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END-OF-LIFE MODELLING FOR POWER TRANSFORMERS IN AGED POWER SYSTEM NETWORKS

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SUMMARY

Although the design lifetime of transmission transformers was 40 years or less, operational experience has been very good with transformers up to this age, as the majority of transformers on National Grid's UK system were installed between 1955 and 1975 it is important to understand and predict the future reliability of ageing transformers.

This paper presents a statistical analysis of the failure history of the transformer fleet and its age profile in order to understand the trend and whether/how the failure rate is associated with age. Data from failures to date only show random failure modes and no correlation with transformer age. As we know that transformers are subject to ageing mechanisms it is not reasonable to base a prediction of future reliability on this historical data. A further problem arises because with the asset condition assessment techniques available, transformers are being replaced somewhat ahead of actual failure, so a method of predicting the 'age of failure' of the replaced transformers has had to be developed using DP analysis. For in-service transformers a calculation of life based on the physical ageing process of paper insulation using design data, loading condition and ambient temperature, under the normal IEC assumptions, has been made. This analysis shows that for a typical network transformer, the ageing rate depends more on transformer design and cooler operation temperature settings than on loading. If the cooler on temperature setting is low and the transformer thermal behaviour is as designed, then the expected lifetime would be in excess of 100 years. Despite this there have been examples of age related failures indicating that operating temperatures for at least some transformers are significantly higher than designed.

Further statistical and thermal modelling is required to fully understand how the range of thermal parameters of transformers will affect the ageing rate of the transformers, their future reliability and hence the replacement plans required to maintain the future reliability of the power system.

KEYWORDS

Transformer end-of-life, statistical analysis, transformer thermal model, DP value, power system reliability

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1. INTRODUCTION

Power transformer ageing is one of the critical issues utilities are facing, since a large number of units are approaching or have exceeded their designed lifetime. A good end-of-life model is required to optimize asset replacement investment whilst maintaining system reliability. Analysis of failures of HV assets and end-of-life analysis, particularly of power transformers, has been carried out since the 1990s [1]. CIGRÉ working group 12.09 published its findings on transformer lifetime evaluation in 1993 [2]. This pioneering work provides an insight into the failure rates and mechanisms and thus suggests the replacement strategy from a system operator/asset owner view point. In addition, other utilities, insurance corporations and academic researchers have presented their methods for asset lifetime estimation; these are referential experience for the analysis of the UK National Grid operation records [1, 3, 4].

National Grid has recorded the installation and movement of its 400 and 275kV power transformers since 1952 and failures since 1962. The analysis here considers the information up to 2004. Power transformer installation number and capacity were significantly developed during the period 1961-1970, this results in a large number of transformers in-service after 1970. The installed capacity has been steadily increasing since then. Now transformers, aged over 36 years form the majority of the population.

2. NATIONAL GRID TRANSFORMER DATABASE ANALYSIS

2.1 General Analysis

Fig. 1 shows the number of power transformers installed by year from 1952 to 2004. In the peak year of 1966 a total transformer capacity of 23 GVA was installed. Since then installation numbers fell up to privatization in 1989 when increased market activity required a somewhat higher level of investment, subsequently maintained with the start of asset replacement.

A transformer in-service number profile is deduced from the installation chart and the transformers removed from service. This profile is displayed in Fig. 2. Not all transformers removed from service actually failed, some were scrapped due to poor condition or inadequate rating.

