ELECTRICAL DEGRADATION AND AGING OF NEW MATERIALS INSULATING UNDER MULTISTRESS CONDITIONS

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1. Introduction

Dielectrics properties play an important role in insulating systems since the beginning of high voltage engineering 100 years ago. At that time, porcelain and oil impregnated paper were the dominating materials. It is interesting to note that these dielectrics have kept a good part of their position up today although new materials like polymers, synthetic liquid or artificial gases have come to application. Nowadays, a broad variety of solids and liquids, or combinations of both, form the material base for high voltage insulating systems.

As the main task, dielectrics have to insulate energized conductors against each other and against ground. In addition, they have to withstand mechanical and thermal stresses, and under outdoor conditions also environmental stresses like moisture, ozone, oxygen, UV radiation or pollution attacks may accrue. In most cases one has to deal with the simultaneous application of multi stresses, and such combined stresses and their mutual influences are under strong discussion today.

The subject under consideration covers, as mentioned above, a broad variety of materials and the whole range of power engineering equipment. Consequently, we first of all have to introduce some restrictions since it is impossible to deal with all aspects in a limited time and on a limited space. The first restriction is that this paper will mainly deal with engineering approaches, and not so much with physical aspects of material science. Secondly, it will concentrate on some fields which presently are under strong consideration, or where a remarkable progress has recently been achieved.

According to the above, when regarding the main activities in solids and liquids toda, one finds two fields of top importance: one condemns interfacial phenomena in composites, and the second concentrates on ageing, degradation, diagnosis of properties, maintenance and refurbishment of insulating systems in power engineering apparatus. Consequently, the paper will mainly deal with these items.

2. Interfacial phenomena

Only few high voltage insulating systems consist of a single uniform dielectric, but most are composed from several insulating materials operating in a series and/or parallel arrangement. In such composite systems interfacial problems may arise which are caused by the fact that interfacial polarization can enhance the dielectric characteristics like loss tangent and permittivity, but also the treeing stability and the breakdown strength may suffer a distinct reduction.

Composites have been in use since the early beginning of HV insulation technology. The fact that interfacial phenomena offer severe problems today is caused by two technical trends: First, modern systems are subjected to higher stresses for economical reasons, and higher stresses force weak points to occur. Interfaces are such weak points. Second, polymeric composites are increasingly applied for HV outdoor insulations where moisture penetrates the polymers by diffusion processes and affects both the dielectric and the electric properties. It has been demonstrated that the microscopic interfaces are especially sensitive against water attack. Consequently, in the following composites under wet conditions will first be dealt with [1].

a) Dielectric properties.

The dielectric properties are normally written in terms of the complex permittivity

$$\varepsilon^* = \varepsilon' - \varepsilon'' \quad (1)$$

However, it turns out to be advantageous[5] to display the data in any of the following dielectric function which are all related to the permittivity as follows

$$M^* = M' + jM'' = 1/\varepsilon^* \quad (2)$$

$$Z^* = Z' - jZ'' = 1/ j\omega C_o \quad (3)$$

$$Y^* = Y' + jY'' = j\omega\varepsilon^* \quad (4)$$

where M* is the electric modulus, Z* is the impedance and Y* is the admittance, $j= (-1)^{1/2}$, ω is the angular frequency ($2\pi f$) and C_o is the geometrical capacitance. For a thin parallel plate or disk, the geometrical capacitance and hence the (real) dielectric constant ε' can be calculated from[3].

$$C_o = \varepsilon_o A/d \quad (5)$$

$$\varepsilon' = C / C_o$$

and $$\tan\delta = \varepsilon''/\varepsilon' \quad (6)$$

where ε_o is the vacuum permittivity (8.854×10^{-12} F/m), A is the area of the sample, d is the thickness and C the capacitance measured.

All of the above dielectric quantities will only be a constant as a function of frequency if there is no dielectric dispersion. Dielectric dispersion may arise in a material as a result of polarization of electronic, atomic, ionic, or interfacial dipoles. The best known dipolar relaxation is the Debye relaxation which relates the real and imaginary parts of permittivity to the frequency responsible for the relaxation as follows.

