Portál pre odborné publikovanie ISSN 1338-0087

An overwiev to power equipment lifetime

Firický Eduard · Elektrotechnika

07.01.2013

The most important part and usually most ageing sensitive part of electrical equipment, which determines its life, is electrical insulation system. The total lifetime of the equipment is determined by external and also internal (operational) factors. One important factor which mainly influence lifetime of electrical equipment and thus electrical insulation systems are temperature. But the resulting lifetime is involved by humidity, overvoltage, vibration, radiation and other factors.

1. Introduction

Thermal ageing model using Arrhenius model provide approximation of the lifetime of the equipment. Another factor influencing the equipment life is the operating modes. By method of short-term overloads, number of starts and surge phenomenas derives the total lifetime of the device. Paper mainly shows equipment some degradation factors to devices and Arrhenius model. In this paper we will attempt to assess the durability of the power equipments with reference to the possibilities of device lifetime influence.

2. Electrical equipment lifetime, degradation mechanisms and effects

The most important part and usually most ageing sensitive part of electrical equipment, which determines its life, is electrical insulation system. The determination of the prospective life is a fundamental task when developing and designing an electrical insulation system. Estimated service life of an electrical insulation system needs to be established for several reasons [1]:

- for type testing when introducing a new electrical insulation system into production,
- for quality assurance of production,
- for estimating the life expectancy of new equipment,
- for estimating the remaining life for maintenance purposes.

Ageing of electrical insulation system is defined as the irreversible changes of the properies of an electrical insulation system due to action by one or more stresses. Ageing stresses may cause either intrinsic or extrinsic ageing. Intrinsic ageing is defined as the irreversible changes of fundamental properties of an electrical insulation system caused by the action of ageing factors on the electrical insulation system. Extrinsic ageing is defined as the irreversible changes of properties of an electrical insulation system caused by action of ageing factors on unintentionally introduced imperfections in the electrical insulation system.

The type and level of contamination and/or the extent of imperfections in an electrical insulation system will, in many types of electrical apparatus, significantly affect the service performance. In general, the fewer and less severe the contaminant and/or defects in the electrical insulation system, the better is its performance. To avoid obtaining misleading results from functional tests, a candidate electrical insulation system should contain, as far as practicable, the full range of contaminants and/or defects expected when the actual system is used in service. A schematic representation of the basic ageing process is shown Figure 1 [1].

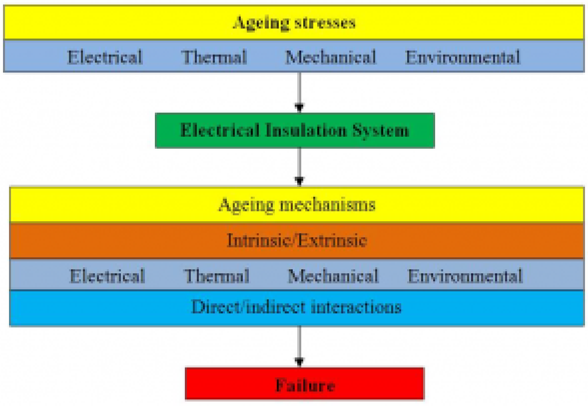

Figure 1: Ageing of an electrical insulation system.

Also, mode of operation power equipment in power electrical systems may influence and actually influence they lifetime [2]. Standard projected lifetime by producers is 20 to 40 year of operation depending to device type [3]. Device lifetime strongly depend on production quality, used construction materials and mode of operation. Mode of operation may significantly reduce or extend the device lifetime. Electrical equipment lifetime indicators are given by statistic values for example by percentual lifetime, middle lifetime, middle lifetime between repairs, middle accumulated lifetime and others. They are indicators which are based from failure rate statistic made by device operators or producers [4].

Technical documentation of every manufactured device should be instruction to device operation and maintenance procedures and also proposals and timetables of periodic inspections of individual device components respectively whole device. An important contribution to the real equipment lifetime is technological aspects of device preparation and actual production quality. Partial, respectively complex device life tests results have a role in the production of device and they application may significantly affect the final quality. However, time and financial cost of lifetime tests (or accelerated ageing tests) makes the tests are performed only in some cases and often only on selected device sub-assemblies.

