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Transformer life prediction using data from units removed from service and thermal modelling

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SUMMARY

Understanding how and when transformers are likely to fail is of critical importance to the asset management of large networks. Ideally a reliable end-of-life model would be established based on years of previous experience over several lifecycles of equipment of a type representative of that still in service. For large power transformers however establishing such a model is not easy because we are still in the first asset lifecycle and many of the transformers installed when the National Grid system was first developed are still in service well beyond their original design life.

Maintaining the reliability of the network is clearly a priority, but this must be done efficiently and economically . Replacement plans must therefore be properly targeted both tactically, to replace those transformers in the worst condition and at the most critical sites, and strategically to make sure the replacement numbers are sustainable in terms of available resources such as outage capacity, supplier capability and investment funding. Given the expected strongly non-linear relationship between system reliability and plant reliability and the possibility of hidden failures in the system where plant in service has aged to a condition where it cannot withstand the power flows resulting from a system failure elsewhere, the best possible understanding of ageing and failure is required.

This paper gives the historical failure rate of the transformers used on the National Grid system in the UK and shows that failures to date are random in nature and not statistically age related. This means that traditional approaches to building a statistical end-of-life model cannot be used. Analysis of the insulation of transformers removed from service for any reason indicates a very wide range of condition, some samples show severe thermal ageing and it is clear that age-related failures can be expected if replacement is not carried out, other samples show little ageing and for these transformers it appears that very long lifetimes might be expected if other ageing mechanisms do not become apparent.

Transformer condition assessment techniques are now very good and provide a sound basis for replacing transformers before failure. A condition assessment scoring system based on anticipated remaining useful lifetime has been implemented and condition based replacement has made a major contribution to maintaining system reliability. The success of the condition based replacement process however has a profound biasing effect on the failure statistics as transformers are not left in service to fail, so that these statistics cannot be used directly for lifetime modelling.

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Condition assessment has allowed the development of a replacement planning process that operates to replace unreliable transformers on a 2 to 5 year timescale, probabilistic techniques are used to predict replacement numbers on longer timescales based on perceived lifetimes. There is however a need for a more deterministic process to operate in the 5-10 year timescale and a requirement to validate the lifetimes. Comparison of the existing condition assessment data with predicted lifetimes tends to indicate that only a proportion of the transformers that are expected to fail for age related reasons in the next 10 years are presently identified.

The analysis of paper samples from scrapped transformers indicates that the thermal ageing rate is very strongly related to design. Thermal modelling shows that the ageing rate is almost independent of loading for transformers with thermostatically controlled coolers under most operating conditions on the network. This modelling also indicates that thermal ageing is unlikely to be the life limiting process for network transformers with a good thermal design and low cooler thermostat settings. Overall the work reinforces the need for conservative specification and excellent thermal design if a long life is to be expected for power transformers operating in a transmission network.

KEYWORDS

Power Transformers – Ageing – Failure – Modelling – Reliability

BACKGROUND

National Grid owns and operates in England and Wales approximately 780 transformers over 100MVA at 400kV and 275kV, the first 275kV units were installed in 1952. Figure 1 shows the age profile in terms of years in service of units that have been installed on the system including the 57 transformers that have subsequently been scrapped. In the case of transformers that have been scrapped, the years in service shown in Figure 1 includes years from scrapping to the present day (as if the transformers had remained in service).

Figure 1: Transformer Age Profile (includes scrapped units)

