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Introduction to Transformer Loss of Life

Based on Models From IEC and IEEE Loading Guides

This work introduces the concepts of Hot-Spot Temperature (HST) and transformer ageing due to temperature and how the HST affects transformer life expectancy. The relative ageing rate of two models are compared for various scenarios and the Transformer Loss of Life (LoL) is estimated for two HST profiles.

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LoL is the term used to express how much life a transformer has lost since being commissioned. One factor which accelerates ageing of the transformer and increases its LoL is the HST. The IEEE [1] and the IEC [2] loading guides provide models for estimating the LoL utilising the HST.

DETERMINATION OF THE HST

Figure 1 shows a simplified model of the temperature distribution within an oil-immersed power transformer, with the following assumptions [3]:

- the oil temperature inside the windings increases linearly from bottom to top regardless of the cooling mode;
- the temperature rise on the conductor at any position up the winding increases linearly and parallel to the oil temperature rise, with a constant temperature difference of 'g'; and
- the HST rise is higher than that of the conductor at the top of the winding to allow for increases in stray losses and is accounted for by multiplying 'g' by the hot-spot factor 'H'; which may vary from 1.1 to 1.5, (1.0 to 2.1 [2]) depending on transformer size, short-circuit impedance and winding design.
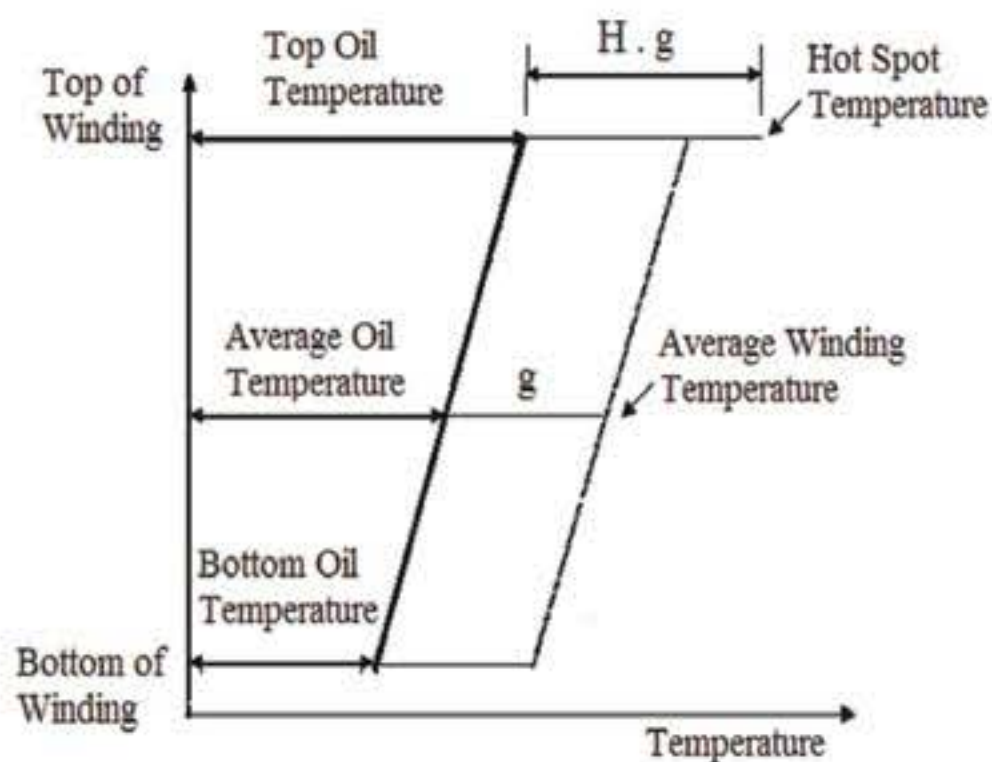

Figure 1 *Thermal diagram of a transformer [4]*

The HST is the sum of the ambient temperature θ_A, top oil temperature rise $\Delta\theta_{TOP}$, and the hot-spot to top oil temperature rise $\Delta\theta_H$.

$$\theta_H = \theta_A + \Delta\theta_{TOP} + \Delta\theta_H \dots (1)$$

AGEING MODELS

Ageing of the transformer paper insulation is dependent on temperature and contents of moisture, oxygen, and acid. Models presented here focus only on temperature and in particular the HST since deterioration is normally highest at the top of the winding. The IEC standard refers to the relative ageing rate, V whereas the IEEE standard refers to the ageing acceleration factor, FAA. Both are utilised in the same way to calculate lifetime consumption. In this work we adopt V.

