LIFE ESTIMATION OF HIGH VOLTAGE POWER TRANSFORMERS

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Abstract: To investigate the reliability of the large power transformers, a reliable measurement of the degradation characteristics with suitable sensors and condition monitoring is necessary. Particularly for 550 kV power transformers where few or no failures are expected, such measures can provide considerably more useful information than would be available from traditional life tests. Moreover, we shall also collect the data from the international test standards or previous published research results that relates equipment's quality level to the failure probability. Therefore, a relationship between component failure and amount of degradation makes it possible to use degradation data to make inferences and predictions about failure time. It is demonstrated with some practical examples that the reliability of the large power transformers will be expected under condition monitoring and diagnosis systems.

1 INTRODUCTION

The large power transformers are crucial and expensive equipment in transmission systems, they usually are well maintained and consequently have very high reliability. So in reality failures of transformers are relatively rare, and it is impossible to obtain statistically significant failure data with on-site measurement or it is expensive to assess reliability with traditional life tests that record only failure time.

On the other hand, it is possible to record the actual level of degradation on components as a function of time during condition monitoring. Diagnostic technique which tracks the deterioration of various failure modes is readily accessible for many power transformers. Such measures, particularly for 550 kV power transformers where few or no failures are expected, can provide considerably more reliability information than would be available from traditional failure – time data.

A degradation analysis is to find variables that are closely related to failure time and then predict the degradation performances at various conditions. The degradation model can be associated with the service conditions according to the different ageing mechanisms. The test standards as reference will relate equipment's quality level to the failure probability. The reliability estimation with degradation information may be achieved by linking the equipment's quality level with the condition-monitoring data. Therefore, a relationship between component failure and amount of degradation makes it possible to use degradation data to make inferences and predictions about failure time. Such a methodology is extremely valuable in assessing transformer's reliability and preventing further failures, using a data bank of condition monitoring for support.

2 DEGRADATION PERFORMANCE

An important and difficult engineering challenge of degradation analysis is to find performance variables that are closely related to failure time and develop methods for accurately evaluating these performance variables. Hence, aging diagnosis and evaluation can be realized by resorting to observation of appropriately selected properties, which are sensitive to aging deterioration [1-2]. Figures 1-12 show the measured and calculated degrading characteristics of the 550 kV power transformers for the total dissolved combustible gas (TDCG) concentration, all hydrocarbon concentration, CO_2 concentration, acidity, interfacial tension (IFT), power factor, water content, withstand voltage, as well as insulation resistance 60/600 (high, middle, low – ground or high, middle – low, ground). It can be observed that those parameters have increasing or decreasing trend with respect to degradation and can be used as an indicator of the degradation degree of the 550 kV power transformers.
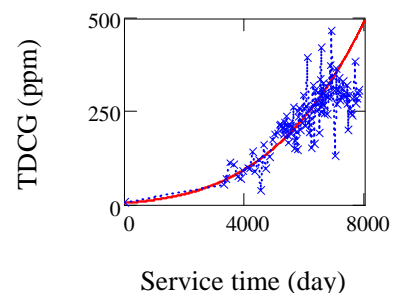

Figure 1: Calculated (line) and measured total dissolved combustible gas (TDCG) concentrations of transformer oil with service time
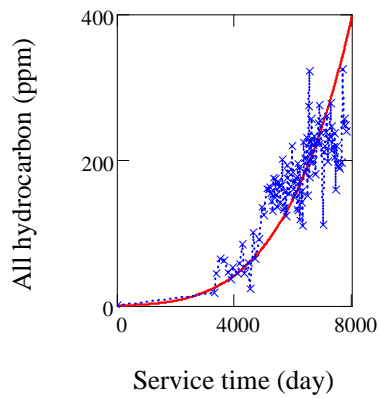
Figure 2: Calculated (line) and measured all-hydrocarbon concentrations of transformer oil with service time
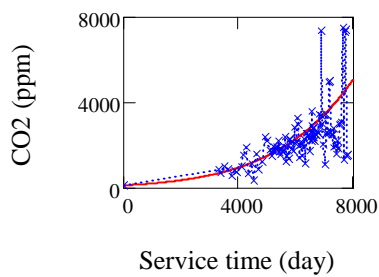