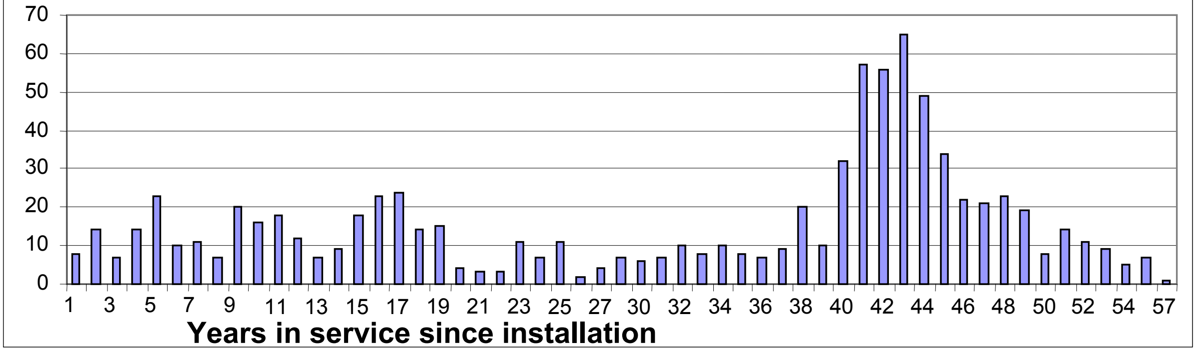
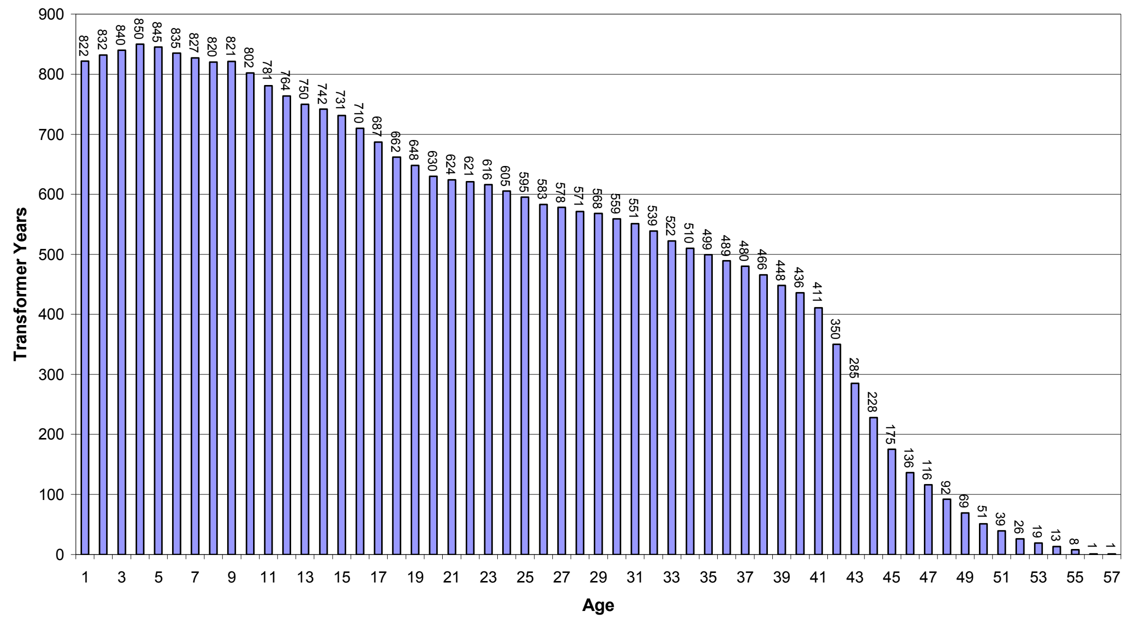


Figure 2 shows the transformer years experience on the system for each transformer age since 1962 [1]. Good data on transformer failures is only available since 1962 and so transformer years experience in service is only counted since that date in order to be consistent with the failure data.

Figure 2: Transformer years of service experience against transformer age



It may be seen that there is substantial operating experience of transformers up to about 40 years in service but the experience is limited beyond that, making statistical analysis of the reliability of older transformers problematic.

CONDITION ASSESSMENT

The condition of each transformer in service is assessed on the basis of Dissolved Gas Analysis in oil (DGA) results, other oil tests, the results of off-line tests (such as Frequency Response Analysis (FRA) and dielectric spectroscopy) and operational experience with similar transformers [2]. Transformers are then individually assigned an asset health index (AHI) on a six point scale as follows.

