

ACCURACY OF FURAN ANALYSIS IN ESTIMATING
THE DEGREE OF POLYMERIZATION
IN POWER TRANSFORMERS

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ABSTRACT

The life of a transformer is determined by the life of its paper insulation. The age of the paper insulation is determined by the mechanical strength of the paper and is measured in terms of its Degree of Polymerization (DP). The traditional method of determining the DP, called the direct method, requires actual paper samples and is therefore intrusive and costly. The method used more recently, called the indirect method, estimates the DP value from the furan compounds dissolved in the oil. The aim of this research was to investigate the accuracy of the indirect method in determining the remaining life of a transformer. This was achieved by first considering the ageing processes, as covered in the literature, and checking whether the existing mathematical models, relating the furan content to the DP, have integrated all the factors of the ageing process. It was found that the indirect method is not 100% accurate, and that the inaccuracy increases with age as more external factors come into effect. It is recommended that results based on the indirect method be treated as an approximation. To reduce the degree of inaccuracy it is recommended that a good history of the transformer oil be kept, the DP be determined using the direct method before a transformer is dispatched from the factory, and to not use the indirect method if oil has been replaced within the past five years.

ABBREVIATIONS

DP	Degree of Polymerization
DGA	Dissolved Gas Analysis
PPB	Parts per Billion
PPM	Parts Per Million
TU	Thermally Upgraded
2FAL	2-Furaldehyde

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CHAPTER 1 BACKGROUND

1.1 Introduction

Transformer failures are costly. Utilities prefer to retire a transformer just before it reaches the end of its useful life. This 'end of useful life' point is determined by the remaining life of the paper insulation. A well established method of determining the remaining life is to determine the degree of polymerization (DP) of the paper. New paper has a DP of more than 910 and aged paper, that has reached the end of its useful life, has a DP of about 200. To measure the DP, a paper sample from the hottest spot of the winding should be removed. This method is, however, intrusive, which makes its application limited.

An alternative method is to estimate the DP from the oil furan concentration - 2-furaldehyde in particular. This method is non-intrusive and is therefore preferred by utilities. Since this method determines the DP based on a byproduct of the ageing process, it needs to be investigated in terms of accuracy.

This research project was aimed at investigating the accuracy of the indirect method by critically analyzing the existing mathematical models used to determine the DP from the furan concentration. Recommendations are included after discussing the findings.

1.2 Overview Of The Report

In Chapter 2, transformers and their associated ageing processes are discussed, followed by reflecting on the work already done by various researchers in terms of ageing and the relation of DP to the ageing process. Finally, the mathematical models that have been developed for the correlation of DP to the furan concentration are discussed.

In Chapter 3, the models are compared using arbitrary data from a transformer over its service life. This is done in an attempt to reflect how these models differ from each other as they were developed based on particular considerations, and to identify if there is a model that can best represent all these models irrespective of the different criteria originally used.

Chapter 4 gives some case studies to demonstrate the findings of Chapters 2 and 3. In Chapter 5 conclusions are drawn in terms of the findings of this research and recommendations are given on how these models can be applied taking into consideration their limitations.

CHAPTER 2 TRANSFORMER ASPECTS

Oil-filled power transformers have been used for more than a century. Although the principle of operation of power transformers has remained the same for all these years, advancements have been made in transformer insulation systems. If compared with other key assets, such as motors and generators, a power transformer has the advantage of being stationary, which means that mechanical wear is minimal (limited to the tap changer mechanism).

The power transformer also forms a significant percentage of the total investment in the power system. Every transformer owner therefore requires implementation of the best practices available to effectively manage transformer life and in turn get a good return on investment and revenue from the asset, and to minimize costly failures.

2.1 Transformer Design, Construction and Life Expectancy

Although publications such as IEEE C57.91-1995 mention a life span of about 20 years for a power transformer, today the common belief is that an oil-filled transformer is designed for a life expectancy of 30 to 40 years. There are however transformers that have gone beyond this age and are still in operation. Fundamentally, the major components of a transformer are windings with associated solid insulation, and the steel parts e.g. core, frame, and tank. The steel parts can last for many years. This is true also for the copper, from which the windings are made. This is however not the case with the insulation system.

The transformer insulation system, primarily consisting of mineral oil, paper and other cellulosic materials, has a finite life, even under ideal operating conditions. The paper insulation life is defined by a chemical process normally called ageing which depends primarily on temperature and time. Moisture and the presence of oxygen are other factors that accelerate the ageing process.

When the insulating oil degrades, it can either be regenerated by treatment or even replaced if necessary. For the cellulosic materials, in contrast, there is no easy and cost effective way of replacing the paper insulation and its lost life cannot be recovered. This is the reason why transformer owners are concerned with estimating the remaining life of their transformers and the reason why good management of transformer life is important right from the start.

Through research it has been found that there is a relationship between the tensile strength of the paper and the associated DP value. The DP value indicates 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 [1]. The current practice is to measure the quality of the cellulose (remaining life) in terms of the DP value. To determine the DP value, paper samples are taken from various locations within the transformer windings and sent to a laboratory where they are analyzed. This is called the direct method.