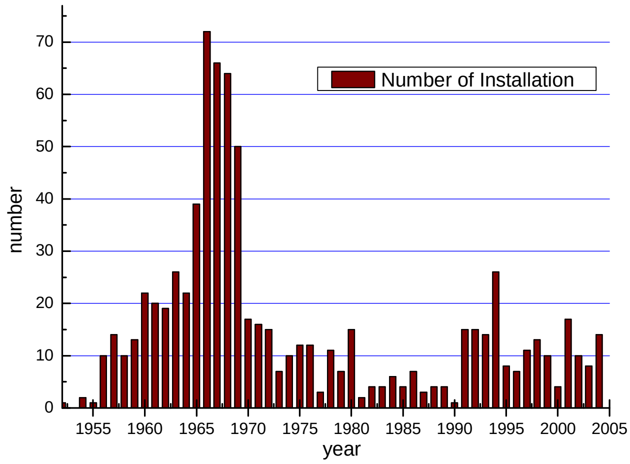

Fig.1 Transformer Installation Numbers

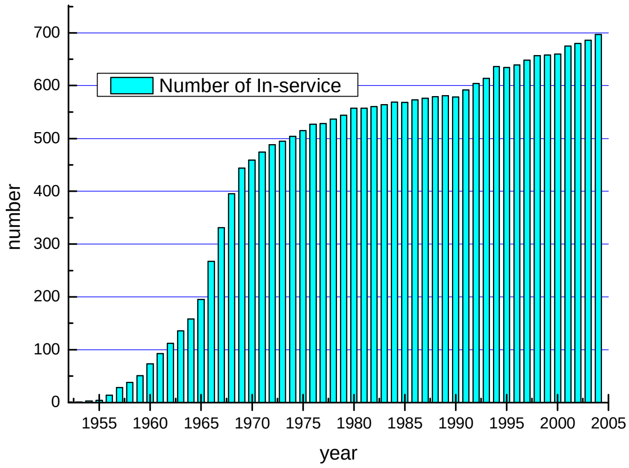

Fig.2 In-service Transformer Number

2.2 Failure Analysis

There are 56 records of transformer failures, of which the 1st was in 1962. A failure is taken as a sudden event requiring that the transformer is removed from the site. The number of failures against age at failure is shown in Fig. 3. The exposed number against age is shown in Fig. 4, where the exposed number is defined as the total number of transformers which have had the year service experience of a particular age. The ratio of these two charts is shown in Fig. 5 and is the conditional hazard rate against age. The conditional hazard rate is the chance that a transformer will fail during a particular year in its lifetime conditional on its not having failed before reaching that age. This is often called the bathtub curve.

The average conditional hazard rate up to age 36 is 0.25% and is sufficiently stable and low to show that the transformer failure rate up to this age is random. Unlike the traditional bathtub curve, an early high infant mortality cannot be seen in Fig. 5. This tends to show that factory testing before installation is adequate. At older ages a single random failure yields a high value of hazard, as may be seen from the single hazard rate of 0.05 at age 48 in Fig. 5, because of the limited number of exposed transformers. This limited experience with older transformers makes conclusions about lifetime from this failure data impossible. In other words, a conventional statistical tool to predict transformer population end-of-life is not suitable for the right-censored data available at present unless we assume that there are no age related failure mechanisms operating, this would not be a safe assumption.

