# Determination of the life time behaviour of different electric insulation systems

C. Sumereder, M. Muhr, R. Woschitz
Institute of High Voltage Engineering and System Management,
Graz University of Technology,
Inffeldgasse 18,
8010 Graz, Austria
E-mail: surname@hspt.tu-graz.ac.at

**Abstract:** Often diagnostic expert systems can not give an exact answer to the condition or the residual lifespan of electric power equipment. In these cases it can be helpful to look at the electric insulation system from every angle. Beside the non-destructive diagnosis methods different destructive tests enables a better description of the life time behaviour.

The life time behaviour of an electric insulation system can be mathematically described by the so called life characteristic curve. The mathematical model of the life characteristic curve bases on the exponential characteristic of natural processes for aging mechanism, which was already described by the law of Arrhenius. The determination of this curve can be done with successive discharge tests and long-time breakdown tests. The evaluation of the successive discharge test is to do under statistical methods with the two-parametric Weibull distribution. In a next step the breakdown voltage level has to be estimated and gives the parameter for the following long-time breakdown tests. To achieve a statistic correct result it is important to ensure that only wear-out failures and no early and random failures are included to the examination. These different failure types can be distinguished by the exponent of the Weibull distribution, also the bathtub curve gives this information. The reason for the necessity of this differentiation finds its reason in the miscellaneous kinds of breakdown respectively aging processes.

The life characteristic curves of generator bars and polymer insulation systems were determined by several measurements. The results present an essential fact for the evaluation of the condition of the electric insulation system. The life characteristic curves can be helpful for strategic decision of further operation, maintenance measures or reinvestment of the power equipment.

## Theory of Aging Mechanism

Ageing is defined as the irreversible changes of the properties of an electrical insulation system due to action by one or more factors of influence. Factor of influence is a specific physical stress imposed by operation, environment, or test that influences the performance of an insulation material, insulation system, or electric equipment. Ageing stress causes an irreversible change (usually degradation) to take place with time. Aging leads to an irreversible change of the insulating properties [1].

The condition of an electric insulation system is influenced by different physical loads. Beside electrical and thermal stress also chemical and mechanical loads and their common reaction to the insulation material (multi stress) cause degradation of the insulation behaviour. The basic process at degradation is the thermal aging, where molecular bonding forces break and recombination is not possible any more. For this reason insulating materials have thermal borders for operation, e.g. at IEC 60085 “Electrical insulation - Thermal classification“ the maximum long time temperature is defined.

Since the condition of electric machines has to be evaluated models with the focus to aging were developed. For electrical aging the inverse power law describes the degradation process due to electric stress. The lifetime degreases with rising electric field in a double logarithmic function. It has to be taken into account that the inverse power law is limited by the minimum electric field strength – threshold. Below the threshold field no degradation caused by electrical occur. Equations 1 give the two forms of the mathematical function.

$$E = k_D * t_D^{-1/r}, \qquad t_D = c_D\, E^{-r} \qquad \text{Equations 1}$$

E … electric Field, r … lifetime exponent,
$k_D$, $c_D$ … constants

Thermal aging was mathematically described generally by Arrhenius and especially for paper oil insulation systems by Montsinger [2]. The idea of Arrhenius was that all natural processes operate on exponential functions. Montsinger found out that the degradation speed of transformer board doubles at 8 degree rising over the maximum operating temperature. Thermal aging is essentially caused by current losses and partial discharges. The functions for thermal aging are shown in Equations 2.

$$LT\,Arrhenius = A^{\left(\frac{BxT}{C}\right)}$$

$$LT\ Mont\sin ger = 2^{\frac{T-90°C}{8°C}} \qquad \text{Equations 2}$$

LT … Lifetime, A, B … constants, T … Temperature

Thermal aging is not relevant for short processes. For this reason electric aging can be observed at tests for short duration or at tests with low (very low) operating temperature. Is the test object exposed to a high electric field, thermal aging can be observed, e.g. partial discharges may accelerate thermal aging. In Figure 1 the processes of thermal and electric aging were shown. Other processes (multi stress) were not considered in this diagram. Beside the early and stochastic failures due to the bathtub curve the failure aging should represent the group of drop outs in the sphere of residual life time.

