ABSTRACT

There is precious little basic information openly available on how insulating materials in transformers behave over longer periods of time. However, such information is very important for ensuring that aging equipment works adequately. It is valuable both from the perspective of transformer maintenance/asset management, and as background information necessary for making informed choices on which type of insulating liquid to employ in new equipment.

KEYWORDS

transformer oil, inhibitor, oil oxidation, in-service oil, inhibitor top up

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MINERAL INSULATING OILS IN SERVICE

Monitoring and their properties

Introduction

Infrastructure of electricity grids in the hitherto industrialized world was to a large extent built up in the decades following World War II, with a peak in investments around 1960 - 1980. This means that the flotilla of power transformers is now starting to reach projected lifetime of around 40 years. Over the last couple of decades there has also been an ongoing deregulation and privatization of electricity generation and distribution. This has led to higher utilization of existing equipment to meet an ever higher power demand. Demands for planned asset management, investments and reliability of power delivery have also increased. The need to ensure that aging equipment works adequately and will do so for some time yet has generated an increased interest in aging behaviour of power equipment. Yet there is precious little basic information openly available on how insulating materials in transformers behave over longer periods of time. Such information is valuable both from the perspective of transformer maintenance/asset management, and as background information necessary for making informed choices on which type of insulating liquid to employ in new equipment.

In this study there is a total of 145 separate oil samples from separate transformers (all samples appeared around the same time for analysis), 114 of which are inhibited and 31 uninhibited (as defined by IEC 60296). The inhibited oil samples, comparable to ASTM D3487 Type II, came from transformers in the Nordic region in Europe, whereas the uninhibited samples came mainly from the Middle East. The age of transformers ranges from only a few years up to 45 years.

The samples were analysed for acidity (neutralization number), interfacial tension, dielectric loss (DDF or power factor) and peroxide content. The inhibited samples were also analysed for inhibitor content.

All of these parameters except peroxide content are standard measurements, but little information exists on how they relate to each other statistically. The peroxide measurements, performed according to a method we have developed, should tell us more about oxidation behaviour and efficiency of oxidation inhibitors.

Monitoring and maintenance of insulating oils in service

Insulating oil in a power transformer accounts for only about 5 % of the initial cost of the complete system (information collected from OEMs), but it is a very vital part both for monitoring of the functioning of the transformer and for the ultimate lifetime under which the investment cost should be regained with interest. Ideally, a high quality insulating oil should not contribute to premature ageing of non-replaceable parts such as winding or solid insulation. Through DGA the oil also serves as an information carrier about what is happening inside the transformer.

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However, it is vital to ensure that aging of the oil is not excessive and that it performs adequately. For this reason there are guides to follow to check the oil performance including IEC 60422 [1] and IEEE C57.106 [2]. IEC 60422 is a much more elaborate document with more detail than the corresponding IEEE document, which provides very few direct limiting values for physical and chemical properties.

IEC 60422 oil vs. IEEE C57.106

IEC 60422 is a guide for supervision and maintenance of mineral insulating oil in electrical equipment. This standard, revised and published in 2013, is used worldwide. The purpose of revision is to bring the standard in line with current methodology and best practice as well as to ensure compliance with requirements and regulations affecting safety and environmental issues.

IEEE C57.106 has a different scope as it additionally includes acceptance tests for new oil in new equipment. The number of physical and chemical tests listed in this guide is significantly fewer than that in the IEC document (see comparison in Table 1). The two standards also list different limiting values depending on voltage class. In this article the limits for highest voltage classes have been used (IEC >170 kV, IEEE >230 kV).

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Group 1 Minimum tests required to monitor the oil and ensure that it is suitable for continued service.

Group 2 Additional tests which may be used to obtain further specific information about the quality of the oil and to assist in the evaluation of oil for continued use.

Group 3 Tests which are mainly used to determine suitability of the oil for the type of equipment in use and ensure compliance with environmental and operational considerations.

Individual tests for each group are listed in Table 1 of IEC60422 [1]. It should be noted that if test results for *Group 1* do not exceed recommended action limits, usually no further tests are considered necessary until the next scheduled inspection period.

Classification of oils in service

To assist in the assessment of the condition and subsequent actions, oils in service may be classified into three categories, both according to IEC 60422 and IEEE C57.106.

Aging of mineral oils

Even if there are different types of wear and tear on the insulating oil, the main force of aging is oxidation. For oxidation to take place there has to be something to oxidise (oil), oxygen, and heat to provide the activation energy.

Details of the oxidation process will not be covered here, and they can be found in the earlier contribution to TechCon AP [3], but a brief outline is nevertheless necessary for the continued discussion.

