Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.12, No.3, 2022

# Life Span Assessment of the Insulation for Power Transformers: A Review

Ganiyu Adedayo Ajenikoko Abass Balogun
Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, P.M.B, 4000, Ogbomoso, Nigeria
Corresponding Email: ajeedollar@gmail.com

## Abstract

A power transformer is a vital link for any electrical transmission and distribution network, used to raise the voltage levels of the generators, and transformers at local substations to supply loads. However, an unexpected failure of power transformers cause an electricity shortage to the consumer, involve the loss of millions of dollars for utility companies, industrial failure costs, environmental hazard costs due to oil spillage and also indirectly to the national security. Hence, predicting the lifespan of a power transformer has been considered an important issue for energy companies in order to reduce the transformer failure. Power transformers that reach the end of its life usually do so unexpectedly, causing power reliability problems, which cost a lot of money. Therefore, knowing the factors that play part in the degrading process of a power transformer could help power companies determine how long a power transformer have before breaking down and allow them to perform any necessary action before the power transformer starts giving problems. This research paper therefore focuses on the life assessment of the insulation for power transformers. In this paper, different approaches used for the evaluation of lifespan of power transformers were reviewed. These approaches have become powerful tools to overcome the problem of transformer failure and aging, because these tests are carried out more frequently by utilities. This research paper therefore, will help utilities to monitor the major parameters, to determine the remaining life and the lifespan of power transformers.

**Keywords:** Power Transformers, Electrical Transmission Network, Electrical Distribution Network, Lifespan, Consumers, Transformer Failure, Reliability, Transformer Aging.
**DOI:** 10.7176/JETP/12-3-02
**Publication date:**August 31st 2022

## I. Introduction.

Power transformers are vital assets in electric power systems, as they are essential in maintaining a reliable supply and very high in cost. Nowadays, society has become more and more dependent on the availability of power, putting pressure on the reliability, availability and cost efficiency of power supply [1, 3]. These transformer operate under high electric stresses and this resulted in high heat dissipation thus limiting its factor for the maximum loading. Moreover, the point at which a transformer must be replaced or its remaining lifespan, are very important issues for power system managers. The life of a power transformer mainly depends on the condition of the paper-oil insulation system. In fact, most of the power transformers use paper and oil as the main insulation and the mineral oil play an important role of insulating and cooling of it [2, 6, 9].

There are few possible mechanisms that are subjected to the insulation degradation because of the ageing, high temperature and chemical reactions such as the hydrolysis, oxidation and pyrolysis [2]. The insulating medium must be capable of dealing with large electric stresses, strong electro-mechanical forces and high temperatures. Also, the condition of oil has to be checked on regular basis. Failures of transformer can lead to strong effect on security and reliability of power supply and cost. The temperature inside a power transformer varies with the load. Due to that higher operating temperature, faster degradation of paper/oil insulation system in transformer and (thermal ageing) leads to change of some insulation characteristics, consequently the remaining life span of the power transformer is degraded [1, 10, 13, 25].

Power transformers play a vital role in maintaining reliable and efficient electricity supply. Manufacturers often define the expected life of power transformers to be between 25 and 40 years [4]. Some transformers in service are now approaching this age, and it is important to estimate their remaining lifetime in order to prevent premature shutdown of transformers and to provide an uninterrupted power supply to consumers. Knowing the condition of the transformers is an essential factor to make an economical decision for transformer replacement and maintenance [5, 11, 27].

Nowadays, there are many condition monitoring techniques available for transformers and some measured conditions such as temperature, moisture, Degree of Polymerization (DP), and furan content have a direct relationship with transformer insulation paper which can be interpreted mathematically. Furan compounds are generally recognized as the most practicably obtainable and reliable indicator of cellulose insulation and degradation. Also applying IEEE transformer loading guide during a transformer operation could help to understand the "health" condition of an operating transformer and assess the remaining life of the transformer [5, 7, 8, 12, 40].

## II. Transformer Ageing

Ageing is a critical issue many machines face. Most machines are designed with a specific life span, after which it is expected that the machine is changed for optimum service delivery as the case may be. Some machines are designed such that different components of it are expected to be changed at different times within the whole unit still with the aim of quality service delivery [14]. Most operators pay less attention to the age/ageing factor in the effectiveness of their machine/machine parts. It is usually of less concern until major breakdown occurs. This could however lead to disruption in the delivery of quality service. The CIGRÉ working group 12.09 pioneered the work on transformer lifespan evaluation and published its findings in 1993. The work gave an insight into the failure rates and mechanisms and suggested the replacement strategy from a system operator/asset owner view point [17, 20].

[34] described natural ageing or deterioration of insulation as a time function of temperature, moisture content and oxygen content. Hence insulation used in transformers is based on how long it is be expected to last by limiting operating temperatures. The temperature that insulation is allowed to attain under standard operating conditions essentially determines the output rating of the transformer, otherwise referred to as the kVA rating [18]. Standardization has led to temperatures within a transformer being expressed in terms of the rise above ambient temperature, since the ambient temperature can vary under operating or test conditions. Transformers are designed to limit the temperature based on the desired load, including the average temperature rise of a winding, the hottest spot temperature rise of a winding, and, in the case of liquid-filled units, the top liquid temperature rise [15, 16, 19].

Power transformer ageing is one of the critical issues utilities are facing, since a large number of units across many utility companies usually approach the end of their designed lifespan while many even exceed their designed lifespan. A substantial number of these units are also observed to fail or begin to fail before proper attention is given.. Failure rate is one of the parametric indices used for assessment of electrical power system. It is defined as the inability of the system to perform its designated function adequately without interruption over a period of time [4, 5, 22].

Failure of any machine, unit and by extension transformers interrupts service delivery which in turn results in a loss in revenue of the utility companies and discomfort to consumers. Failures not only reduce reliability of the power system, but also have significant effects on power quality since one of the important components of any system quality is reliability of that system [28]. Hence, in order to avoid failure, a good end-of-life model is required to optimize asset replacement investment while still maintaining system reliability. Analysis of failures of HV assets and end-of-life analysis, particularly of power transformers, has been carried out since the 1990s [47].

