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Modeling Thermal Life Expectancy of the UK Transmission Power Transformers

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Abstract- According to the current operating experiences, the dominating failure mechanism of the UK transmission power transformer population has been verified by the forensic tear-down investigations to be of a random manner. In long term consideration, it is widely acknowledged that due to the thermal aging, the mechanical breakdown of the insulating paper is responsible to the ultimate failure of the transformer. Conventionally the insulating paper's thermal usage shall only be reliably learnt via measuring paper's degree of polymerization (DP) after transformer scrapping, which is infeasible in assessing the active units. In dealing with this problem, a systematic model, based on the thermal model in IEC transformer loading guide 60076-7, is presented in this paper to estimate individual active transformer's thermal life via evaluating its operating condition and thermal design characteristics. The model features the incorporation of the practical aging mechanisms of the insulating paper, and the derivation of the conventionally unknown hot-spot factor (HSF) via utilizing the information gained from scrapped units. As the modeling result, the thermal life expectancy of 185 transformers has been estimated as 83 years. A thermal life matrix is also presented as an attempt to reveal the general trend of the transformer's thermal life under different combinations of load and thermal design characteristic.

I. INTRODUCTION

As the essential infrastructure and the most expensive single piece of equipment in the power network, the reliability of the transmission power transformer has been addressed as a vital issue in every utility over the world. Looking at the UK power network, although the transmission power transformer is considered reliable with an annual failure rate of as low as 0.27%, the failure incident in service does occur with approximately 2 per year [1, 2].

In order to fully understand the failure mechanism of the transmission power transformer, the UK National Grid Company (NGC) has been performing thorough tear-down investigations on every failed unit. As the result, all evidences point to the fact that by far, most of the units have failed out of random manner with only one exception that was due to the age-related insulation deterioration [3, 4].

In long term considerations, it has been widely acknowledged that the ultimate life expectancy of the transmission power transformer is critically governed by the mechanical integrity of its insulating paper, reflected by the value of the paper's Degree of Polymerization (DP) [5, 6].

Since examining paper's DP is not physically possible on any active units, furan analysis from oil sample has been under study however the attempts in DP-furan relationship establishment show large discrepancy [7]. As an alternative approach, the thermal models presented by IEC and IEEE transformer loading guides [8, 9] are recommended to assess insulating paper's thermal usage based on estimating the winding Hot-spot Temperature (HST), however the models have shortages that limit their practical use.

In this paper, a systematic thermal model is developed, which is based on the IEC thermal model, to examine the thermal life expectancy of the UK transmission power transformer population through modeling the thermal lives of individual active units. The two major innovations of the developed model will be presented, namely the incorporation of the insulating paper's practical ageing mechanisms (i.e. oxidation and hydrolysis), and the derivation of the conventionally unknown hot-spot factor (HSF) via utilizing the information gained from the NGC scrapped units.

II. THERMAL MODEL DEVELOPMENT

A. Life Modelling Using IEC Thermal Model

In the IEC transformer loading guide 60076-7 [8], a thermal model is presented to calculate the insulating paper's ageing rate via evaluating transformer's operating conditions and thermal design characteristics. The modeling procedures are shown as the first three stages in Fig. 1 below i.e. inputs, modeling and ageing rate calculation. The model inputs are fed into a set of differential equations to calculate the instantaneous winding HST. By using the ageing equation (1), the instantaneous ageing rate k_{ins} can be calculated based on the winding HST. The ageing rates over the time of investigation, which is one year as in this study, are summed to quantify the accumulated ageing rate k_{year} using (2). The procedures of the conventional IEC thermal model terminate here.

To model the transformer thermal life, the IEC thermal model is extended to quantify the transformer thermal life. Equation (3) is a well-documented relationship that describes the kinetics of the DP reduction from DP_0 to DP_t over the time t under the constant ageing rate k . Assuming the DP of new and the mechanically worn-up paper are 1000 and 200 respectively, the transformer's thermal life can be quantified under the

yearly ageing rate k_{year} which is assumed to be constant throughout the transformer life.

