Transmission Transformer End-of-life Modelling: Incorporating Insulating Paper's Thermal Lifetime Analysis With Ordinary Statistical Analysis

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Abstract: Intensive statistical analysis on the UK transmission transformer's historical reliability data has confirmed a constant hazard of 0.27%. However the hazard at older ages cannot be accurately predicted due to the lack of older transformers operating in the system. 77 scrapped transformers' thermal lifetimes are assessed to assist the statistical approaches by assuming transformer's lifetime equals to its insulating paper's thermal lifetime. To improve the statistical significance, the life samples are further enlarged by transformer thermal modelling. The enlarged sample contains 158 transformers and yields a median thermal lifetime of 95 years.

1 INTRODUCTION

Transmission transformers are considered as an important part of infrastructure and its failure-in-service could lead to unaffordable costs in terms of both asset loss and interruptions in electricity supply. In the UK, the majority of the transmission transformers were installed during the 1960s and many of them are approaching, or even have passed their designed lifetime which is suggested as 50 years [1, 2]. Asset managers desire to develop a model which is able to predict transformer's end-of-life, in order to optimise the capital re-investment.

A great amount of work has been done on transformer's end-of-life modelling, including either performing the statistical analysis upon transformer population's historical reliability data and predicting future failure trend by engineering judgements [3-5], or assessing individual transformer's health by examining the conditions of transformer component(s), and then predict transformer population's future failure trend [6-9]. These failure trends obtained however lack evaluation.

This paper starts with ordinary statistical analysis on the transformer population's historical data, and yields a constant hazard rate. By evaluating this hazard with 95% confidence band, the small number of older-age transformers has been identified as a major limitation of statistical approaches. Therefore, 77 scrapped transformers' information and thermal modelling are utilised to produce a transformer thermal lifetime distribution, which suggests a reasonable thermal lifetime for the population.

2 STATISTICAL ANALYSIS ON HISTORICAL RELIABILITY DATA

2.1 Transformer hazard

The UK transmission transformer's historical reliability data dates back to 1952 and covers the installation and failure number till 2010. For the sake of performing statistical analysis, the reliability data has been rearranged according to transformer age, in which the reference year 2010 is chosen in deriving each individual transformer's age.

In life data analysis, the term hazard is often used to measure the sample's proneness to failure as a function of age [10]. At each age, transformer's hazard $h(t)$ can be calculated using (1).

$$h(t) = \frac{failure(t)}{survivor(t)} \quad (1)$$

The failure number at Age t indicates how many transformers fail with that age, while the survivor number at Age t is interpreted as the number of transformer that has already survived t years. Looking at the UK transformer historical data, the failure and survivor number is tabulated as:

i. As long as a transformer was installed and commissioned to the network and has survived the first year of service, it contributes to the bin of survivor number in Age 0. For any additional years of its surviving, the contribution would be counted in their corresponding survivor bins.

ii. If a transformer fails after t years since its installation, this failure is marked in the bin of failure number at Age t. Meanwhile this particular transformer would also be spotted in the survivor bins from Age 0 till Age $t-1$ but no longer for further years. For those transformers which never failed since installation, they contribute into the survivor bins from Age 0 all the way till its age at the reference year, 2010.

The tabulated failure and survivor transformer number at each age are shown in Figure 1 and 2 respectively.

In Figure 1, the failure number appears to be randomly distributed within 5. As National Grid has been proactively retiring transformers with poor conditions which effectively truncates the failure number in old ages, one shall not simply infer that the reliability of old transformers is still in “safe zone”, as Figure 1 might have implied.

In Figure 2 the survivor number is decreasing with age, and apparently with different rates. The early stage until Age 46 indicates that most transformers survive their early years due to strict factory testing. Then from Age 47 the number drops drastically. 57 is the oldest transformer age in the UK network system at year 2010.

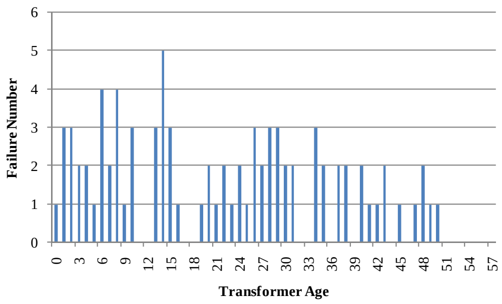

Figure 1: The UK transmission transformer’s failure number from Age 0 to 57.

