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Citation for published version (APA):

Gorgan, B., Nottingher, P. V., Wetzler, J. M., Verhaart, H. F. A., Wouters, P. A. A. F., Schijndel, van, A., & Tanasescu, G. (2012). Calculation of the remaining lifetime of power transformers paper insulation. In *13th International Conference on Optimization of Electrical and Electronic Equipment, 24-26 May, 2012, Brasov, Romania* (pp. 293-300).

Document status and date:

Published: 01/01/2012

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Calculation of the Remaining Lifetime of Power Transformers Paper Insulation

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Abstract—This paper presents the remaining lifetime calculation of power transformers paper insulation and consequently of power transformers. The calculations are performed based on two models, which are related to the thermal degradation of the cellulose winding paper insulation: the common IEC loading guide and a paper degradation model. The paper insulation model's prediction can be improved by involving data from furfural analysis.

The remaining lifetime is extracted from the fault probability (reliability) of the paper insulation. The two models are brought together, to aid the asset manager in the decision making process. A probabilistic approach is used, which can be coupled to analysis in terms of risks, benefits, costs, and availability by the asset manager.

I. INTRODUCTION

Power transformers are important assets in electrical power grids, in terms of both reliability and investments (costs). 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 [1-2]. These assets are components that operate in a high voltage, high current and consequently high power environment. Although transformers are extremely energy efficient, the dissipated heat is a limiting factor for the maximum loading of power transformers. The insulating medium must be capable of dealing with large electric stresses, strong electromechanical forces and high temperatures [1].

The life of a power transformer mainly depends on the condition of the paper-oil insulation system [3-5]. According to present statistics, tap-changers and bushings can also contribute to transformer failure [2, 6]. However, they can be more easily repaired or replaced than transformer windings and their insulation. In this paper, the transformer life and the remaining lifetime prediction is focused mainly on thermal degradation of its paper insulation.

Most transformers manufactured in Europe before 1990 use Kraft paper as winding insulation, which was later replaced by thermally upgraded paper. In the USA, the winding insulation predominantly uses thermally upgraded paper [7]. Oil has a high insulating strength and at the same time serves as cooling medium by either natural or forced convection.

The oil-impregnated paper provides electrical insulation

between windings and serves as a mechanical barrier between the individual windings and between winding layers. Thus, the paper is a critical factor in paper-oil insulation. A bad paper quality leads to premature insulation degradation, which in turn can lead to transformer failure after, for example, a winding short circuit [1].

Manufacturers often define the expected life of power transformers to be between 25 and 40 years. Some transformers in service are now approaching this age, and a few are already 60 years old. Therefore, it is important to estimate their remaining lifetimes in order to prevent premature shutdown of transformers [8].

II. PAPER DEGRADATION

The cellulose paper used in power transformer insulation systems is an organic polymer which contains glucose rings $C_6H_{10}O_5$ joined together by covalent bonds and oxygen atoms (Fig. 1) [9]. Cellulose degradation is an irreversible process which is characterized by the breakdown of macromolecular chains. In order to estimate the degree of degradation, the number of $C_6H_{10}O_5$ glucose rings that compose the cellulosic macromolecule is taken as measure, i.e. the degree of polymerisation DP. The degree of polymerisation is a valuable indicator that provides information about the degradation state of cellulose and its mechanical strength [10].

A practical value for the DP of un-aged paper is 1000–1200 [11-12]. The paper tensile strength is a measure for the sensitivity to paper rupture. The tensile strength is directly related to the degree of polymerisation of the insulating paper. If the DP-value is found in a range of 200-300 then the paper insulation is considered to be at its end of life [13].

Winding paper insulation failure is coupled with the DP-value, the DP-value is strongly influenced by the rate of cellulose macromolecule scission. This rate of cellulose macromolecule scission is directly correlated with the hot-spot temperature, which is the temperature at critical locations influenced by transformer loading. Due to the above described mechanism and the fact that transformer loading is expected to increase in future, winding paper insulation failure may become the dominant cause of transformer failure

Fig. 1. Chemical structure of cellulose macromolecule [9].

if the loading approaches the rated load [1, 12].

