An Early Degradation Phenomenon Identified through Transformer Oil Database Analysis

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ABSTRACT

Ageing of large transformer fleets is a challenge for utilities. To assess the condition of existing transformer fleets, transformer oil is commonly tested for multiple parameters and the data are recorded in large databases for subsequent interpretation. Through analysing multiple databases including oil test results and individual transformer details pertaining to UK in-service transformers operating at primary voltage levels of 33, 132, 275 and 400 kV, population analyses revealed a generic early degradation phenomenon as indicated by an early peak in acidity and 2-FAL trends with in-service age. By exploring the phenomenon from manufacturer, loading and oil chemistry change perspectives, results suggested that the early degradation was most likely due to an oil chemistry change resulting from hydrotreatment oil refining method introduced in the late 1980s. Judging from the faster degradation trend of the affected transformers, a separate asset management strategy may be needed.

Index Terms - **Power transformers, in-service units, database analysis, acidity, abnormal ageing, early degradation, asset management.**

1 INTRODUCTION

TRANSFORMER design lifetimes are estimated to be about 45 years for transmission and around 60 years for distribution transformers [1-3]. With transformer insulation well understood to deteriorate in service and knowing the commissioning of large transformer populations in the 1960s (as seen in Figure 1), ageing assessment is therefore an important practice to facilitate transformer asset management [1].

As transformers age, the insulation system consisting of a liquid (typically mineral oil) and one or more solids (typically Kraft paper and pressboard) will degrade, releasing ageing products that are not just traceable but also capable of changing insulation properties. Due to its ease of access, transformer oil is commonly sampled and tested for multiple parameters to assess ageing of the oil itself and also the solid insulation.

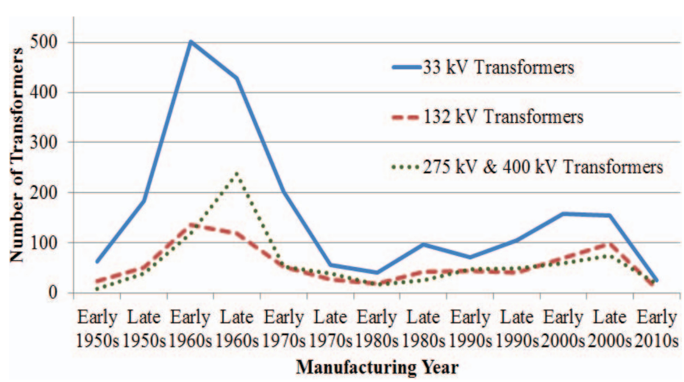

Figure 1. Manufacturing year distribution for transformers at different voltage levels contributed by three UK utilities.

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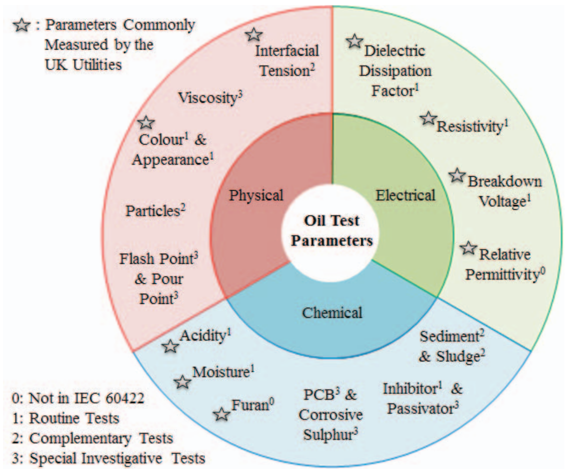

Figure 2. Oil test parameters for transformer ageing assessment [4].

Figure 2 shows the general categorisation of oil test parameters into electrical, chemical and physical groups [4]. Star shaped symbols indicate parameters typically measured by UK utilities. The superscript numbers of '1', '2' and '3' represent routine, complementary and special investigative tests, respectively, as suggested in IEC 60422 [4, 5], whereas the superscript number '0' stands for other tests that are not included in IEC 60422.

One of the parameters is acidity which has generally shown an exponentially increasing relation with ageing from both in-service transformers and lab experiments [6-9]. Oil degradation through oxidation, particularly in the termination stage involving the reaction between peroxy radicals, produces carboxylic acids [10]. As for paper, initial oxidation and the subsequently dominant acid-catalysed hydrolysis also produce carboxylic acids [11-14]. Considering the oil-paper partitioning and the molecular weight of the acids produced, High Molecular Weight Acids (HMA) produced predominantly from oil ageing would contribute more to the acidity measured in oil samples compared with the Low Molecular Weight Acids (LMA) linked to paper ageing [14-16].

Another parameter commonly measured is 2-furfural (2-FAL) which is attributed to paper decomposition but soluble in oil thereby permitting an indirect and a non-intrusive assessment of paper ageing [17, 18]. 2-FAL increases exponentially with ageing; not just observed in laboratory experiments [19-21], but also from in-service transformer oil measurements [9, 22, 23]. The reason for the late production of 2-FAL is that it is the end product involving several intermediate compounds such as glucose, pentose or levoglucosan arising from paper ageing through hydrolysis (dominant), oxidation or even pyrolysis at high temperatures (> 140°C) [16, 24, 25].