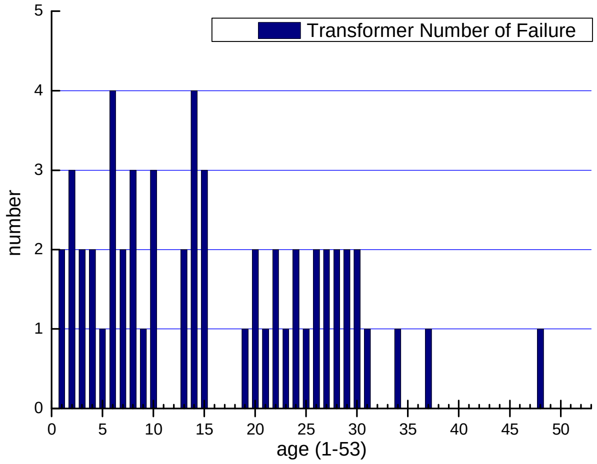

Fig. 3 Power Transformer Number of Failure

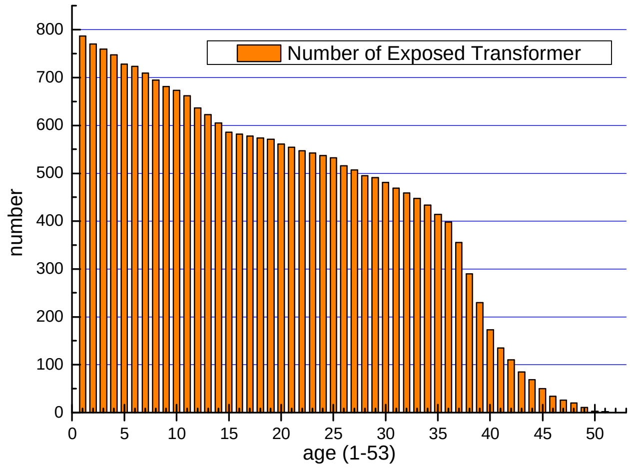

Fig. 4 Transformer Exposed Number

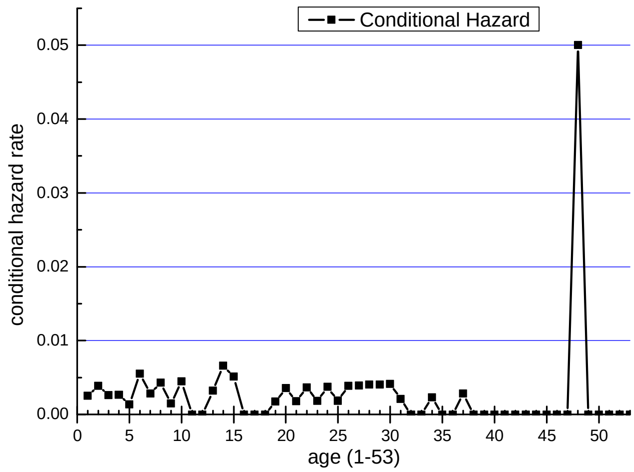

Fig. 5 Conditional Hazard Rate against Age

In particular it is known that thermal degradation of insulating paper does occur and will eventually limit transformer lifetimes. Individual lifetime simulation using the transformer thermal model suggested in the IEEE and IEC loading guides has been carried out as an alternative approach to predicting transformer end-of-life.

A transformer is designed and tested to have sufficient dielectric and mechanical strength, with some spare margin, to withstand the maximum operational stresses. The normal ageing process, represented as the reduction of oil quality and paper mechanical strength, will degrade the spare margin until it no longer sustains the stress caused by external events and thus the transformer is prone to fail. However, it is noticeable from the past operation experience that transformers do not fail due to normal ageing only. A transformer may develop a fault, in addition to normal ageing, which results in a faster than normal ageing/degradation process, with a higher consequent probability of failure at a particular age. Statistically, these are treated as random events (often triggered by a system event e.g. system short circuit, lightning, or/and switching transients) together with other events such as maintenance induced failures.

Overall, transformer failure is a probabilistic phenomenon with three main controlling parameters: design, ageing and external trigging events. Since a quantitative relation between the ageing conditions and transformer intrinsic dielectric strength is lacking, transformer thermal life, expressed as the operating years to lose the mechanical strength of conductor paper under particular conditions, is used as the basis for the end-of-life model in the following sections.

3. INDIVIDUAL FAILURE SIMULATION BY THERMAL MODEL

The thermal end-of-life can be predicted according to the transformer design, historical loading and ambient temperatures, since the insulation deterioration as a function of time and temperature follows the Arrhenius reaction as stated in loading guides [5, 6] as:

$$V = 2^{(\theta_{HS}-98)/6} \qquad (3.1)$$

where V is the relative ageing rate, θ_{HS} is the hotspot temperature in °C. The loss of life L over a certain period of time is equal to:

$$L = \int_{t_1}^{t_2} V.dt \text{ or } L = \sum_{n=1}^{N} V_n \times t_n \qquad (3.2)$$

in which V_n is the relative ageing rate during interval n, according to equation (3.1), t_n is the n^{th} time interval, n is the number of the interval and N is the total number of intervals during the period.

The thermal model in [5] is used to calculate the winding hot-spot temperature. Normally in the UK, power transformers have a dual cooling mode, ONAN/OFAF, which is controlled automatically by a WTI measurement. When the simulated hot-spot temperature exceeds a certain value (normally 75^{o}C), the pumps and fans will be switched on. The change in cooling mode is typically represented by changing winding and oil parameter values in the thermal model. The effect of transformer cooling mode change temperature (WTI cooler on) setting and hot-spot factor on anticipated lifetime is studied here.