Chemical decomposition of cellulosic paper can be attributed to three different processes, namely oxidation, hydrolysis and pyrolysis. Cellulose decomposition due to the pyrolysis reaction is performed at temperatures much higher than those to which the paper is subjected during the power transformers operation [13].

For this reason, the degradation of paper used in power transformer insulation systems is attributed to the oxidation and hydrolysis reactions and the degradation rates have Arrhenius type temperature dependence. Moreover, the oxidation reactions present a greater importance because their activation energy value is lower than the activation energy of hydrolysis [14].

Under the combined action of oxygen and temperature, many reactions products are formed which can be used to indicate the degradation condition of paper insulation.

The most important ones are furans (2-furaldehyde, 5-methyl-2-furaldehyde, 2-acetylfuran, 2-hydroxymethylfuran), CO, CO₂, H₂O, H₂, CH₄, carboxylic acids (with low molecular weight) [1, 3, 10, 11, 15]. Apart from these products, as a result of cellulose thermo-oxidation reactions, highly unstable free radicals are formed which generate reactions (in avalanche) leading to the cellulosic macromolecular chain depolymerisation. The presence of water and acids as a result of cellulose oxidation leads to the initiation of acid hydrolysis. The process for producing this type of reaction is the dissociation of carboxylic acids in water, after which the process produces rapidly the growing concentration of H⁺ ions [16].

III. QUALITY PARAMETERS

Parameters describing the condition of an asset are defined as quality parameters (QP). Table I summarizes the quality parameter types [1, 7, 17]. Ideally, the value of a QP is

TABLE I
QUALITY PARAMETER TYPES ORDERED ON THEIR
INFORMATION CAPACITY WITH EXAMPLES

QP			Example
	Explicit (observable/measurable)	Directly linked to degradation process	DP-value of the paper
		Indirectly linked to degradation process	PD activity, DGA analysis
	Implicit	Induced/Deductible	Loss of life of the paper insulation

Fig. 2. Representation of degradation mechanism modeling, relating ageing to fault probability through quality parameters [1, 17].

directly linked to the condition of the asset, but the QP may also be indirectly linked with the condition.

In Fig. 2 three distinctive methods [1, 17] for predicting the quality parameter QP, the fault probability and the level of degradation are depicted.

Based on increasing strength of linkage between QP and degradation process, they are placed in order of: an expert judgment model, a regression model and a physical model.

The overall fault probability may be determined from a combination of the three types of information.

- *Expert judgment model* - is a set of knowledge rules based on expert judgment. With these rules, a classification of the degradation level and rate can be derived.
- *Regression model* - With a regression model, observed correlations and trends are employed to match key properties of an asset. The available data is matched to a mathematical relationship. Examples of regression techniques are polynomial interpolation, artificial neural networks, Bayesian regression.
- *Physical model* - By understanding the physics behind the degradation process, parameters can be defined that are representative for the process. This physical model relies on accurate input data, which may be hard to obtain. Having defined parameters based on physics, it allows tracking the progress of degradation. The results can even be fed back into the physical model to improve the accuracy of the modeling.

The concept of QP was introduced for power transformers in [1, 7, 17] to obtain a measurable quantity which relates the degradation process to an observable quantity.

In other words, the QP is the link between a degradation mechanism and a degradation model, a parameter that describes the condition of a system.

The use of QPs allows tracing the evolution of a degradation process. Table I summarizes the quality parameter types [1, 7, 17].

IV. REMAINING LIFETIME ESTIMATION

The remaining lifetime is estimated based on two models: the common IEC loading guide model and a paper degradation model. One of the virtues of the paper model is that its parameters can be updated according to a measured QP [1-2]. Thus, the paper model prediction can be improved (reducing the error) by involving data from furfural analysis.

