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Estimation of Residual Lifetime – Theory and Practical Problems

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Abstract

The estimation of the residual lifetime is a very important part in asset management. The reasons for the importance of condition evaluation on the one hand and lifetime estimation on the other hand can be summarized as follows: the technical risk of a breakdown has to be minimized, the economical decision of further operation or renewal depend on the technical risk and the legal aspects and consequences of a failure or fall out have to be evaluated. For residual lifetime estimation different aging models have been developed but in dependence of operation respectively type of stress these models can only be applied with narrow bounds. Aging models often do not meet the real behaviour over all operating conditions and full lifetime. The extrapolation results in unreal residual life values. For this reason the operation dates and experience of the power equipment, behaviour of insulation medium, results of technical diagnostics, optical investigations and failure statistics of comparable units have to be taken into account. This paper should give a view to aging models and their application for lifetime estimation.

Introduction

The save operation of electric power equipment with high reliability and effectiveness, low risk of fallouts and costs for maintenance is dominated by the condition of the electric power devices. Taking a look to failure statistics the insulation system takes a very high percentage. The condition and reliability of electric insulation systems is marked by ageing mechanism. The common expression ageing is defined as the irreversible changes of the properties of an electric insulation system (EIS) due to action by one or more factors of influence [1]. Ageing stresses may cause either intrinsic or extrinsic ageing. Electric insulation systems are mostly predominated by extrinsic ageing because, in practice, they include some imperfections and contaminations. The ageing stresses can be divided into the so called TEAM stresses: Thermal, Electrical, Ambient (environmental) and Mechanical causes, which have an effect on the EIS. In dependence of the strength and their interaction the EIS is subjected to the ageing mechanism. These ageing mechanisms involve a decrease of the condition. A temporarily reduction of the condition is called degradation and a permanent deterioration.

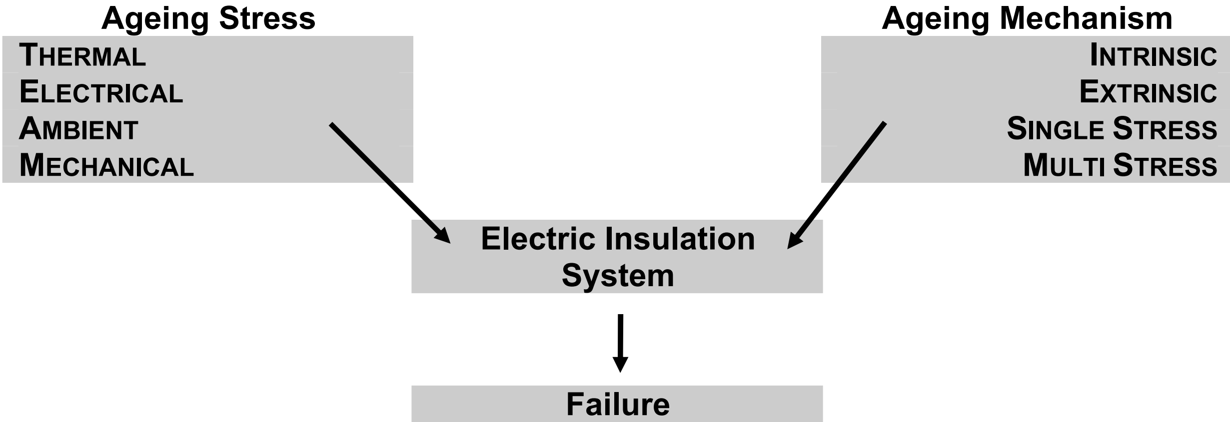

Figure 1: Ageing of an electric insulation system

The speed of ageing depends on different factors as operating conditions, single or multi stress mechanism or maintenance strategies. Several models for the condition evaluation and determination of the residual lifetime were developed; the following flow chart should show the systematic process to determine the condition and residual lifetime. Under consideration of a risk analysis and the technical, economical and juridical effect of a failure or fallout the decision about renewal or further operation has to be done.