Asset Health index	Description
1	In a state requiring replacement, failure expected within 5 years
2a	Faulty transformer expected to deteriorate to reach AHI 1 within 5 years
2b	Faulty transformer expected to deteriorate to reach AHI 1 within 5-10 years
2c	Faulty transformer but not expected to deteriorate
3	Transformer of a design with known potential problems but with no active fault
4	No known faults or problems (normal transformer)

CONDITION BASED REPLACEMENT

The AHI is used together with information on the criticality of a particular transformer within the network, to plan and carry out replacement. Although the replacement is based on AHI and not age, there are proportionately more older than newer transformers replaced because condition will deteriorate (or at least not improve) with time unless a repair is carried out. In order to avoid replacing repairable transformers, for example where an oil change can improve condition, the AHI is based on the expected condition after the repair or refurbishment.

Figure 3 shows the historical hazard rate (conditional probability) for both failure (blue line) and replacement (pink line) against age for the transformer population. The failure and replacement numbers are normalised using the data in Figure 2 to arrive at the rates shown in Figure 3 [1].

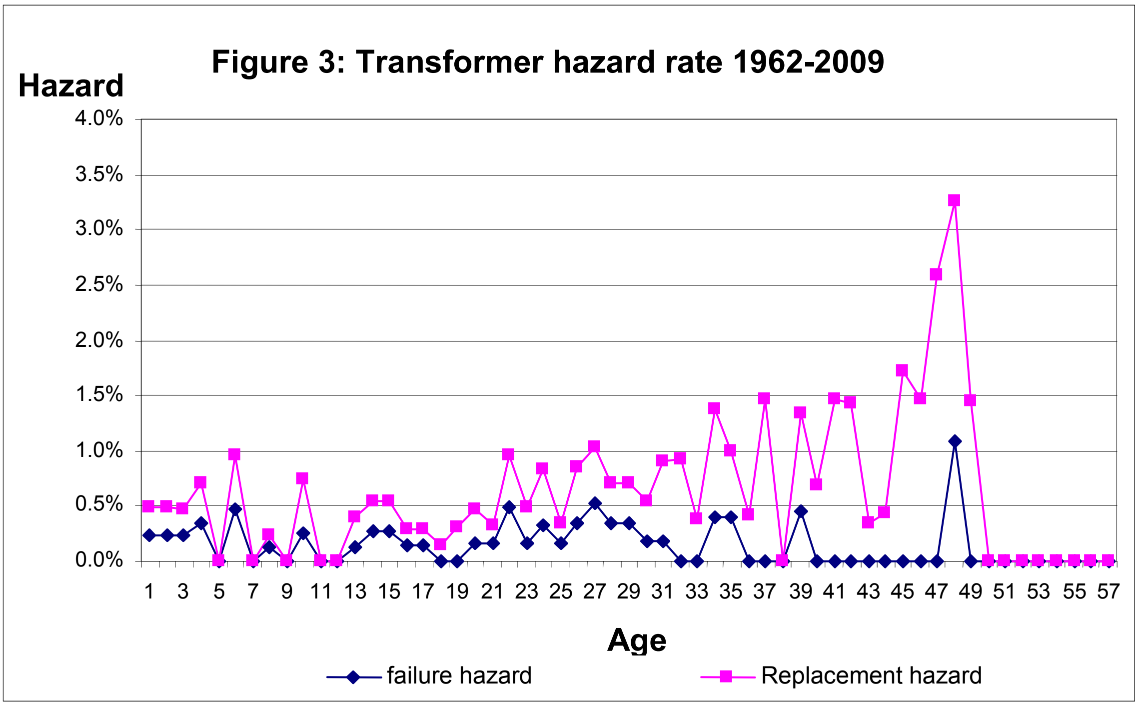


Figure 3: Transformer hazard rate 1962-2009

Figure 3 shows that although replacement becomes more likely as the transformer gets older, due to the operation of the condition based replacement scheme, the probability of failure does not. This shows that a condition based replacement scheme does appear to be capable of controlling the failure rate of an ageing population, at least at the early stages, however the operation of the scheme also means that the historical failure hazard rate curve will not be a useful predictor of transformer lifetimes. The fact that the failure hazard rate (blue line) is essentially independent of age shows that these failures are occurring randomly. This is borne out by an analysis of the causes of these failures that are only age related in a very few cases.