## III. Power Transformer Life Expectancy

The life expectancy of the power transformer is principally dependent on the design parameters of the transformer. Every transformer has a nameplate on which the design parameters are clearly stated. The design parameter primarily determines how long the manufacturer has in mind that the transformer may last in useful life, subject to the condition of usage of the transformer [5, 21, 25].

The normal life expectancy of power transformers is generally assumed to be about 30 years of service when operated within their ratings. However, they may be operated beyond their ratings, overloaded, under certain conditions with moderately predictable "loss of life" [29]. Situations that may involve operation beyond rating are emergency re-routing of load or through-faults prior to clearing. When transformers are operated beyond their normal rating, it could lessen the lifespan or life expectancy of the transformer. On the other hand, effective usage on the transformer below the rating may attract more life [21, 23, 41, 47].

The expected life of a 65°C rise transformer is based on a continuous hot-spot temperature of 110°C. That is, for each hour that the transformer is operated at a hot-spot temperature of 110°C, the life is reduced by 1 hour. The *IEEE Guide* assumes a normal life of 180,000 hours which is about 20years [24, 34].

Many utility companies and academic researchers have predicted and pegged the life expectancy of power transformers at different number of years. Most life expectancy (years) adopted by the researchers has been used as reference to validate their models. This to a large extent is dependent on the parameters and metrics involved in their models (since the power transformer is a complex unit) [24, 27, 37].

[29] mentioned a life span of about 20 years for a power transformer. The study however took the position which it described as common belief that an oil-filled transformer is designed for a life expectancy of 30 to 40 years. The study explained that keeping transformers cool will extend their normal life and utilities prefer to retire a transformer just before it reaches the end of its useful life. [9] reviewed degradation and life modelling of paper and illustrated different approaches, showing their advantages and applicability limits as well as problems relevant to practical applications of degradation indicators and degradation rate models as well as evaluation of

paper durability. The study dealt with the fundamentals of paper degradation rate theory and life modelling. It sought to develop the degradation rate equations of paper that will closely track real degradation experimental results over extended period under practical service conditions towards a more reliable prediction of rate and life of paper degradation over a long time period under real in-service conditions.

[34] defined the end of life of a transformer as the state of an insulation system where dielectric stress or short circuit stress or mechanical movement which could occur in normal service, would cause an electrical failure. The study asserted that most power transformers should last approximately 40 years while distribution class transformers are slightly less. The study also stated that the ageing of paper is a cumulative effect and operating above these temperatures will increase normal ageing, while operating below these temperatures will decrease normal ageing.

[20] discussed the different types of insulations system and the ageing process of insulation system used in power transformers such as solid insulation and liquid insulation. The estimated load factor and ambient temperature of transformer are input and used to find out hotspot temperature using hotspot temperature. Using IEC (international electro technical commission), the study easily find out ageing rate and loss of life of insulation. The result showed that the relative ageing rate of the insulation system increased rapidly, as the temperature increased. It was shown that the method could be used to predict loss of insulation life in power transformer due to ageing.

[43] identified the key factors influencing transformer normal operating conditions and predicted the asset management lifespan of transformer utilizing the data source from a Remote Terminal Unit (RTU) system for sensor-data driven analysis. This paper therefore, developed an innovative real-time lifespan forecasting approach applying logistic regression based on the Weibull distribution. The methodology and the implementation prototype were verified using a data series from 161 kV transformers to evaluate the efficiency and accuracy for energy sector applications. The asset stakeholders and suppliers significantly benefit from the real-time power transformer lifespan evaluation for maintenance and replacement decision support.

[3] implemented prognostic models for generator step-up transformers in the Fleet-Wide Prognostic and Health Management (FW-PHM) Suite. The prognostic model discussed was based on the functional relationship between degree of polymerization, the most commonly used metric to assess the health of the winding insulation in a transformer and fural concentration in the insulating oil. The other model was based on thermally induced degradation of the transformer insulation. By utilizing transformer loading information, established thermal models are used to estimate the hot spot temperature inside the transformer winding. Both models are implemented in the remaining useful life database of the FW-PHM suite. The remaining useful life advisor utilizes the implemented prognostic models to estimate the remaining useful life of the paper winding insulation in the transformer based on actual oil testing and operational data.

[32] reviewed degree of polymerization equations which relate one or more properties of the insulating system with the life expectancy of the power transformer. These equations were used in a fleet of transformers in order to estimate the accuracy of these mathematical models. Results showed that the methods achieved the most reliable estimation when the transformers have operated less than 8 years. Nevertheless, when the transformers are older, the estimation of lifetime based on furanic compounds is quite erratic and should be improved.

[30] presented a novel Adaptie Neuro Fuzzy Inference System (ANFIS) approach to estimate the paper degree of polymerization based on dissolved gas analysis and oil characteristic. In this context, data of oil insulation characteristic, DGA, and furan compounds of 200 150/20 kV and 42 500/150 kV operating transformers are collected from PT. PLN. The Calculated degree of polymerization from furan data of each investigated transformer was analyzed using the corresponding oil insulation characteristic and DGA data. The results showed that carbon oxide compounds, acidity number, interfacial tension, and colour of the oil are statistically correlated with the degree of polymerization of the insulation paper. The results of the developed ANFIS model revealed an overall accuracy more than 86% for the two investigated transformers' data.

[31] developed a two-stage hybridized model for determining the lifespan of power transformers using the furan content and the Degree of Polymerization (DP) of transformer. 2-Furaldehyde (2FAL) content values of 0.01ppm and 10ppm corresponding to DP values of approximately 1200 and 250, respectively were used in developing a DP model using Jacobi and Gauss Seidel numerical analysis iterative techniques. The techniques were implemented in Matrix environment. The second stage involved the hybridization of the developed DP model with another rate constant model adopted from Arrhenius. This stage was also implemented in Matrix environment. The life span of the transformer was determined by adding the service age at any point in time to the remaining lifetime at that point. Factors such as the hotspot temperature, activation energy and pre-exponential factor were useful for the determination of lifespan.