The problem with this method is that it is invasive, and every utility wants to maximize the time its assets are in service. An alternate method of determining the DP value, without taking the transformer out of service, involves analyzing the insulating oil for furanic compounds, which are produced during the ageing of the cellulose insulation.

This method is referred to as the indirect method. Studies have been done which correlate the DP value with the furan content in the oil. Mathematical models showing this correlation have also been developed [2-3].

Furanic compounds that are formed during cellulose ageing include 2-furaldehyde, 5-methyl-2-furaldehyde, 5-hydroxymethyl-2-furaldehyde, 2-acetyl furan, and 2-furfuryl alcohol. It has been found that the most stable by-product is 2-furaldehyde, and its concentration is therefore used by the indirect method for estimating the DP value.

2.2 Ageing of Transformer Insulation

The insulation system of a power transformer consists of hydrocarbon oil and cellulose paper. Both oil and paper have been used as insulating materials in oil-filled transformers for more than a century. These are effective insulators more especially in their combination as it is revealed in their observed synergism [3].



Figure 1 : Transformer solid insulation system in a winding block.

Even under ideal conditions these two insulators age. Their ageing is a function of the operating conditions, with thermal stresses being the fundamental and biggest contributor to the rate of the ageing. Oil ageing can be easily detected from oil sample analyses and oil can either be rejuvenated by some process or be replaced if the end of its useful life has been reached.

With the paper insulation, this is not the case. The lost life cannot be recovered. In addition, there is currently no cost-effective method of replacing the paper once it has reached the end of its useful life. Once the paper has reached the end of its useful life, the transformer is also declared as having reached the end of its useful life. According to many publications the expected life of the paper under normal operating conditions is approximately 20 years [4 - 5]. This life expectancy is based purely on the thermal ageing, and does not consider other factors that accelerate the ageing process.

Cellulose, which is the major constituent of the Kraft paper, is a long straight chain of glucose molecules. Kraft paper is used in preference to other paper types because of its

high purity. This paper is prepared for the electrical industry to a specific electrical resistivity, and is a cheap source of insulation. The latter point is an important consideration in the construction of the transformer taking into consideration the quantity of paper that will be required. In this paper, the glucose rings are linked by glucosidic bonds, and much of the mechanical strength of the paper comes from the long chain cellulose polymer.

As the cellulose ages, the polymers are cleaved and become shorter, hence the mechanical strength is reduced. The main factor causing degradation of paper insulation is thermal stress. Degradation occurs even under normal operating temperatures, however this process is accelerated at higher temperatures. Other factors that accelerate the ageing process are the presence of moisture and the presence of oxygen.

Paper ageing in transformers is not uniform. The ageing will follow the thermal, oxidation and moisture gradients. Transformer windings and leads are often wrapped with a number of insulation paper layers, typically from seven layers up, depending on the voltage stress levels. These paper layers constitute a great percentage of the entire cellulose insulation. The purpose of the Kraft paper layers is to act as both electrical insulation and to offer mechanical strength to the windings during faults and vibration stresses. Like the rest of the insulation, this paper will age as the transformer continues in service. It is normally in these layers that the weakest spot is developed during service life. This is because the paper layers are greatly exposed to all factors of the ageing process.

For a transformer that is running with inadequate cooling, overloading, and/or localized hot spots, the paper layers that are the closest to the conductor will age faster than those further away. The reason for this, is that the conductor is the source of heat. The paper around the conductors/turns that are at the upper part of the winding age faster than those at the bottom due to the heat gradient along the axial length of the winding block. The paper of the hotter winding (HV or LV) will also age faster than that on the other

2.2. 1 Effects of Oxygen

Paper ageing is influenced by the presence of oxygen. Thermally upgraded paper is less sensitive to the presence of oxygen than the normal Kraft paper [5]. For a transformer that is subjected to a high concentration of oxygen, the outer paper layers will have a lower DP value than those inside, judged purely by the effect of oxygen. This is true for the entire winding length because the oxygen gradient is along the radial axis of the conductor or lead. Such a gradient pattern is because the paper provides a physical barrier for the gas diffusion. This pattern is more visible on transformers that have free breathing conservators as they have a high oxygen content.

2.2.2 Effects of Moisture

The effect of moisture (water) on the ageing of paper insulation is significant. The rate at which the paper will degrade is directly proportional to the water content. Through research it has been found that decreasing the water content from 1% to 0.5% doubles the life of the paper insulation [6]. In a transformer, where there is a high water content, the ageing will depend on the loading. For a transformer that is heavily loaded, the inner layers are much warmer than the outer ones. This will make the water that has been trapped in the inner paper layers move to the outer layer and to the surrounding oil

wherein it will get dissolved. The outer layers will, however, still be in contact with oil and hence moisture. Therefore the outer layers will be more affected by moisture than the inner ones.

For lightly loaded transformers, the temperature gradient is not significant since temperature distribution is almost uniform. The water effect is therefore also relatively uniform in all the layers.

These facts are to be considered when paper samples are taken from a transformer for DP value determination. If these are not taken into account the wrong conclusion could be drawn for a particular transformer.

