Life Management of Large Power Transformers

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Abstract—In order to evaluate the actual condition of large power transformers, a reliable measurement of their ageing and failure characteristics with suitable sensors and condition monitoring is necessary. In this paper, the reliability models are developed for individual characteristic parameter such as DGA analysis, insulation resistance, power factor, water content, etc. The physics – experimental based life models are developed and improved on the basis of the data collection which describes the electrical, thermal, and mechanical ageing behaviour of equipment by individual parameter, depending on the condition monitoring.

Keywords-characteristic parameter; condition monitoring; degradation prediction; life management; reliability model; transformer

I. INTRODUCTION

There are many situations where the actual failure of the units, especially at stress levels close to the normal operating condition, may not fail catastrophically but degrade within the allotted service time. In such cases, measurements of the degradation characteristics of interest are frequently taken during the monitoring and diagnosis. The degradation data is then analyzed and used to predict the time to failure at normal conditions. In this paper, we define the physics-of-ageing model as mathematically derived, usually deterministic model based on knowledge of the ageing mechanisms and the root causes of ageing. Ideally the effect of the variables that collectively describe the ageing mechanism can be mathematically modelled on the basis of known physical principles and constants or empirically derived through experiment and observation. Once the model has been developed, individual use and environmental conditions can be considered to develop a reliability estimate tailored to a particular application. A detailed understanding of the ageing processes is required, engineering analysis may be based on empirical data obtained from testing or laboratory experiments, and may use least-squares technique or likelihood method for parameter estimation.

II. DEGRADATION MODEL

For some products it is possible to record the actual level of degradation as a function of time. Depending on the application, degradation data may be available continuously or at specific points in time where measurements are taken. Such data, particularly in applications where few or no failures are expected, can provide considerably more reliable information than traditional failure-time data. In some reliability studies, modelling performance degradation could be complicated because performance may be affected by more than one underlying degradation process.

Since 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 difficult to obtain statistically significant failure data. On the other hand, condition data which tracks the deterioration of various failure modes is readily accessible for many power transformers.

When it is possible to measure degradation, such measures often provide more information than failure-time data for purposes of assessing and improving equipment reliability. Therefore, a degradation model which describes the functional relationship between the degradation and every measured variable will be established by the general rate theory

\[ \frac{d\chi}{dt} = -\alpha R \chi^\beta, \quad \chi|_{t=0} = \chi_0 \]  

\[ \frac{d\chi}{dt} \text{ is the change in performance at time } t; \]
\[ \chi \text{ is the performance parameter; } \]
\[ \beta \text{ is the shape parameter of the degradation model; } \]
\[ \alpha \text{ is the acceleration factor; } \]
\[ R \text{ is the constant with the initial conditions. } \]

III. LIFE MODELS

In oil-impregnated transformers, much attention has been paid to the condition diagnosis of the cellulose insulating materials (paper and pressboard). The insulating paper around the conductors decays if it has been previously aged due to the heat dissipation of windings, the loss induced by eddy-current or the presence of water. Thus, the effects of temperature and water on the actual conditions of paper-insulated transformers can be approximated by the Arrhenius Model, and by the Inverse Power Model, respectively [1]. Generally, life tests are used to obtain information about one particular, relatively simple failure mechanism (or corresponding degradation measure). If there is more than one failure mode, it is possible that the different failure mechanisms will be accelerated at different rates. On the basis of the investigations, a thorough electro-thermal life models derived from a suitable...
combination of single-stress models, e.g. the Inverse-Power-Model and the Arrhenius-Model. This can be simply done by assuming that the aging rate under these combined stresses is the product of the aging rates under each single stress:

\[ A_w = \exp\left[T_0 \left( \frac{1}{293} - \frac{1}{\theta \left( \frac{P}{167\text{kVA}} \right)^{0.40} + 273} \right) \right] \cdot \exp(0.77W) \]  

(2)

or

\[ A_w = \delta \cdot \frac{\theta}{t_w} \cdot \exp(0.77W) \]  

(3)

where \( \theta, W \) and \( P \) are the absolute temperature, the water content and the electric power. \( R_0, T_0 \) and \( \delta \) are coefficients for the life models.

In many situations – such as the case of the development of a new component or a product – failure data at normal operating conditions are lacking and the reliability measures become difficult, if not impossible, to estimate. Indeed, there are cases where the reliability of a component is “high” and failure data of the component when operating at normal conditions (design conditions) may not be attainable during its expected life. In such cases, accelerated life testing induces failures, and the failure data at the accelerated conditions are used to estimate the reliability at normal operating conditions. It is useful to investigate previous attempts to recognize failure mechanisms similar to the ones of interest. There are many research reports and papers that have been published in the physics of failure literature [1 - 3].