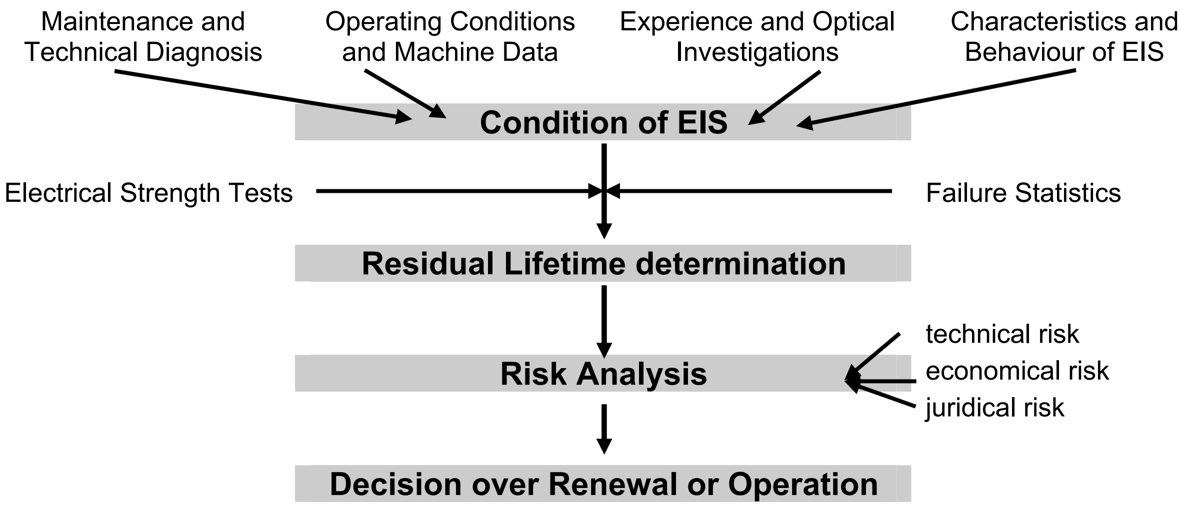

Figure 2: Assessment of condition and residual lifetime

Ageing and Lifetime Models

In dependence of the type of stress different ageing models were developed. For electrical ageing physical effects of partial discharges, tracking, treeing electrolysis, dielectric losses or space charges are the cause of deterioration. For these processes one empirical relationship was found. The inverse power law is often used for the relation between electrical stress and lifetime. The lifetime is dependant on the electric field strength as a linear decreasing function in a double logarithmic scale. In a double linear scale it can be expressed as a potential function.

$$L \approx E^{-nt} \qquad (1)$$

L	… lifetime
E	… electrical field strength
t	… time
n	… exponent of the electrical life time

Thermal ageing involves the progress of chemical and physical changes as a consequence of chemical degradation reaction, polymerization, depolymerization, diffusions or similar and thermomechanical effects caused by forces due to thermal expansions or contractions. The thermal ageing was described very early by Arrhenius as a chemical reaction. It can be interpreted that chemical processes in nature proceed in same percentages per constant time intervals.

$$L \approx A \cdot e^{\left(-E/kt\right)} \qquad (2)$$

L	… lifetime
A	… constant
E	… electrical field strength
k	… Boltzmann factor
t	… absolute temperature [K]