When a hydrocarbon molecule (oil molecule) encounters the combination of heat and oxygen (air), it can form a peroxide (Figure 1). Peroxides are inherently unstable and therefore rather reactive. They can easily form alcohols, aldehydes or ketones. These are polar types of molecules that

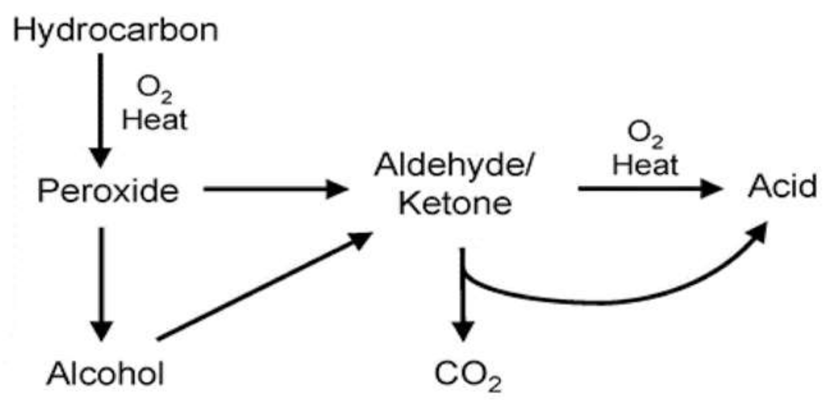

Figure 1: Principle of oil oxidation

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will change the properties of the oil medium in which this occurs. For instance, this will affect interfacial tension and solubility of water in the oil. Water is also a by-product of several of the reactions that underlie these phenomena.

Aldehydes and ketones can react again with oxygen to form acids directly, or be oxidised and lose carbon dioxide to form acids. Carbon dioxide is in fact the most oxidised form of carbon. However, both aldehydes and acids can react with each other to form complex compounds that are not soluble in oil, i.e. sludge.

This is in essence an oxidative reaction in a mineral oil-based insulating liquid, although in a very simplified form. What is lacking in this simple picture is the positive feedback loop of the reactions of peroxides; peroxides react and form even more peroxides in the same process as other oxidation products are formed. This comes about by chain reactions of radicals of peroxides. Ester-type of liquids follows the same general pattern, but the details differ.

Oxidation inhibitors (natural or synthetic) moderate or stop the reactions of peroxides to protect the liquid from oxidative reactions.

Among these different products one can measure peroxides, the effect of polar compounds formation on interfacial tension (IFT), acidity as well as carbon dioxide by DGA.

Study of field samples

The data for this study was retrieved from the analyses database within Nynas Insulating Oil Management (IOM). In this case, the peroxide content of oil samples was also analysed using a Gas Chromatography Mass Spectrometry (GCMS) based method developed by Nynas Group Research Department [4].

For maintenance and reinvestment strategies, the development of different oil parameters over time is perhaps the most interesting insight to be elucidated from this and similar sets of data. If asset managers know what signs to look for and what development to expect, at least on a statistical level, this should be very helpful to secure power delivery at a minimum cost. Other types of correlations may also be interesting, especially to enable maintenance decisions on less complete data, a situation that is all too common.

Oxidation inhibitors (natural or synthetic) moderate or stop the reactions of peroxides to protect the liquid from oxidative reactions

Once the values for age, IFT, acidity (neutralization number), peroxide concentration, power factor and inhibitor content had been gathered, the data was divided into two categories depending on whether the oil was inhibited (containing di-tert-butyl-paracresol (DBPC)) or uninhibited.

The data was then analysed for linear correlations. This naturally does not give the whole truth, but even a weak linear

Picture 1: New vs. aged oil

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correlation between sets of data may indicate that there are other types of interesting correlations. Finally, different data sets were plotted against one another to enable elucidations of more complex correlations. The results were then compared to the limits set in IEC 60422 and IEEE C57.106 for the highest voltage classes.

The weakness of this approach is that it cannot provide any information on the development over time in the same transformer as it only provides statistical correlations.

Inhibited vs. uninhibited oils

Before going into details of correlations of different measurable parameters, a broad comparison of the sets of oil samples properties should be considered (Table 1). Uninhibited oils in their true sense (without any added synthetic oxidation inhibitor) only exist according to IEC 60296, but in some cases can be compared to ASTM D 3487 Type I oils (with maximum 0.08 % added inhibitor).

Even if the data is a bit skewed because of the much higher number of inhibited oils, it is clear from what most of the numbers indicate that inhibited oils remain much more pristine during the service life of a transformer. It is very indicative to look at the oldest complete data (oldest c.d.) where the IFT of the uninhibited sample has gone down to alarming levels, whereas the inhibited sample of almost the same age is still in very good shape.

Also, take note of the fact that peroxide concentrations in uninhibited oils are at least an order of magnitude higher than in the inhibited samples. This indicates that destructive oxidation processes occur to a much larger extent in uninhibited samples. It also explains why the extreme values are much worse for uninhibited oils as processes of oxidation will yield these results.