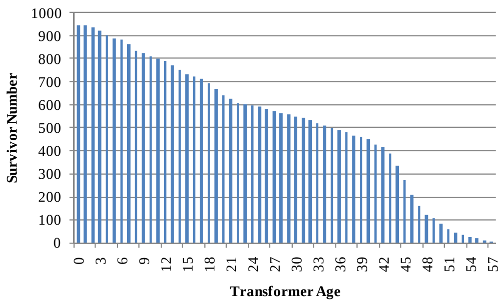

Figure 2: The UK transmission transformer’s survivor number from Age 0 to 57.

The transformer hazard can be calculated using (1) and the corresponding hazard plot is then shown in Figure 3.

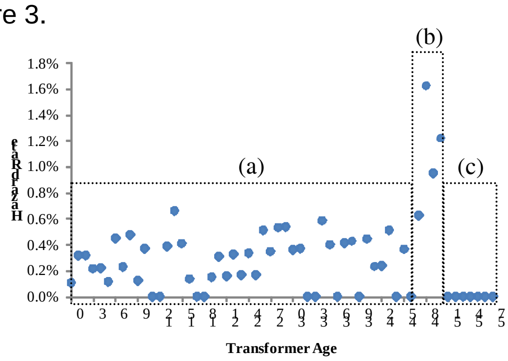

Figure 3: The UK transmission transformer’s hazard from Age 0 to 57.

Although Figure 3 shows that the highest hazard has never exceeded 2%, the trend shows a rather uneven pattern. For better understanding the whole age span is split into three regions and analysed accordingly.

Region (a) consists of ages from 0 to 46, in which the hazards are fluctuating within the level of 0.8%. In these ages the transformer survivor numbers are fairly big (i.e. larger than 200). The fluctuation is caused by the different failure number, i.e. the numerator in (1).

Region (b) consists of ages from 47 to 50, where the hazards increase up to 1.6%. The reason to this sudden increase is the drastic decrease of the survivor numbers. This effectively results in small denominator in (1), and hence very large hazards.

Region (c) consists of the oldest ages from 51 to 57. In this range the hazards are 0%, because no failure has been observed among the very small transformer population in these ages.

Since Figure 3 has shown hazard disagreements between different age regions, they all indicate that hazard is sample size dependent. The uncertainty in hazard as sample size shrinks which can be quantified by hazard’s 95% confidence band.

2.2 Hazard rate’s 95% confidence band

At each age, the confidence band of the hazard is calculated by examining hazard’s likelihood, L_{h}’, by Binomial Distribution in (2). For certain transformer age, the failure number *f* and the surviving number *n* are both fixed.

While no prior knowledge is available regarding the transformer hazard, the hazard rate is assumed to be randomly distributed from 0% to 100%. By artificially assigning hazard from 0% to 100% uniformly, the likelihood corresponding to each hazard can be calculated with (2). This likelihood is then unified by (3).

$$L_{h'} = \frac{n!}{f!(n-f)!} h'^{f} (1-h')^{n-f} \qquad (2)$$

$$L_{h'}(\%) = \frac{L_{h'}}{\sum_{h'=0\%}^{100\%} L_{h'}} \qquad (3)$$

The 95% confidence band of a certain age’s hazard is obtained by extracting the hazards which correspond to the 2.5% and 97.5% of the cumulative likelihood and then regarding them as the lower and upper limits of the confidence band. The quantified hazard’s 95% confidence band at all ages is shown in Figure 4.

Figure 4 has shown that the hazard’s 95% confidence band is restricted from Age 0 to 46, beyond which the upper limit exceeds 2%. As age progresses, the band’s upper limits increase into whopping levels. In an extreme case, the hazard’s upper limit at Age 57 indicates that even a hazard rate of as high as 52% is statistically possible, which obviously disobeys the engineering judgement. Such appearance in hazard’s confidence band does not suggest any increasing in transformer risks as age progresses whatsoever, but is purely due to the lack of data in older transformer ages.

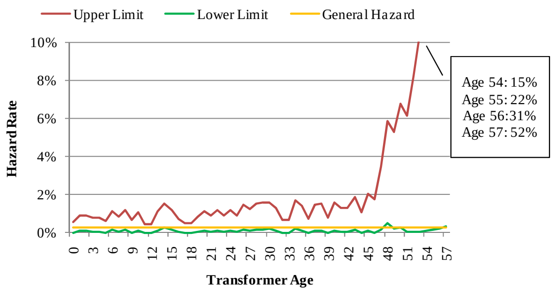

Figure 4: The hazard rate's 95% confidence bands of all transformer ages.

