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SURFACE PHENOMENA ON RESIN-TYPE INSULATORS UNDER DIFFERENT ELECTRICAL AND NON-ELECTRICAL STRESSES IN THE EARLY STAGE OF AGEING

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Abstract. Phenomena at the interface of solids and the insulating gas are of high interest since they are responsible for changes finally leading to a reduction of the insulating ability in this 'weak' zone. Depending on the type of stresses of electrical as well as of non- electrical nature and on the type of the solid and of the insulating gas, specific ageing mechanisms have to be considered. Recent investigations have focused on the so-called 'early stage of ageing' and the physical and chemical effects responsible for the attack of the surface of the organic solid insulators. For the study of the 'early stage of ageing' various ageing procedures and diagnostic tools have been developed and applied and numerous model post insulators made of epoxy and polyurethan resins with different types of mineral fillers have been tested. A model of surface ageing could be developed

Key words: Surface phenomena, indoor insulation, outdoor insulation, 'early' stage of ageing.

1. Introduction

The importance of interfaces between solid and gas has been adequately stressed [1]. Interfaces and related fundamental phenomena may greatly influence the design of medium and high voltage equipment. The present paper intends to comment on a number of aspects of interfaces appearing for indoor and outdoor applications. Indoor applications differ from outdoor ones in that they are electrically stressed much more and in that they are subjected to a different type of environmental influences. Indoor insulators may be subjected occasionally to condensation [2]. The interface in question consists of a solid

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insulating material and a gas at normal pressure. Of great interest is the behaviour of such an interface during the initial (or 'early') stage of ageing. Water droplets, formed from condensation, combined with light contamination may exist on the surface of the solid insulator and, under sufficiently high electrical stress, partial discharges (PD) may ensue. PD may change the properties of the solid insulator surface. Such changes may endanger the entire insulation system.

This paper presents a review of results which aims at a better understanding of the fundamental surface processes during the early period of ageing of model post insulators made of epoxy and polyurethan. The role of material composition during the aforementioned period is also discussed. A model of surface ageing under multi- factor stressing is presented.

2. Stress Conditions of Different Types of Surface Insulation

Outdoor insulators are subjected in general to lower electrical stresses than Air- Insulated-Switchgear (AIS) or Gas-Insulated-Switchgear (GIS). Outdoor insulators are subjected to very high environmental stresses with the consequence of formation of layers of foreign matter on their surface which are characterized from high volume conductivity. The latter leads in turn to high layer conductivity [3]. On the other hand, indoor insulators present a much smaller degree of pollution. A common danger, however, to all types of switchgear technology, is the combination of the electrical stress and the pollution layer. Having said that, it should also be pointed out that surface phenomena depend on the stress and design parameters of each technology. Surface phenomena are further determined by the insulating materials used for each technology [4].

3. Modelling of Surface Contamination

A dry and clean surface of a solid insulator can be represented by a chain of n capacitors where the applied electric field is accordingly distributed. A wet and/or contaminated surface, on the other hand, can be represented by a chain of n capacitors and n resistors in parallel. Fig. 1 shows such a superposition of the ohmic and capacitive components of the applied electric field [4]. The droplets and/or conducting particles on the insulator surface cause a change in electric field distribution and the local overstressing in the gaseous domain between the droplets may give rise to local PD, termed "surface partial discharges" [4]. Change of the electric field distribution because of the influence of humidity is common to all aforementioned three technologies. Since humidity combined with light contamination may occur to all three technologies, it is worth trying to find some common denominators of the early stage of ageing.

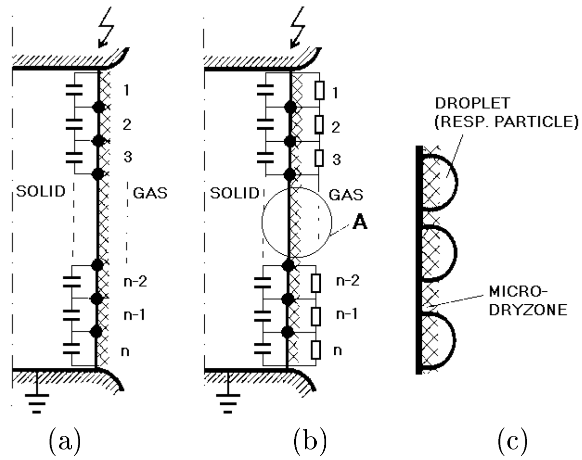


Fig. 1 Modelling of an insulating surface (after [4]).
(a) Dry and clean conditions.
(b) Wet and/or contamined conditions.
(c) detals of a wet hydrophobic and/od contamined surface (droplets, resp. conducting particles.

4. Surface Ageing Mechanisms

Resin-type insulators generally present hydrophobic properties as a result of residual traces of mold release agents containing silicones [5]. Depending, however, on the insulation system, if the condition of local electric overstress is satisfied and the generation of local PD starts, subsequent stages leading to ultimate failure may be different.

In the case of high pressure SF_6/solid insulation the electric stress is very high and local high electric overstress will result to a "spontaneous" flashover without any intermediate stages of ageing. In the case of moderate pressure SF_6/solid insulation, however, local electric overstressing will lead to 'electrochemical surface erosion' because of the attack of SF_6 byproducts. The latter combined with humidity become chemically agressive. Evidently, a low dew point is of vital importance for the lifetime of such an insulating system [6]. The period during which the solid surface deperiorates, is termed 'early stage of ageing' [2].