1. Loading guide model

The first model for calculating the remaining lifetime of a transformer is based on the IEC 60076-7 loading guide (1-4) [18]. The parameters of the equations are assumed to be distributed according to normal distributions. This type of distribution is appropriate for physical processes with modest deviations. The result is the estimated fault probability $P(x)$ as a function of remaining lifetime RL, and is calculated by statistical simulation (Monte-Carlo technique, normal fitting).

The remaining lifetime RL can be determined from the loading guide by subtracting the loss of life LOL from the expected lifetime EL under nominal conditions. The loss of life LOL, between the moments t_0 and t is calculated by [18]:

$$LOL = \int_{t_0}^t V(\tau) d\tau \quad (1)$$

where $V(t)$ is the (time dependent) paper relative ageing rate. The relative ageing rate can be obtained from the IEC loading guide for Kraft and thermally upgraded paper. For Kraft paper, the relative ageing rate $V_{Kraft}(t)$ is given by [18]:

$$V_{Kraft}(t) = 2^{\frac{\theta_{hs}(t)-98}{6}} \quad (2)$$

where $\theta_{hs}(t)$ is the time dependent hot-spot temperature of the insulating paper. For thermally upgraded paper, the relative ageing rate $V_{TUP}(t)$ is given by [18]:

$$V_{TUP}(t) = \exp\left(\frac{15000}{110+273} - \frac{15000}{\theta_{hs}(t)+273}\right) \quad (3)$$

The hot-spot temperature is calculated according to the IEC loading guide (ON - oil natural cooling) [18]. The steady-state hot-spot temperature $\theta_{hs}(t)$ is calculated with:

$$\theta_{hs}(t) = \theta_a(t) + \Delta\theta_{or} \cdot \left(\frac{1+R \cdot K(t)^2}{1+R}\right)^x + \Delta\theta_{hr} \cdot K(t)^y \quad (4)$$

where θ_a is the ambient temperature at time t , $\Delta\theta_{or}$ is the top-oil (in tank) temperature rise in steady-state at rated losses (no-load losses and load losses), R is the loss ratio (ratio between the load losses P_{LL} and no-load losses P_{NL}), K is the ratio between the load current at time t and rated current, x is the oil exponent, y is the winding exponent and $\Delta\theta_{hr} (H \cdot g_r)$ is the hot-spot to top-oil (in tank) gradient at rated current (H is the hot-spot factor and g_r is the average winding to average oil in tank temperature gradient at rated current).

All parameters, except the load factor K and the ambient temperature θ_a are assumed to have normal distributions.

For the parameters from (4) to follow normal distributions, a Monte-Carlo simulation was applied. If the individual parameter uncertainties (standard deviations) are relative small, the distribution function of these parameters convert to a normal distribution [19]. Multiple operations on a set of

normal distributions, with small standard deviations, result in a normal distribution [19].

After a series of steps of Monte-Carlo simulation (generation of random numbers) and normal fitting (calculation of the mean and standard deviation), for the hot-spot temperature θ_{hs} , paper insulation relative ageing rate V_{Kraft} or V_{TUP} , loss of life LOL and expected lifetime EL, the remaining lifetime RL is estimated (mean and standard deviation).

The fault probability $P(x)$ is calculated as cumulative distribution function by:

$$P(x) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot \int_{-\infty}^x \exp\left(-\frac{(x-\mu)^2}{2 \cdot \sigma^2}\right) \quad (5)$$

where μ is the mean value of the RL and σ is the standard deviation of the RL.

In this analysis, the fault probability $P(x)$ is defined as the risk of failure, at any moment, due to paper degradation (thermal ageing). It must be noted that the fault probability given by (5) is not the same as the failure probability. For a failure, an event (such as a passing short circuit) has to occur in order to have a breakdown.