The hazard's 95% confidence band has verified that transformer's hazard strongly depends on the sample size of age data. Under this context, a general hazard, $h_{general}$, is calculated using (4), i.e. dividing the sum of failure number by the sum of the survivor number at all ages. Base on the historical reliability data by 2010, the UK transmission transformer's general hazard is calculated as 0.27%.

$$h_{general} = \frac{\sum_{t=0}^{57} failure(t)}{\sum_{t=0}^{57} survivor(t)} \quad (4)$$

The general hazard 0.27% is plotted with hazard's 95% confidence band in Figure 4, and is found to be encapsulated by the confidence band in most ages except for Age 14, 48, 50 and 57. The hazard's lower limit at Age 14 is 0.29% as this age is with the most failure number. At Age 48, 50 and 57 the confidence band becomes sensitive to the failures observed due to a very small sample size, and hence their lower limits have higher values and exceed 0.27%.

3 TRANSFORMER THERMAL LIFETIME ANALYSIS USING SCRAPPING INFORMATION

3.1 Transformer's thermal ageing mechanism

Statistical analysis has confirmed a constant transformer hazard of 0.27% but cannot predict transformer life. In reality, due to the degradation of transformer components, transformer's hazard is supposed to rise with operation period. Consequently, age-related ageing model is studied in this paper to investigate transformer thermal lifetime by assessing insulating paper's condition.

Paper is used in oil-filled transformers as solid insulation to provide dielectric strength. In transformer's operation, the paper-oil insulation system subjects to elevated temperature, and by-products produced such as moisture and acid compromises paper's integrity [11, 12] by the means of reducing its mechanical strength and jeopardises transformer's reliability [13-15]. In practice, the paper's mechanical integrity is commonly quantified by the degree of polymerisation (DP). In a new transformer, the paper's DP value is normally around 900~1300 [12], and at the paper's end-of-life, the remaining DP of 200 has been widely accepted as a criterion due to the very little mechanical strength retained at this DP level [16].

Studies on the kinetics in paper degradation [17] have revealed that the paper's ageing rate, k, is proportional to the inverse of paper's remaining DP. After degradation time t, the correlation between the remaining and initial DP values, DP_t and DP_0, is expressed in (5).

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt \quad (5)$$

Considering paper's ageing mechanism, latest studies have identified paper ageing mechanisms to be oxidation or hydrolysis [13, 18]; oxidation dominates at paper temperature within 110°C and hydrolysis at higher. Equation (6) is used to calculate the relative ageing rate of a transformer's paper, k_r, comparing with the ageing rate in reference environment. HST is paper's hot-spot temperature, A and E_A are environmental factor and activation energy respectively, A_0 and E_0 are their reference values, and R is the gas constant. Different mechanisms correspond to different sets of values and are listed in Table 1.

$$k_r = \frac{A}{A_0} \exp\left[\frac{E_0}{R \times (98°C + 273)} - \frac{E_A}{R \times (HST + 273)}\right] \quad (6)$$

Table 1: Environmental factor and activation energy values [13].

	Reference	Oxidation	Hydrolysis
A (hour^{-1})	4.1×10^{10}	4.6×10^{5}	1.5×10^{11}
E_A (kJ/mol)	128	89	128

If transformer operating condition and the design information are available, a sophisticated set of differential equations in [19] can actually be used to estimate transformer's thermal lifetime. However as one of the inputs, transformer's hot-spot factor (HSF) is unknown. Fortunately a number of in-field transformers have been retired and scrapped to provide valuable information in deriving it.

3.2 Scrapped transformer's thermal lifetime

The National Grid has proactively retired over 100 transmission transformers and performed forensic tear-down examinations on most of them, including measuring the retained DP in insulation paper samples at different locations. The lowest DP measurement has then been picked out to evaluate transformer's thermal lifetime, as it measures the worst degradation occurred inside the transformer.

Assuming that the paper's initial DP in new transformer and the DP at transformer thermal end-of-life are 1000 and 200 respectively, and that the ageing rate k is constant throughout the transformer's whole life. Using (5) the ageing rate k of scrapped transformer can be calculated with the lowest measured DP and the transformer's in-service year, and the corresponding thermal lifetime can then be derived. By this means 77 scrapped transformers' thermal lifetime distribution is shown in Figure 5.