In insulating materials for the specific dielectric losses P_{diel} in an field the statement,

$$P_{diel} = E^2 \omega_o \varepsilon_r \tan\delta \quad (7)$$

These losses increase the temperature of the dielectric and are themselves dependent. In regions in which the dielectric losses increase steeply with temperature, there is danger of overheating in solid insulating materials, and this eventually leads to breakdown[4].

b. Water Diffusion in Polymers Material

The diffusion process may described by fick's first law:

$$J = - D.\text{grad } c \quad (8)$$

where J is the particle flow density, D the coefficient of diffusion and c the particleconce concentration. When regarding the particle flow density in a small volume element. we obtain the second law of Fick:

$$\frac{\partial c}{\partial t} = \text{div } (D.\text{grad } c) \quad (9)$$

For plate shaped test samples as applied in our investigations, we can assume a one-dimensional diffusion in the direction of (x ranging perpendicular to the plate), and the second law of Fick then can be written as

$$\partial c/\partial t = D(\partial^2 c/\partial x^2) \quad (10)$$

with c : concentration, D : diffusion coefficient.

If there are any interactions between the polymer and the absorbed water the polymer shows an anomalous, non-Fickian water absorption behavior. This problem can be regarded as a diffusion process in which some of the absorbed molecules become immobilized. If the reaction is reversible some of the bond molecules become mobile again. In this case the diffusion is governed by a modification of Fict's law:

$$\partial c/\partial t = D(\partial^2 c/\partial x^2) - (\partial s/\partial t^2) \qquad (11)$$

where c : concentration of free molecules
s : concentration of immobilized molecules.

An analytical solution of eq. (2.17) on condition that the diffusion process is very rapid compared to the reaction:

$$M \approx M_s\{\tau\, e^{-\alpha t}\, y(t) + \tau(e^{-\beta t} - e^{-\alpha t}) + (1-e^{-\beta t})\} \qquad (12a)$$

and $\tau = \beta / (\alpha-\beta)$ (12b)

$$y(t) = 1 - 8/n^2 \sum_{n=0}^{\infty}\{ \exp[-(2n+1)^2\pi^2 D/(2l)^2] / [2n+1]^2 \} \qquad (12c)$$

where M_s: saturation moisture content, 2l: sample thickness.

The reaction coefficients α and β are the probabilities per unit time by which molecules are immobilized and immobilized molecules become mobile again.

Fig. 1 demonstrates such a case for an epoxy without filler or fiber reinforcement. It is characterized by a steady increase of the water content over the time after the initial Firkin water absorption. We assume that there are sites in the polymer where water molecules become bound. Such sites may be chemical sinks, impurities or cavities. We note that different materials absorb different amounts of water, and we see that rather high amounts of water, as much as a few percent of volume, nay penetrate the dielectric[5].

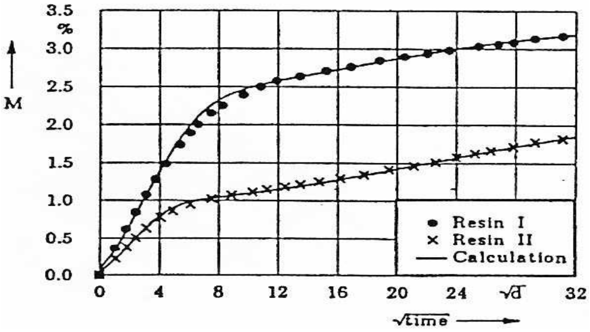


Fig. 1. Moisture absorption of epoxy resin

It is well known that in polymers we have to deal with three principal loss mechanisms. Under 50 Hz and at room temperature, dipole orientation is the dominating mechanism. Dipole polarization is caused by polar groups in the structure which constitute permanent dipoles that can be orientated in an applied electric field. At higher temperature, also electrical conduction due to ion movement is involved, and in heterogeneous polymers interfacial polarization becomes an important quantity.