Notwithstanding the current understanding about the behaviour of parameters with respect to transformer ageing, there are factors that would affect observations. One such factor is transformer manufacturer which implies different designs. Moreover, the loading level of transformers as well as the chemistry of the insulating oil used could be influential in trend analyses of parameters with transformer in-service age. Therefore, care needs to be taken in handling and interpreting oil test records of a large transformer fleet to provide justifiable recommendations for optimised asset management of in-service transformers.

This paper involves analysis on in-service UK transformers, most of which are free breathing with silica gel breathers, and a small number of which are fitted with a rubber bag in the conservator. These transformers are mostly insulated with non-thermally upgraded Kraft paper and filled with mineral oil. These transformers operate at primary voltage levels of 33, 132, 275 and 400 kV. The oil test results of those transformers were provided in multiple large databases by National Grid, Scottish Power and UK Power Networks. Through population analyses, an early degradation phenomenon was observed for transformers at all voltages. The reason behind this phenomenon was analysed in terms of manufacturer, loading and oil chemistry.

2 METHODOLOGY

Figure 3 shows a work flowchart. Transformer detail databases from three UK utilities were acquired before databases with historical oil test records up to 2012 were linked with the respective databases of individual transformer details. Oil test databases have oil test dates and the records of several oil test parameters, while transformer detail databases have information of manufacturer, manufacturing year, rating, voltage and etc.

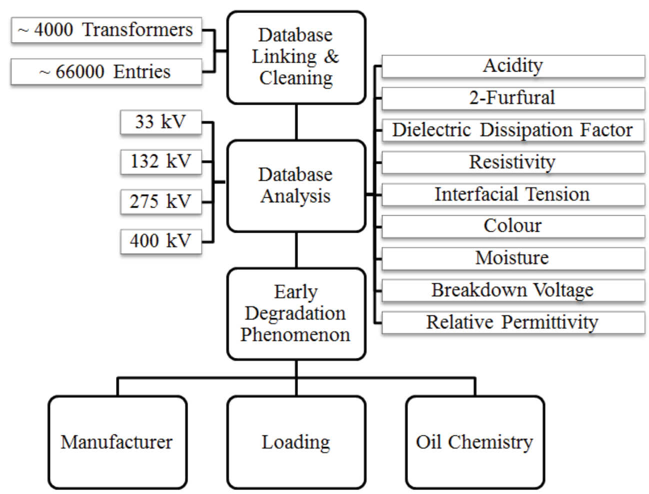

Figure 3. General work flowchart.

After linking of databases, database cleansing procedures were performed which include eliminating entries with errors in measurements, accounting for transformers that have undergone oil treatment procedures and transformers potentially filled with oil from contaminated sources [26, 27]. Population analyses were then performed on the "cleansed" databases pertaining to transformers operating at primary voltages of 33, 132, 275 and 400 kV. Different oil test parameters were considered as well in analysing their trends with transformer in-service age.

In-service age of a transformer denotes the difference between a particular oil test date and the manufacturing year of that transformer. Transformers with more than 5 years of their life not in service were not considered in the final analysis. Note that commissioning year information is not readily available for most transformers and hence manufacturing year will be used. In cases where both commissioning year and manufacturing year are available, commissioning year will be used instead of manufacturing year in calculating transformer in-service age.

Through analysing the trends of different parameters with respect to in-service age, an early degradation phenomenon was observed irrespective of the different operating voltages. The reason behind this early degradation phenomenon was then subsequently analysed from the perspectives of transformer manufacturers, loading levels and oil chemistry.

3 EARLY DEGRADATION PHENOMENON

This section aims to demonstrate the early degradation phenomenon through population analyses based on acidity as well as 2-FAL. In essence, parameters like dielectric dissipation factor do portray similar information as well, but only acidity and 2-FAL will be shown as these two parameters are the common parameters tested across transformers operating at primary voltages of 33, 132, 275 and 400 kV [4]. Besides that, acidity and 2-FAL show good correlation with in-service age [4]. In addition, acidity can be used to assess oil ageing whereas 2-FAL can be used to assess paper ageing, thus covering both aspects of a transformer insulation system.

Figure 4a and 4b depict the trends with transformer in-service age of acidity and 2-furfural (2-FAL), respectively, for 33 kV transformers owned by Utility A. Due to the large number of entries in the databases available for this work, there would be some degree of scattering in the ageing trends. Nevertheless, a clear early peak in acidity and 2-FAL can be seen (circled in the figures) around a transformer in-service age of 20 years.