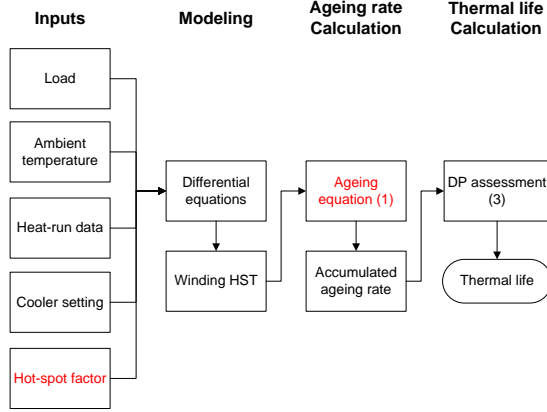


Figure 1. Thermal model procedures.

$$k_{ins} = 2^{\frac{HST-98}{6}} \quad (1)$$

$$k_{year} = \sum_{t=1}^T k_{ins,t} \quad (2)$$

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt \quad (3)$$

As introduced previously, the IEC thermal model has shortages as remarked in red letters in Fig. 1 which are stated as:

- The HSF is conventionally unknown, because the accurate determination relies on the deployment of the winding optic fiber sensor which is still under investigation.
- The ageing equation (1) was established upon Montsinger's ageing theory and merely considers temperature as the only ageing factor [10]. In practice the paper's ageing mechanism is far more complicated that not only elevated temperature is responsible for the material degradation. Therefore using (1) would greatly underestimate the paper's ageing rate in practical transformers.

The following section discusses the improving of the IEC thermal model by modifying the ageing equation and deriving of the transformer HSF.

B. Modifying the Ageing Equation

Intensive studies have been carried out on understanding the detailed ageing mechanism of the insulating paper in oil-immersed power transformer. It has been verified by the ageing experiments that during transformer operation, by-products such as acid and moisture are released from oil-paper system which initiate chemical reactions and reduce the mechanical strength of the insulating paper [11, 12]. Latest work have identified explicitly the two ageing mechanisms within the practical transformer operating temperature range, namely oxidation and hydrolysis [13]. In describing the ageing kinetics, each mechanism has specified dominating temperature range,

activation energy E_A and pre-exponential factor A as shown in TABLE I below. Note that the A values under hydrolysis at 1.0% and 2.0% moisture contents are derived as interpolated from the values under dry, 1.5% and 3.5% moisture contents (values of dry and 3.5% moisture content are not shown here).

TABLE I
INSULATING PAPER'S PRACTICAL AGEING MECHANISMS AND THEIR CHARACTERISTICS [13]

	Oxidation (within 60°C)	Hydrolysis (above 60°C)		
	Dry, oxygen access	1.0% moisture	1.5% moisture	2.0% moisture
E_A (kJ/mol)	89	128		
A (hour ⁻¹)	4.6×10^5	8.7×10^{10}	1.5×10^{11}	2.2×10^{11}

To reflect the chemical reactions during the paper ageing, the Arrhenius equation (4) is proposed to replace (1) to incorporate these ageing mechanisms into the thermal model:

$$k = A \times \exp \left[-\frac{E_A}{R \times (HST + 273)} \right] \quad (4)$$

where R is the gas constant and equals to 8.314 J/mol/K, E_A and A are the activation energy and pre-exponential factor for either oxidation or hydrolysis, depending on the value of HST.

In practice, during transformer operation, increase in insulating paper's moisture content has been found to be in accordance with the paper ageing with an approximation of 0.5% increase every time the DP is halved [11]. To feature this dynamic increase in moisture, it is assumed in the thermal model that the paper's moisture content is 1.0, 1.5 and 2.0% within the DP range of 1000-500, 500-250 and 250-200 respectively to reflect the accumulative effect of the moisture. Accordingly different A values will be utilized in (4).