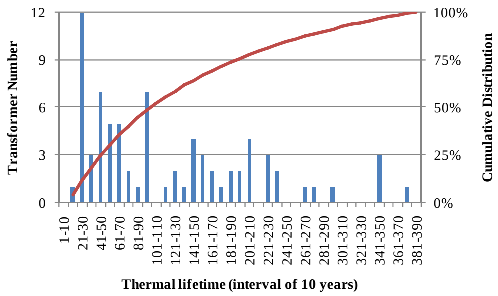

Figure 5: The thermal lifetime distribution and the curve fitted cumulative distribution of 77 scrapped transformers.

In Figure 5, the thermal life spans from 16 to 373 years; the earliest onset and the expected life (corresponding to the 2.5th and 50th percentile in the cumulative distribution) are 17 and 92 years respectively. The thermal life follows a shape of bimodal distribution, with the boundary between two modes at around 100 years. According to engineering judgement the lifetimes falling into the left mode are attributed to either not-so-good designs or severe conditions such as heavy load, or both.

4 TRANSFORMER THERMAL MODELLING

4.1 Deriving hot-spot factor from scrapped transformers

As stated previously, the main obstacle in modelling transformer's thermal ageing and lifetime is the unknown *HSF*. Since now 77 transformers' thermal lifetimes have been derived, this paper proposed an algorithm to inversely derive *HSF* value from thermal lifetime by using the thermal model. The derived *HSF*s can be applied to the transformers within the same design family, as *HSF* is strongly dependent on the design.

The method in deriving *HSF* is illustrated in Figure 6. The steps are explained as:

1. Thermal model needs four inputs, and three of them have been obtained, i.e. load profile and ambient temperature profile in the year 2009, and the heat-run data.

2. At the beginning, assign the *HSF* with a small initial value e.g. 1. The *HSF* will be corrected through the following iteration.

3. Input the four parameters into the thermal model differential equations [19] to calculate the *HST*.

4. Use (6) to calculate relative ageing rate k_r base on the calculated *HST.* Since yearly load and ambient temperature data are used, the loss-of-life, *LOL*, over one year time is then calculated using (7); t_1 and t_2 denote the first and the last time frame of the inputs as well as the calculated k_r.

$$LOL = \int_{t_1}^{t_2} k_r dt \qquad (7)$$

5. As end-of-life criterion, DP of 200 corresponds to 150,000 hours [16], the thermal end-of-life, *EOL*, can be calculated as dividing 150,000 by *LOL*, given that the unit of *LOL* is converted into hours.

6. Compare this thermal model derived *EOL* with the lifetime derived from the lowest DP measurement. Most probably the initial *HSF* would not result in modelled *EOL* equalling to the DP derived life. Adjust the *HSF* and repeat the steps from 1 to 5 until a good agreement of two lifetimes is established (relative difference less than 5%). Hence the *HSF* of this scrapped transformer is derived.

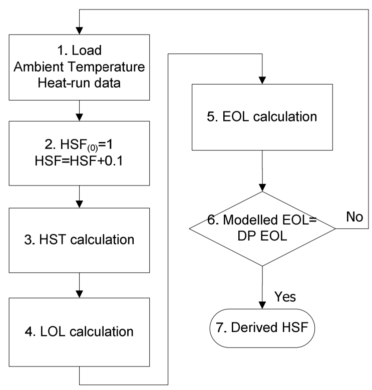

Figure 6: Procedures in deriving scrapped transformer's *HSF*.

Due to the availability of the input data, 23 scrapped transformers' *HSF*s have been derived. The range of these *HSF* spans from 1.46 to 7.8 and follows lognormal distribution with a mean value of 3.52, as shown in Figure 7.

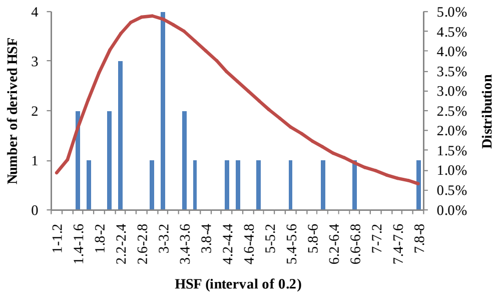

Figure 7: The distribution of 23 scrapped transformers' derived *HSF*s.