2. Paper degradation model

The paper degradation mechanism is modeled as proposed in [1-2]. The paper model was validated on an industrial transformer installed at an aluminum plant [1]. The decline in the DP-value is a result of a cascaded chemical reaction resulting in the scission of the cellulose chains. The link between the temperature and the DP-value is given by the Arrhenius relation (through the reaction rate k), which is discussed, among others, by Emsley and Lundgaard [15-16]. Thus, the DP-value as a function of time t is given by:

$$DP(t) = \frac{DP(t_0)}{1 + DP(t_0) \cdot \int_{t_0}^t k(\tau) d\tau} \quad (6)$$

where $DP(t)$ is the DP-value at time t , $DP(t_0)$ is the DP-value at an initial time t_0 and $k(t)$ is the time dependent reaction rate. The time dependent reaction rate has the Arrhenius form:

$$k(t) = A \cdot \exp\left(-\frac{E_a}{R_g \cdot T(t)}\right) \quad (7)$$

where A is a process constant (which depends on water content, oxygen or acidity), E_a is the molar activation energy of the degradation reactions (hydrolysis and thermo-oxidation), R_g is the universal gas constant, and T is the temperature in Kelvin calculated with (4) (which is related to both the current load and ambient temperature).

To estimate the parameters' uncertainties (standard deviations) from (6) and (7), the equation presented in [20] is used. Supposed that $x_1, \dots, x_n$ are variables with uncertainties

$\sigma x_1, \dots, \sigma x_n$ and these values are used to compute the function $q(x_1, \dots, x_n)$. If the uncertainties in $x_1, \dots, x_n$ are independent (uncorrelated), then the uncertainty in q is [20]:

$$\sigma q = \sqrt{\left(\frac{\partial q}{\partial x_1} \cdot \sigma x_1\right)^2 + \dots + \left(\frac{\partial q}{\partial x_n} \cdot \sigma x_n\right)^2} \quad (8)$$

Therefore, the uncertainty of the reaction rate $\sigma k(t)$ based on (8), corresponding to (7) is:

$$\sigma k(t) = k(t) \cdot \sqrt{\left(\frac{\sigma A}{A}\right)^2 + \left(\frac{\sigma E_a}{R_g \cdot \theta_{hs}(t)}\right)^2 + \left(\frac{E_a \cdot \sigma \theta_{hs}(t)}{R_g \cdot \theta_{hs}(t)^2}\right)^2} \quad (9)$$

where σA is the uncertainty of the parameter A , σE_a is the uncertainty of the activation energy E_a and $\sigma \theta_{hs}(t)$ is the uncertainty of the hot-spot temperature $\theta_{hs}(t)$. For the hot-spot temperature in (4), the uncertainty $\sigma \theta_{hs}(t)$ is also calculated using (8).

The uncertainty of the DP-value, corresponding to (6), is calculated with:

$$\sigma DP(t) = DP(t) \cdot \sqrt{\frac{(\sigma DP(t_0))^2 + DP(t_0)^4 \cdot \left(\int_{t_0}^t \sigma k(\tau) d\tau\right)^2}{DP(t_0)^2 \cdot (1 + DP(t_0) \cdot \int_{t_0}^t k(\tau) d\tau)^2}} \quad (10)$$

where $\sigma DP(t_0)$ is the uncertainty of the initial DP-value.

A fault situation might occur when the DP-value drops below a threshold value. The estimated DP-value at a certain time and the threshold level value for possible failures are stochastic in nature and may be described by distribution functions.

The parameters in the depolymerisation rate (7) contain uncertainties, which propagate to an uncertainty of the projected DP-value with time. Also, the DP-threshold for possible failure is considered as a distribution with finite width [1].

Therefore, the fault probability $F(t)$ is defined as the probability that the DP-value is lower than the threshold value. This involves two probability distributions.

The first is the probability distribution of the DP-value at time t . The probability of DP to have a value between x and $x+dx$ at time t is denoted as $p_{DP}(x, t)dx$ and is calculated according to (11). The second distribution is that of the threshold DP-value below which the insulation fails. The probability of the threshold to have a value between x and $x+dx$ is denoted as $p_{DP_{th}}(x, t)dx$. The probability that the threshold is above a certain DP-value x is given by (12) [1, 7].