Figure 3: Calculated (line) and measured CO_2 gas concentrations of transformer oil with service time
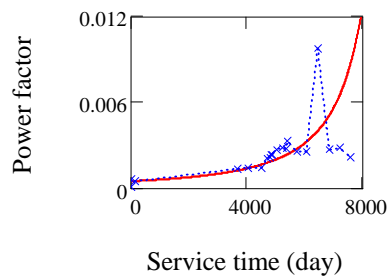

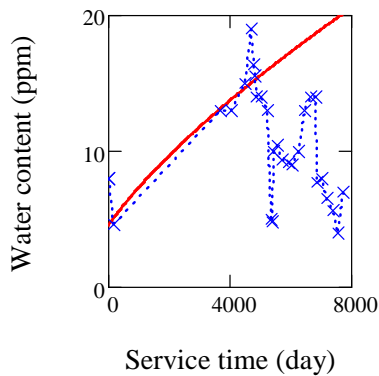**Figure 4:** Calculated (line) and measured power factors of transformer oil with service time

Figure 5: Calculated (line) and measured water content of transformer oil with service time
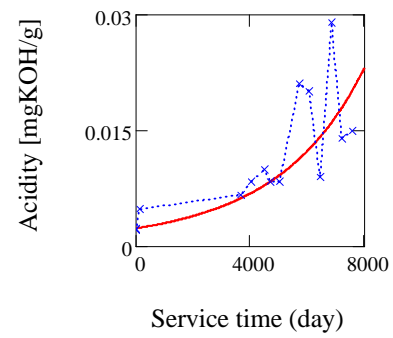

Figure 6: Calculated (line) and measured acidity of transformer oil with service time
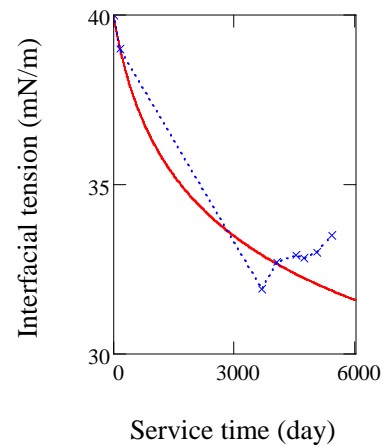

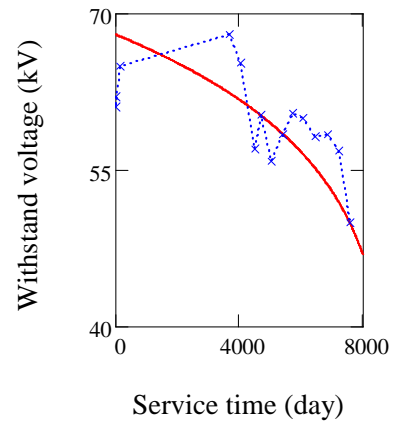**Figure 7:** Calculated (line) and measured interfacial tensions of transformer oil with service time

Figure 8: Calculated (line) and measured withstand voltages of transformer oil with service time
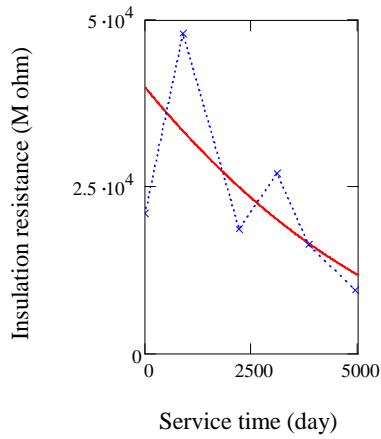
Figure 9: Calculated (line) and measured insulation resistances 600 (high, middle – low, ground) of transformer oil with service time
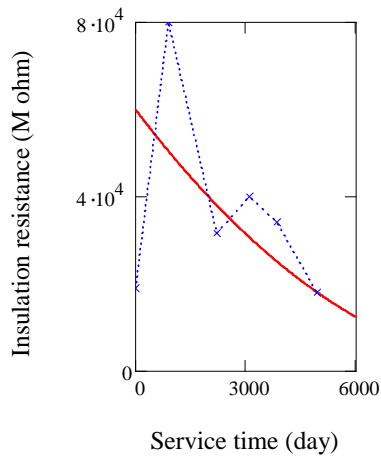

Figure 10: Calculated (line) and measured insulation resistances 600 (high, middle, low – ground) of transformer oil with service time

Figure 11: Calculated (line) and measured insulation resistances 60 (high, middle – low, ground) of transformer oil with service time