On the other side, untested mutual interactions of device subsystems and the used materials e.g. insulation system can cause significant shortening of their lifetime. Just a simple composition of these sub-assemblies into a single unit (to complete device) potentially can cause operational problems and in some cases device breakdown. For example, some types of high voltage circuit breakers caused the accident resulting in fire. The following two types of stressors should be considered for ageing [2]:

- Environmental. These are stressors that exist continuously in the environment sorrounding the equipment, whether it is operating or shut down. Examples include vibration, heat, radiation and humidity.
- Operational. These stressors arising from equipment operation. Examples are internal heating from electrical or mechanical loading, physical stresses from mechanical or electrical surges, vibration, and abrasive wearing of parts.

A stressor that stems from fabrication, preoperative, or service conditions may produce ageing mechanism and effects or immediate degradation of equipment. Ageing degradation of electrical equipments usually is a function of the duration, range and intensity of stressors experienced by the equipment. It necessary to consider significant stresses, when electrical equipment assessing and lifetime predicting, and are mainly the following [2]:

- temperature
- electrical stress
- radiation
- huminidity
- chemicals
- dust/dirt

The equipments parts and construction materials should be identified for evaluation under their service conditions. In cases where it is not possible to determine all materials or the exact materials of construction, the goal is to have reasonable assurance that age-sensitive materials have been identified. Adjustment in the, operating environment or operational practices is an effective method of mitigating ageing degradation. One method of determining the susceptibility of equipment to ageing mechanisms and consequent ageing effects is by understanding the behavior of the individual materials that make up the equipment, when subjected to environmental and operational stressors. These mechanisms may apply to solid-state electronic components as well as electrical equipment. Some examples of stressors, ageing mechanisms, and ageing effects are provided as follows [2]:

- High-temperature environments can cause organic insulating materials to become brittle.
- High-humidity environments can accelerate bearing wear in rotating machinery lacking special seals or pressure lubrication. High humidity can increase pitting and corrosion of contacts on relays and controllers. Exposure to moisture can result in delamination of insulated wires or physical contact may result in loss of dielectric integrity.
- Vibration can loosen fasteners on linkages causing misalignment of components or loss of electrical contact integrity. Misalignment accelerates wear in moving parts; loose electrical contacts may lead to heat-related degradation.
- Support structures subject to high humidity or contact with water and/or chemicals may corrode if not protected by coatings or covers. Chemicals may be borid acid, oils and lubricants and other relatively common materials in production.
- Radiation can break down the antioxidation chemicals in organic insulation materials and produce embrittlement similar to that caused by high temperature. Radiation exposure

may change dielectric properties, increase leakage current or weak electric strength of polymers.
- Continuous operation of certain electronic components (diodes, resistors ect.) at high ambient temperatures can cause operation outside of their performance specification or circuit drift.
- Excessive voltage cycling can results in premature failure of electrolytic capacitors.

Very important factor which mainly influence lifetime of power equipments and they important part – electrical insulation systems – is temperature. In terms of correct operation and ensure long-term electrical equipment reliability is especially important amount of thermal energy (heat) evolved either by directly in equipment or supplied from surrounding environment. Electrical heat origin is related with transport (motion) of electric charge in material structures. Electrical equipment internal thermal energy generation originates from alternating magnetisation processes (hysteresis and eddy currents losses), in electric wires (Joule losses, skin effect), in dielectric and insulation (dielectric losses – polarisation, conduction and ionisation) [5].

Models of thermal ageing shows that only by increasing the temperature of 7-10 °C the lifetime of such organic insulation system reduces up to half [6]. These approach is so-called Montsinger rule. Temperature impact to solid insulation systems materials and selected devices lifetime and reliability are shown and described in [5]. Electrical stress after the temperature is further important operational degradation factor. Electrical ageing (either by AC, DC or impulse) involves [1]:

- the effect of partial discharges when the local field srength exceeds the breakdown strength in the liquid or gaseous dielectric adjacent to, or included in, the electrical insulation system,
- the effect of tracking,
- the effect of treeing,
- the effect of electrolysis,
- the effects, related to those above, on adjacent surfaces of two insulating materials where tangential fields of relatively high value can occur,
- the effect of increased temperatures produced by high dielectric losses,
- the effect of space charges.