As these cellulosic materials deteriorate, some by-products are formed, and these can serve as indicators of the ageing process. The two most used by-products of the ageing process are the furanic compounds and the carbon-oxide gasses. The advantage of using these by-products is that the ageing process can be monitored while the transformer is in service as opposed to taking a paper sample - which requires the unit to be taken out of service. In most utilities the outage of the unit for analyses may not be favoured because of production losses and other costs that are incurred during the analyses.

The paper deterioration leaves the transformer vulnerable to stresses generated by thermal, mechanical and electrical transients.

2.3 Degree of Polymerization (DP)

The solid insulation used to insulate transformer winding conductors is a sheet of material made from cellulose.

The main source of this cellulose fiber is wood, since wood contains up to 50% of cellulose in a dry condition [3]. Cellulose is a linear polymer composed of individual anhydrous glucose units linked at the first and fourth carbon atoms through a glucosidic bond. The mechanical strength of cellulose is a function of the polymeric and fibrous nature. The number of monomer units in the polymer chain is known as the DP value. The quality of the cellulose material is measured in terms of this DP value [1].

The DP value is currently used by utilities as a diagnostic tool to determine the condition of the solid material (particularly paper). New paper is estimated to have the DP value of 1000 to 1500. The DP value is first reduced by the drying processes that take place during the assembling of the transformer. It is believed that after this process the DP value of the paper is about 950 [3]. The paper will age in service as mentioned in the previous section until a critical point is reached (see figure 2). This is when the paper is declared to have reached the end of its useful life. This is also regarded as the end of the transformer service life.

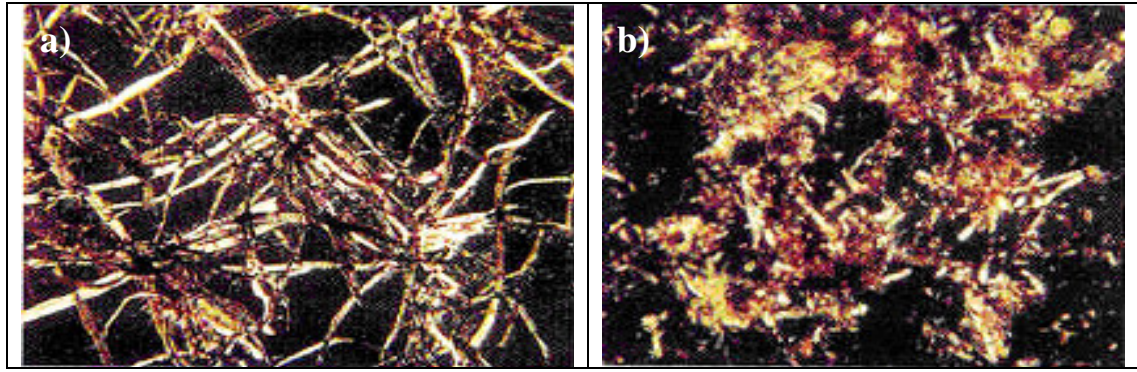


Figure 2: Microscopic view of a) new paper with high DP value, b) aged paper with low DP value

Over the years, there have been a number of studies on insulation ageing. However even today there is no conclusion as to what the end of life DP value is, although many researchers specify it for a DP value of 300 and lower. Comprehensive literature is now available based on accelerated ageing of paper/oil insulation. Most of these papers take the end of paper life criterion as 50% of its original tensile strength, which is an equivalent of DP value between 200 and 250 [1],[3].

Traditionally, to determine the DP value of the insulation of a particular transformer, paper samples from various points and different windings are required. The general practice is to target the spots of highest temperature i.e. winding hot spots. However it is not always at the winding hot spot where much ageing will be experienced. For example, for a transformer that is wet or has a high oxygen content, the pattern of the ageing gradient across and along the winding will be different to that of the transformer that is purely ageing thermally.

Some of the transformers in service, more especially transmission transformers, are idling for a significant portion of their service lives because substations are designed with redundancy; however, they may have high oxygen levels and high water content and will therefore exhibit a different ageing pattern to other transformers which have a high loading factor. Examples of transformers with high loading factors are generator step-up transformers, which must transform the total power generated by generator.

This brings us to the critical point of acquiring the paper sample from a transformer insulation system i.e. the direct method. It is critical to understand the operating conditions of the transformer, in order to identify or to choose the relevant spots for sampling and hence obtain most accurate results. In addition to this, the disadvantage of this direct method is that it requires the transformer to be taken out of service.

Moreover, it may be required to dismantle a transformer that has not failed in order to access the paper in the inner windings of the concentric winding assembly, and in turn poses risks such as reduced insulation integrity and poor workmanship for transformers that are expected to continue in service.

This direct method gives real results, however the acquiring of the sample itself is not that straightforward at all. Utilities avoid it for the above mentioned reasons.

2.4 Furanics

An alternative method for estimating the DP value of the paper insulation is non-intrusive. Since some byproducts are formed during ageing and get dissolved in oil, the oil can therefore be analyzed for furan content. The reason the furan content analysis is preferred to carbon-oxide gas analyses, is that the carbon-oxide gasses are not only formed during paper ageing. They are also formed from other activities such as partial discharges and overheating. During an electrical discharge, carbon monoxide and carbon dioxide are formed.