3.1 Transformer Dual Cooling Mode

For illustrative purposes, one year load and ambient temperature profiles were used to determine the loss of life of a 240MVA, 275/133kV transformer, with the assumption that the yearly profile remains the same throughout its lifetime. In order to see the loss of life variation with load increase, the loads are simulated with a different peak load value by scaling the load profile. Two sets of cooler settings were studied, the first cooler setting has the fans and pumps turn on at 75 ^{o}C and turn off at 50 ^{o}C (normal settings), and the other case study has the cooling set to come on at 95 ^{o}C off at 70 ^{o}C (a high setting found on some transformers).

The resultant transformer life expectancy plotted against peak load is shown in Fig. 6. The relationship between the life expectancy against the peak load is nonlinear, and almost independent of load when the transformer operates at loads between 0.6p.u to 0.9p.u of rating for the case of a 75/50 cooler setting. This is due to the dual cooling mode, as ONAN/OFAF switching over being controlled by WTI measurement. This intermittent switch causes the nonlinearity of transformer thermal loss-of-life. It is therefore clear that for transformers with thermostatically controlled cooling, the cooler settings need to be considered in calculating transformer thermal end-of-life, as well as the load and ambient profiles.

3.2 Transformer Hot-spot Factor

The hotspot rise in the previous calculation is estimated using a hot-spot factor, H of 1.3 as given in [5]. A statistical analysis of thermal test data by CIGRE Working Group 12.09 showed that the value of H is distributed between 1 and 3 [7]. IEC 60076-2 states that, the hotspot factor varies considerably in large power transformers depending on transformer design. The effect of assuming an H of 1.3 when the real value is higher is studied here.

Based on the typical daily ambient and load profile, the hot-spot temperature is computed by varying the hot-spot factor from 1.3 to 2.1. The results are shown in Fig. 7. Cooler WTI on/off settings of 75/50^{o}C and 95/70 ^{o}C are both simulated.

The (log) daily loss-of-life increases linearly as the hot-spot factor increases, as can be seen from each of the 4 cases: summer loading under 75/50 ^{o}C, summer loading under 95/70 ^{o}C, winter load under 75/50 ^{o}C and winter load under 95/70 ^{o}C. The underestimated hot-spot temperature leads to the pumps and fans running less and the transformer will be running hotter with a significantly reduced lifetime.