Inhibited oils (corresponds to ASTM D3487 Type II)

In this study 113 samples were used from separate transformers. For 78 of the samples the age of the transformer (and the oil) was known. A total of 103 transformers were known to be of the free-breathing type with silica drying of the ingoing air. Inhibitor content, acidity and peroxide content was measured for all samples. 73 samples were analysed for IFT, and 61 for DDF (dielectric dissipation factor, i.e. dielectric loss similar to power factor).

The greatest correlation is found between IFT and inhibitor content. This actually shows that the inhibitor really works. As long as there is enough inhibitor left, there will be very little oxidation and, therefore, very few polar compounds affecting IFT are formed.

Age correlates best to DDF, and second best to acidity. The most likely explanation is that it is chiefly ionisable compounds like acids that affect DDF, but this seemingly high correlation should be taken with a pinch of salt because it is only based on 9 data pairs. In contrast, the correlation between age and acidity is based on 78 data pairs and is therefore much more real (see below). Peroxide content shows a certain correlation to acidity, which might result from the fact that during oxidation peroxides are first formed and then gradually turned into acids. From a chemical point of view, it should also be said that acids can be formed from aldehydes via peroxyacids which contain a peroxide functionality. The correlation between inhibitor content and peroxide content is weakly negative. The explanation of why the cor-

Table 1: Comparison of inhibited and uninhibited oils (c.d. = complete data)

	Age years	IFT (mN/m)	Acidity mg KOH/g	Peroxide (mM)
Inhibited				
median	15	39	0.00	0.06
average	16	38	0.02	0.07
extreme	45	24	0.27	0.55
oldest c.d.	37	41	0.03	0.09
Uninhibited				
median	25	27	0.04	0.41
average	21	30	0.07	0.47
extreme	45	14	0.36	2.18
oldest c.d	38	23	0.03	0.32

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relation is not stronger may lie in the fact that they are not simultaneous; as long as there is enough inhibitor, there will be very few peroxides.

Development over time

There is no point in showing all parameters as function of transformer age since most parameters do not show any trend at all. This includes peroxide and inhibitor contents, which are likely to be more dependent on specific loading patterns and the resulting temperature than time alone.

A certain linear correlation between age and acidity was found (vide supra), which calls for a more in-depth analysis. The data for acidity over time clearly indicate that no acidity levels developed before about 15 years of service (Figure 2). After this period there is an increasing trend with a few more extreme outliers.

The only type of simple regression analysis that gives a reasonable result for the complete data gives a logarithmic expression (black curve). For this to work, all values of zero acidity were substituted by the value 0.001 mg KOH/g, i.e. very close to zero and in practice not measurable, which ensures that these data are taken into account in the regression analysis. This indicates that statistically the acidity would not reach the IEC 60422 fair region (0.10-0.15 mg KOH/g) until after the service life of 50 years, but the regression curve is very sensitive to the weight of low values at low ages (which are also more uncertain).

If the more extreme outliers are treated separately in an attempt to model a worst-case scenario, a linear regression (red line) can be made. This indicates that oil acidity could reach IEC 60422 fair region/IEEE C57.106 Class I limit (of the same value) after about 27 years, and would in that case pass into the poor region after about 32 years.

Other Correlations

The greatest linear correlation found in the data for inhibited oils was that between inhibitor content and IFT. IEC 60422 recommends that inhibitor levels should be kept above 60 % of the original value in order for the oil to be considered in good condition. The lower value under which the oil is poor is set to 40 %, which for an oil that originally contained 0.40 % inhibitor would mean a limit of 0.16 %. The limiting value in IEEE C57.106 is much lower (0.09 %). Figure 3 shows this dependence.

Linear regression does not give a very good curve fit, but the trend is very clear; lower inhibitor content is associated with lower IFT. Presumably the reason is that oxidation, which consumes inhibitor, leads to formation of compounds that decrease IFT. It is evident that in these data there are only very few samples that contain less than 0.16 % inhibitor, and also very few samples that would not be classified as being in good condition when it comes to IFT according to IEC 60422 (IFT>28 mN/m). The limiting value for IFT in IEEE C57.106 is higher (32 mN/m) which is clearly not in line with the lower limit for inhibitor content.

This data analysis shows that an inhibitor content of at least 0.16 % is just enough to keep the IFT within the fair limits according to IEC 60422.