C. HSF Derivation using Scrapping Information

Transformer HSF describes the extra winding temperature rise over top winding temperature due to the eddy current loss [8, 14]. The precise value of HSF is a function of various design and manufacturing parameters and could be quantified through the direct measurement of the winding HST using optic fiber sensor [15]. However this can only be implemented in the transformer prototypes due to the technical limitations such as the uncertain HST location and the vulnerability of the sensor to the rigorous environment [16]. As a consequence, the IEC loading guide could barely offer a suggested HSF value of 1.3 for power transformer.

To deal with this problem, it is proposed to use the individual NGC scrapped transformer's DP measurement to predict the unit's thermal life, and further utilize it as a benchmark in the thermal model to derive the HSF.

The scrapped unit's thermal life is predicted by the following manner: the lowest DP measurement is inserted in (3) to calculate the DP reduction rate k over the service year t assuming the new paper has DP of 1000. Inserting k into the same equation the thermal life could then be calculated assuming the DP of the mechanically worn-up paper is 200.

Regarding this DP predicted thermal life as a benchmark, the unit's HSF can be derived in the thermal model by incrementing the HSF from 1.0 with steps of 0.05 until a good agreement between the modeling life and the DP predicted thermal life is established (i.e. difference being less than 5%). The flow chart shown in Fig. 2 illustrates the derivation procedures. Note the bolded boxes represent thumbnails as in Fig. 1.

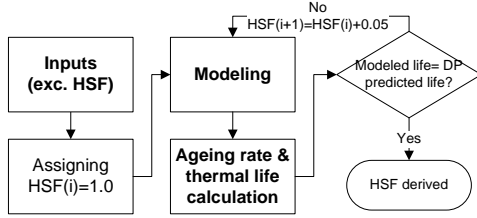


Figure 2. Procedures of deriving individual scrapped unit's HSF.

Subject to the availabilities of load and heat-run data, a total number of 35 scrapped units' HSFs have been derived as span from 1.4 to 9.1 with an average value of 3.5. Although these values seem much larger than the loading guide suggested value of 1.3, the rated HST under the derived HSF is within the acceptable level.

According to the steady state HST equation (5) where T_{amb} represents ambient temperature, TOR_{rated} and Gr_{rated} represent top-oil temperature and oil-to-winding temperature gradient under rated load, under the derived HSF the highest rated HST among 35 scrapped units is 130°C which is less than the critical level that causes the direct bubble formation [17]. In fact the UK transmission power transformers are loaded far lower than the nameplate, therefore the derived HSFs are considered as reasonable estimation.

$$HST_{rated} = T_{amb} + TOR_{rated} + HSF \times Gr_{rated} \quad (5)$$

In terms of using the derived HSFs, since it is strongly dependent on the design, the derived HSFs will be directly assigned to those active units that belong to the same design families as the scrapped units.

III. THERMAL MODELING ON ACTIVE UNITS

At this stage a systematic thermal model has been developed which features the practical ageing mechanisms of the insulating paper and the derivation of HSF based on scrapped unit's DP predicted thermal life. As the model application, the thermal life modeling of a total number of 106 active transmission power transformers in the UK power network has been carried out. Combining with the 79 scrapped transformers' DP predicted thermal lives, a histogram plot of the 185 thermal life samples have been produced as shown in

Fig. 3 in green bars. As comparison, the 79 scrapped units' DP predicted lives are shown in red bars.

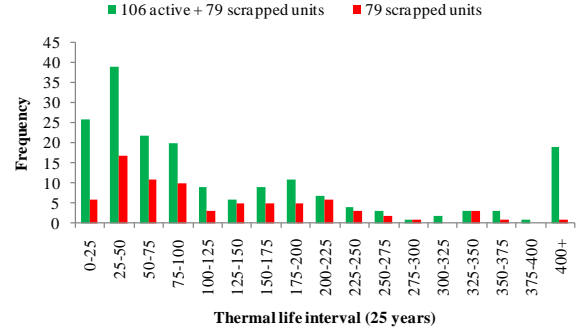


Figure 3. The 185 and 79 sample sets' thermal life histogram plots.