Model A: Non-thermally upgraded paper. The relative (thermal) ageing rate, V, is referenced to unity for a HST of 98°C [θ_{Href}], at an ambient of 20°C where the HST rise over ambient is 78°C and operating in the range of 80°C to 140°C.

$$V = 2^{\left(\frac{\theta_H - \theta_{Href}}{6}\right)} \dots (2)$$

V doubles for every 6°C rise in HST.

Model B: Thermally upgraded paper. V is referenced to unity for a HST of 110°C [θ_{Href}], at an ambient of 30°C where the HST rise over ambient is 80°C. 15000 is an empirical constant provided in Annex I [1]. Equation (3) may also be used to model non-thermally upgraded insulation, with V referenced to unity in the case where the average winding temperature rise is 55°C and at a HST of 95°C, with a HST rise over ambient of 65°C.

$$V = e^{\left(\frac{15000}{\theta_{Href}+273} - \frac{15000}{\theta_H+273}\right)} \dots (3)$$

Equations (2) and (3) are based on the Montsinger [5] and Dakin [6] life expectancy models, a simplification of the Arrhenius relation equation given in A.1 [2].

Figure 2a (below) compares the performance of hot-spot on paper types and shows that the use of thermally upgraded paper can decrease ageing by a factor of as little as 3.4 and at most by 7.4.
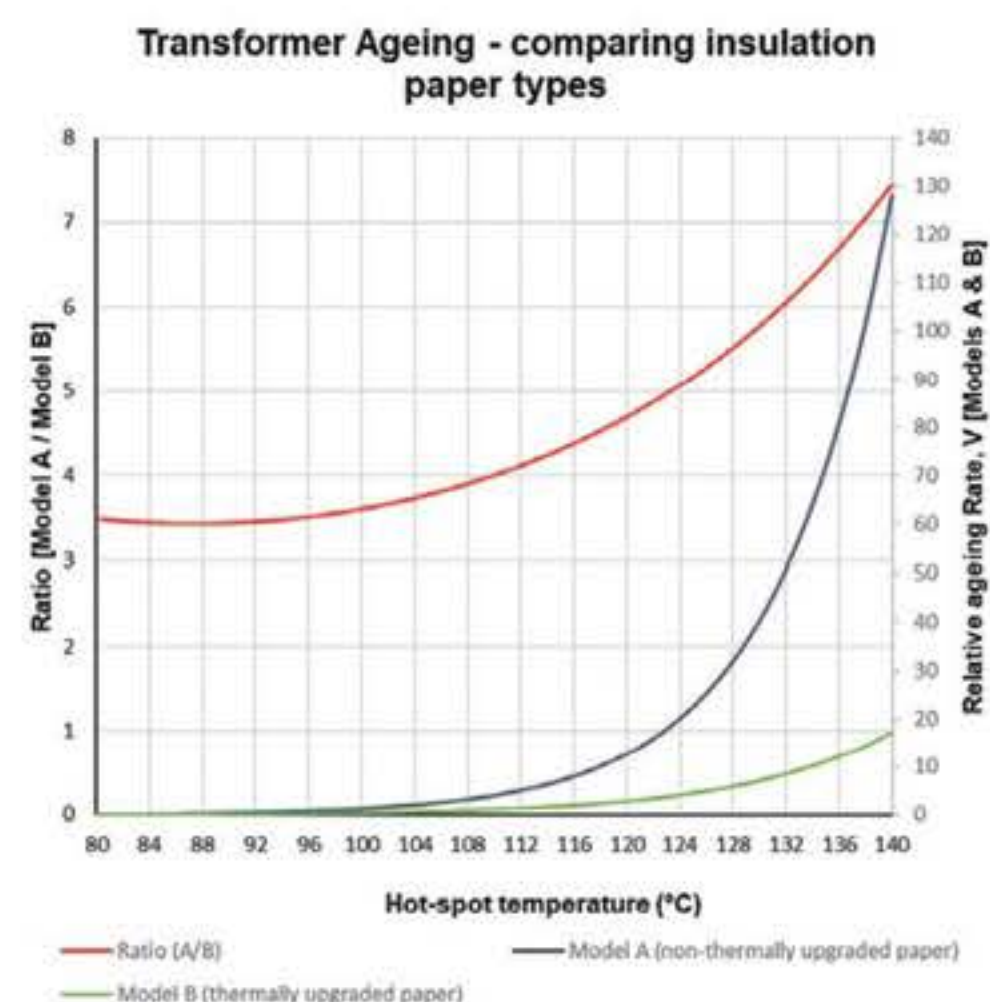