Due to high electric dipole moment of the water molecules, a distinct influence of absorbed water on the permittivity of polymers is to be expected. In fact, Fig 2 confirms this expectation: The pure resin exhibits a roughly proportional increase of the permittivity with the moisture content. However, again the fiber reinforced structures show a completely different behavior. Initially, the permittivity increases with water content in the same way as the resin. But after reaching a threshold value which is different for different materials, a steep increase occurs. The only explanation is that this increase is induced by interfacial polarization. We assume that charge carriers are produced in the interface.

The second important dielectric characteristic, the loss tangent, exhibits in principle the same sensitivity against absorbed water as the permittivity. Some differences concern the moisture threshold value, and this effect is presently under investigation. Since the product of permittivity and loss tangent is the main quantity to describe the dielectric losses of a material, for practical applications it is most important to know exactly the influence of absorbed water on these dielectric characteristics.

Without giving detailed examples, it should be noted that filled polymers, for instance quartz filled cycloaliphatic epoxies or alumina oxide filled silicone rubbers, under moisture influence demonstrate a very similar behavior of their dielectric properties compared to GFR.

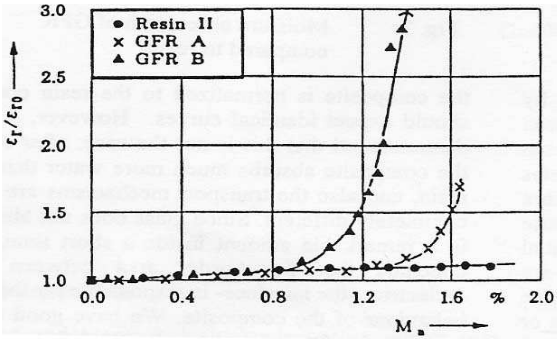


Fig.2. Normalized dielectric constant vs. absorbed water

c. Pollution Contamination

Outdoor insulators are more or less covered by a pollution layer. The electrical performance of insulator under pollution is governed by conductance of the pollution layer on the insulator surface. When being wetted, e.g. by rain, dew, fog etc., the soluble salts contained in the pollution layer are solved and lead to a certain conductivity of the surface layer. Under the influence of the operating voltage a leakage current is flowing. The assumption of constant layer conductivity σ_s for axisymmetrical insulator, we have for calculation of the differential contamination layer resistance dR over the section dx [4]:

$$dR = (dx/\pi D)(1/\sigma_s) \qquad (13)$$

Due to above phenomenon, the silicone rubber show superior insulating property in polluted environments, such are known that silicone rubber are able to transfer hydrophobic properties to pollution layers on their surface. When water is sprayed on their surface it is not absorbed by the pollution, but distinct water droplets are formed on the surface. Droplets of sufficient size move according to the force of gravity and tend to run away. Thus, the pollution is prevented from being wetted and consequently does not become conductive.

d. Ultra Violet Radiation

Polymer insulators subjected to outdoor environments can fail due to several factors, either is the UV radiation of the sun. The energy in Joules of photon e is related to its associated wave length (meters) by the relation

$$e = hc / \lambda \qquad (14)$$

where h is plank constant $6.63\text{x}10^{-34}$ Joule, C is velocity of light $2.998\text{x}10^{8}$ ms^{-1}. The excitation energy per mole E = Ne;

$$E = 0.0284 / \lambda , \qquad (15)$$

N being Avogadro's number $6.023\text{x}10^{23}$.