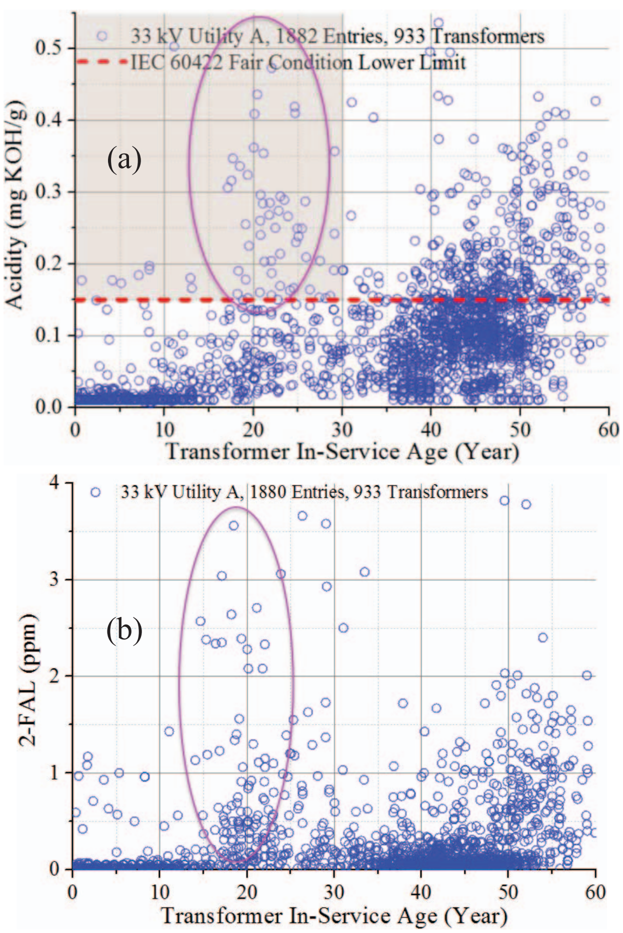

Figure 4. Early peak seen for 33 kV transformers, (a) acidity, (b) 2-FAL.

As both parameters are known to increase continuously with time, and with high values generally recorded after an in-service age of around 40 years, the early peak observed is abnormal and could mean an early degradation phenomenon. With reference to the IEC 60422 condition classification for acidity, it can be seen from Figure 4a that the transformers contributing to the early degradation phenomenon appear to transition into a fair condition at an earlier in-service age than normal ageing transformers.

Apart from confirmation from different oil test parameters, the early degradation phenomenon was also observed for transformers operating at other voltage levels such as 132, 275 and 400 kV in addition to the 33 kV transformers shown in Figure 4. Although the ageing trends for other voltage levels are not shown here (to avoid repetition), it appears that the early degradation phenomenon was not only an issue for a specific voltage level or a specific utility, but more of an issue that most probably affected the UK utilities.

4 CAUSE IDENTIFICATION OF EARLY DEGRADATION PHENOMENON

Considering the repercussion on asset management that early degradation phenomenon will potentially impart, this phenomenon needs to be further analysed by first extracting subpopulations of transformers deemed to have most probably been affected by early degradation. The first of the criteria is transformers with an in-service age of up to 30 years. The second of the criteria is dependent on IEC 60422 condition classification for acidity.

Although the early degradation phenomenon can be seen across different oil test parameters, including 2-FAL in Figure 4b, only acidity will be used as the second of the criteria as acidity is not just a common parameter with high correlation with age that is measured by different utilities for different voltage transformers, but also a parameter with recommended value ranges for condition classification already given in international standard such as IEC 60422 (2-FAL condition classification is still unclear and remains an ongoing research topic [9, 17, 28]).

As an illustration, the shaded region in Figure 4a shows a subpopulation for Utility A 33 kV transformers. Table 1 summarises the criteria for extracting subpopulations. Note that 275 kV and 400 kV transformers were grouped as one voltage class due to how IEC 60422 recommends the same subsequent actions for transformers at both voltage levels [4]. In addition, an acidity value of 0.05 mg KOH/g instead of 0.10 mg KOH/g as recommended in IEC 60422 was used for 275 kV and 400 kV transformers. This is motivated by the relatively much lower acidities for 275 kV and 400 kV transformer populations likely due to greater care, attention or stricter design requirements [4].

Table 1. Criteria for subpopulation extraction.

Primary Voltage	In-Service Age	Acidity (mg KOH/g)	
33 kV	≤ 30 Years	≥ 0.15	IEC 60422 Fair Condition Lower Limit
132 kV		≥ 0.10	
275 kV & 400 kV		≥ 0.05	Set for Greater Detection

With subpopulations established, further analyses can be performed to identify the reason behind the early degradation phenomenon. As discussed in Section 0, aspects such as oil contamination and errors in measurements have already been accounted for and thus they are not the reason. Considering that, the early degradation phenomenon will be subsequently investigated from different perspectives such as manufacturer, loading and oil chemistry.