Carbon-oxide gasses can also be formed from materials other than those comprising cellulose, such as oil, under some conditions. Recent studies [5] have shown that furanic compounds are generated also if the cellulose is subjected to electrical discharges, but in very small quantities. During thermal ageing, large quantities of furanic compounds can be generated when cellulosic materials are exposed to very high temperatures (typically above 120°C). The rate of accumulation will also be a function of other factors: oxygen concentration and water content.

According to the findings of [5], once formed, the furanic compounds can then survive for prolonged periods of time in bulk oil, which is at a much lower temperature than the hottest spot in the insulation (winding). The types of furanic compounds that can be formed are

- 2-furaldehyde
- 5-methyl-2-furaldehyde
- 5-hydroxymethyl-2-furaldehyde
- 2-acetyl furan
- 2-furfuryl alcohol.

The stability of the furanic compounds is of much interest in order to be able to draw some conclusion from the analyses. Compounds which are not stable for a long period of time will lead the analyst or the engineer to inaccurate conclusion. Some of the above-mentioned furanic 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. The studies have revealed, through laboratory tests, that 2 furfural also referred to as the 2-furaldehyde (2FAL) is the most stable byproduct 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 [5].

In the literature there is still debate on the issue of furanic compound accumulation from thermally upgraded paper and from normal Kraft paper. Some literature [5] states that the behaviour is different if using thermally upgraded paper while there are a few who state that there is no difference in furanic compound behaviour between the thermally upgraded paper and normal Kraft paper. This report assumes a different pattern for the two types of insulating paper.

2.5 Correlation Between 2FAL and Degree of Polymerization

The removal of paper from a transformer is extremely difficult, especially if the transformer is still expected to continue in service, and may lead to the failure of the unit if not done with appropriate skill. The ability to estimate the condition of the paper

without exposing the transformer to such a risk is therefore desirable. It has been found that indirect testing can be done by analyzing the oil for the concentration of the furanic compounds, which are formed during the ageing process. After their formation during the ageing process, the furanic compounds migrate from the paper into the oil and hence by analyzing the oil the, DP value can be estimated.

Although the measurement of furanic compounds from an oil sample is relatively simple, the interpretation is complex. As it has been mentioned before, 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 furanic compounds are dominant at intermediate temperatures and are unstable at high temperatures [3]. Several authors have studied paper ageing and have attempted to relate furanics to the DP value [1- 7].

Such studies have been done based on data obtained from various specimens including laboratory studies and transformers taken out of service for repair or investigation. Mathematical models have been developed for the observed relationship between the DP value and the furanic compound (2FAL) concentration.

The transformer loss of life model by Arrhenius is well known. It is 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. This model is given by equation 1 below [2].

$$LoL\% = 100 \times \Delta t \times 10^{-\left[A + \frac{B}{\Theta + 273}\right]} \quad (1)$$

where:

LoL% - loss of life

A,B – ANSI standard parameters

Θ - hot spot temperature in degrees Celcius

Δt – transformer operating time in hours, with hot spot temperature of Θ

The Arrhenius model assumes that the paper ageing is caused only by temperature. It is therefore based on the prevailing hot spot temperature on the winding blocks and the associated time duration of the thermal excursion. From these two main parameters (temperature and time), the % lost life is estimated.

The challenge to get accurate estimation of remaining life from this model is due to

- The difficulty of accurately measuring the hot spot temperature and its duration as these can only be estimated.
- The fact that ageing is not only due to thermal excursion but also from normal operating temperatures and is aggravated by the presence of moisture and oxygen.
- The requirement to continually integrate all calculated lost life and deduct it from original life (100%) to determine the residual life.

The Arrhenius model will tend to over estimate the remaining life.

Cheim and Dupont [6] built upon the Arrhenius model to come up with the expression that will relate the universal parameter 2FAL to the DP value. In their model they considered that ageing should be an indication of the average degradation of the winding. They came up with the expression.

$$LoL = \alpha \cdot \ln(2FAL) + \beta \quad (2)$$

where:

α, β - fitting parameters based on type of paper

2FAL – average value, in ppm, for a transformer operating t hours, having a temperature gradient of the winding being $\Delta\Theta$.

This model, like Arrhenius's, can be used determine the remaining life by deducting the lost life from the original i.e. initial life.

In relation to the DP value, the Cheim-Dupont expression is:

$$DP = \left(\frac{2FAL}{\lambda} \right)^{\frac{1}{\psi d}} \quad (3)$$

where,

λ - representing shortened expression [2]

d – parameter representing type of paper (thermally upgraded paper or normal Kraft)

The model by Cheim-Dupont is a better expression of the ageing process because it relates paper ageing to both the hot spot gradient temperature and the paper type. Above all, it gives a DP value that is based on the by-product of ageing (2FAL). The shortcoming of this model is that when oil is either processed e.g. regenerated or replaced, the 2FAL concentration will change and this will bring about more inaccuracy. Further to this, the 2FAL concentration is an average value of different paper ageing rates from various spots of the winding block, and is therefore not the accurate measurement of the weakest spot.