A molecule when bombarded by photons and absorbs on of them becoming energy rich or exited. Specifically in the case of polymer, such excitation results in weakening of the weak bonds to the extent of the excitation energy absorbed. Therefore laws governing chemical reaction should be applicable. The temperature dependence of chemical reaction is given by the Arrhenius equations,

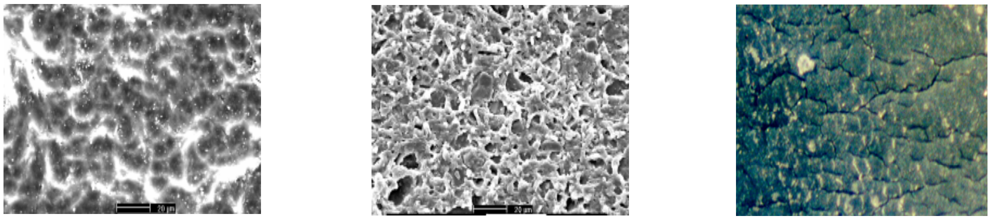
$$\text{specific reaction rate} = A\, e^{-E/kT} \qquad (16)$$

where E : Energy of activation, T is absolute temperature in k, A is frequency factor and k is Boltzmans constant.

If a polymer is subjected to both UV and temperature, the activation energy E is apparently reduced by amount BI, where B is a constant and I is the intensity of UV exposure. Therefore a reaction rate of the following type may be obtained:

$$r = A\,e^{-(E+BI)/kT} \tag{17}$$

Fig 3a shows the surface condition of new material, where the higher filler content silicone rubber causes higher roughness of surface. Fig. 3b shows surface condition of aged material after exposure in outdoor thus removing the pollution accumulation on their surface by isopropyl alcohol. It shows that the surface of aged material shows much more cracks than virgin material. This phenomenon is caused by uv radiation exposure.



(a) Virgin material (b) Aged material (erosion) (b) Aged material (tracking)

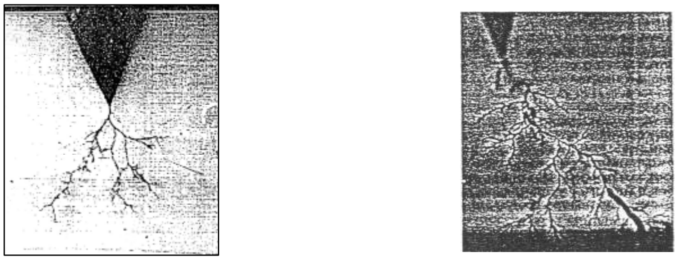
Fig. 3. Material surface degradation (analysis by SEM)

e. Thermo-Electrical Breakdown

Mobile ionic charge carriers generated from ion exchange, ion salvation and silica corrosion mechanisms increase the electrical conductivity in the interfacial region. As a consequence, Maxwell-Wagner polarization is strongly increased at the microscopic interfaces. This effect leads to an increase in the loss tangent and the permittivity with high polarization and conductive power losses at electrical service stress. The insulation is heated up while the loss tangent is increasing and the electrical breakdown strength is decreasing with rising temperature. Finally, if heat generation is larger than heat emission, the electro-thermal stability is lost and an electro-thermal breakdown appears [6].

e) Electrical tree degradation and breakdown strength

Other dominating properties for dielectric system are the treeing and breakdown stability. Again, one can expect a reduction of these key properties in materials with large internal interfaces since it is a fact that the electrical strength of a contact area between two materials may be much lower than the intrinsic strength of each component. For investigating materials with large microscopic interfaces, test samples have been developed which are shown in Fig. 4. For filled polymers, a cylindrical probe with a conical insert has been successfully applied (Fig. 4a).



(a) (b)

Fig.4: Illustration of electrical trees

(a) Branch type tree (b) Beginning of catastrophic breakdown initiated

The insert is covered with a gold evaporated-electrode which acts as HV electrode, and the puncture place is the well defined area before the tip of the conductive cone. This design allows determining the intrinsic breakdown strength of filled polymers under both dry and wet conditions. For investigating fiber reinforced structures, for instance from the filament winding type, sections from GFR tubes are used where the voltage is applied via a needle electrode. Such inhomogeneous arrangements are especially good for treeing tests. With these samples tests under dry and wet conditions can easily be performed.