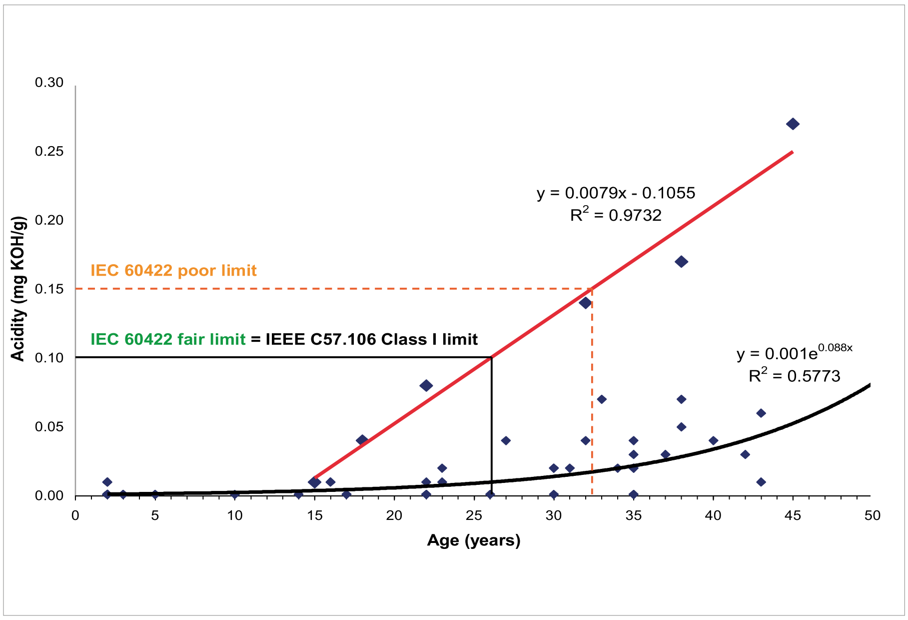

Figure 2: Development of acidity over time for inhibited oils

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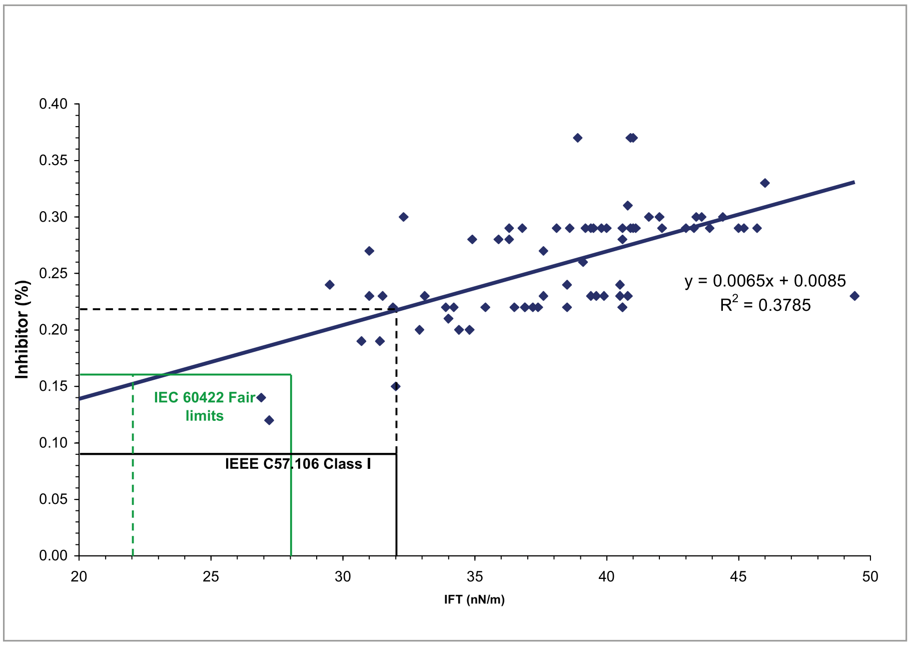

Figure 3: Correlation between IFT and inhibitor concentration for inhibited oils

This data analysis shows that an inhibitor content of at least 0.16 % is just enough to keep the IFT within the fair limits according to IEC 60422

Conclusion

The first 15 years of service are totally free of acids for inhibited oil, and in the worst-case scenario the acidity goes above the fair-poor limit after about 33 years. The average development points to a service life of more than 50 years for high quality inhibited oils.

This research confirms the lower limit of inhibitor content of 0.16 % in order to keep the oil virtually free of acids. At these inhibitor levels there are also no active peroxides to drive formation of polar compounds. This means that for inhibited oils measurement of peroxides adds no information.

In the case of uninhibited oils acids form from the start (which contributes to paper degradation), but it nevertheless, even in (statistically) worst-case scenario, takes 25 years of service before acidity exceeds the fair limit if high quality oils are used. Peroxide levels in uninhibited oils were found to have some correlation to other measurable properties such as acidity and interfacial tension, and might serve a similar purpose as measurement of inhibitor level in inhibited oils indicating when natural inhibitors have been consumed.

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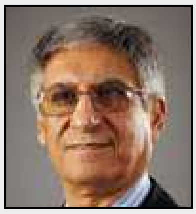

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