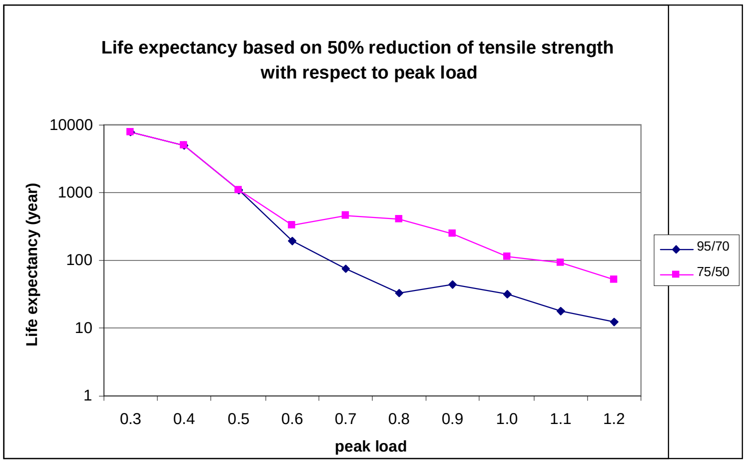

Fig. 6 Life expectancy .vs. peak load

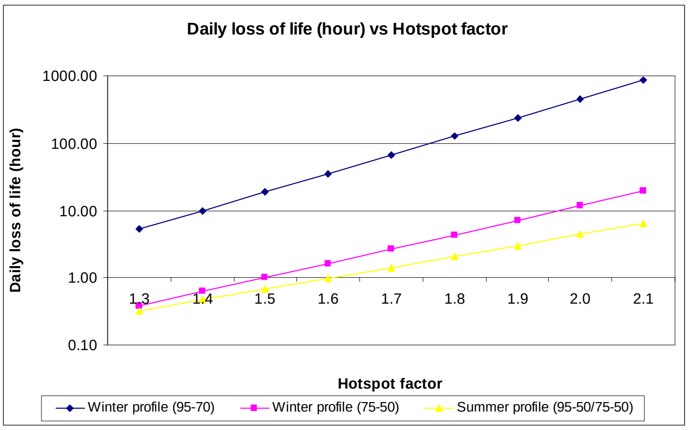

Fig. 7 Daily loss-of-life .vs. hot-spot factor

4. FAILURE PREDICTION BY DP VALUE

As the winding hot-spot factor is the most important element in estimating the thermal lifetime some knowledge of the distribution of this parameter throughout the transformer fleet is required but is not directly available. It is however possible to examine the lowest DP of paper found in each scrapped transformer and to infer the hotspot factor and remaining life. Again ambient temperature, oil condition, loading experience and design parameters are all key factors which determine the unit's loss of life and thus its end-of-life. DP is the index which covers all the information from the above factors. If the small number of scrapped units is a representative sample then, the fleet end-of-life is may be estimated. There are however significant biasing factors that need to be taken into account.

The cellulose molecules are composed of long chains of glucose rings or monomers, and the degree of polymerization (DP) of the molecular is used to describe the average number of glucose rings in the molecule [8]. The cellulose degradation is a complex sequence of chemical reactions whose rate is influenced by water, oxygen and heat [8, 9]. The DP value is a valid indicator of solid insulation ageing.

Many publications endeavour to identify the precise DP values for initial insulation status and the end of thermal life [6, 8, 9], and it is widely accepted that DP of 1000 indicates the new insulation before commissioning and 200 represents the exhausted paper. The reduction of DP against age can be represented by a linear equation using the transformer ageing rate factor (k) [9], which is expressed as:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt \qquad (4.1)$$

where DP_t is the DP value at time t, t is the time elapsed, DP_0 is the initial DP when the insulation assumed new, and k is the ageing rate factor, which is a constant.

61 transformers owned by National Grid have been scrapped. Cellulose insulation samples were extracted from different points along the transformer windings and the lowest DP (DP_{lowest}) was obtained, usually from the hottest spot. Individual transformer end-of-life is predicted from its lowest DP (DP_{lowest})

via Equation 4.1, using the following steps. The distribution of transformer predicted lifetimes is shown in Fig. 8.

Step 1: Estimate the average ageing rate factor (k) of a scrapped unit by its given lowest DP (DP_{lowest}) and operation life (t_1).

Step 2: Assume a certain unit will continue ageing by the estimated k, calculate the residual year to reach DP of 200, as end of its thermal life. This is the remaining life (t_2) of this transformer.

Step 3: Transformer operation life (t_1) plus its corresponding remaining life (t_2) yields the total life time, or thermal end-of-life (T).

Step 4: Repeat Step 1 to 3 for each scrapped transformer. Their end-of-life are denoted as ($T_1,T_2,\ldots,T_N$), N is the number of scrapped transformers.

Step 5: Generate the arithmetic average of $T_1,T_2,\ldots,T_N$. This is the derived end-of-life for the transformer population, assuming the scrapped transformer group is representative for the transformer fleet.