Figure 2a *Comparing insulation paper types*

Figure 2b (below) compares the models for non-thermally upgraded paper insulation. The results for both models are plotted for the hot-spot range 80°C to 140°C and for the restricted (rest.) range of 80°C to 124°C so as to better highlight the differences. The two models are monotonically increasing, initially with Model B yielding higher values of V, and intersect at a HST of approximately 123°C, after which they commence to diverge and Model A yields higher values of V. The value of V below 80°C is negligible for both curves.
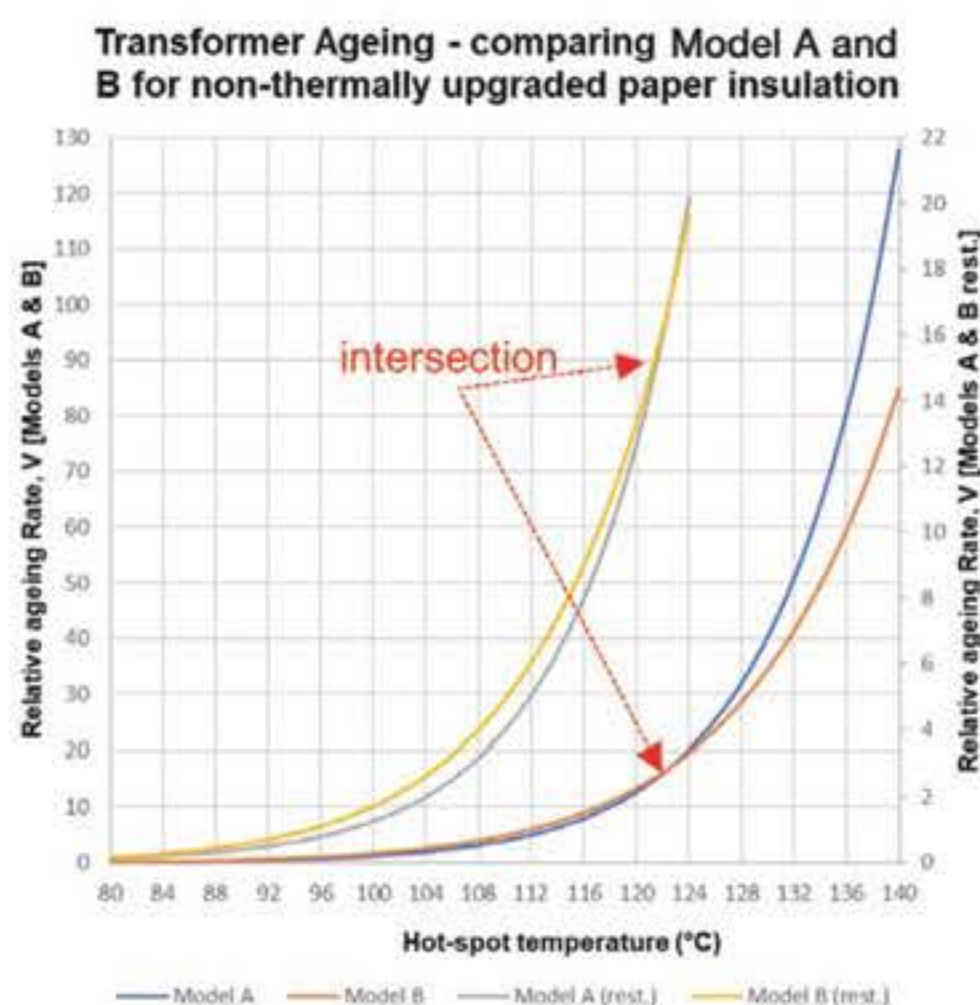
$$L = \int_{t_1}^{t_2} V \, dt \quad or \quad L \approx \sum_{n=1}^{N} V_n t_n \dots (4)$$

Worked Example: Lifetime consumption estimation for non-thermally upgraded paper.