LIFETIME DATA FROM FORENSIC ANALYSIS

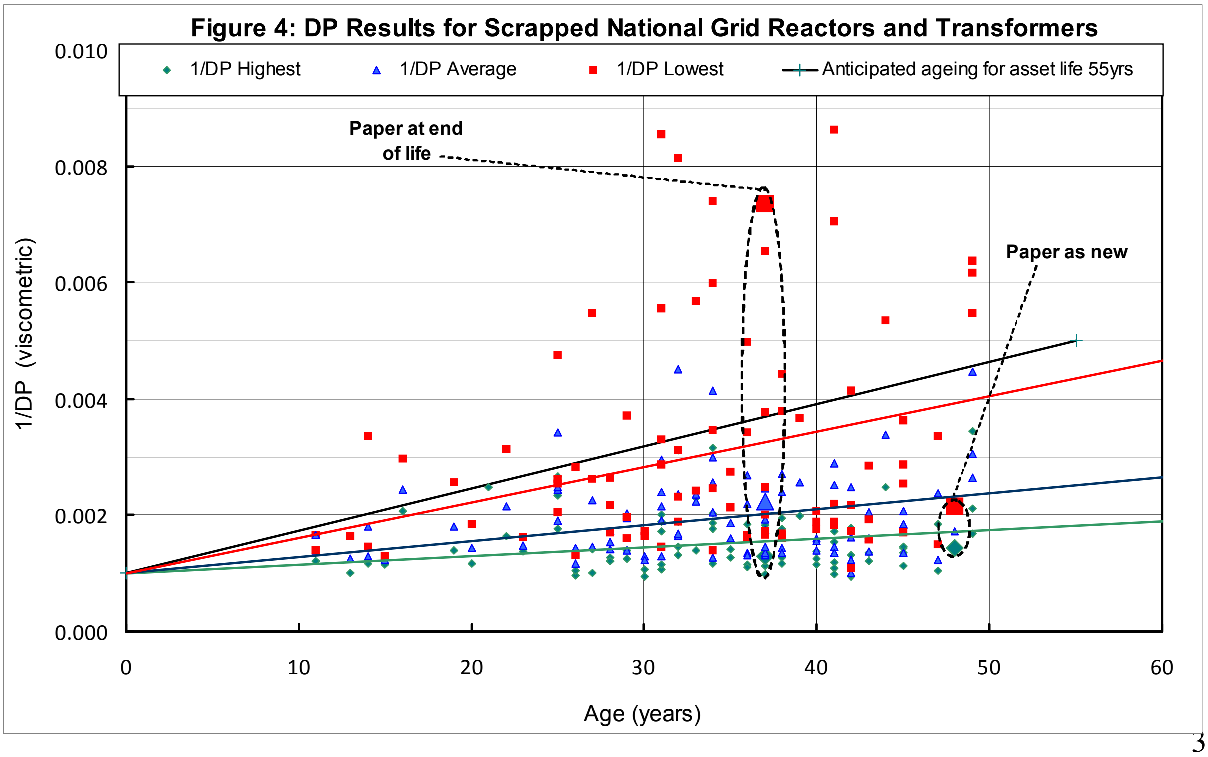
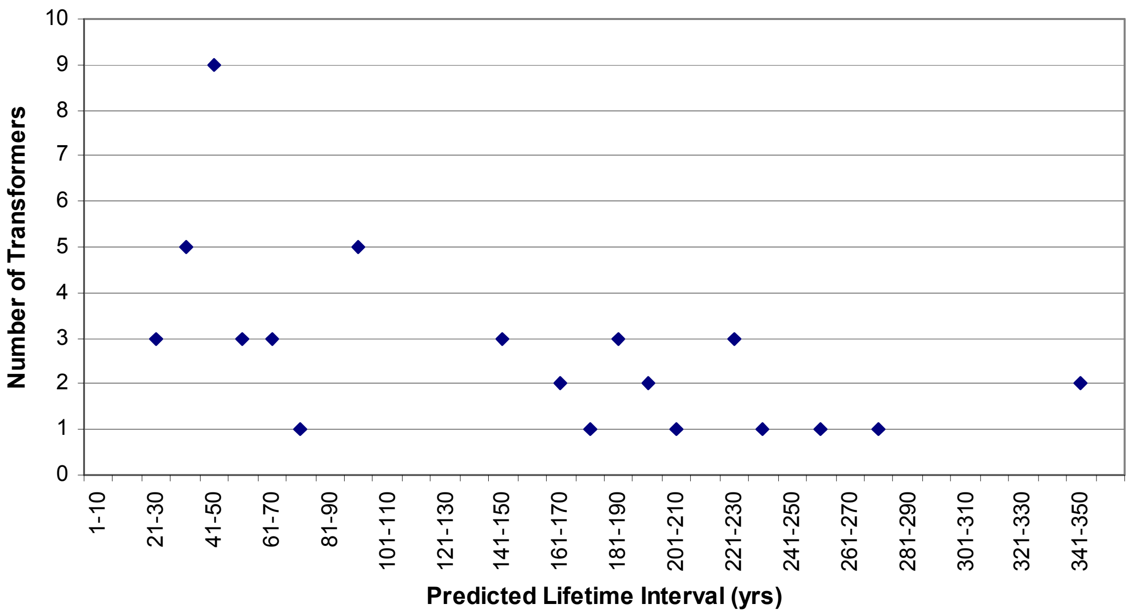