4.1 MANUFACTURER PERSPECTIVE

Different designs from different manufacturers could have been the cause for the early degradation phenomenon; hence the need to explore the perspective of different manufacturers in the early degradation phenomenon. Focusing on the subpopulations, Figure 5 illustrates not just manufacturing year distributions for all three voltage classes, but also the composition of different manufacturers. The manufacturing year periods are represented in half-decades, i.e. Early 1970s for 1970 – 1974; Late 1970s for 1975 – 1979 and so forth.

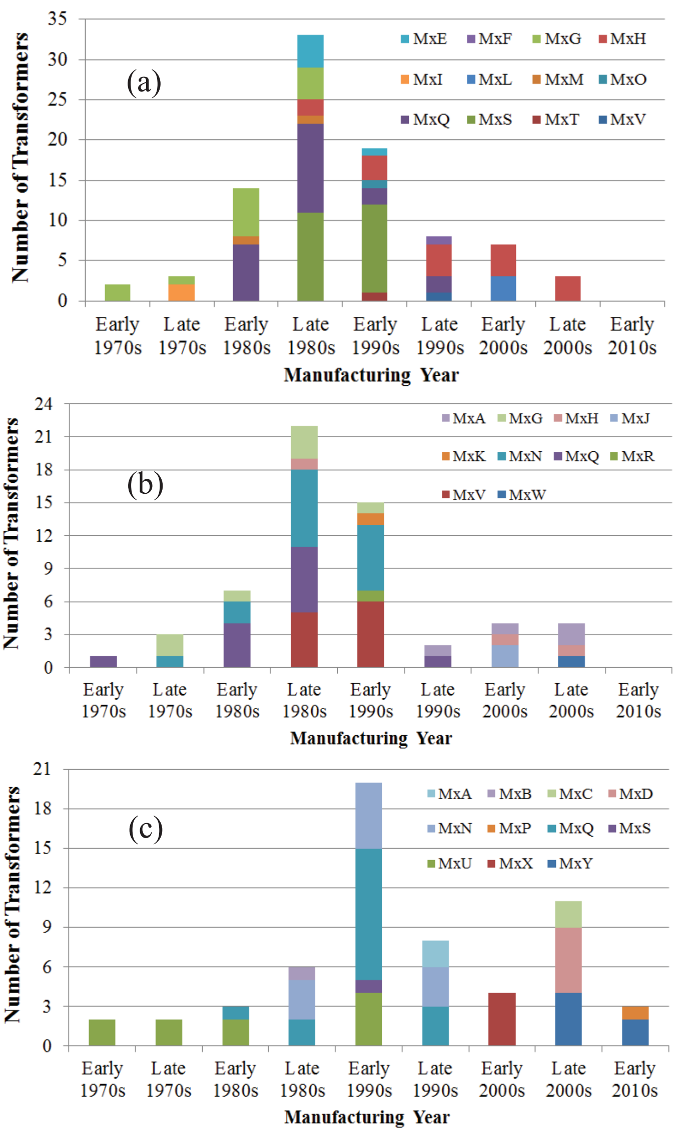

Figure 5. Transformer manufacturing year distributions, (a) 33 kV subpopulation, (b) 132 kV subpopulation, (c) 275 kV and 400 kV subpopulation.

Overall, there are 25 manufacturers with certain manufacturers contributing to units that are operating at different voltages. The manufacturer composition shows no dominant manufacturer (s) contributed to the units in the subpopulations. In other words, the early degradation phenomenon was not attributed to possibly poor designs from specific manufacturers.

Another finding from Figure 5 is the high contribution of units manufactured in the late 1980s and the early 1990s. This suggests that units potentially linked to the early degradation phenomenon were mostly manufactured during those periods. With databases holding records up to 2012, those periods would mean units having an in-service age of about 20 years, which is when early peak was also observed in Figure 4.

Placing the emphasis on transformers manufactured in those periods (the late 1980s and the early 1990s), a study was conducted with focus particularly on the proportion of affected and unaffected transformers from each manufacturer deemed associated with the early degradation phenomenon.