To calculate the fault probability $F(t)$ with (15), the normal probability density functions have been used. More precisely, truncated normal distributions are used since it can handle a finite domain of DP-values (1 to 1300), whereas a standard normal distribution involves an infinite range of values. The density and cumulative distribution functions of a truncated normal distribution are defined as [1, 7]:

$$p_{DP(t)} = \frac{p(x)}{P(X_{\max}) - P(X_{\min})} \quad (11)$$

$$P_{DP_{th}(t)} = \frac{P(x) - P(X_{\min})}{P(X_{\max}) - P(X_{\min})} \quad (12)$$

with $X_{\min}$ (value 1) $\leq x \leq X_{\max}$ (value 1300), in which $p(x)$ and $P(x)$ denote the density and cumulative functions for a normal distribution:

$$p(x) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \exp\left(-\frac{(x - \mu)^2}{2 \cdot \sigma^2}\right) \quad (13)$$

$$P(x) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_x^{\infty} \exp\left(-\frac{(x - \mu)^2}{2 \cdot \sigma^2}\right) \quad (14)$$

with $-\infty < x < \infty$, μ is the mean for the estimated value (DP-value at a certain time or $DP_{threshold}$ value) and respectively σ the standard deviation. Finally, the fault probability at time t , $F(t)$ is obtained [1-2]:

$$F(t) = \int_0^{\infty} P_{DP_{th}}(x) \cdot p_{DP}(x, t) dx \quad (15)$$

The reliability is defined as $R(t) = 1 - F(t)$. Once again, as in section IV.1 it must be noted that the fault probability given in (15) is not the same as the failure probability. The transition from fault to failure requires a trigger, an event (such as a passing short circuit or a mechanical force). If $F(t)$ would result with a steep slope there is a well defined moment in time where the transformer is expected to fail. A gradual slope implies a relatively large uncertainty in the predicted time to failure.

3. Improved paper degradation model

The paper model prediction can be improved by measuring furfural content within the oil. The furfural method is an additional, indirect way to obtain the paper DP-value by measuring the furfural content from the transformer oil. Furfural (2-furaldehyde or 2-FAL) is one of the main products that are released due to the degradation of all cellulose containing materials inside the transformer. The furfural content can be measured by High Performance Liquid Chromatography (HPLC) [3, 9, 15].

In order to estimate the DP-value of the paper insulation a relation is proposed by Wetzer et al. in [21]:

$$DP(furfural) = A - B \cdot furfural \quad (16)$$

where A and B are material constants and $furfural$ is the measured furfural content in ppm.

The furfural concentrations from the oil and the DP-value have been measured on 13 disassembled transformers [21]. The curve $DP(furfural)$ has been drawn based on their measured values. In order to find the parameters A and B a

Fig. 3. The structure of the software.

first order polynomial curve fit was applied. Consequently, it was found that $A = 564$ and $B = 187$. The minimum DP-value is estimated from the measured furfural content with (16) and has a standard deviation $\sigma = 27$ from measurements.

V. SOFTWARE FOR REMAINING LIFETIME ESTIMATION

For the calculation of the remaining lifetime with the two models, a software tool was developed.

It is based on the schematic representation of degradation mechanism modeling according to Fig. 2. These two models, presented in Fig. 3, consist of a regression model and a physical model:

- the common IEC loading guide technique (regression model described in IV.1, the quality parameter QP being implicitly induced, namely the loss of life LOL of the paper insulation) and
- a paper degradation model (physical model described in IV.2, the quality parameter QP being explicitly directly linked to the degradation process, namely DP-value).

The software is user-friendly, fast and reliable.

VI. RESULTS AND DISCUSSION

The remaining lifetime calculation is shown for a hypothetical study. A typical transformer (ONAN cooling – oil natural air natural cooling) is assumed to be in service with thermal and operational parameters presented in Table II. In Table III, the assumed paper insulation characteristics, the furfural content assumed to be measured in the transformer oil and the assumed transformer's age are shown.