4.2 Thermal Model Results

Now with all the four inputs available, thermal lifetimes of 81 active transmission transformers have been derived by the thermal model. The modelling procedure on an active transformer can also be understood from Figure 6, except the *HSF* is now assigned with the derived value according to the design family the transformer belonging to; no iterative correction is required. In order to increase the statistical significance, the 81 lifetime samples have been combined with the 77 scrapped transformer samples to form an enlarged sample set, i.e. totally 158 transformers. The corresponding lifetime distribution is shown in Figure 8.

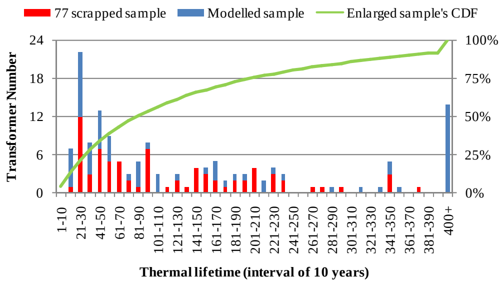

Figure 8: The thermal life distributions of the modelled samples, 77 scrapped samples and the CDF of enlarged 158 samples.

The design family and load distributions in both scrapped and modelled samples are plotted in Figure 9 to analyse their effects on the life distribution. According to the design family distribution (upper Figure 9), the ratios of the modelled samples to the scrapped ones are not uniform. On the other hand the load distributions in both samples are separately plotted according to the derived life range (lower Figure 9), and the ratios of the modelled sample to the scrapped sample are very close, especially at the life within 100 years. Although both design and load have such different ratios in scrapped and modelled samples, the two life samples' cumulative distribution plots have close shape especially in the first 50%, shown in Figure 10. This has verified that both design and load synergistically influence transformer's thermal lifetime.

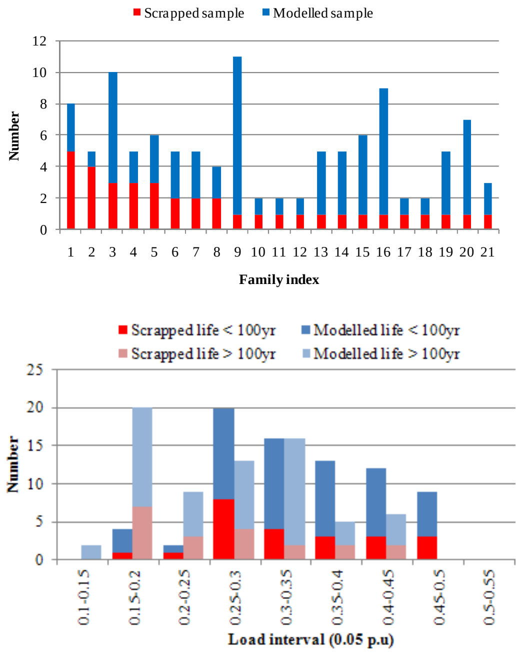

Figure 9: The distributions of design family (upper) and load (lower) in scrapped and modelled samples.

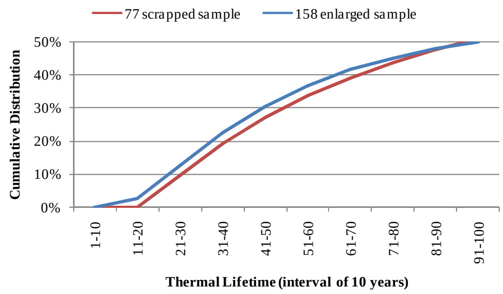

Figure 10: Comparing the CDF in scrapped and enlarged samples (lives longer than 100 years are omitted).

The enlarged life sample indicates an earliest onset of 15 years and expected life of 95 years. These values are very close to what 77 scrapped transformers have suggested which are 17 and 92 years respectively, as summarised in Table 2. The tails in both samples are very long and are probably not of asset manager's interest, as from an engineering standpoint a transformer cannot be in service for such a long period without replacement.

Table 2: The critical ages in two life sample sets.