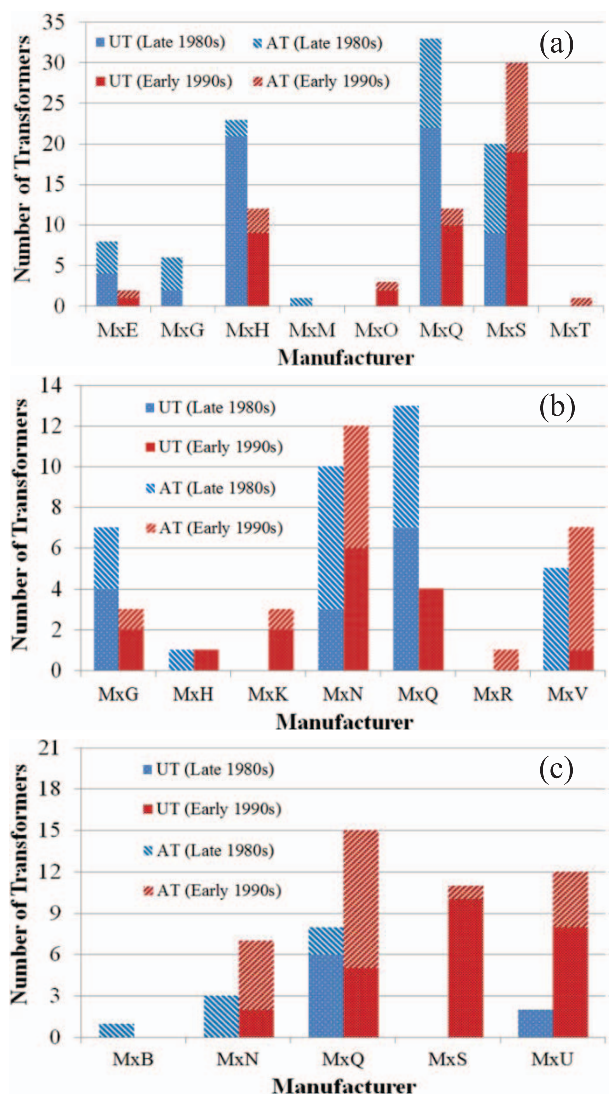

Figure 6. Manufacturer distribution of unaffected transformers (UT) and affected transformers (AT) from the late 1980s and the early 1990s, (a) 33 kV, (b) 132 kV, (c) 275 and 400 kV.

Note that the acronym UT in Figure 6 means unaffected transformers which are the ones not considered to have acidity higher than the designated limit. The context is still about units with an in-service age of up to 30 years. Conversely, the acronym AT denotes affected transformers which are those considered in subpopulations previously identified as having an in-service age of up to 30 years and acidity greater than or equal to the respective designated limit.

Figure 6 reinforces the conclusion from Figure 5 that the early degradation phenomenon is independent of transformer manufacturer as different manufacturers contributed towards the AT units and those manufacturers with AT units generally have UT units as well.

This observation not only consolidates that the early degradation phenomenon is not a manufacturer specific issue, but also suggests that the simultaneous introduction of computerised designs in the 1980s perhaps did not cause the early degradation phenomenon. This is again due to the presence of UT units for the same transformer manufacturers that contributed to AT units regardless of whether the manufacturing year period was the late 1980s or the early 1990s.

Proceeding from the distributions of transformers across different manufacturing year periods and manufacturers, the scope of analysis is now narrowed to a particular manufacturer which had manufactured transformers spanning a sufficiently long period of time. This period also includes the periods that were known from previous analysis as most likely the contributors to early degradation transformers, which are the late 1980s and the early 1990s.

With the trend of acidity plotted with respect to transformer in-service age, it would be worthwhile to observe how transformers from the same manufacturer or of the same design family would behave if the transformers were manufactured from different time spans.

Figure 7 depicts acidity trends of units manufactured by MxQ only. MxQ was taken as an example as it has units manufactured since the early 1970s till the early 2000s and having both affected and unaffected units for different utilities. Moreover, MxQ units are operated at all the three voltage classes that have been considered in this paper.

Note the box plot contains the 25th, 50th (median) and 75th percentiles with 1.5 times interquartile range as the whisker boundaries. Values further away from the whisker boundaries are outliers and are shown in respective colours according to the different half decade groups. The width of the box plot is designed to be based on the span of the in-service age that each half decade group covers. Each group also has number of entries (E) and number of transformers (T) shown.

A noticeable visual observation from Figure 7 is again the rather distinct behaviours of the bulk of transformers around an in-service age of 20 years. This is similar to what was observed in Figure 4 where all transformer manufacturers were considered. Hence, the MxQ transformers analysed here with respect to different half decades of manufacturing year revealed that the early degradation phenomenon is again not a manufacturer specific issue.