Because it is actually difficult to find a transformer, for which the required data are completely available, the data needed for the models are assumed. The data from Table II are chosen according to the values recommended by IEC standard loading guide 60076-7 [18]. The data presented in Table III are chosen according to the results obtained by Lundgaard et al. through measurements on paper insulation [16]. Therefore, the data from Tables II and III are

Table II

The assumed operational and thermal characteristics values, according to [18]. The standard deviation (σ) values of all the parameters are assumed 5% of the mean

Cooling	K [p.u]	θ_a [°C]	R	$\Delta\theta_{or}$ [°C]	$\Delta\theta_{hr}$ [°C]	x	y
ONAN	0.8	30	6	52	26	0.8	1.3

Table III

The assumed dry Kraft paper characteristics values, according to Lundgaard et al. [16]. The standard deviation (σ) values of all the parameters are assumed 5% of the mean

A [h ⁻¹]	E_a [kJ/mol]	$DP_{initial}$	$DP_{threshold}$	Furfural content [ppm]	Transformer's age [years]
$2 \cdot 10^8$	111	1000	250	0.4	8

representative for the estimation of the transformer remaining lifetime.

Fig. 4 shows the calculated DP-values in time represented by the solid line with the paper degradation model (6). The dotted lines define one standard deviation (σ) confident bound, representing a 68% probability margin (10).

The calculated DP-value with (6) after 8 years in service is 440 (Fig. 4), with a standard deviation of 119 (25%). The DP-value predicted curve has a high uncertainty. This is due to the inaccuracies taken into account in the load, ambient temperature, transformer's thermal parameters (Table II) and paper's characteristics (Table III).

The “star” symbol from Fig. 4 represents the minimum DP-value based on the furfural content assumed to be measured (value that corresponds to the hottest spot of the winding paper insulation). The DP-value is calculated with (16) based on the assumed furfural content, measured after 8 years in service. The estimated value is 490 with a standard deviation of 27 (6%) (Fig. 4).

Within the (wide) error margins, these values agree. The uncertainty of the furfural method is about a factor four lower. The reason is that the furfural method implicitly takes a measured value after 8 years into account, whereas for the paper model the calculation is based on the initial value only ($DP_{initial}$). This indicates the importance of sampling the DP-value to enhance prediction accuracies when they become large.

Therefore, the paper's parameters A , E_a and $DP(t_0)$ from (6) and (7) must be known accurately for a specific paper, before the transformer becomes operational. In addition, the load and ambient temperature as well as thermal parameters values of the transformer from (4) must be recorded. The type of the paper used in the transformer affect the rate of the degradation and thereby the furfural content.

Using the DP-value (and its uncertainty $\sigma = 27$) based on a furfural content (0.4 ppm) at time $t = 8$ years (Fig. 4), the prediction of the paper model can be improved by using these values as a new starting point. Fig. 5 presents the time variation of the “updated” DP-value together with the uncertainty margin. With incorporation of the measured furfural the accuracy margin is reduced. For example, at $t = 13$ years, the calculated DP-value is 328 ± 106 (Fig. 4) with

Fig. 4. The DP-value versus time calculated for dry Kraft paper. The dotted lines are the 68% error margin of the simulated result. The “star” symbol is the DP-value based on the measured furfural content together with its uncertainty margin.

Fig. 5. The “updated” DP-value versus time starting from the new $DP_{initial}$ based on the measured furfural content. The dotted lines are the 68% error margin of the simulated result.

the classic paper model and 354 ± 49 (Fig. 5) with the improved paper model. Further improvement is possible when incorporating measurements at certain time intervals.

In Fig. 6 the time variation of fault probability $F(t)$, is shown. The fault probability $F(t)$, calculated with (15) provides the likelihood that the predicted DP-value is below the threshold value (chosen 250). Remaining lifetime is based on the risk profile of the asset manager. If a high risk is accepted, the lifetime is longer. If it is not accept almost any risk, the lifetime is much shorter.

