compounds is typically performed using High-Performance Liquid Chromatography (HPLC) and extraction method can be either liquid/liquid extraction or solid phase extraction. In liquid/liquid extraction, transformer oil samples are mixed with a solvent, usually acetonitrile, to extract the furanic compounds. The mixture is then allowed to separate into two phases, with the furanic compounds migrating into the solvent layer and later injected into the HPLC system. The compounds are separated based on their interaction with the stationary phase of the chromatography column. Finally, the separated compounds are detected using a diode array detector, and their concentrations are quantified based on calibration curves prepared from known standards.

The analysis of furanic compounds also need to consider the migration of furans in oil-paper system. The concentration of the furanic compounds measured in oil is the quantity left in the oil after being partitioned between oil and paper. Typically, furanic compounds are absorbed more readily into paper than in the oil. This partitioning is influenced by factors such as temperature, humidity of paper and oil quality. In addition, furans may generated by other components of paper and paper ageing by-products.



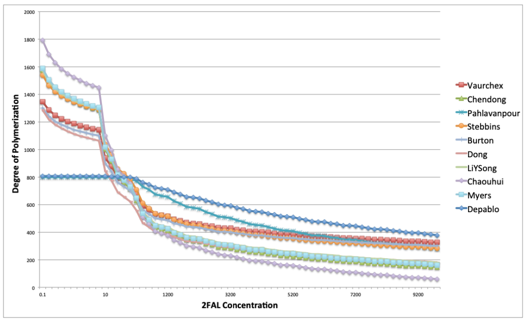
Effect of various factors in the partitioning of 2-FAL between oil and paper (Ref: CIGRE TB 779)

Although the analysis of furanic compounds presents a certain level of transformer reliability, the limits or threshold values of furanic compounds use for diagnostic purposes is not well established yet. Nevertheless, the industry has agreed to use the following threshold limit to show different states of insulating paper based on the concentration of 2-FAL in the insulating oil.

2FAL Concentration (ppm)	Condition
2FAL < 0.5	Good
0.5 < 2FAL < 1	Acceptable
1.1 < 2FAL < 1.5	Need caution
1.6 < 2FAL < 2.0	Poor
2FAL > 2.1	Very poor

Correlation of 2FAL and the state condition of paper insulation

The increase of 2-FAL concentrations in oil has been found in accordance with the reduction of paper's DP and previous works under laboratory experiment has established the correlation of 2FAL and DP of the paper inside the transformer. Several equations have been developed to correlate 2FAL concentration in oil with paper's DP. Nevertheless, an attempt to use these equations must be treated with caution because the ageing of transformer and furan formation depends on transformer design, oil to paper ratio, loading, operating and ambient temperature.



Correlation between 2FAL and paper's DP

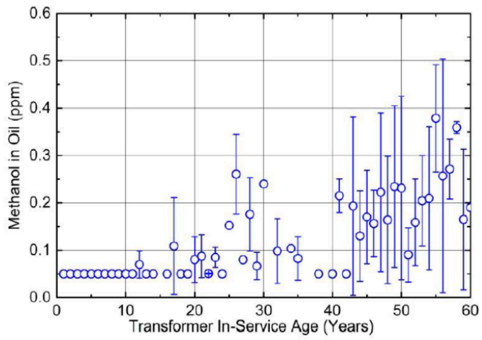
Carbon Gases

The detection of fault gases using Dissolved Gases Analysis (DGA) is widely accepted as diagnostic tool to assess the condition of oil and paper insulation in the transformer. During degradation process, CO_2 and CO are produced as by-products. The concentration of these gases in the transformer oil can be correlated with the degree of paper degradation. The analysis of CO_2/CO in oil for transformers in normal operation is typically greater than seven. When the value of CO_2/CO is less than six, it may indicate that the existence of fault leads to rapid aging of the insulating paper. When the value of CO2/CO is less than two, it may indicate that there is a serious paper insulation fault in the transformer. However, care should be taken when analysing the paper ageing through CO_2 and CO, as theses gases may also produced from the degradation of other organic materials in the transformer and may interfere with the interpretation results.

Methanol

Traditional indicators like furans and dissolved gases have been used for decades to monitor transformer aging process. However, recent research has identified methanol (MeOH) as a promising new marker for early detection of insulation degradation. Methanol is produced during the thermal degradation of cellulose occurs at a molecular level and can be detected even at early stages of degradation, making methanol a valuable indicator. Unlike 2-FAL, methanol can detect the degradation of thermally upgraded paper, which is commonly used in modern transformers

Methanol can be detected using several advanced techniques such as Head-Space Gas Chromatography-Mass Spectroscopy (HS-GC-MS), Gas chromatography-Mass spectrometry (GC-MS) and Spectrophotometry. These methods allows for precise measurement of methanol concentrations in transformer oil, providing reliable data for assessing the condition of the insulation.



Variation in methanol for in-service aged transformer oil samples

There is a good correlation between the content of methanol in oil and the DP of cellulose according to various research. Compared with furans, methanol is not easy to oxidize, has higher content in oil, and is easier to be detected. Methanol can be detected in the oil at the early stage of cellulose aging, while the content of furans is very small at the early stage of aging, and the content gradually increases in the middle and late stages of aging.

Low Molecular Weight Acid

Low molecular weight acids (LMAs) is another significant indicators used for assessing the aging of transformer paper insulation. These acids, primarily short-chain carboxylic acids, are produced during the thermal degradation of cellulose in the paper insulation. Similar to furans compound analysis, LMAs are measured in the oil and there is no need for physical sampling of the paper thus preserving the integrity of the transformer. Even so, research studies have shown that the concentration of LMAs varies with different types of transformer oils.

Ketone Compound Analysis

Acetone and other ketone compounds are valuable indicators in the analysis of paper insulation aging in power transformers. In the early days, acetone indicator use to monitor the insulation performance of cellulose paper was rarely studied. Analysis of the collected oil samples from field transformers found that the concentration of acetone was about 100 ppb or even more than 1000 ppb in many samples aged for 10 years or more. Moreover, it was found that the concentration of acetone in the insulating oil has a good correlation with DP and the experimental value was in good agreement with the actual measured value. However, the formation mechanism of acetone indicator remains to be studied in the future.

CONCLUSIONS

This article outlines different ageing indicators for monitoring the aging condition of oil-impregnated transformer paper insulation. It is emphasized that the aging condition of paper insulation is critical in determining transformer service life, and the mechanical properties of insulating paper serve as the foundation for monitoring the aging degree. Overall, the systematic monitoring of aging markers is an essential practice for optimizing the performance and longevity of power transformers, thus ensuring a reliable power supply.

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Transformer Type Testing: Key to Quality and Safety Assurance

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