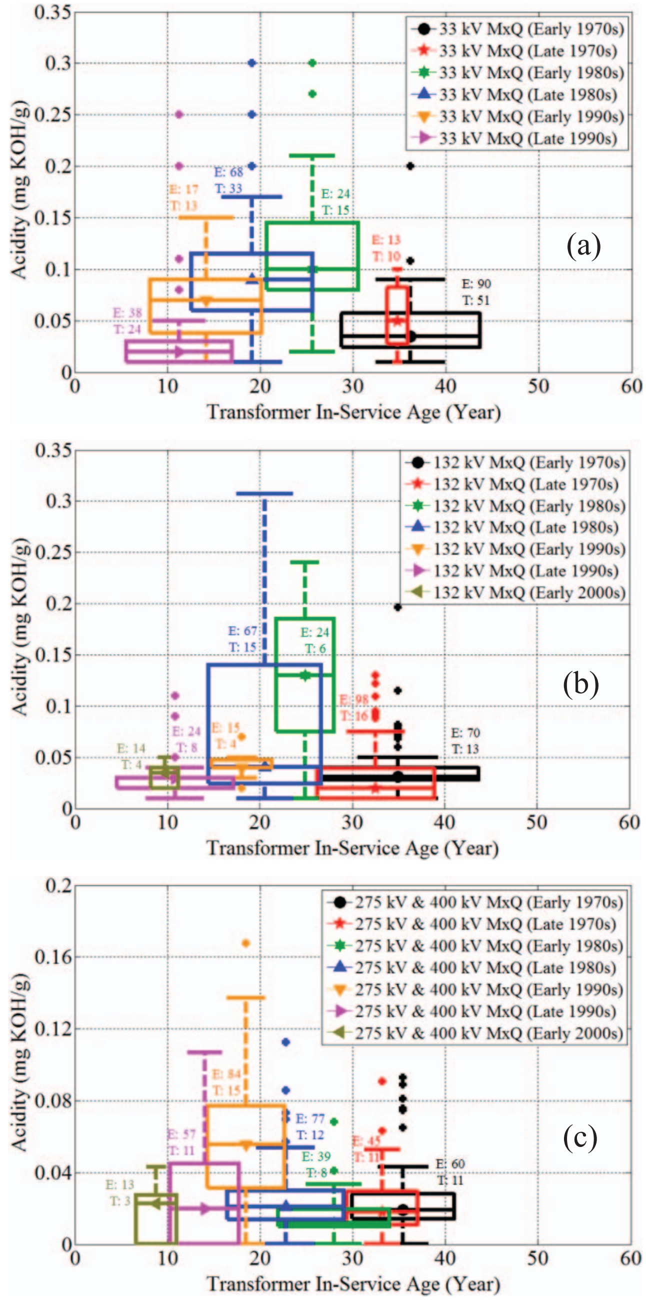

Figure 7. Ageing trends of acidity for MxQ transformers manufactured in different time periods, (a) 33 kV, (b) 132 kV, (c) 275 kV & 400 kV E: number of entries, T: number of transformers.

4.2 LOADING PERSPECTIVE

With manufacturer regarded as not the issue in causing the early degradation phenomenon, the focus now turns to the possible influence of transformer loading level. Only Utility E has loading records for a certain number of its in-service transformers. To be more specific, loading information was extracted for 23 transformers deemed to have the early degradation phenomenon and 506 transformers considered to undergo normal ageing.

Loading information was obtained in the form of half-hourly actual loading level of each transformer where the values recorded from 1 January 2009 to 31 December 2010 were used to represent a particular transformer loading level.

With that two years' worth of half-hourly loading data, equivalent loading, L_{eq} was calculated based on IEEE C57.91 – 2011 [29]. The equation is shown below in equation (1).

$$L_{eq} = \left[\frac{L_1^{\,2} t_1 + L_2^{\,2} t_2 + \ldots + L_N^{\,2} t_N}{t_1 + t_2 + \ldots + t_N} \right]^{0.5} \tag{1}$$

where L_1, L_2 ... represent load steps in per unit; N denotes total number of load steps considered and finally t_1, t_2 ... symbolise respective durations of each of those load steps which are just half an hour considering the nature of the loading data acquired. With equivalent loading calculated for each transformer, Figure 8 provides the platform for comparing the loading levels of normal transformers and transformers deemed to undergo early degradation.

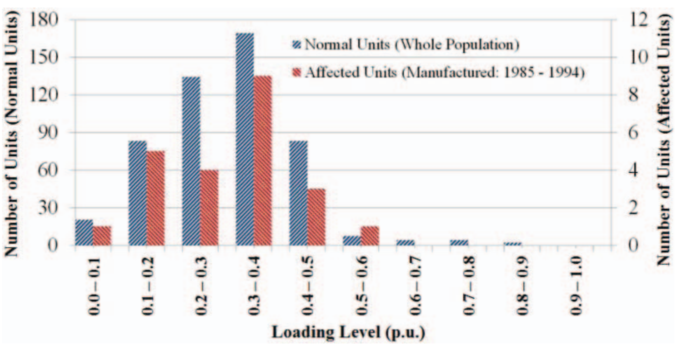

Figure 8. Loading distributions of normal and affected units from Utility E.

Focusing on the manufacturing year periods of the late 1980s and the early 1990s, Figure 8 indicates that the transformers manufactured in those two periods and which are associated with the early degradation phenomenon actually portray a similar loading distribution to that of the normal unit population. This normal unit population is again the resulting population after eliminating units deemed to have the early degradation phenomenon.

With similar loading distributions observed, it suggests that transformer loading level is not the reason behind the early degradation phenomenon as the affected transformers are not loaded more towards the higher loading region if to be compared with their normal ageing transformer counterparts.

4.3 OIL CHEMISTRY PERSPECTIVE

With transformer manufacturer and loading dismissed as potential causes for the early degradation phenomenon, this section will investigate oil chemistry change. Such a change will be explored more from the viewpoint of oil refining technique. Different refining techniques adopted throughout the long history of mineral oil usage could have led to different ageing performance of transformers manufactured from different points in time.