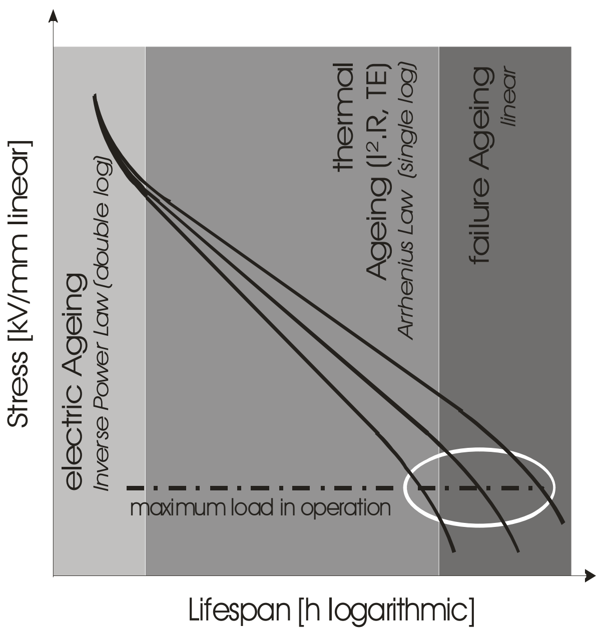


Figure 1: Aging processes, Lifetime in dependence of stress

**Measurements**

Two examples of lifetime measurements should be given. On the one hand the electrical aging of polymer insulation systems was determined by a cryogenic insulation system and on the other hand a conventional insulation system is represented by generator bars. The lifetime curve was measured in two steps. At first a successive discharge tests was done, the AC step voltage with 5 kV steps up to the breakdown was supplied. Then the statistic distribution was found out with a fitting test as shown in Figure 2.

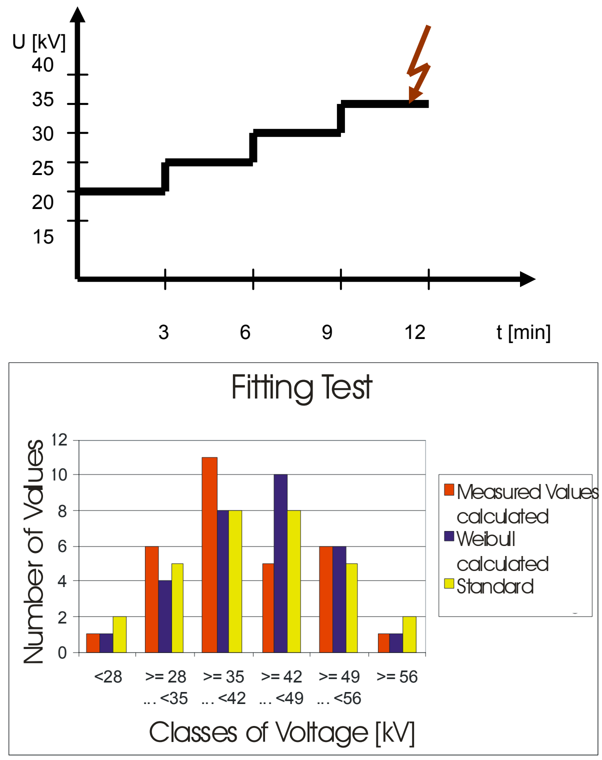


Figure 2: successive discharge test (up) and fitting test (down)

To determine the lifetime curve it was important to know about the distribution of the breakdown voltages. In this case a two parametric Weibull distribution was given; the function is shown in Equation 3.

$$F(u) = 1 - e^{-\left\{\frac{u}{44,3}\right\}^{4,9}} \qquad \text{Equation 3}$$

The exponent of the Weibull distribution gives very important information about the failure type. If it is grater than 1 stochastic and early failures can be excluded, electric aging can be assumed, see Figure 3.

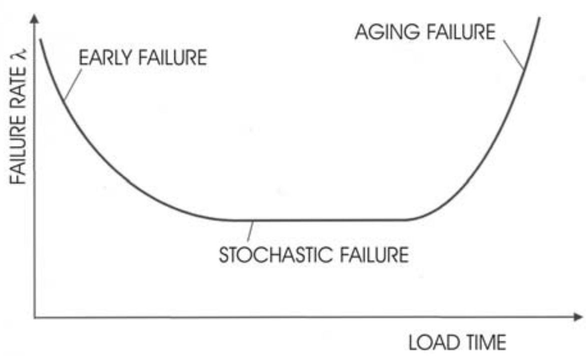


Figure 3: Bathtub Curve

In the next step the long-time breakdown tests can be started: characteristic loads were applied on the test object. After the breakdown tests the lifespan curve can be constructed and lifetime behaviour can be determined.