Electrical stress is usually considered the ageing factor, if are present external or internal partial discharges, or their generation during operating voltage are expected. Electrical discharges presence at overvoltages can be taken into consideration, when these overvoltages occur in operation frequently. It is possible that electrical stresses become ageing factor only in presence of other factors or secondary to their impact (such as temperature, humidity or mechanical stress). These other factors modify system properties on reversible or an irreversible ways.

Ageing degradation due to a single stressor may usually be represented as a simple first-order relationship involving stressor intensity and time. However, ageing degradation due to a combination of more than one stressor may exceed the sum of the individual effects (for example combinated electro-thermal stress). These themes about electrical, multifactorial and environmental stresses (also radiation environmental conditions) are more detailed and mentioned in [2,7].

The paper [2] provides, iter alia, a summary and list of typical ageing mechanisms and their effects on polymers, lubricants and metals. Information may be supplement by other mechanisms of the effect of ageing such as operation experience, manufacturers data, expert opinion and others. For example, there are more different documents for equipment qualification in harsh environments of nuclear power plants (e.g. IEEE 323-2003 for qualifying equipment in general, IEEE 344-2006 for qualifying motors, EPRI 1011223 for ageing identification and assessment and others).

3. Accelerated life tests and thermal ageing model

One of the most demonstrable devices testing are so-called accelerated life tests. They consist of different types of tests. As accelerators of accelerated ageing can be chosen various types of stress, such as increased temperature, increased voltage, increased humidity and others. Often used combinated stress. This means that as regards the current impact of elevated temperature and elevated voltage. The condition is that the accelerated test applying the same mechanism of degradation. Following is the result of such test can be extrapolated to the behavior of real objects and determine their lifetime, respectively their residual life [8].

The accelerated life tests uses thermal ageing model. It is based on Arrhenius relationship, which is described for example in [2,9]. The model establishes ageing degradation as a function of temperature and allows an estimation of thermal life at a given temperature. It is also used to relate remaining life at one temperature to remaining life at another temperature. It can be used to determine a maximum continuous temperature for a specific length of time. Arrheinius model for thermal ageing is based on chemical reaction rate, which is significantly dependent on temperature. The reaction rate (dg/dt) according to Arrhenius and Nelson is given in equation (1):

$$\frac{dg}{dt} = Ae^{-\frac{\phi}{KT}} \quad (1)$$

Neglecting the effect of depletion of the reactants on the reaction rate to solve this differential equation gives equation (2):

$$t = Be^{\frac{\phi}{KT}} \quad (2)$$

where t is the time to reach a specified end of qualified life condition or lifetime, A is a constant of proportionality, B is a constant [related to the amount of degradation that will have occurred at end of time t or B=g(t)/A where g(t) is the amount of reactions occurring through time t], Ø is the activation energy (eV) for a chemical reaction, k is the Boltzmann's constant ($0{,}8617.10^{-4}$ eV/K), T is the absolute temperature (K) of the service condition.

Equivalent degradation can be applied to the Arrhenius relationship to allow calculation of a lifetime t_2 at an actual (or expected) installed temperature T_2, given a different test temperature T_1 and a test period t_1 [see Equation (3)]:

$$\frac{t_2}{t_1} = e^{\left\{\left(\frac{\phi}{k}\right)\left[\left(\frac{1}{T_2}\right)-\left(\frac{1}{T_1}\right)\right]\right\}} \tag{3}$$

Equation (3) can be used in conjunction with appropriate testing results (to a marginal degradation condition) at a higher temperature to theoretically derive a maximum continuous-use lower temperature for a longer specified period of time. Alternatively, this expression can be used to approximate remaining life given a known exposure temperature history and a conservative expected future temperature. It should be noted that Arrhenius thermal age modeling has the following assumptions, sensitivities, and limitations [2]:

- A single stressor type, i.e. thermal ageing is assumed at work throughout the life of the material. (Radiation exposure degradation and other forms of ageing would need to be addressed separately.)
- One dominating chemical reaction corresponding to one dominating ageing mechanism causing the identified ageing effect (e.g., corrosion, embrittlement, ect.) is assumed. (Test temperatures should be selected to assure that the dominating ageing reaction at the test conditions is also dominating and equivalent at the installed service condition temperature.)
- The coefficient A is assumed to be independent of temperature. According to gaseous reaction theory, A increases at approximately the square root of temperature.
- The activation energy is considered to be constant with temperature and time. (The selected activation energy should be at the conservative end of the range of possible activation energies.)
- Equations (1) to (3) are very sensitive to the accuracy of the selected activation energy.
- The reaction rate is assumed to be not affected by depletion of the reactant concentration; in other words, the end of life (amount of degradation) is selected to be before depletion effects are noticeable.
- Equation (3) assumes the same amount of degradation damage when converting from one set of time at temperature conditions to another set of conditions.