Like the Arrhenius model, the Chem-Dupont model does not directly take into consideration the effect of moisture and oxygen in accounting for the paper ageing. The effect of these two parameters is indirectly accounted for by the fact that the 2FAL is produced by ageing process and not only by thermal ageing.

The other most discussed models in literature are those of

- Chendong
- De Pablo and
- Burton

The Chendong model is expressed as shown in equation 4:

$$DP = \frac{\log(2FAL) - 1.51}{-0.0035} \quad (4)$$

where the concentration of 2FAL is in ppm

This equation was developed based on the data collected from transformers that have normal Kraft paper and free breathing conservators. Stebbins proposed a modified Chendong equation to be used for thermally upgraded paper. Stebbins's equation is given by equation 5.

$$DP = \frac{\log(2FAL * 0.88) - 4.51}{-0.0035} \quad (5)$$

For this equation the concentration of 2FAL is expressed in parts per billion (ppb).

Both the Chendong's and Stebbins's models are limited to only certain transformers, i.e. according to the type of paper used for insulation. These models calculate the prevailing DP value by purely considering the concentration of the furans in oil. The use of furans is better than using purely hot spot gradient, because the former is based on the by-product of the ageing process, which may be due to even the other factors.

The major setback with these models is in case where the oil has been replaced or regenerated, which will vary the concentration of the furans as indicated in the case studies. Like in the Cheim-Dupont model, the concentration of 2FAL is an average value and not the real presentation of the weakest point.

De Pablo came with the model that is given by

$$DP = \frac{7100}{8.8 + 2FAL} \quad (6)$$

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

The De Pablo model was also modified by Pahlavanpour et al.[3] 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. The modified De Pablo's equation is

$$DP = \frac{800}{[0.186 * 2FAL] + 1} \quad (7)$$

and 2FAL is expressed in ppm.

The models wherein the DP value is calculated from 2FAL present a better estimation of the DP value if compared to the earlier models where a hot spot gradient and its time duration are used to calculate lost life. The use of 2FAL compound to calculate the DP value is a better method because it indirectly takes into consideration the other factors of ageing because 2FAL is a by-product of ageing. Various models, using 2FAL concentration, as given above (equations (3) – (7)) differ from each other either because of data samples they are based upon or certain assumptions considered, but they do not present a total different new way of determining the DP value i.e. they all use furans as a key parameter.

The common limitation with all these models [(3) – (7)] is that the concentration of 2FAL is affected by oil replacement or by oil-reconditioning processes e.g. regeneration. In such cases, when oil has been replaced or regenerated, the total picture in terms of 2FAL concentration is distorted and very inaccurate results are the only outcome. This distortion of 2FAL is because oil processing that is done to treat the oil for better insulation properties will discard or vary the furan concentration.

Such oil processes are [6]:

- Degassing by partial vacuum
- Mechanical filtration
- Oil reclamation

- Oil Change

Other sources of furan (2FAL) concentration distortion are

- The stability of the furanic compounds itself at various temperature levels
- Use of mixed paper i.e. normal Kraft and TU paper
- Electrical discharge and high temperatures which also yields 2FAL
- Transformer oil preservation systems
- Partial rewinds on a transformer

These models can therefore only be used in transformers where the oil has never been replaced or reconditioned.

CHAPTER 3 DISCUSSION AND ANALYSES

Of much interest to the engineer or the transformer owner is knowledge of which model gives more accurate estimation of the remaining life, determined as a DP value. The purpose of this chapter is to bring together the models introduced in Chapter 2 so that they can be evaluated from a common set of transformer history.

Such a comparison will assist in demonstrating if any of these models can be generally used for any transformer, and not only limited to certain categories as was mentioned in the previous chapter.

Chendong's model, although based on the data from units containing normal Kraft paper and free breathing conservators, has come to be used by some to evaluate the paper DP value for all transformers. Is this application justified?

Table 1 below shows the difference between DP values given by the four models, for the range of furanic concentrations, using synthetic data (data not taken from any existing unit). This will be used to explain what has already been discussed in the literature. It can be noted that there is no literature that has compared these four models together. In the literature, different combinations of models are compared as is the case with [2]. From Table 1, Figure 3 was obtained.

Table 1 : Data of arbitrary 2FAL concentration vs. DP values using models

Furan	Degree of Polymerization			
[2FAL]	Chendong	Stebbins	De Pablo	Pahlavanpour
0.01	1003	1316	806	799
0.1	717	1031	798	785
0.5	517	831	763	732
1	431	745	724	675
2.5	318	631	628	546
5	232	545	514	415
10	146	459	378	280
15	95	409	298	211