If the acceptable risk level (fault probability) of 50% is chosen as an end of life criterion, the expected lifetime is approximately 21 years (Fig. 6). Knowing the present age of the transformer, namely 8 years, the remaining lifetime will be about 13 years, for the same operating conditions. The

Table IV
Nominal life of Kraft paper ($DP_{initial} = 950$ and $DP_{final} = 250$, $\rho_v = 10^{12} \Omega m$) and of thermally upgraded paper ($DP_{initial} = 1000$ and $DP_{final} = 200$) [7, 22]:

Kraft paper				
Based on	IEC [18]	Emsley [15]	Lundgaard [14]	Badicu [22]
Life [years] at $T = 90^\circ C$	38	30	16	13
Life [years] at $T = 98^\circ C$	15	14	7	6
Thermally upgraded paper				
Based on	IEC [18]	Emsley [15]	Lundgaard [14]	
Life [years] at $T = 110^\circ C$	17	17	9	

estimated lifetime of 21 years, in the operational conditions from Table II (a hot-spot temperature of about $88^\circ C$), is comparable to the results presented in different papers (Table IV). It can be seen that, at full load (for a temperature of $98^\circ C$), the expected lifetime for Kraft paper is 15 years, according to the IEC loading guide (Table IV). This value derived from the loading guide seem to be in agreement with the work of Emsley [15], whereas Lundgaard [14] and Badicu [22] predict a much lower nominal life.

Using the IEC loading guide model (Fig. 7), the remaining lifetime is about 27 years (assuming an expected lifetime of 30 years [8]). In general, the expected life of 30 years fits best in case of a transformer used in a transmission or distribution grid [23]. Such kind of transformers has a cyclic load, high load during day and low load during night. This might not apply to our transformer, for which the load has constant high values (Table II).

As it can be seen in Fig. 7, the fault probability is very low in the first remaining years and increasing to the end. At the end, we know for sure (100%) that the transformer has failed. Of course, this heavily depends on the loading of the transformer. Depending on the chosen risk level, the remaining lifetime is 27 years. In this case, the acceptable risk level is chosen at the median of the fault probability curve (50%).

Fig. 6. Paper insulation fault probability $F(t)$ versus time, based on the “improved” paper degradation model.

Fig. 7. Fault probability $P(x)$ in terms of remaining lifetime of the transformer based on the IEC loading guide model.

The fault probability curve from Fig. 6 is not as steep as the curve presented in Fig. 7.

This is due to parameter uncertainties, which are accounted for in (6). For the loading guide uncertainty is just ignored by defining an expected life of 30 years for some specified conditions in (4) resulting in a seemingly precise prediction accuracy.

The loading guide model has several drawbacks, which have been overcome by the paper degradation model [1].

- As stated above the IEC loading guide predicts ageing relative to a reference lifetime, the nominal life of the paper insulation, assumed 30 years.
- Its prediction cannot be verified or calibrated by measuring externally accessible indicators, e.g. DP-value [7]. It does not directly allow varying the end of life threshold, chosen always 200 [1, 18].
- The IEC loading guide model is only capable of predicting the degradation of dry paper and not of any type of paper exposed to different contaminants (water, oxygen or acids), appearing during transformer operation. It should be taken into account that the presence of water and oxygen may seriously affect the transformer lifetime [7].

VII. CONCLUSIONS

The remaining lifetime calculation is based on two models: the IEC loading guide model and a paper degradation model. The calculations involve a probabilistic approach. The final goal is to combine the technical model discussed in this paper with a management tool allowing the asset manager to analyze risks, benefits, costs, and availability.

The remaining lifetime value calculated with the paper degradation model for the case evaluated in the paper is smaller than the value calculated with the IEC loading guide with about 45%.

The paper model prediction can be narrowed down (minimizing the accuracy margins) by involving the measured values, e.g. based on the furfural content.

To help the asset manager in the decision making process, the two models are combined into a single software tool. The software used for remaining lifetime calculations is fast, stable and easy to use.

ACKNOWLEDGMENT

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/88/1.5/S/60203 and by KEMA Nederland B.V. (Arnhem, the Netherlands).

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