## IV. Transformer Winding Insulation

The insulation system of a power transformer consists of hydrocarbon oil and cellulose paper [29]. Insulation systems consist of paper insulation and mineral oil [34]. Both oil and paper have been in use as insulating materials in oil-filled transformers for more than a century. They have been found to be very effective insulators more especially in their combination as it is revealed in their observed synergy. There are several factors that contribute to transformer winding insulation ageing. Among all factors, temperature is generally accepted as the most important factor. Temperature influences not only the ageing of the paper, but also ageing of the oil. It is commonly accepted that mineral oil impregnated cellulose in insulation ages with time and the ageing doubles for every 6-8ºC increase in temperature [26, 32, 45].

Electric load losses occur primarily in the transformer windings, causing thermal stress in multiple transformer components. This leads to ageing and decomposition of paper insulation material and cellulose [5]. As the paper insulation ages, its mechanical strength depletes, making it to become more susceptible to tearing and ultimately bursting under stress caused by faults or vibrations of the operating transformer. Once mechanical damage of the insulation has occurred, movement of the conductors is likely, resulting in changing voltage stresses and electrical discharge. These eventually lead to catastrophic failure in the transformer [40, 44, 46].

The three mechanisms that lead to transformer winding insulation degradation are oxidation, hydrolysis and thermolysis (pyrolysis) [39]. Thermolysis is predominant at temperatures above 120°C, which are usually limited to local defects (e.g., winding hot spot). The mechanisms weaken and break cellulose molecules in paper insulation, leading to reduction of its Degree of Polymerization (DP). Based on the analysis of dissolved gas in oil, the concentration of furan derivatives, DP, tensile strength of the insulation paper and other characteristic parameters affect the life of oil–paper insulation [45]. Each split in the cellulose chain liberates a glucose monomer, which undergoes further chemical reaction and becomes one of several furan compounds [8].

When moisture or oxygen are present in the insulation, the activation energy of the chemical reaction in hydrolysis is reduced, causing degradation leading to accelerated insulation decomposition [19]. Degradation also releases larger molecules such as 2FAL, which can be detected in the oil and could give a more specific indication of the condition of the paper. The formation of 2FAL content in the insulating oil lowers the average DP of the paper which in turn leads to loss of tensile strength of the paper, making transformer insulation more susceptible to physical damage. Paper insulation reaches its end of life when the paper has lost 50% of its tensile strength [34, 36].

## V. Different Approaches used for Assessment of Life Span of Power Transformer

Different approaches have been proposed to estimate the life assessment of the insulation for power transformers. Various methods, such as Furaldehydes (Furans), Degree of Polymerization (DP), Carbon Oxides Concentration (CO and CO2) and Ageing Acceleration Factor (AAF) have been used for the estimation. These approaches have become powerful tools to overcome the problem of transformer failure and ageing, because these tests are carried out more frequently by utilities [33, 39, 43].

### a. Furaldehydes

Furaldehydes (Furans) are chemicals formed when cellulose paper degrade due to overheating. They are the major degradation products of insulating paper in transformer oil [2].The status of Solid insulation can be measured using liquid oil insulation. This is an alternative method for estimating the Degree of Polymerisation (DP) value of the paper insulation. Furans are one of the most important age-related by-products of cellulose paper ageing dated back to 1980. It has been shown by ageing experiments that no furan is produced in a blank oil sample (i.e. oil with no paper insulation). When a cellulose chain breaks down during paper ageing, the chain liberates a glucose monomer, which undergoes a further chemical reaction to form furan compounds [8, 42]. Therefore, furan concentration is directly related to insulation paper degradation.

Furans are rapidly produced during paper pyrolysis at very high temperatures. At typical transformer operating temperatures, the primary mechanism of furan formation is paper hydrolysis. Five main furan compounds have been identified in transformer insulating oil, namely 2-Furaldehyde (2FAL), 2-Acetylfuran (2ACF), 5-Methyl-2-Furaldehyde (5MEF), 2-Furfurol (2FOL), and 5-hydroxymethyl-2-furaldehyde (5HMF) [19, 35, 38]. However, the stability of the Furan compounds is very essential. Compounds which are not stable for a long period of time will lead to inaccurate conclusions drawn from the analysis. Some of the above mentioned Furan compounds are formed during ageing but are very unstable under a number of conditions. These therefore, cannot be used or are not useful for diagnostics [1. 20, 31, 45].

Studies by [15] have shown that Furan compounds are generated also if the cellulose is subjected to electrical discharges, but in very small quantities. During thermal ageing, large quantities of Furan compounds can be generated when cellulosic materials are exposed to very high temperatures (typically above 120°C). Once formed, the Furan compounds can still survive for prolonged periods of time in bulk oil, which is at a much lower temperature than the hottest spot in the insulation (winding) [7].

[24] identified the following as affecting the generation, stability, and accumulation of furan compounds:

i. Effects of oil degassing by partial vacuum
ii. Effects of mechanical filtration (reconditioning)
iii. Effects of oil reclamation

iv. Effects of oil change-out
v. Stability of furan compounds in oil
vi. Kraft, thermally-upgraded (TU) Kraft, varnish and epoxy coatings and insulation systems
vii. The Generation of 2-Furfural in Kraft, TU and mixed insulation including the effects of dicyandiamide (DICY) and "Cross Pollination"
viii. Partition coefficients
ix. Effects of electrical discharge and high temperatures
x. The role of the transformer preservation system

Studies have revealed, through laboratory tests, that 2 furfural also referred to as the 2-furaldehyde (2FAL) is the most stable by-product of cellulose ageing as it is stable for years. It is therefore widely used as an indicator in order to predict the paper DP value [15]. However, there is still debate on the issue of furan compound accumulation from thermally upgraded paper and from normal Kraft paper. Some researchers have shown that the behaviour is different if using thermally upgraded paper while there are a few who state that there is no difference in furan compound behaviour between the thermally upgraded paper and normal Kraft paper.