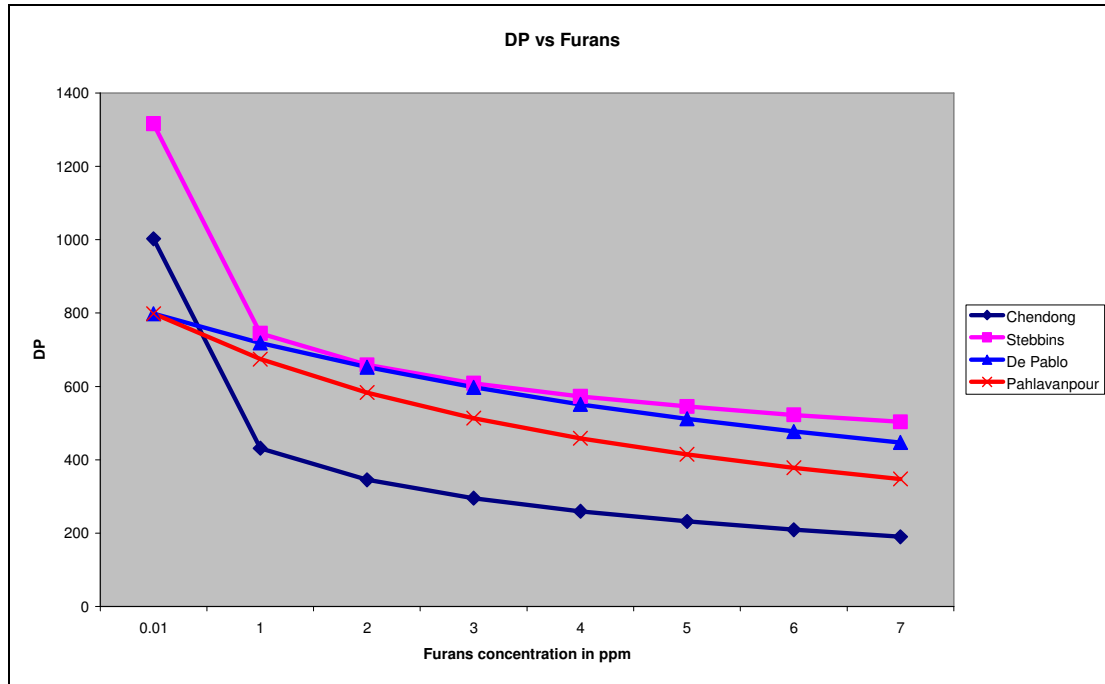


Figure 3: Graphical presentation of DP values determined from furans by different models

The graphical representation of the synthetic data reflects a similar pattern to that shown by the Chendong's and Depablo's plots in [2]. Chendong's model suggests that the furan production is slow initially with rapid production once the DP reaches a value of approximately 450. The end of life value (200DP) is reached at about 7ppm of 2FAL.

Chendong's model gives the lowest DP value, for a given furan concentration, if compared to all other models. As can be deduced from the previous chapter, the indirect method will tend to overestimate the residual life. The Chendong's model will give the lowest overestimation or possibly underestimation for transformers with thermally upgraded paper, which is safer. This research therefore accepts the use of the Chendong model as a general model.

Stebbins model suggests that the thermally upgraded paper produces more furans than normal Kraft paper for a given ageing. This can be seen from the fact that for the same level of furans, there is still more DP value remaining on the thermally upgraded paper as presented by Stebbin's model. The Chendong model and that of Stebbin show a similar pattern.

This is expected as these models differ only on the type of paper (normal Kraft or thermally upgraded) used in a transformer. The thermally upgraded paper produces more furans than the normal Kraft paper for a given ageing.

Depablo's model shows that the DP starts at a value of about 800. This is contrary to what most literature says and what is found in reality from direct samples. Some fairly new transformers, around three years of service, have shown DP values of about 900.

This model also shows steady ageing. Compared with Chendong's model, there is a big discrepancy. For example, for the same value of 2FAL = 7ppm, Chendong's model says a transformer has reached the end of its useful life while from the De Pablos' model a transformer has not even reached 50% (400DP) of original value (800DP). The model developed by Cheim and Dupont as it appears in [3] is close to Chendong's but shows a very rapid production of furans only when the DP value falls below 300.

The discrepancy among these models is an indication that more work is still required in coming up with a more accurate method. Deviations from model to model are also due to different ageing factors and ageing assumptions being considered by different models.

In order to identify which model is more accurate, case studies form part of this research. In this way DP value determined using the direct method was compared to the DP value by the indirect method, given by each of the discussed models. It was expected that no model would be 100% accurate because of these facts:

- 2FAL, which is a commonly used parameter for the indirect method, is an average value and is not an actual reflection of a most aged spot.
- 2FAL is not produced at all ageing temperatures [3].

There was difficulty in obtaining good specimens because:

- No specimen was available which contained oil that was put in from the beginning of the transformer service life. Most of the failed units from which the physical paper samples were taken had undergone oil replacement a few months (mostly 6-30 months) previously, and the others had no available age assessment reports at all. The effect of oil replacement is shown in the first case study given below.
- On the failed units, the oil is interfered with quickly. In most cases due to the nature of failure, the 2FAL would not be from ageing in service alone.

Therefore, the analyses that could be done with these samples would not be an accurate reflection of the ageing process.

CHAPTER 4 CASE STUDIES

Case Study No.1

A generator step up transformer with serial number 28042 was manufactured in 1984 by ABB and was first commissioned in 1985. This was double-wound, with normal Kraft paper, and free breathing conservator unit. The other name plate information is shown in table 2 below.