Figure 4: DP Results for Scrapped National Grid Reactors and Transformers

Almost all the transformers that have been scrapped, either due to failure or replacement, since 1993 have had insulating paper samples taken from representative parts of the windings and analysed for degree of polymerisation (DP). DP is widely accepted as an indicator of thermal ageing of paper with a value of 200 taken as end of life [3,4]. Figure 4 shows a plot of 1/DP against age for each of the sampled transformers. The plot shows three points (red, blue and green) for each sampled transformer, the red square indicates the lowest DP sample (highest value of 1/DP) the blue triangle represents the average DP of the samples taken from a single transformer and the green diamond the highest. The straight red, blue and green lines are linear regression lines taken through the respective data points assuming a starting DP of 1000. It may be seen that the lowest DP values from each transformer (shown in red, one point for each scrapped transformer) are widely scattered above and below the black line representing the expected value of 1/DP against age for a transformer lifetime of 55 years. Two particular cases are highlighted, one where the paper insulation in the transformer was at end of life at 37 years and one where the paper was almost as new at 47 years.

An alternative view of some of the same data is given in Figure 5 where the lifetime of individual scrapped transformers is predicted from the lowest DP obtained assuming that ageing would have continued at the same rate if the transformer had remained in service [1].

Figure 5 - Distribution of Lifetimes Predicted by DP



This data is not representative of the whole transformer population as some transformers were scrapped because of their aged condition, however the longer predicted lifetimes are from transformers that were removed from service for other than age-related reasons (for example tap-changer failure) and these show a wide spread of predicted thermal lifetimes.

THERMAL MODELS

To try to understand how thermal ageing will affect the remaining transformers in service, a computer thermal model of a transformer was built taking into account the loading profile of the system, the ambient temperature profile over the year and the setting of the thermostatically controlled cooling system [1,5,6]. The cooling system is normally controlled from a Winding Temperature Indicator (WTI) that measures the top oil temperature and adds an additional load dependent temperature according to the assumed design parameter (Hotspot factor [7]) of the transformer. Figure 6 shows the life expectancy of the transformer (using the standard Arrhenius relationship between temperature and ageing rate [3]) against annual peak load at two cooler on/off temperatures (in °C).