Test results demonstrate again interfacial problems. Puncture tests with filled epoxy and silicone rubber sample exhibit a high electrical strength of the dry specimen of normally more than 1500 kV/cm which goes down to 200 kV/cm under moisture attack. However, for open air application, this value is still extremely good since outdoor insulations can be stressed with 20 kV/cm in maximum due to the limited strength of the surrounding air. Consequently, even under extreme humidity conditions, the safety margin is still one order of magnitude. Treeing tests with samples according to Fig. 4b showed that partial discharges only happen in the interface.

3. Ageing, Degradation and Deterioration

The life of power engineering equipment is an important economic problem. Other than with microelectronic devices, for power apparatus the life expectation is in the range of some decades. Consequently, when designing a high voltage apparatus, the engineering must regard the fact that the material properties suffer a more or less distinct reduction when the device is aged. He should know the amount of degradation or deterioration to which the material is subjected. Unfortunately, we miss detailed knowledge in this important field, and much scientific and engineering work is necessary in the future to overcome this situation.

First of all, the subject needs some definitions. According to an interdisciplinary CIGRE working group which presented a state of the art report a few years ago in a Paris meeting, we should distinguish between ageing, degradation and deterioration:

AGEING: refers to the passage of time and is only linked to changes of properties in the persistence of an influencing factor (a stress)

DEGRADATION: the physical meaning is a temporary reduction of properties which disappears with the removal of the influencing factor (a stress).

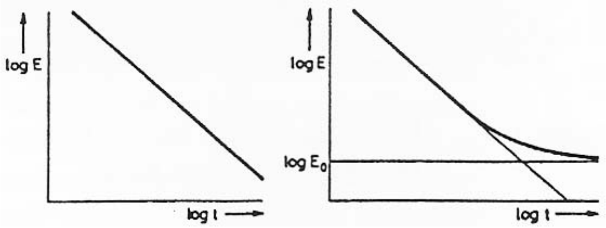
DETERIORATION: is a permanent reduction of physical/chemical properties caused by the application of an influencing factor (a stress).

We will follow these definitions in the further comments. In addition, only electrical stresses will be regarded.

3.1 Lifetime laws

It is commonly agreed that an electrical stress only leads to degradation or deterioration provided that treeing or petering effects occur. The lifetime/stress relationship can in this case well be described by the inverse power law which in a log E – log t plot (E: field strength; t: life time) is represented by an inclined straight line with an inclination of – 1/n with n marking the voltage endurance coefficient (Fig. 5a).

The weak point of the inverse power law is the fact that it predicts a limited life even for very low stresses. If we believe partial discharges, treeing or petering effects to be the only deteriorating factors, we must fix a threshold stress value below which none of these effects occur. Consequently, for stresses below this threshold life must be infinite. Fig. 5b shows the modified inverse power law which is well backed for many materials by experimental results.



(a) (b)

Fig. 5. Life Time Curve

For a precise forecast of the life of an equipment, the lifetime curve should be known, and it should be known not only for the dielectric material but for the whole complex insulation system. The latter is simply impossible, so we must live with lifetime curves which have been obtained from material samples, for instance according to Fig. 4. Here we have to face some problems. One concerns the fact that test results suffer a large scatter, even in the case of well manufactured small test specimen, another is a scaling problem: how can we transfer the results from small laboratory made samples to large systems produced under industrial conditions? Much car and experience is necessary to effect a reliable property transfer.

3.2 Lifetime estimation

Unfortunately, we have to face some problems. Let us regard Fig. 6 where we assume that we have available an ideal lifetime curve which exhibits a certain slope and reaches the threshold stress E0 after an infinite time. This is represented by the upper curve, and we conclude that we have done a good design. But during life, the lifetime curve may be shifted by overstresses. As an example, at time t' a short stress E' shall occur (for instance a lightning or switching surge), which does not puncture the insulation but leads to a partial deterioration. Consequently, the residual life will be changed, and this will effect a change of the lifetime curve either by an increased inclination or by lowering the whole curve. In Fig. 6 we have assumed the latter effect, and, as a consequence, we now note a limited life of the equipment: we find that we will reach the threshold stress E0 after the limited life span tR. Although we have well designed our equipment at the beginning, we are running the risk of a puncture due to expected or unexpected overstresses. What are the consequences? For important equipment, it seems necessary to monitor the overstresses during life. However, this will only be of use when we also know the influence of overstresses on the position of the lifetime curve. Here again we have a great lack of knowledge, and we urgently suggest to start basic research work in this field.