Lifetime characteristics under thermal stress – Arrhenius plot – is a graph, in which is plotted the logarithm of the time required to achieve the prescribed threshold value depending on reciprocal thermodynamic (absolute) temperature at which thermal ageing is in progress (Figure 2). Accelerated temperature stress tests, procedures of accelerated thermal ageing and driers for ageing are shown in [10].

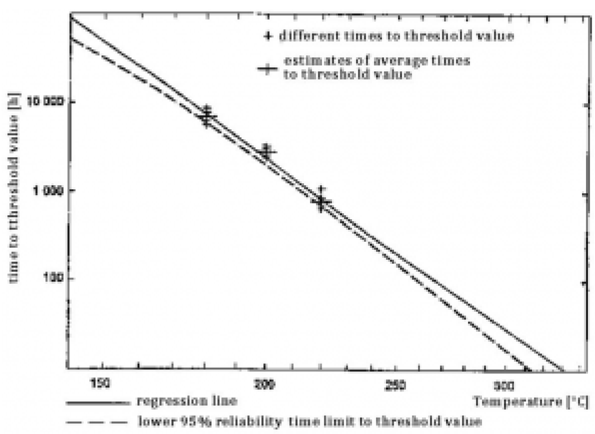

Figure 2: Lifetime characteristic under long-term thermal stress (Arrhenius plot)

(according to IEC 60216-1).

4. Main results

The equipments used in in power electrical systems are usually made in the projected life approximately for 30 years. Technological quality and discipline affect their life influenced by the manufacturing company as well as the conditions in which the device operates (external conditions). Manufacturing companies have implemented system of quality and described technological processes. Breach of manufacturing rules, respectively in some cases replacement of a component from another producer may cause unexpected complications. If they do not perform life tests on whole device but only for selected subsystems, technical problem become. Interaction of replaced parts effects may occur, where the action of synergistic effect lifetime increased, but the adverse case can also be reduced.

An important factor to ensure the reliability of electrical devices is external conditions. Increased temperature, humidity, dust, radiation and so on the designed service life can be shortened considerably. Above models of thermal ageing shows that only by increasing the temperature of 7-10 °C the lifetime of organic based insulation system reduces up to half. In the summer temperatures reach up to 40 °C. In long-term higher temperatures warm up substations as well as all technology areas including cable trays. For example, ageing of many times used PVC cables insulation material is manifested by an increase of ionic conduction losses at elevated temperature. Along with them dissipation factor tan δ increases. This process is a consequence of the cable thermal load. Increase of tan δ round the limits of operating temperatures can cause an increase of the dielectric loss resulting into the thermal dielectric breakdown [11].

Therefore, temperature monitoring and thus the potential load control regard to the lifetime is very important. Because of the limitations and assumptions stated in thermal ageing model, the Arrhenius model for thermal ageing should be considered to provide only an approximation of the lifetime of the equipment. When feasible, condition monitoring or other means should be considered to validate remaining or residual life of equipment. Such a monitoring mechanism may be long-term monitoring of equipment operation [2]. Monitoring and diagnostic methods provides partial look to insulation systems condition. There are well established measurement methods such as insulation resistance measurement, leakage current measurement, dissipation factor measurement and others. Paper [12] shows insulation system diagnostic methods and tests.

Next factor influencing the equipment life is the operator and operating modes. By method of short-term overloads, number of starts, surge phenomenas derives the total lifetime of the device. Therefore, the requalification of equipment for a further period is necessary to consider not only the results of prophylaptic measurements, but also the type of product and its operating modes. This can provide a comprehensive view of increasing reliability and thus the energy security of the whole energetic system. At our department of materials and technologies we solved high voltage tap changer problem, where as a mechanical support part was used glass-textile material, which caused re-operation problems. This glass-textile material interacted with the insulation oil and released to oil compounds, which substantially reduced its electric strength.