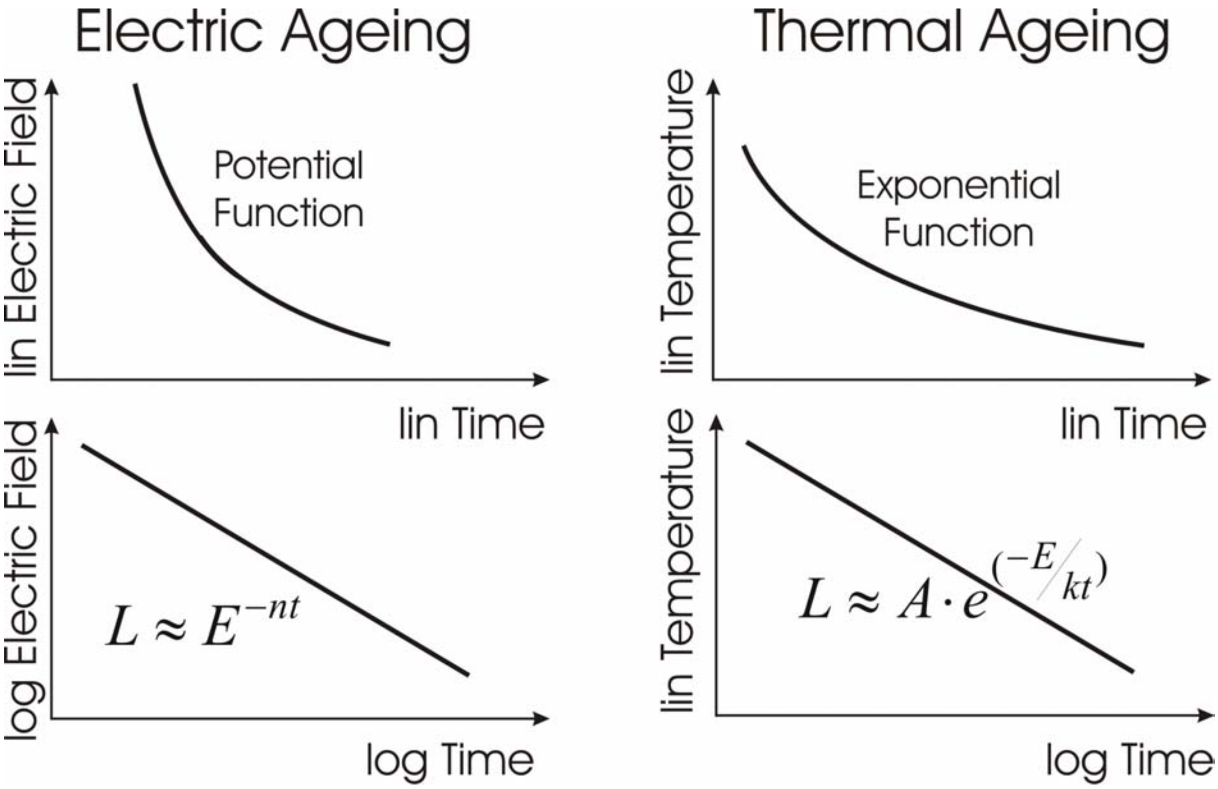

Figure 3: Inverse Power Law and Arrhenius Law

The other ageing mechanisms were also described with mathematical models but they will not be discussed now. In the figure 3 the electrical and thermal ageing models are illustrated in different scales. The inverse power law is a potential and the Arrhenius law an exponential function. For the application on lifetime models the single ageing models have to be completed with a threshold value. The reason can be found in a simple explanation. E.g. partial discharges disappear at the inception voltage; no electric ageing would occur under this level, the mathematical formulation of the inverse power law is limited to this threshold. Every mathematical description of the ageing behaviour does not meet the real behaviour exactly, a deviation of the lifetime values has to be taken into account in form of a tolerance band.

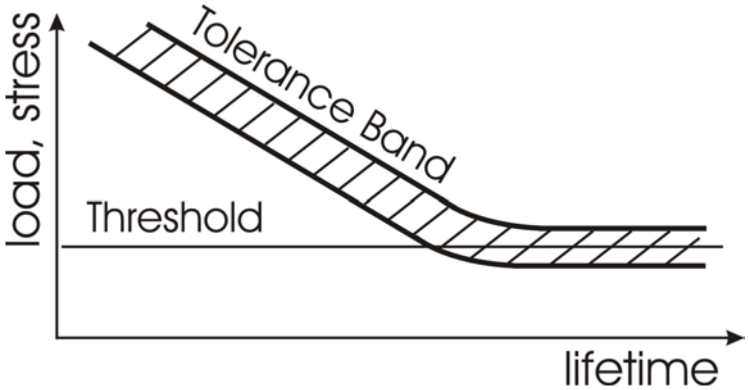

Figure 4: Lifetime model with tolerance band and threshold

Residual Lifetime Estimation

For the estimation of the residual lifetime the maximum expected lifetime has to be found out. The expected lifetime is a function of the operating conditions. In dependence of the average load level it can get shorter for higher load conditions. E.g. Montsinger found out that the average lifetime of a paper oil insulation system decreases for the half if the operating load occurs a temperature of 8 degrees over maximum level (8 K Formula). The so called technical lifetime mostly is defined by statistic methods with a database of empirical values of the bathtub curve. It is an average value of the fall out time of similar devices. The residual lifetime can be defined as the difference between the expected lifetime and the actual age. Figure 5 shows the connection of load and residual lifetime.