### b. The Degree of Polymerisation (DP)

Degree of polymerization (DP) is average number of Cellulose molecules in the Cellulose chain. It is a direct technique applied to assess the condition of insulating paper in power transformer and best indication value to predict the actual transformer age [33]. Degree of polymerization value reveals a strong correlation between the insulation paper deterioration and formation of ageing products. For a new transformer DP is around 1200 and when transformer insulation paper reaches its end of life it falls below 200 [2]. It can be measured accurately by performing chemical tests for insulation paper sample. However, measuring this parameter is a challenging process due to the difficulty in acquiring paper samples from hot spot locations of operating transformers. Insulation oil characteristics and Dissolved Gas Analysis (DGA) of power transformers have become powerful tools to overcome this limitation, because these tests are regularly performed by utilities [40].

However, the solid insulation in a transformer is cellulose based, consisting of long chains of glucose rings. When degradation of the cellulose occurs, these chains get shorter. The Degree of polymerization (DP) is the average number of these rings in the chain and it indicates the condition of the paper [9]. The Degree of Polymerization (DP) is a test done on the paper to reveal its mechanical strength. According to [22], new paper has an average DP number of 1200-1400. A DP less than 200 means that the paper has reached a poor mechanical strength that it can no longer fulfill its function.

An inverse relationship exists between the DP (paper test) and the Furans (oil test); the higher the Furans in the oil, the lower the DP of the cellulose paper. This relationship holds however, only when paper or oil is degrading evenly. The DP of the paper usually varies with the solid insulation. Furan analysis in the insulating oil can indirectly reveal the status of the solid insulation. During ageing, some by-products are formed. These get dissolved in oil and hence the oil can therefore be analysed for furan content [7, 12, 36]. Although the measurement of Furan compounds from an oil sample is relatively simple, the interpretation is complex and more than one mechanism is involved in the ageing process. At low temperatures, moisture and carbon-oxide gasses are the more dominant products of the ageing process. The Furan compounds are dominant at intermediate temperatures and are unstable at high temperatures [12, 26, 39].

One way of determining the DP value without taking the transformer out of service, involved analysing the insulating oil for furan compounds, which are produced during the ageing of the cellulose insulation [38]. This method is referred to as the indirect method. Several researchers have worked on relationship between the DP value and the Furan compound (2FAL) concentration. However, few of the researchers came up with some models, while others justified the models. The DP value indicated the number of monomer units in the polymer as the cellulose is a linear polymer composed of individual anhydrous glucose units linked by glucosidic bonds. The DP value is currently used by utilities as a diagnostic tool to determine the condition of the solid material (particularly paper) [2, 40, 45].

Furan content has an exponential relationship with DP value and this relationship can be predicted by using different methods [9, 19].

[36] calculated the DP value as a function of the amount of CO, $CO_2$ and furfurals in the oil for the elapsed life in years where it assumed that un-aged transformer cellulose insulation has a DP value of about 1100 as:

$$ElapsedLife = 20.5 \times \ln\left(\frac{1100}{DPValue}\right) \quad (1)$$

[29] developed Arrhenius transformer loss of life model based on the concept that temperature is the only ageing parameter. According to this model, transformer ageing is dictated by the ageing of the most thermally stressed location i.e. the hottest spot usually referred to as just the hot spot as:

$$LoL\% = 100 \times \Delta t \times 10^{-\left[A + \frac{B}{\Phi + 273}\right]} \quad (2)$$

where:

LoL% = Loss of life
A, B = ANSI standard parameters
$\Phi$ = Hot spot temperature in degrees Celsius
$\Delta t$ = Transformer operating time in hours, with hot spot temperature of $\Phi$

In addition, some of the developed mathematical models showing this correlation between furan content with DP value are [10, 13, 17, 19, 20]:

i. **The Chendong Model:** This equation was developed based on the data collected from transformers that have normal Kraft paper and free breathing conservators [10, 13] as:

$$DP = \frac{\log(2FAL) - 1.51}{-0.0035} \tag{3}$$

where the concentration of 2FAL is in ppm

ii. **Stebbins Model:** This model is a modification of Chendong model which is to be used for thermally upgraded paper. Stebbins's equation is given by [13]:

$$DP = \frac{\log(2FAL \times 0.08) - 4.51}{-0.0035} \tag{4}$$

The concentration of 2FAL here is expressed in parts per billion (ppb).

However, both the Chendong's and Stebbins's models are limited to certain transformers. This is dependent on the type of paper used for insulation. The models calculate the prevailing DP value by considering the concentration of the furans in oil [11].

iii. **De Pablo Model:** The De Pablo model was also modified by Pahlavanpour *et al.* (2002) [33] in order to take into consideration that paper ageing is not uniform and the assumption that 20% of the inner paper layers in the winding degrade twice as fast as the rest of the insulation paper. This model is given as:

$$DP = \frac{7100}{8.8 + 2FAL} \tag{5}$$

where; 2FAL is in ppm, and the equation is linear.