Table 2 : Name plate information

Rated Power	700MVA
Rated Voltages	22/400 (388.5 to 451.5 kV OLTC)
Rated Frequency	50 Hz
Vector Group	YNd1
Oil Volume	103 000 Litres

This unit was, on average, kept at about 70% loading for its service life. It underwent normal maintenance schedules. In April 2002, an oil replacement was done on the unit together with the fitting of an air bag (rubber bag) in the conservator.

The age assessment was done in November 2003. The report indicated that the DP value was greater than 910. In the same month abnormal gassing was observed on the unit and in January 2004 it was taken out of service due to high acetylene levels.

Internal inspection done on site indicated overheating on the LV windings. The unit was then sent to the workshop for further investigation.

Direct samples were taken from various areas of the windings. The results indicated DP values ranging from 250 to 570.

From this it can be seen that oil replacement has a large impact in the change in concentration of furans (2FAL). Lots of information gets distorted and cannot be recovered in a short period of time.

Case Study No.2

Two 80 MVA sister units installed at the same substation failed on 3 May 2007 after they were subjected to a network fault. These two transformers were manufactured by GEC in 1977. The other name plate information is shown in Table 3 below.

Table 3: Name plate information

Voltage	132/66/22kV autotransformer
Vector Group	Yyn0d1
Frequency	50Hz
Oil Volume	30 000L

Age assessment that was done approximately 4.5 years prior to the failure indicated the following:

Table 4: Extracts from the age assessment reports

	7282/2	7282/1	Remarks
DP value calculated from furans	590	650	The Furanic content indicates significant paper deterioration but still well away from the critical point for 7282/2 and mild to minimal paper ageing for 7282/1
Acid in oil	0.09	0.08	High acidity levels but not yet critical for both units.
Tan delta	0.0507	0.027	This is still within the specification level of less than 0.15
Colour	2.5	2	The colour grading indicates oxidation on both units but just below the limit of less than 2.5 for 7282/1
Estimated remaining life	76%	80%	Transformers have only lost less than 30% of original life in the past 25 years

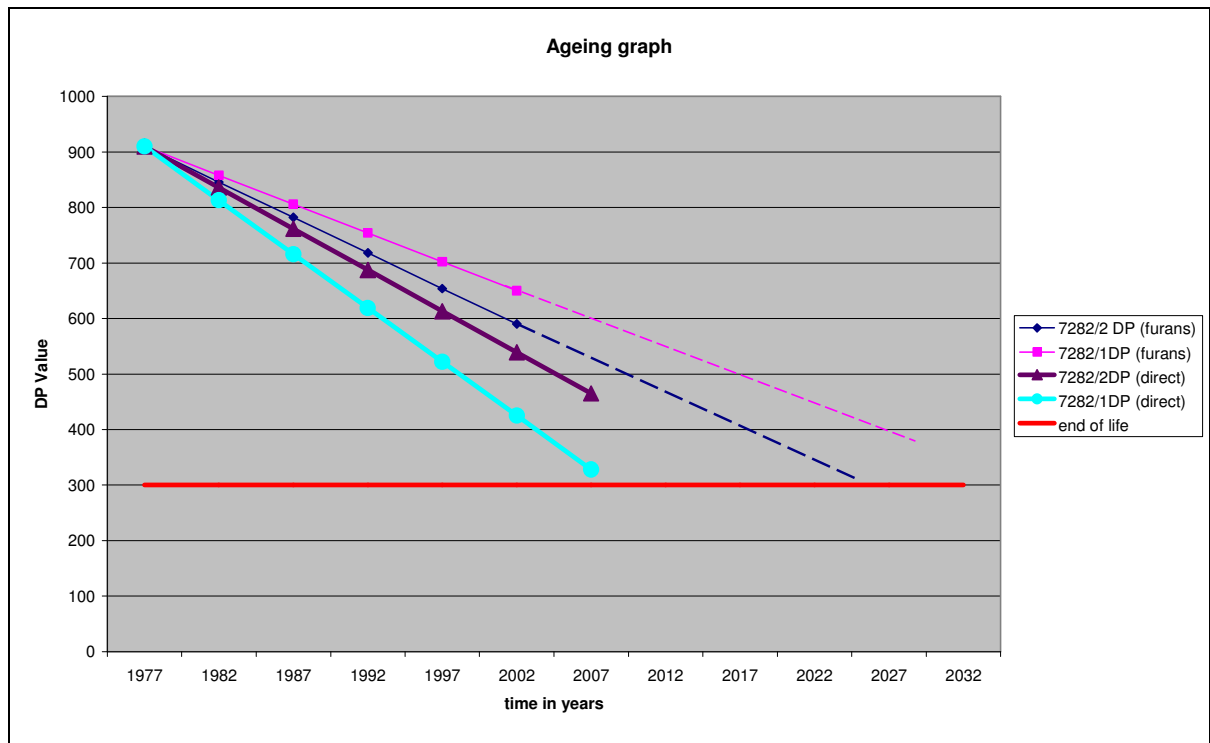


Figure 4: Trends of DP values based on furans and on direct method

For both these units the only available data, in terms of the age assessment reports, was for the year 2002. After the units were sent to the workshop, following their failure, paper samples were taken during the tear down in order to determine the DP value using the direct method.