A valid statistical analysis does not require that all test units fail. This is especially true in situations where the accelerated stress conditions are close to the normal operating conditions and failures may not occur during the predetermined test time. The information about non-failed units at such stress levels is more important than the information about failed units, which are tested at much higher stress levels than the operating conditions. Therefore, the information about the non-failed units must be incorporated into the analysis of the failed-data. The basic assumption of accelerated stress testing is that at the higher stress levels the same failure mechanism will be present and act in the same manner as at normal stress levels and will behave in the future as it has in the past. For practical purposes, we assume that the time-scale transformation is referred to as acceleration factor \( A_F > 1 \), thus the relationships between the accelerated and normal conditions are summarized as following

\[ t_o = \text{time to failure under normal stress}; \]
\[ t_s = \text{time to failure at high stress level}, \]
then the relationship between the time to failure is

\[ t_w = A_F \times t_s \]  

(4)

The cumulative distribution functions are related as

\[ F_w(t) = F_s \left( \frac{t}{A_F} \right) \]  

(5)

The failure rates are given by

\[ h_w(t) = \left( \frac{1}{A_F} \right) h_s \left( \frac{t}{A_F} \right) \]  

(6)

IV. CASE STUDIES

To estimate the failure rate and the remaining lifetime of large power transformers, useful information about the parameter diagnosis and the monitoring conditions for 550 kV oil impregnated transformers were collected from China State Grid with the operating history. The measured parameter and the operating conditions on failure and deterioration probability are collected from practical operational experiences. The set of data comes from a large population of oil-filled power transformers. In this case, all measurements from field diagnosis are known.

![Figure 1. Measured total dissolved combustible gas (TDCG) concentration of transformer oil with service time for various substations with different phases A, B, C (blue-167 kVA; red-334 kVA; green-500 kVA; yellow-750 kVA; black-1000 kVA).](image1)

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![Figure 2. Measured KOH-value of transformer oil with service time for various substations with different phases A, B, C.](image2)

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In order to evaluate the actual condition of large power transformers, a reliable measurement of their ageing and failure characteristics with suitable sensors and condition monitoring is necessary as shown in Figures 1-5. With these measurement values it is possible to develop a reliability model, from which conclusions can be drawn about the future operational behaviours of equipment based on condition
monitoring, service conditions, operating age and equipment type. The failures reported from the utility are not consistent since separate, smaller regional companies exist, from which ageing data are mostly lost or incomplete. Compared with the total population, the number of failures is small; but the impact of a failure is high and the replacement of a transformer is costly. The spare transformer policy, that showed to be successful in the past, can be continued in the near future without impairing the system’s reliability.

From the Figures 1-6 it can be seen that for some properties such as TDCG, insulation resistance and power factor, KOH, interfacial tension, withstand voltage, the transformers show ageing features at service time compared to other characteristics. A failure analysis is performed, and the results fitted to a two-parameter Weibull distribution, Figures 7-12. The Weibull parameters are estimated by means of the least squares method, resulting in a shape parameter. Considering the acceleration factor of the equation (2) or (3), together with the results of the diagnostic measurement, the performance parameter of the equation (1) can be simulated. Because $|A_p| > 1$, it can be concluded that aging is the degradation cause.

V. C ONCLUSION

Of prime importance in the application of parametric methods is the modelling of life data. In this paper, a general approach to the investigation of generalized cumulative damage function is developed for service aged transformers, which can describe the endurance of components subjected to electrical, mechanical stresses and temperature. Furthermore, the life model is obtained starting from the condition diagnosis so that time-to-failure percentiles fit life curves showing upward curvature and tendency to infinite life. On the basis of the introductory remarks and the presented case studies, some additional statements can be made:

- Aging is the main reason for degradation; the transformers are in the steep slope region of the performance curve.
- A very slow increase in ageing can be expected in the coming years. Considering the age distribution of the total
population, together with the results of the theoretical analysis, it can be stated that the population is still young when only the transformer’s ages are taken into account.

![Figure 8. Calculated (line) and measured KOH-value of transformer oil with service time.](image)

![Figure 9. Calculated (line) and measured interfacial tension of transformer oil with service time.](image)

![Figure 10. Calculated (line) and measured withstand voltage of transformer oil with service time.](image)

• An active strategy of maintaining and overhauling a certain number of the prior components each year has a positive effect on the number of expected failures. The number of components that have been overhauled in the previous years or have to be overhauled in coming years obtains the same effect.

• Parametric methods, also simple ones, can be applied to support important maintenance decisions, using both the data obtained from diagnostic measurements and life data.

• Modelling of degradation data is a useful tool for the prediction of future failures, even when the amount of ageing data is small. It has to be taken into account that the availability of more diagnostic data gives a higher confidence level of the analysis.

![Figure 11. Calculated (line) and measured power factor of transformer oil with service time.](image)

![Figure 12. Calculated (line) and measured insulation resistance of transformer oil with service time.](image)

REFERENCES