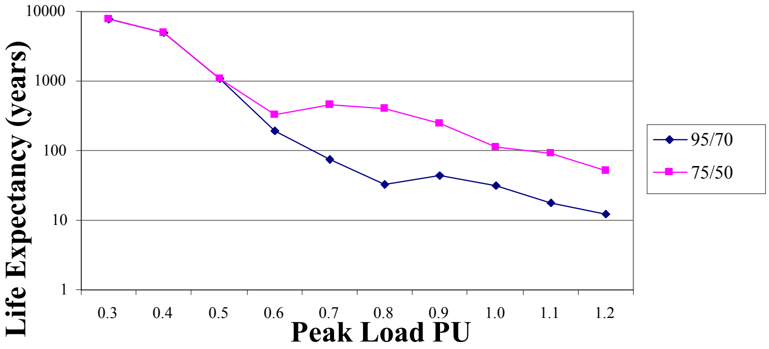


Figure 6: Life expectancy based on 50% reduction of tensile paper strength against peak load PU

Figure 6 shows that over the normal range of peak loadings (0.6 to 0.9PU) the lifetime of a transformer with a thermostatically controlled cooler is relatively insensitive to load but is significantly affected by the cooler control temperature settings.

The other very significant factor that is apparent from the modelling work is that if the hotspot factor [7], which is the ratio between the actual winding hottest spot temperature rise at full load and the top winding temperature rise (based on average winding temperature and oil temperature) is higher than assumed when setting the WTI, then the transformer will be getting hotter than expected and the lifetime is reduced. For example if the generally assumed hotspot factor of 1.3 [6,8]is used to set the WTI and the value for the transformer is actually 2, the ageing will be 100 times faster than expected. The quality of the thermal design in terms of the absence of unexpected hotspots is the primary factor in determining the life of a transformer.

ASSET HEALTH INDEX AND AGE

All the previous evidence indicates that the population of large power transformers in the system do start to experience age related failures or problems that require replacement at about 40 years in service. There is little direct evidence about the likely average lifetime or the maximum lifetime of the population still in service, but the thermal lifetimes indicated by the data presented in Figures 4 and 5 relating to scrapped units show a wide scatter. Existing models assume an effective maximum life of about 80 years implying an average life (50% survival) of around 55 years, validated to some extent by the DP data from scrapped units but not proven for the population as a whole. This assumption is not only based on thermal ageing as it takes into account some additional factors such as tap-changer obsolescence and ageing of other materials. However based on these assumptions and the definitions of the AHI categories in terms of how far ahead a future failure can be detected, a model of the expected progression through the AHI categories against age can be built. This is shown in Figure 7.

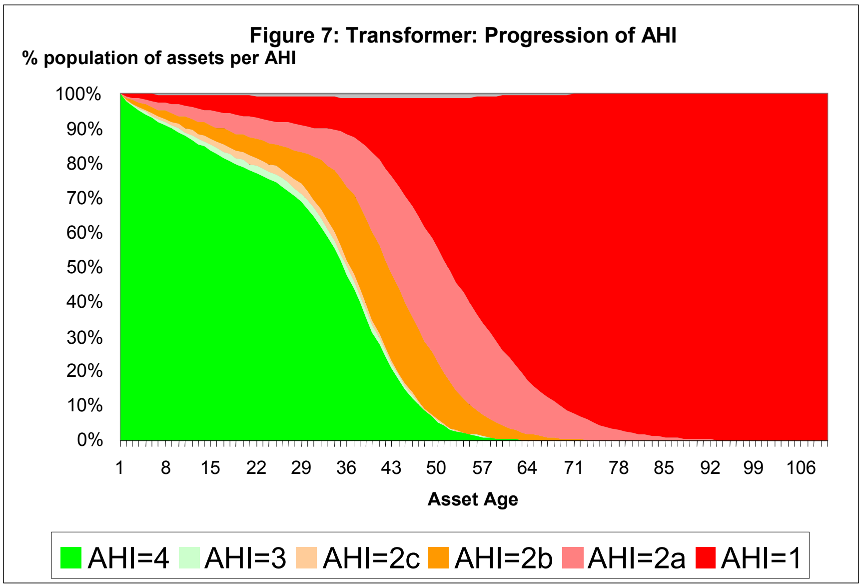


Figure 7: Transformer: Progression of AHI

This model assumes that all transformers in the population are correctly assigned to the appropriate AHI category, in practice however not all transformer fault or degradation conditions will be recognised, tending to increase the apparent prevalence of transformers in AHI 4 and 3.