Tap changer problems repeated failure after a complete clean up and oil change. The cause of device failures were components released from support glass-textile insulation tap changer parts to oil. In doing so, it was a renowned manufacturer of the tap changer. This example also shows that only long-term lifetime tests can demonstrate the interaction between different types of materials used in manufacturing device. However, practical experiences also known otherwise. The insulation system consisting of two materials of lower temperature class from the mutual interaction in the electrical devices can be classified into a higher temperature class as each material separately. In this case the result was demonstrated also by accelerated ageing test.

Overall device service life shows only the minimum amount of producers mentioned directly in the technical documentation. Data based on more or less empirical knowledge arising from the statistical evaluation of failures. Based on such knowledge to establish the scope of guarantee as well periodic inspections. Feedback accurate accounting of the failures can positively influence and then modify the production technology.

5. Conclusion

Durability and reliability of equipment is subjected to technological discipline in the manufacture of the product. They are influenced by the actual device design techniques. Failure to comply may result in unexpected complications during operation. Implementation of accelerated life tests are not carried out throughout the equipment, but only for selected subsystems. This can cause them to interact in an adverse event may reduce the lifetime or failure might appear to be on the individual components did not appear. An important factor to ensure the reliability of electrical devices are external conditions of use.

Increased temperature, overvoltage, humidity, dust or radiation may the designed service life shortened considerably. Only by increasing the temperature of 7-10 °C the lifetime of selected organic insulation systems is reduces by half. Next factor influencing the equipment life is the operator and operating modes. By method of short-term overloads, number of starts and surge phenomenas derives the total lifetime of the device. Therefore to determine the reliability and safety of electrical systems requires a comprehensive look at the optimalization can increase the operational reliability of the electrical system.

References

1. STN EN 60505 (2012). Hodnotenie a klasifikácia elektroizolačných systémov.
2. IEEE Std. 1205 (2000). IEEE Guide for Assessing, Monitoring, and Mitigating Ageing Effects on Class 1E Equipment Used in Nuclear Power Generating Stations.
3. Anderson, J.W. (1995). Technology Transfer Equipment Qualification Methodology for Shelf Life Determination. In: IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 42, NO. 4, August 1995.

4. Birolini, A. (2007). Reliability Engineering: Theory and Practice. 5th ed., Springer, 2007. ISBN 978-3-540-49388-4.
5. Kopča, M., Váry, M., (2012). Vplvv teploty na životnosť a spoľahlivosť tuhých izolačných systémov a vybraných zariadení. In: Volt – príloha časopisu EE, roč.4, apríl 2012, č.2, str. 4 – 7.
6. Montanari, G.C., Mazzanti, G., Smoni, L. (2002). Progress In Electrothermal Life Modeling of Electrical Insulation during the Last Decades. In: IEEE Transactions on Dielectrics and Electrical Insulation; Vol.9, No.5, December 2002; pp. 730 – 745.
7. Kopča, M., Váry, M., (2012). Elektrické, multifaktorové a environmentálne namáhanie elektroizolačných systémov. In: Volt – príloha časopisu EE, roč.4, október 2012, č.5, str. 3 – 7.
8. Cygan, P., Laghari, J. R. (1990). Models for Insulation Ageing under Electrical and Thermal Multistress. In: IEEE Trans. Elect. Ins., Vol. 24, pp. 923-934,1990.
9. IEEE Std. 1205/Cor. 1 (2006). IEEE Guide for Assessing, Monitoring, and Mitigating Ageing Effects on Class 1E Equipment Used in Nuclear Power Generating Stations.
10. Kopča, M., Váry, M., (2012). Procedúry zrýchleného tepelného starnutia. In: Volt – príloha časopisu EE, roč.4, august 2012, č.4, str. 6 – 9.
11. Lelák, J., Ďurman, V., Packa, J., Váry M. (2011). Degradation and Diagnostics of MV Cables – Experiment and Experience. In: Elektroenergetika 2011: proceedings of the 6th International Scientific Symposium on Electrical Power Engineering: 21. – 23.9.2011, Stará Lesná, Slovak Republic.
12. Kopča, M., Váry, M., (2012). Diagnostika stavu izolačných systémov. In: Volt – príloha časopisu EE, roč.4, jún 2012, č.3, str. 11 – 13.

Coauthor of this paper is J. Lelák, Institute of Power and Applied Electrical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovičova 3, 812 19 Bratislava, Slovak Republic