[12] and [23] also gave another modified De-Pablo Model which was referred to as Leibfried model as:

$$DP = \frac{1850}{2FAL + 2.3} \tag{6}$$

iv. **Vuarchex Method:** Relationship expressed by the Vuarchex method is given as:

$$DP = \frac{2.6 - \log[2FAL]}{0.0049} \tag{7}$$

v. **Heisler and Banzer Method:** The Heisler and Banzer method was given by [23] as:

$$DP = 325 \times \left(\frac{19}{13} - \log(2FAL)\right) \tag{8}$$

i. **Burton method:** This method was developed by [12] as:

$$DP = \frac{2.5 - \log[2FAL]}{0.005} \tag{9}$$

The Chengdong and Depablo methods are widely used in the power industry to calculate the DP values of transformer paper insulation using Furan analysis [18]. However, one major setback common to these models is where the oil has been replaced or regenerated, which may vary the concentration of the furans. However, with the assumption that the mineral oil would not be changed, the second setback is based on the range of the values based on the 2FAL content range of 0.01ppm (for a virgin transformer/oil) and 10ppm (for a transformer/oil at end of its useful life). Typically, values of 1200 and 250 may be chosen for virgin transformers and for transformers with the end of useful lifespan respectively for simulations and analysis [38].

### c. Carbon Oxides Concentration (CO and CO2)

An indirect technique for paper insulation assessment is by using a Dissolved Gas Analysis (DGA). As opposed to the Degree of Polymerization method, DGA can be easily applied to an operating transformer [15, 34]. By analyzing the insulating oil of a transformer for specific gas concentrations, its generation rates and total combustible gases can be detected using DGA approaches [44]. Gases dissolved in transformer oil can be extracted using ASTM D3612 – Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography [15] or the IEC Standard 567- Guide for the Sampling of Gases and Oil from Oil-Filled Electrical Equipment and for the Analysis of Free and Dissolved Gases [47].

[36] studied the remaining life of power transformer using the theory of stochastic processes. The work

compared the amount of CO, CO2 and furfurals dissolved in oil where the use of furfurals was preferred for content analysis. Carbon monoxide and Carbon dioxide were mainly produced by the oxidation of paper under normal operation.

[18] reported a strong relationship between the amount of carbon oxides, CO and CO2, dissolved in transformer oil and the degree of polymerization of insulating paper exist. However, the amount of carbon oxides in insulating oil may also originate from oil decomposition due to long-term oxidation process.

[38] reported that water and carbon dioxide are the main by-products of the thermal degradation of cellulose. Hence, the ratio of CO2/CO is normally used as an indicator of thermal decomposition of cellulose. According to the IEEE Standard C57.104, the ratio of CO2/CO is normally around seven, while the respective values of CO2 and CO should be greater than 5000 parts per million (ppm) and 500 ppm respectively in order to improve the certainty factor.

According to [6], when this ratio of CO2/CO is less than 3, it indicates a severe paper degradation. When the ratio exceeds 10, it indicates a fault of temperature less than 150°C. [47] explained that faults start to arise when the CO2/CO ratio is less than 6. In addition, [1] maintained that it arose at a higher CO2/CO ratio after considering the absorption phenomenon of CO2 and CO into paper insulation. Therefore, diagnosing the condition of paper insulation using CO2/CO is not reliable since carbon oxides may be generated from the long-term oxidation of oil components or could present as a result of an atmospheric leak.

**d. Ageing Acceleration Factor**

Another model which researchers have used to assess and predict the lifespan of power transformers involves the use of the hotspot temperature and the ageing acceleration factor to predict the percentage loss of life. The equation that relates the hot spot temperature and ageing acceleration factor is given as [45, 47]:

$$F_{AA} = \left[\frac{15000}{383} - \frac{15000}{\theta_h + 273}\right] \tag{10}$$

where $F_{AA}$ has a value greater than 1 for winding hottest-spot temperatures greater than the reference temperature $110^0$C and less than 1 for temperatures below $110^0$C.

To estimate insulation heating effect, the loss of life factor is integrated over a given period of time. Since insulation ageing is a cumulative effect, the percent loss of life per day is the summation of the percentage loss of life as [3, 19]:

$$Percentage\ loss\ of\ life = \frac{0.0000285 \times ageingfactor \times 100\%}{baselife} \tag{11}$$

The limitation of this model is on the basis of considering the hotspot temperature as the factor determining the lifespan of the transformer. This is a valid but insufficient premise again to determine the lifespan of power transformers.

For a given hot spot temperature, the rate at which transformer insulation ageing is accelerated can be compared with the ageing rate at a reference hot spot temperature [44]. The per unit transformer insulation life function can be used as a basis for calculating an ageing acceleration factor ($F_{AA}$) for a given load and temperature, or for a varying load and temperature profile. The reference value of hotspot temperature is 110°C for 65°C winding rise. The Ageing Accelerating Factor ($F_{AA}$) is calculated as [44, 46]:

$$F_{AA} = \left[\frac{15000}{383} - \frac{15000}{\theta_h + 273}\right] \tag{12}$$

The per unit life equation is the basis for calculating the ageing accelerating factor curve. Table 1 displays per unit life and ageing acceleration factor values for different hot spot temperatures. It shows that these values are very sensitive to hot spot temperature. It also indicates the degree to which the rate of ageing is accelerated beyond normal for temperature above a reference temperature of 110°C and is reduced below normal for temperature below 110°C [36, 40].

Table 1: Per unit life and ageing acceleration factor at various winding hotspot temperatures

| Winding Hotspot Temperature ($T_H$) | Per Unit Life | Ageing Acceleration Factor |
|---|---|---|
| 100 | 2.859 | 0.350 |
| 105 | 1.679 | 0.596 |
| 110 | 1.000 | 1.000 |
| 115 | 0.604 | 1.656 |
| 120 | 0.369 | 2.709 |

Source: [44]

In addition, the equivalent ageing factor is given as [40]:

$$F_{EQA} = \frac{\sum_{n-1}^{N} F_{AA_n} \times \Delta t_n}{\sum_{n-1}^{N} \Delta t_n} \tag{13}$$

where:

$F_{EQA}$ = Equivalent ageing factor for the total time period

N = Total number of intervals
n = Index of time interval
$F_{AAn}$ = Ageing accelerating factor at index n
$\Delta tn$ = Time interval

[14] presented an approach of choosing end of life criteria for transformer based on their requirement which was most applicable to their needs. From the normal insulation life definition, if the unit is run for 20.55 years at $110^0$C hotspot temperature, the life of the insulation will expire. If it runs hotter, the life will expire much sooner and if it runs cooler, the life extends.