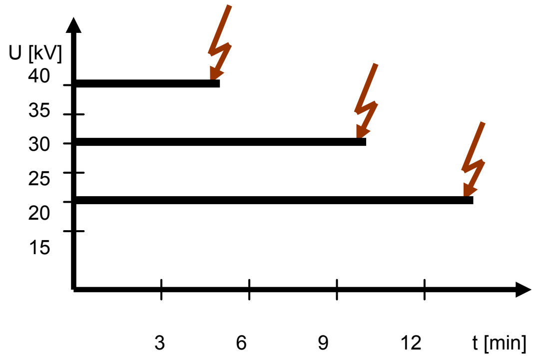


Figure 4: long-time breakdown tests with characteristic loads

The determination of the mathematical function of the measured life time curve was done with numerical methods on PC. For the cryogenic insulation system the inverse power law was taken into account and the Arrhenius law for room temperature systems. The measuring results were compared to life time exponents of insulation systems in the literature.

**Test Set-Up**

In the Figures 5 and 6 the test set-up of the cryogenic insulation system and the generator bars can be seen.

The cryogenic test object was a polymer insulating material in cylinder concentric arrangement. The tested PET has a very similar structure to Mylar, which is an often used insulation material for cryogenic insulation systems. The test vessel was installed in a laboratory where constant thermal and humid conditions were guaranteed, that there was no influence to the quality of LN2. This was very important because former investigations showed a big influence to breakdown behaviour in dependence of ice particles in LN2.

The test voltage was generated with an AC transformer and applied to the centre electrode. The dielectric behaviour was observed with partial discharge measuring system, the applied voltage and load time were recorded with a PC system. Total three measuring series with different voltages and over 90 test objects were done.

Figure 5: Cryogenic insulation system

The tested generator bars were different typs, the most tested were VPI (vacuum pressure impregnation) technology.

Figure 6: Test Set-Up for Generator bars

**Results**

The test results can be seen in Figure 7. The life time curves of room temperature and cryogenic insulation systems were compared. The measured curves were verified to well known life time dates of literature. The polymeric insulation systems have an exponent of 8 to 15 at room temperature and about 40 at the operating temperature of superconducting power equipment (-196 °C = $LN_2$-Temperature). Compared to paper-liquid insulation systems the polymers have a higher exponent because there is no self healing effect. In the case of a defect (crack) the liquid runs into the void and holds the electric field under the critical PD inception value. The aging process is slowed down or in the ideal case stopped.

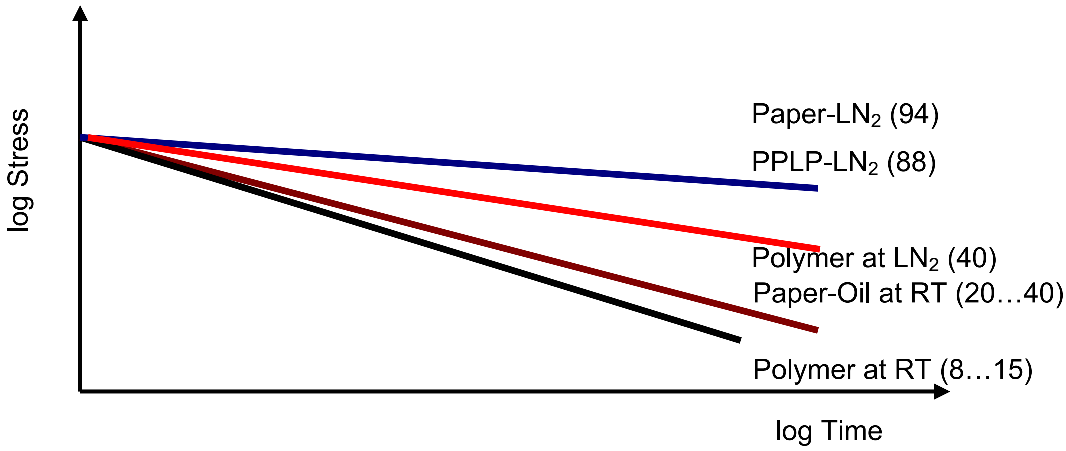


Figure 7: Lifetime curve of different insulation systems, measured and literature of cryogenic and room temperature (RT) insulation systems

**Conclusion**

The lifetime behaviour can be determined by measurements of breakdown tests and described by mathematical models. It has to be taken into account that the load strength (stress) is over the threshold value of the electric field. As the Figure 4 shows the exponent of room temperature (> 20 °C) is much lower as for cryogenic insulation systems at liquid nitrogen temperature (- 196 °C) because of the effect that thermal aging can be excluded at low temperatures.

**References**

[1] IEEE Std 1064-1991, "IEEE Guide for Multifactor Stress Functional Testing of Electrical Insulation Systems", 1991
[2] V.M. Montsinger "Loading transformer by temperature" AIEE transactions, Bd. 49, 1930, p. 776-792