In general, oil refining is used to separate various hydrocarbon types present in crude oil, before chemically converting those separated hydrocarbons into more desirable products while also eliminating undesirable ones [30]. Oil refining starts with fractionated distillation of crude oil which involves separation of fractions with different boiling ranges and subsequent selection of one of those fractions for producing insulating oil [10]. The resulting distillation products (distillates) are then fed to one of the core refining steps in Figure 9.

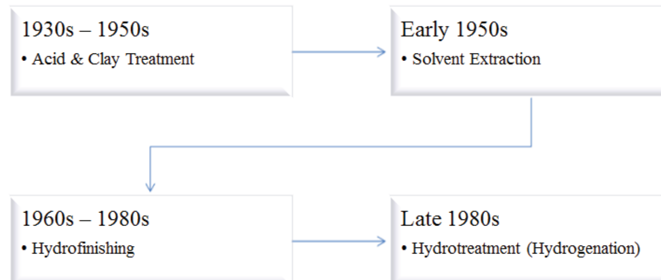

Figure 9. Brief chronology of mineral oil refining techniques [10, 31].

As indicated by Figure 9, acid and clay technique had been the popular choice for oil refining from the 1930s to the 1950s [10]. Subsequently in the early 1950s, solvent extraction was introduced with typical solvents of 2-furfural and phenol [10, 31]. Moving on to the 1960s, hydrotreatment was initially introduced as a finishing process for other refining techniques such as solvent extraction, culminating in an oil refining technique collectively known as hydrofinishing [10, 31].

Such hydrofinishing oil refining technique became popular and was used widely until the 1980s. However, from the late 1980s, following the advances in catalyst science and the use of higher temperatures and pressures, hydrotreatment (hydrogenation) gained popularity as a complete refining technique that can greatly reduce both aromatic and polar compounds [31]. In fact according to articles [32-34], a combination of fuel oil demand shortfall, closure or merger of refineries and increased importance of relative quantity and quality of refined oil culminated in the worldwide preference of hydrotreatment from the late 1980s; all considering hydrotreatment's lower cost, higher yields and lower amount of toxic sludge [32, 35].

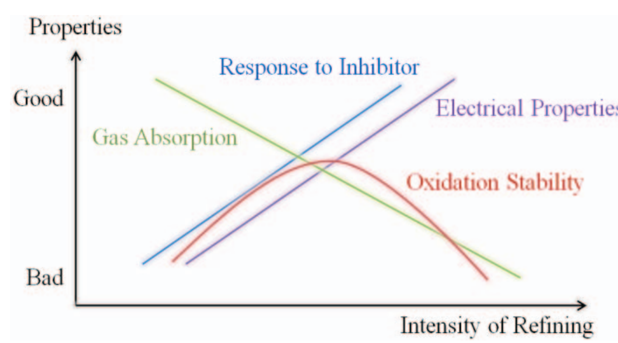

Figure 10. Effects of refining intensity on oil properties [10].

Hydrotreatment (hydrogenation) that became popular from the late 1980s is a process with severe refining intensity. Referring to Figure 10, increasing refining intensity increases oxidation stability which is preferable [10]. Nevertheless, oxidation stability of oil eventually suffers when the refining intensity is too high as not just the undesirable compounds are removed, but also naturally existing antioxidants [10, 31]. Such oil with lower inherent oxidation stability is highly responsive to synthetic inhibitors or antioxidants, thereby capable of yielding an end product with superior oxidation stability that is dependent on the synthetic inhibitor induction period if synthetic inhibitor is added [10, 31].

Nonetheless, when hydrotreatment was introduced in the late 1980s, those transformers manufactured around that period of time without synthetic inhibitors added are currently still in-service in the UK. It was not until the late 2000s that some utilities in the UK began adopting inhibited mineral oil in newly built transformers.

Hence, the early degradation phenomenon observed from analysing in-service UK transformers is most likely contributed by units manufactured around the late 1980s that are filled with uninhibited hydrotreated oil which has lower oxidation stability. This argument corresponds well with the findings previously seen in Figure 5, Figure 6 and Figure 7 where the transformers linked to the early degradation phenomenon were mostly manufactured from the late 1980s and the early 1990s.

It is noteworthy that even though hydrotreatment that involves higher pressure, higher temperature and catalysts was widely used from the late 1980s, hydrofinished oil was still on the market [10]. This could explain why not all transformers manufactured during the late 1980s and the early 1990s contributed to the early degradation phenomenon.

5 DISCUSSIONS

The analysis of in-service transformer oil test databases offers a generic view on the ageing tendencies of transformers operating at multiple voltage levels. From such a database analysis, the early degradation phenomenon was observed and its potential cause was analysed from the perspectives of manufacturer, loading and a change in oil chemistry. Evidence so far has suggested the oil chemistry changed by the adoption of hydrotreatment oil refining technique is the cause of the early degradation phenomenon.