[11] discussed the ambient temperature of $30^0$C, the average winding temperature rise limit of $65^0$C and the hot spot temperature rise of $15^0$C. The study also suggested the transformer's life to be 30 years if the power transformer is continuously operated at the hot spot temperature of $95^0$C. The standards that define the power transformer's life is absolutely subjected to the hot spot temperature; thus, the identification of the power transformer's life requires a clear and exact hot spot temperature. The hot spot temperature is calculated by the winding resistance for reference which was detected during the heat run test. If the hot spot temperature calculated by the winding resistance is different from the actual hot spot temperature, the life of transformer will be estimated as a big error.

## VI. IEEE Standards and Temperatures

Operating a power transformer comes with a number of basic limitations. The temperature produced by the transformer losses for instance can affect the life span of the insulation. To ensure the longevity and optimum performance of the transformer, transformer manufactures must guarantee that their designs are capable of operating within specified standards. The operating limits for instance are bounded by the ambient temperature, the average winding temperature and the maximum winding hottest-spot temperature [2, 10, 23, 30].

According to the IEEE C57.12.00-2000 standard, power transformers are rated on a maximum ambient temperature of 40°C and the average ambient temperature shall not exceed 30° C in a 24-hour period [34]. In other words, based on the ambient temperature criteria, the average temperature of the winding cannot exceed 65° C above ambient, when operated at rated conditions.

[34] explained that maximum hottest-spot winding temperature cannot exceed a value of 80°C above ambient. The IEEE C57.91-1995 stated that under a continuous ambient temperature of 30° C, the maximum hottest-spot winding temperature should not exceed 110° C. If the transformer is operated continuously at this temperature, the normal life expectancy of the transformer is 20.55 years. For many years, the maximum temperature of power transformer insulation would be able to withstand fixed temperature. This is used as the basis of standard kVA ratings and of overload calculations. It was however discovered that the life of the insulation is a thermal-ageing process; so the maximum permissible temperature now became a variable with time.

The classical approach has been to consider the hot-spot temperature as the sum of the ambient temperature, the top-oil temperature rise in tank and the hot-spot-to-top-oil (in tank) temperature gradient. There are two possible methods for hotspot temperature determination [42]. The first method is to measure the hotspot temperature using a fiber optic temperature sensors positioned at the predicted hotspot of the windings [10]. The thermal sensors attached to the end optical fiber are usually placed between the insulated conductor and spacer and their signals transmitted out of the tank via optical fibre. However, due to the cost which may be difficult to justify in terms of cost for every new transformer, it is not practical for the existing transformers. The main difficulty with direct measurement technique is how to accurately locate the hotspot and possibly the sensors [4, 17].

Another method to identify the hotspot temperature is by using transformer thermal model or calculation method [10]. The calculation of the internal transformer temperature (Hotspot temperature) is a very complicated and difficult task. However, simplifying assumptions have been made on the generally accepted methods for calculating the temperature of power transformers as reported in the 1995 IEEE Standard C57.19 and 1991 IEC Standard. The thermal model of the power transformer using thermal electrical analogy based on heat transfer theory is a more accurate method to calculate the transformer hot spot temperature [11, 14].

### a. The Winding Hottest-Spot Temperature Calculations

The insulation's mechanical and dielectric properties are deteriorated at temperatures above normal limits. This shows that if the hottest-spot temperature is allowed to go beyond 110°C, the insulation deteriorates at a faster rate than normal. Therefore, the highest temperatures in the transformer aid in calculating insulation integrity. The hot spot temperature is calculated by adding the ambient temperature to the top oil temperature rise and to the hot spot temperature rise using [16]:

$$WindingHotspotTemperature = \theta A + \Delta\theta TO + \Delta\theta H \tag{14}$$

where: $\theta A$ is Ambient temperature

According to the IEC guide, the ageing of the paper insulation system is such that the stated transformer life can be achieved for a continuous maximum hotspot temperature of 98$^0$C. Beyond this temperature, it is assumed that the rate of ageing doubles for every increase of 6$^0$C. At temperatures of the order of 150$^0$C, accelerated ageing tests in the laboratory demonstrate that the useful life of the paper may only be a few days [17].

### b. Ambient Temperature and its Influence on Loading

Ambient temperature is an important factor in determining the load capability of a transformer since the temperature rises for any load must be added to determine operating temperature [46]. Temperature ratings are based on a 24 hours ambient of 30$^0$C. Whenever the actual ambient can be measured, such ambient should be averaged over 24 hours and then used in determining the transformer's temperature and loading capability. The ambient temperature seen by a transformer is the air in contact with its radiators or heat exchangers. To predict an overload for a 24-hour period, discrete 1-hour ambient temperature increments are necessary. The temperature used should be the maximum daily temperature for the month of interest averaged over several years [4, 10].

Furthermore, the temperature of the insulation depends upon the ambient temperature and the heat generated due to the power losses in the transformer [7]. The power losses consist of iron losses and copper losses. The iron losses are almost constant for the normal operation whereas the copper losses increase with the increase in the current (loading) of the transformer. The loading of the transformer can vary on a daily, weekly, and seasonal basis [12].

Different models have been proposed to estimate the hottest spot winding temperature in transformers. Various measurements, such as the top-oil temperature and the bottom-oil temperature, are also used for the estimation [39].

## VII. Conclusion

This research paper has reviewed different approaches used for assessment of lifespan of the insulation for power transformers. In addition, some of the numerous inherent problems associated with determination of rates of insulation, degradation, accelerated ageing degradation, the Degree of Polymerization (DP) degradation and rate equations employed has been reviewed. The study also presented alternative methodology and recent trends of Degree of Polymerization (DP) towards a more reliable insulation degradation rate and life expectancy prediction of power transformer. This research paper will therefore help utilities to monitor the major parameters to determine the remaining life and the lifespan of power transformers as well as its performance.