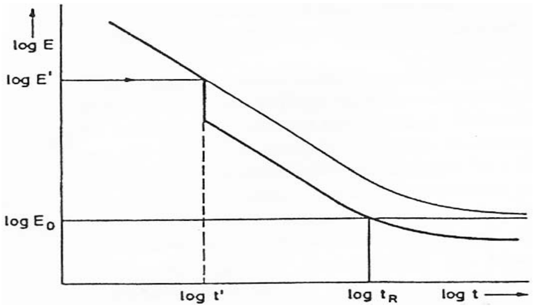


Fig. 6. Life Time Reduction by Overstress

3.3 Diagnostic tools for lifetime estimation

As mentioned above, we hardly have a chance to obtain a reliable lifetime curve for a complex insulating system. How can we get information about the actual conditions of the dielectric system. How can we get information about the actual condition of the dielectric system? Can we find an "early warning system" that switches on the red light in the case that a dangerous situation for the insulation exists? Here the knowledge about breakdown mechanisms may help us. We know three mechanisms which are well understood: the electrical breakdown, the thermal breakdown and the PD induced breakdown. The electrical breakdown is a spontaneous event due to an overstress. There is no long term effect that announces the breakdown. Consequently, the only chance to avoid an electrical breakdown is to suppress excessive surges. In contrast to this, the thermal breakdown is a long term effect and announces it self by an increasing temperature of the equipment which, under constant electrical stress and ambient temperature is caused by a good tool to settle an early warning mark. The PD breakdown, finally, develops from existing partial discharges. Consequently, the monitoring of PD activities can help to detect a dangerous development in time.

As a summary, we recommend for important systems an on-line monitoring of the dielectric quantities and of the PD activities. This recommendation is easy to give but hard to perform, as we have to face severe electromagnetic compatibility problems in sensitive on-line measurement. One more future engineering challenge arises from this situation, namely the development of reliable and insensitive on site diagnostic techniques for the monitoring of decisive quantities should be checked and compared to the initial values under new conditions, since it will be sufficient to follow up their gradient.

4. Summary

In most HV insulation systems interfaces occur which are defined as the contact areas of different insulating materials. Under electrical stress, interfaces may result both an increase of the dielectric characteristics, e.g. the dielectric losses, and a decrease of the electrical strength. Both effects are enhanced by water which in the case of polymeric materials can enter the insulation systems by diffusion processes.

As an example, material properties of polymeric for HV outdoor application are described. Since silicone rubber and cycloaliphatic epoxies, both with inorganic fillers, have shown a promising reliability in the past, these materials in combination with fiber glass reinforced structures have been considered. The internal microscopic interfaces turn out to be of great influence on the electric and dielectric properties especially when humidity is present. This is true for quartz flower filled epoxies in the same way as for alumina oxide filled silicones, and also for fiber glass reinforced epoxies. It is demonstrated that the hydrophobicity of polymers plays an important role both for the bulk and the surface properties. The ability of silicone rubber to transfer its hydrophobicity by diffusion of low molecular cyclic silicones even to the surface of contamination layers results a good pollution-proof behavior.

Further research work is necessary in the field of microscopic and macroscopic, internal and external interfaces. This work should, among other topics, be concentrated on the understanding of the physical/chemical processes in the interfaces, and it should include the intense investigation of bonding problems in all kinds of internal interfaces. For the sake of a reduced water sensitivity, hydrophobicity generation in materials with low intrinsic hydrophobic properties should be considered.

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