Consider the HST profile of a transformer over a 24-hour period as provided by the first three columns in Table 1. Assume that the temperature transition times are negligible. Inserting the HST into equations (2) and (3) yields V for those periods (given in columns 4 and 5). The lifetime consumption for each time period is calculated by multiplying V with the time interval and given in columns 6 and 7.

Figure 2b *Comparing models for non-thermally upgraded paper*

Lifetime consumption (loss of life)

Under constant conditions the relative lifetime consumption L can be calculated by the product of V and time elapsed, t_2-t_1. In practice the load and transformer temperatures change over time, and in which case L is given by (4) [2].

1	2	3	4	5	6	7
Time Period	Time interval (Hours)	Hot-spot temperature (°C)	V (Model A)	V (Model B)	L (Model A) (Hours)	L (Model B) (Hours)
12am to 6am	6	104	2.000	2.646	12.000	15.876
6am to 8am	2	118	10.079	10.998	20.159	21.996
8am to 6pm	10	92	0.500	0.715	5.000	7.153
6pm to 12am	6	110	4.000	4.935	24.000	29.611
Total	24				61.159	74.636
Ageing factor (L/24)					2.548	3.110

Table 1 *Worked example - lifetime consumption estimation*

Summing the lifetime consumptions over the 24-hour period shows the transformer actually aged 61.159 hours (Model A) [0.034%] or 74.636 hours [0.041%] (Model B), of its total life span. The percentages are based on a transformer lifespan of 180,000 hours or 20.55 years and assumes the transformer running constantly at the rated HST. This means that if a transformer was subjected to the same daily load profile as in Table 1, its lifespan would be reduced to 70636 hours [8.06 years] (Model A) or 57881 hours [6.61 years] (Model B).
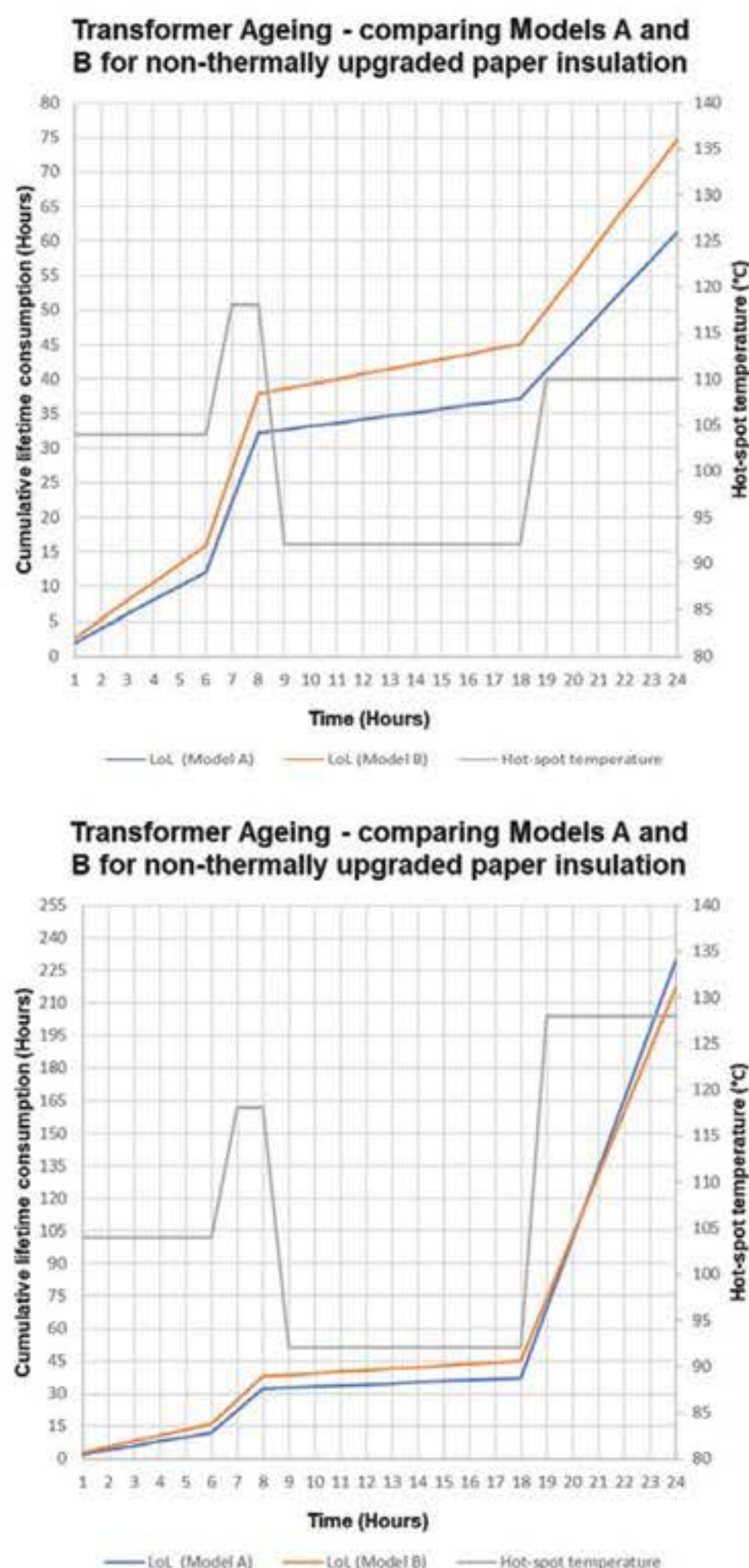
Miro-F TxM Transformer Monitor and Logger