Assuming a linear ageing, the DP values based on the indirect method were calculated for both units at the year of failure (2007). This was done to compare the results of these two methods at the same age of the transformers. The initial DP value of 910 is based on the Eskom laboratory reports that specify DP value up to 910, beyond that. The DP value is indicated as > 910, which is also the accepted upper value in the available literature.

The calculated DP values for both 7282/1 and 7282/2 at the year of failure were 600 and 530 respectively. The results from the direct method showed that for 7282/1 the minimum DP value was 328 and for 7282/2, the minimum DP value was 465. From these calculations and measurements, it is observed that the indirect method gave an overestimation of about 83% for 7282/1 and 14% for 7282/2.

The deviation between the two methods as observed in 7282/2 is within an acceptable range in the view of the author of this report. Such a deviation is justified taking into consideration that the indirect method gives an average value of ageing as opposed to the actual value of the direct method. The deviation as seen in 7282/1 is very wide.

Such a wide deviation can be attributed to oil processing that might have taken place during the life of this transformer, and no records could be found to justify this.

From this case study two observations are made. The first one is that the indirect method can give results that are very close to the direct method i.e. within +20% (which the author assumes to be the maximum deviation – no limit is specified in the literature) of the actual DP value, given by the direct method, as in the case of 7282/2.

It is also possible that such good results were obtained because the weakest spot was missed when the physical paper sample was taken for the direct method. The second observation is that the results from the indirect method can also be very inaccurate as seen in 7282/1. Such a wide deviation is concluded to be due to oil processing and/or oil change during service life, or because the weakest spot was missed during the acquiring of the paper sample for the direct method's measurement.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It is not possible to obtain an 100% accurate DP value from furan analysis as an indication of the most aged spot of the insulation. The DP value obtained from the furan analysis (indirect method) will tend to over estimate the remaining life of the transformer. This is because the 2FAL concentration that is obtained from the insulating oil is the average of all ageing rates, at various winding block positions, and is not a value from the hot spot or from the most aged spot. The degree of inaccuracy will also depend mostly on the external factors that have influenced the concentration of the main furan component, 2FAL, e.g. oil replacement.

Therefore the use of 2FAL concentration in isolation of the history and design of a transformer, i.e. to determine what processes did the oil undergo and what type of insulation paper is in a transformer, will yield a very weak conclusion in terms of the remaining life. These are not to be overlooked during a transformer life assessment.

Correlation exists between the 2FAL concentration in oil and the DP value of a paper insulation. Mathematical models for this correlation have been successfully developed to a certain degree of accuracy, and application of each model is limited by certain assumptions. From the discussion in Chapter 3, the author concludes that the Chendong model can be used for any transformer, irrespective of the type of insulation paper and whether a transformer is free breathing or not, and results with least inaccuracy will be obtained. However oil history must still be traced even when using this model.

The indirect method is used because of its non intrusiveness rather than because it gives a true reflection of the residual life in the transformer. This can be seen from the case studies. The indirect method has still many uncertainties and dynamics which must be researched.

These include, but are not limited to

- The stability of 2FAL in oil in terms of temperature and time
- The periods it takes after the oil processing to have a 2FAL concentration that is a true representation of the ageing process
- What level of inaccuracy is accepted when using indirect method and why.
- The integrity of 2FAL, in terms of stability, taking into consideration the recent discoveries e.g. chemical injection for the process of passivating the corrosive sulphur in oil. This has proved to affect the DGA pattern

The advantage with the indirect method is that if it identifies a problem (very low DP value), a problem definitely exists, however, problems can escape identification because it is an average value and does not pinpoint the weakest spot. Use of furanic analysis to determine the DP value is not an accurate method if this is done purely by mathematical models.

Knowledge of the transformer design (paper type), dominating ageing factor, and oil history is required to reduce the degree of inaccuracy or to bring more understanding of the obtained results.

These models (for the indirect method) can be applied, when integrated with understanding of the transformer design and history of the transformer service life, to get reliable estimation of the DP value. In order to use the indirect method and make as accurate as possible conclusions, some recommendations are made in the next section.

5.2 Recommendations

- At the time of dispatching the transformer from the factory, the DP value, using the direct method, must be determined - or the accepted 910 DP value must be used as the initial DP value. Both the Arrhenius's (equation 1) and Chem-Dupont's (equation 2) models can then be used to calculate the lost life when the unit is in service. The difference between the lost life and original DP value is then the estimated remaining life.
- The other models can be used for the same exercise; however, the transformer must have not undergone oil replacement/processing at least for the previous five years. There is no strong conclusion in literature in terms of this 5 years period.
- The choice of mathematical model used must be based on the understanding of the transformer design in terms of the paper used (TU or normal kraft), and on the dominating ageing factor i.e. thermal or oxidation. The Chendong's model is recommended.
- It must be taken into account when taking decisions, based on the DP value calculated from the concentration of furans (indirect method), that the actual remaining life is less. The degree of inaccuracy is expected to increase with the age of the unit as more external factors would have crept in.

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