## VIII. References

[1] Abu Bakar, N. (2016): "A New Technique to detect loss of insulation life in power transformers", Thesis presented for the Degree of Doctor of Philosophy of Curtin University, Pp. 1-12.
[2] Abu-Siada, A. and Islam S. (2014): "A New Technique to Estimate Concentration through Spectral Response of Transformer Oil"**.** Doble Engineering Company – 81st International Conference of Doble Clients, Pp 1-10.
[3] Agarwal, V., Lybeck, N. J., Pham, B. T., Rusaw, R. and Bickford, R. (2015): "Implementation of remaining useful lifetime transformer models in the fleet-wide prognostics and health management suite", 9th International Conference on Nuclear Plant Instrumentation, Control and Human–Machine Interface Technologies (NPIC & HMIT 2015), Pp. 1-12.
[4] Ajenikoko, G. A., Olaomi, A. A and Aborisade, D. O. (2014): "A failure rate model for reliability assessment of ibadan distribution systems", Computer Engineering and Intelligent Systems Vol.5, Number 5, pp 21 – 33.
[5] Akbari, M., Khazaee, P., Sabetghadam, I. and Karimifard, P. (2013): "Failure modes and effects analysis (fmea) for power transformers", No, E-13-MNG-1970.28th International Power System Conference, Iran. Pp 1 – 7.
[6] Baird, P. Herman, H. Gary, S. and Schaut, A. (2011): Non-destructive dp analysis of kraft paper from shell-type power transformers', 21st International Conference on Electricity Distribution. Pp. 1-4.
[7] Bajracharya, G., Koltunowicz, T., Negenborn, R. R., Papp, Z., Djairam, D., De Schutter, B., and Smit, J. J. (2009): "Optimization of maintenance for power system equipment using a predictive health model". Proceedings of the 2009 IEEE Bucharest Power Tech Conference, Bucharest, Romania, Paper 563. Pp 1 – 7.
[8] Cheim, L., Platts, D., Prevost, T. and Xu, S., (2012): "Furan Analysis for Liquid Power Transformers," IEEE Electrical Insulation, Vol. 28. Pp. 8–21.
[9] Ding, D. (2009): "Review: degradation phenomenology and life modelling of paper", In Advances in Pulp and Paper Research, Oxford 2009, Trans. of the XIVth Fund. Res. Symp. Oxford, 2009, Pp. 947–1000.
[10] Dofan, J. A. R. (2011): "Study on thermal model for calculating transformer hot spot temperature", An unpublished master's thesis Faculty of Electrical & Electronic Engineering University Tun Hussein Onn Malaysia (UTHM), Pp. 1-10.
[11] Dong-Jin, K., Kyo-Sun, K., Jung-Wook, W. and Joo-Sik, K. (2012): "A study on the hot spot temperature

in 154kv power transformers", Journal of Electrical Engineering and Technology Vol. 7, Number. 3, Pp. 312 – 319.

[12] Esmaeilinasab, A. and Vahidi, B. (2014): "Prediction of Power Transformer Insulation Length of Life Using Thermal Model and Pareto Distribution". Sci.Int (Lahore), 26(5), ISSN 1013-5316; CODEN: SINTE 8. Pp 1953-1957.

[13] Fassbinder S. (2013): "Efficiency and Loss Evaluation of Large Power Transformers". European Copper Institute, Copper Alliance, Leonardo Energy. ECI Publication No Cu0144. Pp 1 – 21.

[14] Ferass, A. and Saad, M. (2011): "Predicting transformer end of life using transformer thermal life simulation technique". University Tun Hussein Onn Malaysia (UTHM), Pp. 1-10.

[15] Franzén, A. and Bertling, L. (2007): "State of the Art - Life Time Modelling and Management of Transformers". Royal Institute of Technology, KTH School of Electrical Engineering RCAM Stockholm, Sweden. Pp 1 – 33.

[16] Gouda, O. E., Amer, G. M. and Salem, W. A. A. (2012): "Predicting transformer temperature rise and loss of life in the presence of harmonic load currents", Ain Shams Engineering Journal (3), Pp 113–121.

[17] Hashmi M., Lehtonen M. and Hänninen S. (2013): "Effect of Climate Change on Transformers Loading Conditions in the Future Smart Grid Environment". Open Journal of Applied Sciences, (3), pp 24 – 29.

[18] Hillary, W. D. A., Jayarathna, K. L. I., Ranasinghe, L. I., Samarakoon, S. M. B., Rathnayake, N. M. T. and Lucas, J. R. and R. Samarasinghe, R. (2017): "A tool for estimating remaining life time of a power transformer", Conference Paper, DOI: 10.1109/MERCon.2017.7980513 ,Pp. 1-7.

[19] Hohlein I. and Kachler A. J. (2005): "Aging of Cellulose at Transformer Service Temperatures. Part 1: Influence of Type of Oil and Air on the Degree of Polymerization of Pressboard, Dissolved Gases, and Furanic Compounds in Oil", IEEE Electrical Insulation Magazine, (21), pp. 15-21.

[20] Kalariya, K., Kannad, H., Vyas, D. and Gandhi, P. (2014): "A review on ageing of power transformer and insulation life assessment", Advanced Research in Electrical and Electronic Engineering, Vol. 2, Number 2, Pp. 117-122.

[21] Kalogerakis S. (2009): "Distribution Transformers and Maintenance". Central Ostrobothnia University of Applied Sciences Ylivieska. Pp 1 – 50.

[22] Karlsson, S. (2007). A Review of Lifetime Assessment of Transformers and the use of Dissolved Gas Analysis.An unpublished Msc Thesis.KTH School of Electrical Engineering. Pp 1 – 51.