Figure 12: Calculated (line) and measured insulation resistances 60 (high, middle low – ground) of transformer oil with service time
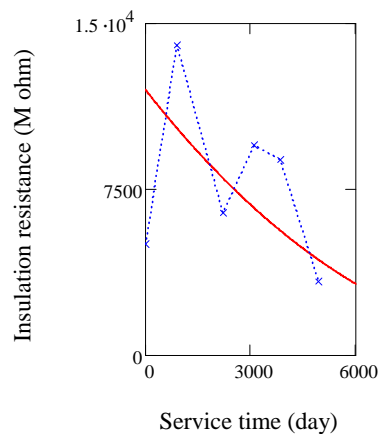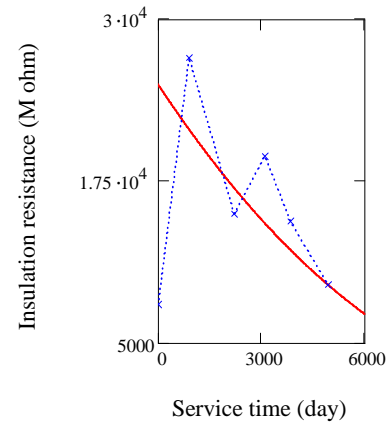
3 FAILURE CRITERIA

When a failure occurs in a large power transformer, component performance will be affected and system reliability will be reduced. The effects of failure on the operation or status of the power transformer may range from complete transformer's failure to partial component's degradation. In some cases failure would be assumed at a specified level of degradation and a failure level or a performance threshold can be defined by [3].

A fixed value of χ_f will be used to denote the critical level for the degradation path above which failure is assumed to have occurred. Often this may be in response to a reliability analysis of power transformers to ensure there are adequate reliability margins designed for the power transformers. A probabilistic evaluation of the magnitude of the stress in comparison with the designed strength may be required. When degradation can be characterized as a function of time, then the variation of the degradation variables is plotted versus the service time. In some cases, the definition of the failure event is clear – the component stops working. With such a failure, failure times will not, in general, correspond exactly with a particular level of degradation. Instead, the level of degradation at which failure occurs will be random from component to component and even over time. This could be modelled by using a distribution to describe component to component variability in χ_f or, more generally, the joint distribution of η and the stochastic behaviour in χ_f. Suppose that a component fails at time t if the degradation level first reaches χ_f at time t. Then

$$P(\chi) = 1 - \exp\left[-\left(\frac{\chi}{\chi_f}\right)^{\eta}\right]$$

(1)

Therefore, an accepted statistical model of determining the likelihood of failure *P* at given stresses is compared with a shape parameter η.

4 CASE STUDIES

Initial probability estimates will be based on the reliability specification and allocation, experience, existing databases, and comparability with components and parts having known reliabilities. The failure probability depends on the expected number of occurrences of each failure mode over a specific time interval. When sufficient data of measurement does not exist for quantifying the probability of failure occurrences, previous published research results provide the possible qualitative grouping of failure frequencies. In the case of the power transformers, there exist specific test standards (e.g. IEEE standards) which give a TDGA analysis of oil for the diagnosis of faults. As development progresses, functional and reliability tests will provide an alternative source for these probabilities. Assessment of failure effect and probability of failure occurrence are related as illustrated in Table 1. These classifications are assigned to each failure probability as a basis for ranking reliability criteria.

Table 1: Parameter of failure criteria and failure probability

Parameter	Unit	P_1	P_2	P_3	P_4
TDCG	ppm	\	720	1900	4600
	%	\	10	35	100
Hydrocarbon	ppm	\	335	1300	3200
	%	\	10	35	100
CO_2	ppm	\	2500	4000	10000
	%	\	15	40	100
Power factor	%	0.05	0.07	2	4
	%	0.5	1.5	10	100
Water content	ppm	10	15	20	25
	%	0.5	1.5	10	100
Acidity	mgKOH/g	0.03	0.1	0.2	0.5
	%	0.5	1.5	10	100
Interfacial intension	mN/m	50	40	30	20
	%	0.5	5	20	100
Voltage	kV	70	60	50	40
	%	0.5	5	20	100
Insulation resistance	MΩ	\	1000	100	10
	%	\	1	10	100