Figure 8 shows the recorded percentages of transformers in each AHI category according to age. To maintain compatibility with Figure 7 which is a cumulative graph, failed transformers are included as AHI 1 at the age they would be at present (rather than the age at failure).

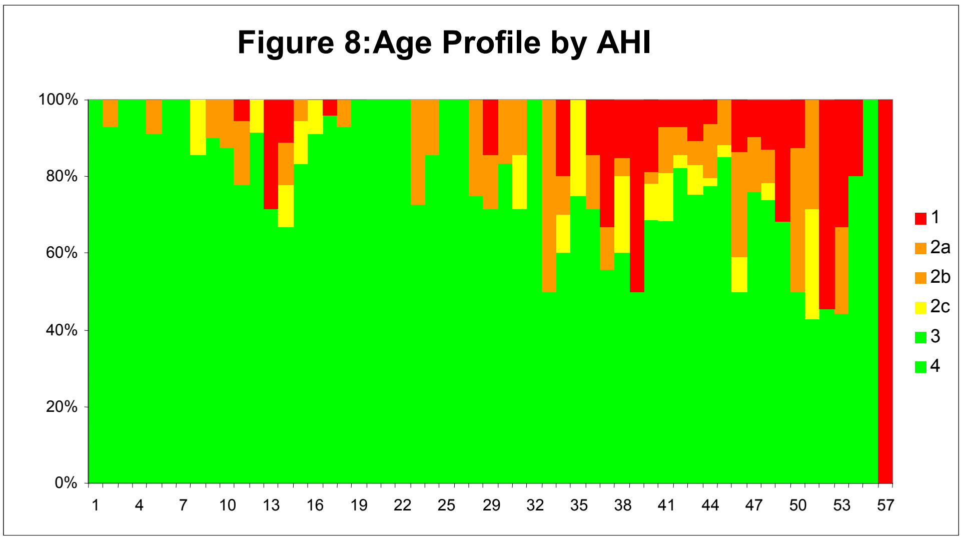


Figure 8:Age Profile by AHI

There is significant statistical variation in the results because of the low numbers of transformers at the later ages, but even so the proportion of AHI 1 transformers is approximately the same as the model. For example, the model predicts between age 40 and 50 the proportion of transformers in AHI 1 will increase from 10% to 40%, the actual proportion of AHI 1 transformers in this age range varies from about 10% to 30%. It is noticeable however that there are fewer AHI 2a and 2b transformers than expected, for example in the age range 40 to 50 years the model predicts 50-60% of transformers will be in AHI 2a and 2b but we only see 15% to 40%. This is probably due to the inability of present tests (including furfural analysis in oil [4]) to detect all units that will fail within 10-15 years, but it may also indicate that the shape of the model curve needs to be modified.

CONCLUSIONS

Historical failure data shows that failures in service are not showing an increasing trend with age, but this is due to an active condition based replacement programme that is replacing older transformers even though age is not directly considered as a factor in the condition assessment process.

Condition based replacement means that statistical analysis of failure rates is not helpful in modelling lifetimes, but data from scrapped and failed transformers has been used to demonstrate that age-related failures (or replacements because of very poor condition before failure) in the population of large network transformers are starting to occur at around 40 years in service.

Experience and thermal modelling indicates that a primary determinant of lifetime is the thermal design of the transformer, in particular whether the hotspot factor has been correctly calculated, or whether the transformer is getting significantly hotter than expected in service.

Further work is needed to determine the range of population lifetimes that result in models that match both the evidence from scrapped and failed transformers to date and the condition assessment results. In particular the number of transformers presently reported to be in poor but not critical condition (10-15 years before failure) appears to be lower than would be indicated by the model. This may indicate that additional effort is needed to identify methods for detecting the early signs of thermal degradation, particularly as the quality of transformer thermal design appears to be very variable and is probably the critical factor in determining transformer lifetime.

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