[23] Leibfried T., Jaya M., Majer N., Schäfer M., Stach M. and Voss S. (2011): "Post-Mortem Investigation of Power Transformers – Profile of Degree of Polymerization and Correlation with Furan Concentration in the Oil"

[24] Lewand, L. R. (2006): "Practical experience gained from furanic compound analysis", Doble Engineering Company – 73rd Annual International Doble Client Conference, Pp 1 – 7.

[25] Lucas J. R. (2000): "Historical Development of the Transformer". The Institution of Electrical Engineers, Sri Lanka Centre. Pp 1 – 16.

[26] Lundgaard, L. E., Hansen, W., Linhjell, D. and Painter, T. J. (2002): "Ageing of oil-impregnated paper in power transformers", Paper accepted for publication in IEEE PWRD, Pp. 1-10.

[27] Mehta, D. and Jariwala, H. (2012): "Predication of Life of Transformer Insulation by Developing Relationship between Degree of Polymerization and 2- Furfural". International Journal of Scientific and Engineering Research, Volume 3, Issue 7.

[28] Mirzai, M., Gholami, A. and Aminifar, F. (2006): "Failures analysis and reliability calculation for power transformers". Iran University of Science and Technology (IUST)-College of Electrical Engineering Narmak, Tehran, Iran. Pp 1 – 12.

[29] Mtetwa N. S. (2008): "Accuracy of Furan Analysis in Estimating the Degree of Polymerization in Power Transformers".MSc Thesis, University of the Witwatersrand

[30] Mulyodinoto, K. U., Suwarno, A., Prasojo, R. A. and Abu-Siada A. (2018). "Applications of ANFIS to estimate the degree of polymerization using transformer dissolve gas analysis and oil characteristic", iMedPub Journals www.imedpub.com, Vol. 4, Number 2, Pp. 11-15.

[31] Olaluwoye, O. O., Okubanjo, A. A., Oyetola, O. K., Alao, P. O. and Olasunkanmi, O. G . (2019): "Development of a hybridized model for predicting the life span of power transformers", J. Appl. Sci. Environ. Manage. Vol. 23, Number 7, Pp.1257-1264.

[32] Ortiz, F., Fernández, C., Santisteban, A., Delgado, F. and Ortiz, A. (2016): "Estimating the age of power transformers using the concentration of furans in dielectric oil", International Conference on Renewable Energies and Power Quality (ICREPQ'16) Madrid (Spain), 4th to 6th May, 2016, Vol. 1, Number 4, Pp. 1011-1015.

[33] Pahlavanpour, B, Martins, M.A and De Pablo, A. (2002): "Experimental Investigation into the Thermal-Ageing of Kraft Paper and Mineral Insulating Oil". IEEE International Symposium on Electrical Insulation.pp. 341- 345.

[34] Penny, B. (2010): “Best Practices For Maintaining Power Transformers”Aappa Fall Professional Development Conference Halifax, N. S. Pp. 1-8.
[35] Perez, J. (2010): “Fundamental principles of transformer thermal loading and protection IEEE”. Reprinted with permission from the 2010 Texas A&M Relay Conference. Pp 1 – 14.
[36] Pradhan. M. K, and Ramu, T. S. (2004): “Diagnostic Testing of Oil Impregnated Paper Insulation in Prorated Power Transformers under Accelerated Stress”. Conference Record of the 2004 IEEE International Symposium of Electrical Insulation, Indianapolis, USA, 19-22 September. Pp. 1-10.
[37] Pranjal. D, Deepchand K., Saddam H., and Sachin B. (2014): “Comparison between Power and Distribution Transformers”. Int. Journal of Electrical, Electronics and Computer Research and Development. Vol. 1, Issue 2. ISSN: 2394-3246. Pp 21-25.
[38] Prasojo, R. A., Karunika Diwyacitta, Suwarno, K. L., .K. D. I. and Gumilang, H. (2017): “Transformer paper expected life estimation using anfis based on oil characteristics and dissolved gases (Case Study: Indonesian Transformers)”, Energies 2017, 10, 1135; doi:10.3390/en10081135, Pp. 1-8.
[39] Radakovic, Z. and Feser, K. (2003): “A new method for the calculation of the hotspot temperature in power transformers with onan cooling”, IEEE Transactions on Power Delivery, Vol. 18, Number. 4, Pp. 1284-1292.
[40] Rosenlind J. (2013): “Lifetime Modelling and Management of Transformers”. Ph.D Thesis Kth Royal Institute of Technology. Pp 1 – 60.
[41] Sim, J. H. and Digby, S. H. (2001): “Power Transformers”. Electrical Power Engineering Handbook Series. University of California, Davis.Pp. 94 – 111.
[42] Srinivasan, M. and Krishnan, A. (2012): “Prediction of transformer insulation life with an effect of environmental variables”. International Journal of Computer Applications (0975 – 8887) Vol. 55, Number 5, Pp 43 – 48.
[43] Trappey, C. V., Trappey. A. J. C., Ma, l. and Tsao, W. (2014): “Data driven modeling for power transformer lifespan evaluation”, Systems Engineering Society of China and Springer-Verlag Berlin Heidelberg 2014, Pp. 80-93.
[44] Vivek, A., Nancy, J. L., and Binh, T. P (2014): “Diagnostic and prognostic models for generator step-up transformers” Idaho National Laboratory, Idaho Falls, Idaho 83415. Pp 1 – 38.
[45] Wang, Y., Gong, S. and Grzybowski, S. (2011): “Reliability evaluation method for oil–paper insulation in power transformers”, Energies(4), Pp. 1362 – 1375.
[46] Yadav, J. M., Reddy, S. A. and Sindhuja, T. (2013): “Determining thermal life expectancy of power transformer under non linear loads using FEM by ANSYS and MATLAB”, International Journal of Engineering Research and Technology (IJERT). Vol. 2, Issue 3, Pp. 1-15.
[47] Zhou, D. (2013): “Transformer Lifetime Modelling Based On Condition Monitoring Data” International Journal of Advances in Engineering & Technology, Vol. 6, Issue 2, pp. 613-619.