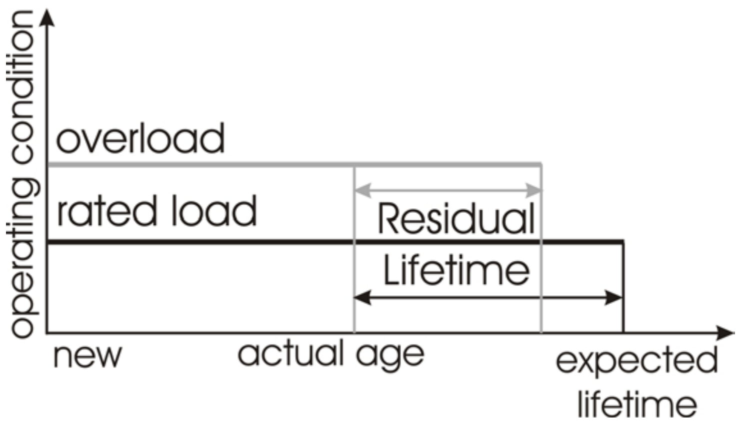

Figure 5: Estimation of residual lifetime

Practical Problems at Residual Lifetime Estimation

The theoretical considerations of ageing and lifetime models and the estimation of the residual lifetime often affect several problems. Determining the lifetime curve with voltage endurance tests a representative number of test samples must be available. A minimum of two load levels has to be applied within applicable test duration;

normally three electrical field strengths are chosen. Figure 6 illustrates how to construct the lifetime curve from voltage endurance tests. The results of breakdown tests were evaluated with the Weibull distribution. The average breakdown voltage of each level (63% values) is calculated and gives one point in the lifetime curve. If there were early failures the deviation of the Weibull distribution is very high and the lifetime curve gets a wide tolerance band. A realistic insulation system is determined by the quality of its weakest part and the lifetime curve gets wide scattered.

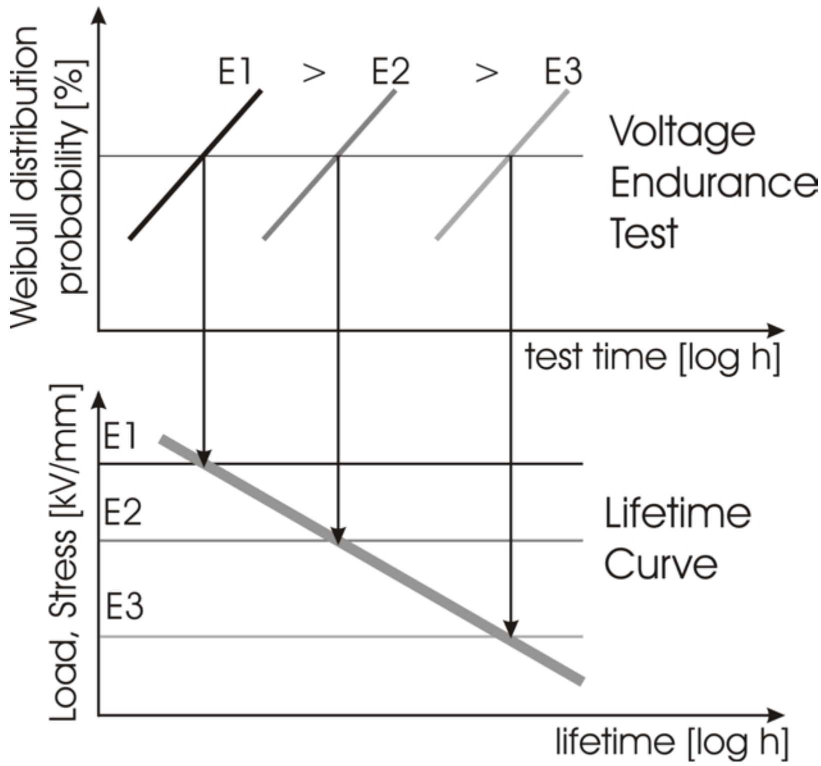

Figure 6: Estimation of lifetime curve from voltage endurance test

To gain short test durations the test samples often were loaded with a very high test level. In this case it can happen the test conditions do not meet realistic operation loads, different physical ageing mechanism were activated. The lifetime curve is subjected a fluctuation according to the tolerance band, see figure 4. The example of Figure 7 shows the different test results of single and multi stress ageing with electrical, thermal and mechanical ageing of generator bars. The residual lifetime decreases in a high range under multi stress load and the breakdown voltage decreases beginning at halve lifetime with the doubled exponent.