With regarding to the degradation of insulating materials, subjected to combined electrical, mechanical and thermal stresses, Weibull function (1) is generally used to treat failure time obtained from the failure criteria. On the basis of probabilistic approach, the measurement values are evaluated whereas the failure criteria and degradation models will be combined into the reliability model. Consequently, the time-dependent failure probability, failure rate,

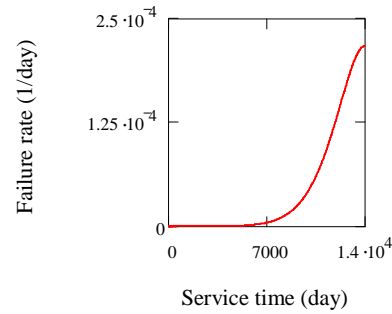remaining lifetime and other reliability items can be calculated (Figures 13 to 24).

Figure 13: Calculated failure rate of transformer with service time according to TDCG concentration of transformer oil
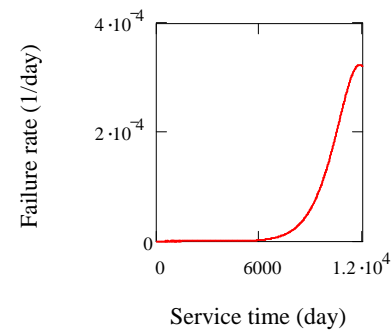

Figure 14: Calculated failure rate of transformer with service time according to hydrocarbon concentration of transformer oil
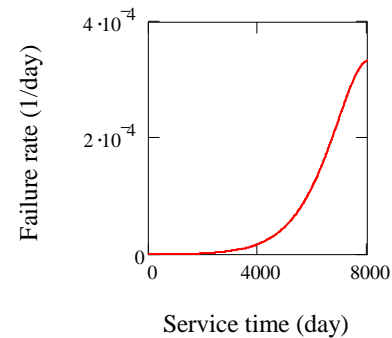

Figure 15: Calculated failure rate of transformer with service time according to CO_2 concentration of transformer oil

On the basis of the presented case studies, some additional statements need to be made. Aging is the main reason for failure, the transformers are in the steep slope of the ageing region of the bathtub curve with the increasing failure rates. It indicates the amount of contaminants (water and oxidation) in oil. As moisture destroys cellulose insulation, moisture will reduce the dielectric strength and the power factor of oil. Oil should be reclaimed to prevent sludge when interfacial tension is improved and the failure rate exhibits a decline. The increase in CO_2 is an excellent indication of abnormally high

temperature and rapidly deteriorating cellulose insulation, or could mean an atmospheric leakage. Due to the noticeable correlation between degree of polymerization and CO_2, the DGA method of obtaining CO_2 values can be considered as the most interesting for operational transformers by virtue of its convenience and low cost.
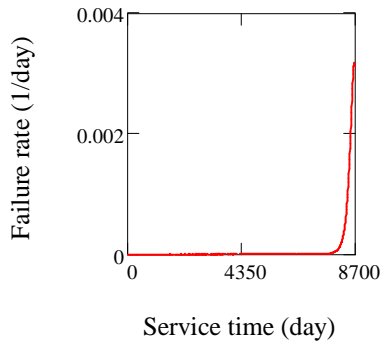

Figure 16: Calculated failure rate of transformer with service time according to power factor of transformer oil
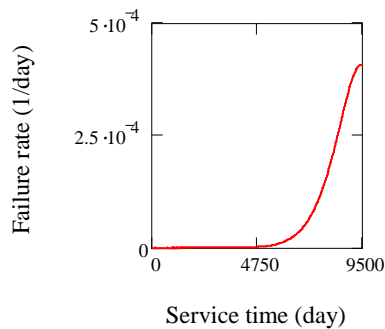

Figure 17: Calculated failure rate of transformer with service time according to water content of transformer oil
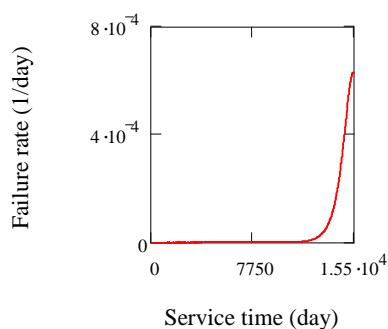