Unit: year	77 samples	158 samples
Earliest onset (2.5%)	17	15
Expected life (50%)	92	95

The thermal modelling result has pointed out that if a certain transformer is well designed and lightly loaded, its thermal reliability must be very high, reflected by a very long modelled thermal life. In real operation, it is hard to believe that any transformer would survive over 100 years considering the existence of other synergetic ageing mechanisms. Even it is thermally possible, there is no reason to allow such severely aged equipment to remain in the network. In this context those transformers having estimated thermal life of over 100 years can be taken out of the life sample and disregarded. Transformer's earliest onset year and the expected life are the vital figures and deserve efforts in their derivations, not the latest onset or longest life possible, which imply the risks asset manager not willing to take.

5 CONCLUSION

Applying statistical approach on the UK transmission transformer's historical reliability data yields a constant transformer hazard of 0.27%, but cannot accurately determine the hazard in older ages because of the limited number of transformers operating in the system.

To compensate statistical tools' incapacity, transformer's thermal failure mechanism is investigated. 77 retired and scrapped transformers' thermal lifetimes have been derived, which suggest the earliest onset of 17 years and the expected thermal life of 92 years.

Scrapped transformers' derived lifetimes have assisted the derivation of *HSF*, which makes the use of thermal model possible. Active transformers' thermal lifetimes have been estimated by thermal model, and the enlarged sample now contains 158 transformers. The corresponding earliest onset and the expected life are now 15 and 95 years.

6 REFERENCES

[1] A. Bossi, *et al.*, "An international survey on failures in large power transformers in service," *Electra,* pp. 21-47, 1983.

[2] A. White, "Replacement versus refurbishment end of life options for power transformers," in *Transformer Life Management*, London, UK, 1998, pp. 10/1-10/3.

[3] W. Li, "Evaluating mean life of power system equipment with limited end-of-life failure data," *IEEE Transactions on Power Systems,* vol. 19, pp. 236-242, 2004.

[4] J. Cota-Felix, *et al.*, "A new method to evaluate mean life of power system equipment," presented at the CIRED 2009. 20th International Conference and Exhibition, Prague, Czech Republic 2009.

[5] R. JONGEN, *et al.*, "A statistical approach to processing power transformer failure data," in *19th International Conference on Electricity Distribution*, Vienna, 2007.

[6] T. Hjartarson and S. Otal, "Predicting Future Asset Condition Based on Current Health Index and Maintenance Level," in *ESMO 2006 IEEE 11th International Conference*, Albuquerque, NM, 2007.

[7] D. Hughes, "The use of health indices to determine end of life and estimate remnant life for distributionassets," in *17th International Conference on Electricity Distribution*, Barcelona, 2003, pp. 1–5.15.

[8] A. Jahromi, *et al.*, "An approach to power transformer asset management using health index," *Electrical Insulation Magazine, IEEE,* vol. 25, pp. 20-34, 2009.

[9] J. Lapworth and A. Wilson, "The asset health review for managing reliability risks associated with ongoing use of ageing system power transformers," in *International Conference on Condition Monitoring and Diagnosis*, Beijing, 2008, pp. 605-608.

[10] W. Nelson, *Applied life data analysis*: John Wiley & Sons Inc, 1982.

[11] A. Emsley, *et al.*, "Degradation of cellulosic insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil," *IEE Proceedings-Science, Measurement and Technology,* vol. 147, p. 115, 2000.

[12] A. Emsley and G. Stevens, "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers," *IEE Proceedings-Science, Measurement and Technology,* vol. 141, p. 324, 1994.

[13] CIGRE, "Thermal Performance of Transformers," *Cigre Working Group A2.24 Technical Brochure No. 393,* October 2009.

[14] H. Ding, *et al.*, "Why Transformers Fail," in *Euro TechCon*, Strelton, UK, 2009.

[15] M. A. Franchek and D. J. Woodcock, "Life-Cycle considerations of loading transformers above nameplate rating," in *Sixty-Fifth Annual International Conference of Doble Clients*, 1998.

[16] "IEEE Guide for Loading Mineral-Oil-Immersed Transformers," *IEEE Std. C57.91-1995,* 1995.

[17] A. Emsley and G. Stevens, "Kinetics and mechanisms of the low-temperature degradation of cellulose," *Cellulose,* vol. 1, pp. 26-56, 1994.

[18] L. Lundgaard, *et al.*, "Aging of oil-impregnated paper in power transformers," *IEEE Transactions on Power Delivery,* vol. 19, pp. 230-239, 2004.

[19] "IEC 60076-7 Power Transformers-Part7: Loading Guide for Oil-Immersed Power Transformers," *IEC Standard,* 2005.