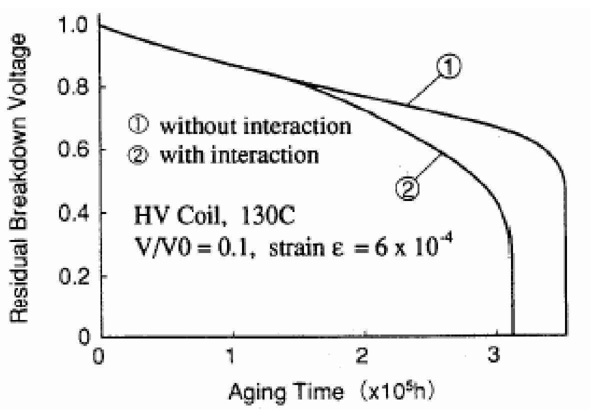

Figure 7: single (electrical) and multi stress (TEM) ageing [2]

A further problem represents the linearization of the lifetime curves. In the theoretical models the time scale is transformed from linear to log description. Short time alternations of the lifetime curve occurs a great difference in the estimation of the residual lifetime in a log scale. An extrapolation of the lifetime curve, which was determined experimentally with hard test conditions, to rated electric field strength can obtain unrealistic residual lifetime. Often a linear time scale is applied; one example is given in figure 8. An asphalt mica system of a pump hydro generator was tested. Both axis of the lifetime curve were in linear scale, the residual lifetime was determined by measurement of two voltage levels. Setting the machine into operation the test level was four times of rated voltage (quality test) and the doubled each following year (maintenance test). The lifetime curve of epoxy mica generators was determined in the same way, but at testing a generator failed at 130 % of the rated voltage. The linear lifetime curves did not meet the realistic insulation characteristic of different insulation materials and the stator had to be rewind.

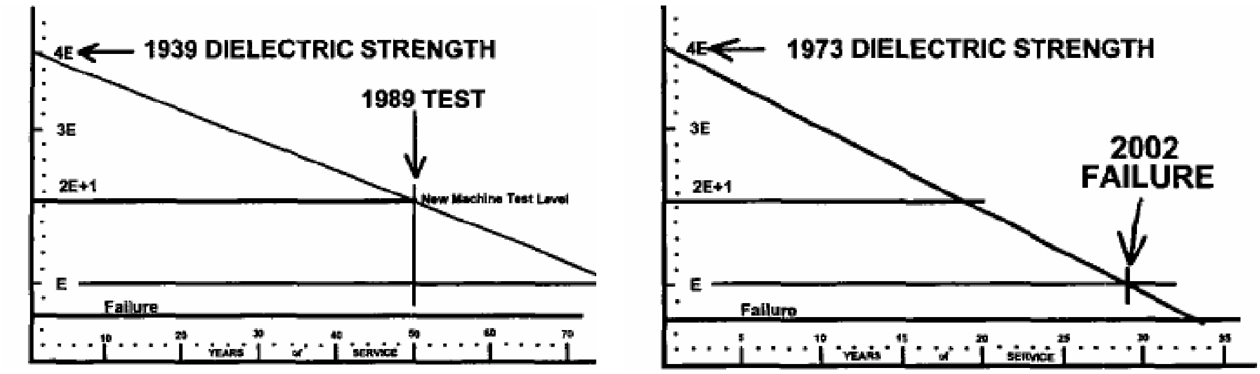

Figure 8: Lifetime curve of asphalt mica and epoxy mica generators [3]

Conclusion

The mathematical formulation of ageing processes can be done in a very small bandwidth and under defined ageing conditions. An extrapolation of the results from accelerated ageing tests to operation condition requires the inclusion of multi ageing models. The electric insulation system is a weak point problem. For condition evaluation and residual lifetime estimation also the insulation characteristics and dates of machines and their operation as well as experience and statistics have to be considered.

References

[1] IEC 60505: Evaluation and Qualification of Electrical EISS
[2] K. Kimura, Multistress Aging of Machine Insulation System, CEIDP 1995
[3] J.E. Timperley, J.R. Michalec, IEEE Transactions on Energy Conversion, Volume 9, Issue 4, Dec. 1994 Page(s):686 – 694