Figure 18: Calculated failure rate of transformer with service time according to acidity concentration of transformer oil
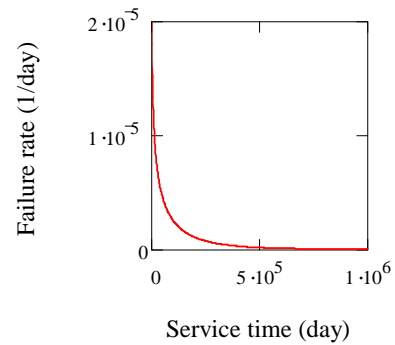

Figure 19: Calculated failure rate of transformer with service time according to interfacial tension of transformer oil
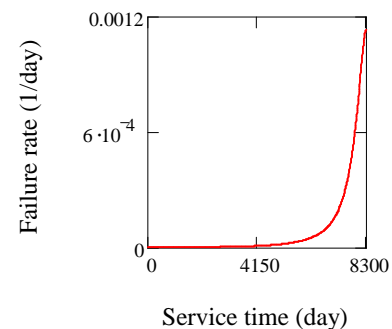

Figure 20: Calculated failure rate of transformer with service time according to withstand voltage of transformer oil
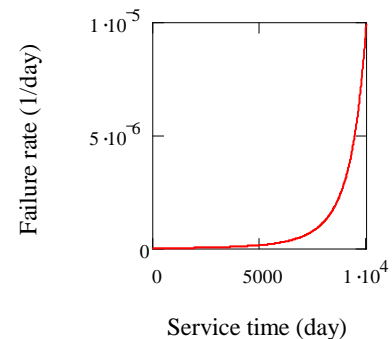

Figure 21: Calculated failure rate of transformer with service time according to insulation resistance 600 (high, middle – low, ground) of transformer

The failures reported from the utility are not consistent since separate, different service conditions exist, from which ageing data is mostly lost or incomplete. There may be two causes leading to the disperse phenomenon. One cause is that the sorption of insulation paper for gases changes with temperature of coil, and the other is that insulation paper cracks too suddenly because the loads changes largely. Surge loads leads to thermal surge, which affect the content of CO and CO2 as well as the aging of insulation paper greatly. The advantages of degradation data can also be compromised when the degradation measurements are contaminated with large

amounts of measurement error or when the degradation measure is not closely related to failure. When there is not a strong correlation between failure times and degradation, there may be little to be gained by using degradation data instead of traditional censored failure-time data.
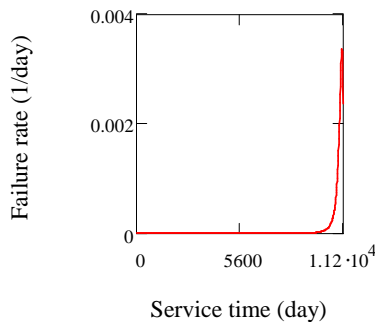

Figure 22: Calculated failure rate of transformer with service time according to insulation resistance 600 (high, middle, low – ground) of transformer
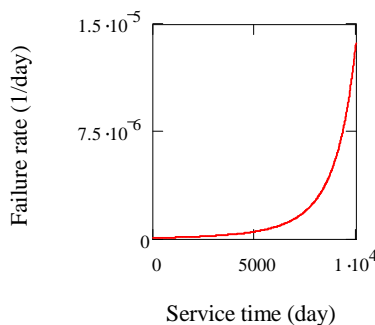

Figure 23: Calculated failure rate of transformer with service time according to insulation resistance 60 (high, middle – low, ground) of transformer
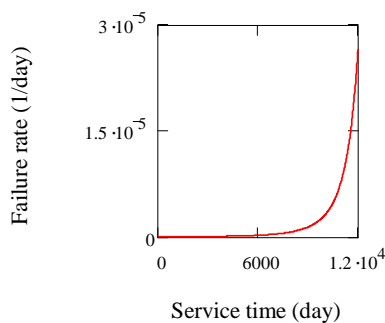

Figure 24: Calculated failure rate of transformer with service time according to insulation resistance 60 (high, middle, low – ground) of transformer

5   CONCLUSION

We developed the statistical distribution for a functional end-of-life criterion that relates transformer's quality level to the failure probability. Therefore, the reliability models make it possible to use degradation data to make inferences and predictions about failure time. These results will exploit the maintenance strategy for gradually deteriorating 550 kV power transformers, with which an optimal maintenance management can be reached.

6   REFERENCES

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[3] DL/T 596, "Preventive test code for electric power equipment", Electric Power Industry Ministry, China, 1997