From this study, with the discovery of the early degradation phenomenon, asset managers perhaps need to have a separate asset management strategy for the affected transformers. Figure 11 shows an example of a 33 kV transformer database from a utility to demonstrate the need for implementing a different asset management strategy.

Such a need arises from knowing the difference in the ageing trends between affected transformers and a transformer population without those affected transformers. As observed from Figure 11a, normal transformers would start having acidity values that are interpretable as fair condition around an in-service age of 35 years, but the affected transformers evidently age faster and can be seen going into the fair condition as quickly as about an in-service age of 15 years.

With a faster rate of degradation not just for the oil, but also for the paper (as interpreted from 2-FAL in Figure 11b), some recommendations could be adopted to uphold the longevity of transformers and the reliability of the electrical power system as a whole. From a population viewpoint, asset managers could consider the seemingly faster rate of degradation of the affected transformers into revising any existing framework for capital investment or long term replacement policies.

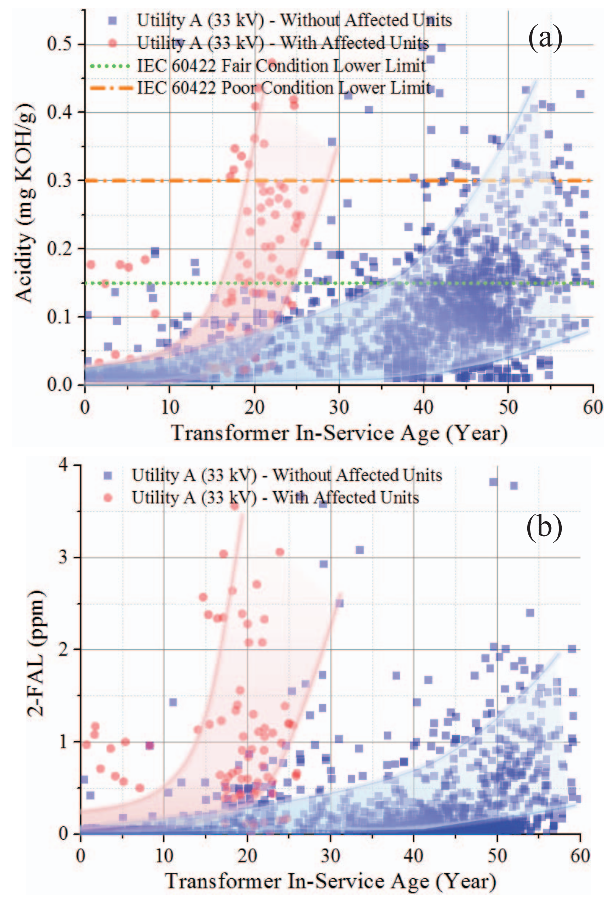

Figure 11. Difference in projected ageing trends between populations with and without affected early degradation transformers, (a) acidity, (b) 2-FAL.

On the other hand, from the perspective of managing individual transformers, asset managers could consider monitoring the affected units more frequently. Also, oil regeneration or reclamation procedures could be prioritised or scheduled sooner for the affected transformers to attempt retarding the future degradation of both oil and paper.

It is worthwhile mentioning that not all transformers manufactured from the late 1980s to the early 1990s are associated with the early degradation phenomenon. Although hydrotreatment was the preferred oil refining method back then, hydrofinished oil was still used [10]. Hence, only those that are affected should be separately monitored and managed from the rest of the normal ageing transformers.

Apart from that, the early degradation phenomenon seen for the UK transformers could also be observed in transformers in the rest of the world considering hydrotreatment was the worldwide preferred oil refining method from the late 1980s.

It is interesting to note that with hydrotreated oil responding well to synthetic inhibitors, the US might not have such an issue of early degradation as the US transformers are known to be filled with inhibited oil. However for other countries where transformers are typically filled with uninhibited oil, more attention should be paid to asset management if the early degradation phenomenon is observed from acidity or any other parameters that have a good correlation with in-service age.

It is also of interest to monitor the performance of transformers manufactured after the 1990s. With a change in oil chemistry possibly occurring from the late 1980s to the early 1990s through the introduction of hydrotreated oil, transformers manufactured after that period should also be given attention specifically when these units age into an in-service age region of about 20 years. It will be noteworthy to observe whether these transformers would follow either the ageing trends exhibited by the affected transformers or the unaffected ones.

6 CONCLUSION

By analysing in-service 33, 132, 275 and 400 kV transformer oil test databases pertaining to three utilities in the UK, an early degradation phenomenon was observed from population ageing trends. Through exploring the influences of different manufacturers, manufacturing year periods, loading levels and oil chemistry, current evidence suggested that such an early degradation phenomenon is caused by a change in oil chemistry occurring from the late 1980s to the early 1990s due to the implementation of hydrotreatment oil refining technique that could have depleted natural oxidation inhibitors in oil. Asset managers might need to formulate different asset management strategies to cater for transformer fleets with both unaffected and affected units.

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