Figure 3 (top) represents the values in Table 1. Figure 3 (bottom) represents the values in Table 1 but where the HST for the last six hours is changed to 128°C. The profiles are purposely changed to highlight a scenario where Model A can yield a higher LoL if the HST is beyond 123°C.

Transformer Ageing - comparing Models A and B for non-thermally upgraded paper insulation

Transformer Ageing - comparing Models A and B for non-thermally upgraded paper insulation

Figure 3 *Transformer ageing for non-thermally upgraded paper and for two hot-spot profiles. Top: HST=110°C for last six hours. Bottom: HST=128°C for last six hours.*

TRANSFORMER MONITORING

CHK Power Quality Pty Ltd offers the Miro-F TxM Transformer Monitor and Logger (TxM), an instrument purposely suited for comprehensive monitoring of transformer health and can provide LoL calculations based on the IEC and IEEE Standards.

The TxM includes two temperature sensors which can be software configured to measure the top oil and ambient temperatures. Where the transformer is equipped with multiple winding temperature sensors the TxM, together with the Miro Auxiliary I/O module (MiroAux), can utilise these inputs in its LoL calculations.

Setting up and configuring the TxM requires the user to populate a template with relevant transformer ratings and other known parameters specific to the transformer. Alternatively, the user can use default values, provided in the TxM, for parameters that are not readily available on the transformer's name plate.

The TxM together with the MiroAux can expand the monitoring to include: geomagnetic DC current; dissolved gases such as oxygen; moisture; on load tap changer (OLTC) operation; bushing leakage current; and fan operation. All these parameters can, not only be displayed alongside critical power quality information, but also correlated for in depth analysis. **T&D**

References

[1] *"IEEE Guide for loading mineral-oil-immersed transformers and step-voltage regulators", IEEE Standard C57.91, 2011.*

[2] *"IEC Power transformers, Part 7: Loading guide for oil-immersed power transformers", IEC 60076-7, 2018.*

[3] *"Loading guide for oil-immersed power transformers", IEC 60354 second edition, 1991-09.*

[4] *M. Srinivasan, A. Krishnan, "Prediction of Transformer Insulation Life with an Effect of Environmental Variables", International Journal of Computer Applications, Vol. 55-No.5, pp 43-48, October 2012.*

[5] *V. M. Montsinger, "Loading Transformers by Temperature", Winter Convention of the A.I.E.E, New York, USA, Jan. 27-31, 1930, p. 783.*

[6] *T. W. Dakin: "Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon", AIEE Trans., Vol. 67, pp. 113-122, 1948.*