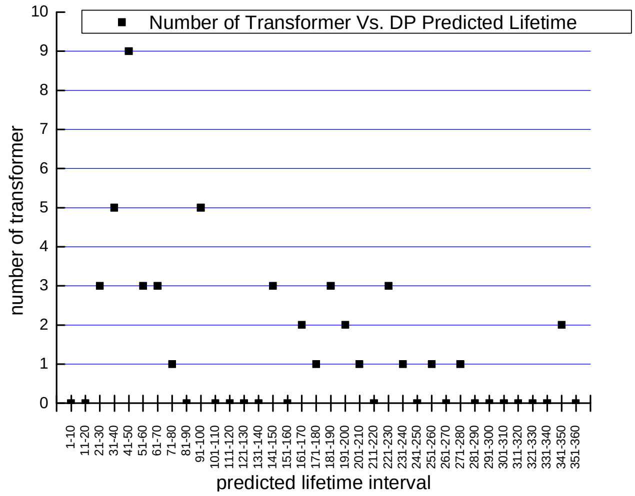

Fig. 8 Distribution of lifetimes predicted by DP

The approach described above is practical only if a considerable amount of DP data exists. In this case 49 lowest DP results have been confidently extracted from all the scrapped transformer reports produced by Doble Powertest up to 2007. The predicted thermal lifetimes are widely distributed (27 – 342 years, average 119 years). This variation reflects the range of hot-spot factors and operating conditions in the sampled transformers.

It is very difficult to predict whether this range is representative of the whole population as the data contains some units, for example one which was 40 years old which suffered a true end-of-life thermal ageing failure, which are ageing faster than average as well as examples of random failures which are probably more representative of the surviving population. However the large range observed is probably representative even if the mean cannot be relied upon at this stage. The categorization of transformer population and how well it is represented by scrapped units will be further discussed in another paper.

5. CONCLUSIONS

National Grid has recorded 56 transformer failures historically between 1952 and 2004. From this data a failure hazard rate has been derived which averages less than 0.3% per year up to age 36. Due to the lack examples of end-of-life failures, the limited failure records and the age censored transformer population, any traditional statistical analysis of the failures cannot be used to predict the end-of-life and future transformer reliability. Transformer thermal analysis using real loading profiles incorporating a thermostatically controlled cooler indicates that the thermal hot-spot factor and cooler temperature settings are probably the most important ageing factors.

Individual thermal end-of-life prediction based on DP measurements for scrapped transformers has been carried and shows a wide range of values reflecting the range of hot-spot factors in real designs. It is not yet clear how representative the scrapped population is of the transformer population as a whole.

Thermal modeling and DP prediction may be improved by studying individual scraped transformers with known DP so that the ageing calculation can be calibrated by real experience. The conclusions drawn from an individual transformer thermal model simulation should contribute to the statistical analysis of the population by predicting the future conditional hazard rate or tip up in the bathtub curve (filling in the blank portion of Fig. 5 after 36 years of age).

Even a complete knowledge of thermal end-of-life for a particular transformer would only give a statistical risk of failure at a particular age since actual failures are observed to have a large random element probably related to system stress.

Further work is needed to properly incorporate the DP data from scrapped units into the observed failure statistics to achieve a reliable end-of-life model, although some of the existing lifetime assumptions have been validated by this work.

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REFERENCES

[1] Xianhe, J., Changchang, W., Changyu, C., Cheng, T. C., and Amancio, A., "Reliability analyses and calculations for distribution transformers", Proc. Transmission and Distribution Conference, 1999 IEEE, 1999, pp. 901-906

[2] Working Group 12.09 CIGRE. "Lifetime evaluation of transformers" (Electra 150, October 1993)

[3] William H. Bartley P. E., "Analysis of Transformer Failures", Proc. International Association of Engineering Insurers 36th Annual Conference, Stockholm, 2003

[4] Mirzai, M., "Failures Analysis and Reliability Calculation for Power Transformers", Journal of Electrical Systems, 2006

[5] "IEC 60076-7 Part 7: Loading Guide for Oil-immersed Power Transformers", 2005

[6] "IEEE guide for loading mineral-oil-immersed transformers", IEEE Std C57.91-1995, 1996

[7] Working Group 12.09 CIGRE. "Experimental Determination of Power Transformer Hot-Spot Factor" (Electra, 1995 pp35-39)

[8] McNutt, W. J., "Insulation thermal life considerations for transformer loading guides", Power Delivery, IEEE Transactions on, 1992, 7, (1), pp. 392-401

[9] Emsley, A.M., and Stevens, G.C., "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers", Science, Measurement and Technology, IEE Proceedings, 1994, 141, (5), pp. 324-334