It can be seen from Fig. 3 that the distributions of both life samples follow similar shape i.e. a skewed form having two modes, with the boundary locates near the thermal life interval of 100-125 years. Understood from the thermal mode, it is learnt that for both active and scrapped transformers, the units with lower lives (on left-end of the distribution in Fig. 3) must subject to heavy load, or poor thermal design, or the combination of both. Vice versa for the samples with higher modeled/DP predicted thermal lives (i.e. on right-end of the distribution). Observing from Fig. 3 that in terms of the frequency in each interval bin, the ratio of the combined sample to the scrapped sample increases as approaching to two ends of the distribution, indicating that the extreme operating conditions and thermal designs that have not appeared among the scrapped samples have been assessed by the thermal model.

The thermal life expectancy of the 185 combined samples, which in this paper is defined as the life projected on the 50th percentile on the cumulative life distribution, is 83 years. This is slightly lower than the thermal life expectancy of the scrapped sample which is 95 years because of the inclusion of the extreme operating conditions and thermal designs.

Since transformer thermal life is multi-parameter driven in which the parameters include ambient temperature, load, heat-run data and HSF (note the cooler setting is neglected here), in order to reveal this combinational effect via a straightforward presentation, a plot of thermal life matrix is presented as in Fig. 4. The content of the grid is produced based on the modeled and DP predicted thermal lives.

The thermal life matrix is interpreted as follows: the x-axis is the transformer yearly equivalent load in per unit; the y-axis is the rated HST calculated by (5) using the derived HSF. The thermal lives of 185 units are mapped into the grids according to the load and the rated HST, and each grid is colored according to the level of the averaged thermal lives falling into it. By this means, the complex function of thermal life is able to be presented by a straightforward 2-D plot with all the inputs been integrated.

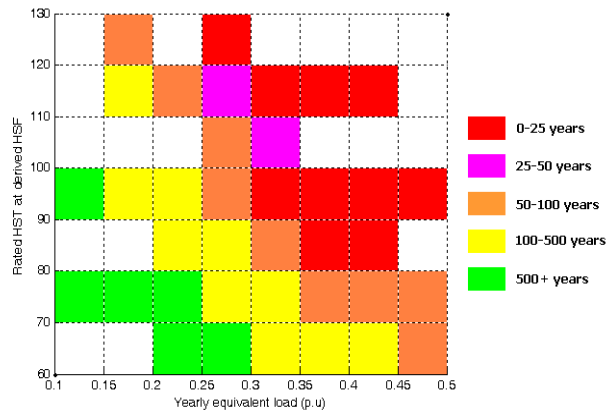


Figure 4. Thermal life matrix of the modeled and DP predicted lives.

As anticipated, the matrix presents a diagonal trend in thermal life such that the life reduces from bottom to top in the vertical aspect (i.e. towards poorer thermal designs) while prolongs from right to left in the horizontal aspect (i.e. towards lower loadings). Looming boundaries seems exist between life ranges (i.e. different colors), therefore it is expected that as more transformers are modeled in the future, parabolas could possibly be drawn in the matrix as an guidance on the transformer thermal life performance under different combinations of operation conditions and thermal design characteristics.

IV. CONCLUSIONS

A systematic thermal model based on the thermal model in the IEC transformer loading guide 60076-7 has been developed to estimate the UK transmission power transformer's thermal life. The developed model features two improvements over the traditional model, namely the incorporation of insulating paper's practical ageing mechanisms, and the derivation of the conventional unknown HSF based on scrapped unit's DP predicted thermal life.

As the model application, 106 active units' thermal lives have been assessed. Combining with the 79 scrapped units' DP predicted thermal lives, the thermal life expectancy of 185 transformers is quantified as 83 years. Mapping the units' thermal lives into a 2-D matrix according to their loads and rated HSTs, the complex function of the transformer thermal life can be straightforwardly visualized.

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