Indoor insulation systems are subjected to rather high electric stresses, which are higher to those of outdoor insulation but still lower to the ones in

GIS. An 'early stage of ageing' as well as a 'late stage of ageing' could be diagnosed and established [4]. The research, however, of most people concentrated on the 'late stage of ageing'. The 'early stage of ageing' has been sadly overlooked although of great importance to indoor insulating systems. The combination of high voltage and moist layers on the surface of an insulator may cause local distortion of the electric field and generate surface PD. By collision mechanism, highly reactive radicals may be formed, particularly ozone. The latter can oxidize the nitrogen of the atmospheric air to create nitrous gases. Nitric acid may result in turn [7]. This constitutes already a pollution phenomenon.

The surface of the solid insulator is attacked by combined chemical and physical stresses which result in 'electrolytic partial discharge erosion' [5]. As was noted in [4], the latter phenomenon may increase the layer conductivity either by chemical attack and subsequent erosion, rendering thus the surface more hydrophillic, or by the formation of soluble nitrates which increases the volume conductivity of the surface layer which in turn results in an increasing layer conductivity [7, 8]. The aforementioned process is a self contamination process. Indoor insulation systems in the 'early stage of ageing' are characterized by relatively low layer conductivities and low energy surface discharges. There are no appreciable thermal effects due to the surface PD [9]. A similar mechanism was proposed for outdoor insulation, where the importance of the hydroxyl radical (OH) and that of the small PD were emphasized [10]. This again validates our viewpoint, namely that there is a parallel between indoor and outdoor insulation phenomena.

An increasing layer conductivity leads to an increased leakage current and a worse flashover performance [11]. If the leakage current becomes greater than a certain value, the formation of dry bands ensues and phenomena such as scintillation, tracking, morning star and final flashover follow. The transition from low energy PD to 'mini'-arcs indicates that the 'early stage of ageing' is over and that the 'late stage of ageing' starts. The relevant threshold given in terms of surface energy consumed is about 50 mW for a special test specimen and relevant insulating materials [12]. On the other hand, temperature-related dry zones have been observed for powers of about 500 mW [4].

The 'late stage of ageing' for AIS indoor insulation is short compared to the 'early stage of ageing'. It is also short compared to AIS outdoor insulation. This implies that the 'early stage of ageing' is important in detecting the initial deterioration and in taking corrective measures. The distinction between the above mentioned two ageing stages has also been observed in outdoor insulation, where it was noted that the 'early stage of ageing' is characterized by uniform erosion of the insulator surface and does not lead to defects that would disqualify the insulation system. The 'late stage of ageing', on the contrary, is characterized by intense damaging processes manifested as cracks and pitting erosion which deteriorate the electrical performance of the insulation system [13, 14].

From the above, it is evident that the distinction between the two aforementioned stages of ageing emerges is of great importance for the technologies of indoor and outdoor insulation systems. This distinction may even imply that to test an insulation up to breakdown takes unnecessarily long time since it extends the test to the stage of intense damaging processes. As is put in [13], the elongation of testing time to the phase of intensive destruction is "... of no interest and even inadmissible from the user's point of view and introduces a wide scatter of data on ageing time and leakage currents". It would be better if a test criterion concentrates on the 'early stage of ageing'. No matter whether the insulator is subjected to more or less severe environmental stresses or whether the insulator is more or less electrically stressed, it may be said that the ageing process at the begenning is driven to a great extent by low energy surface discharges which start at the droplets. In the following chapter, this mechanism is looked upon more closely.

4.1 Surface discharges in droplets and their consequence for the insulation ageing

Condensation droplets on the surface of an insulator can come about from droplet germs. Fig. 2 shows the forces which are exercized on a droplet, in case of absence of an electric field [15]. These forces are the surface tension of the liquid (τ_L), the surface tension of the solid (τ_S) and the interfacial tension between liquid and solid (δ_{SL}). When an electric field is applied, the droplet will deform because of an additional force. In this respect, the state of the insulator surface should not be neglected since ageing causes a partial loss of hydrophobicity [16].

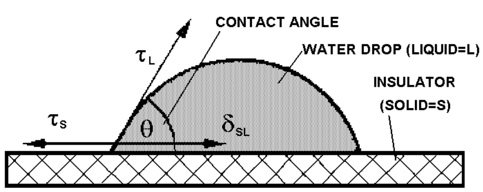


Fig. 2 Force balance at the interface solid/liquid at a water droplet on a solid surface (after [15]).

The tangential electric field on the surface of the insulator creates a force on the surface of the droplet which causes its deformation. The deformed droplet may subsequently influence the field distribution and local field enhancements may result. The latter cause micro-discharges between the droplets. Electrochemical deterioration of the insulator surface ensues and this leads to a partial loss of hydrophobicity. The droplet layer becomes even more inhomogeneous, a decrease of the voltage difference across the droplet follows because of decreased resistivity and, finally, a decrease of the inception voltage of the micro-discharges [17]. When the electrochemical deterioration sets in, solvable nitrates are produced which result in a higher conductivity of the water droplets. The continuation of this process results in the creation of dry zones. The latter are a manifestation of the beginning of the 'late stage of ageing'. In the case of epoxy resin, the crosslinked macromolecules are broken up by the H - groups of the nitric acid. Produced calcium nitrate is an easily soluble salt which may lead to high surface conductivity [7], [12].

Experimental work and computer calculations have shown that under the influence of the electric field, water droplets become unstable and that there is a field concentration at the points where air, solid insulation and metallic electrode meet each other [15]. The observed droplet elongation confirms the results of other researchers [18]. There is a critical voltage, above which, the droplet starts to make a swinging movement. This critical voltage becomes lower as the conductivity of the droplet becomes higher [19]. A reduced conductivity of the droplets means an extended duration of the 'early stage of ageing'. This may suggest that even light contamination can be important for the further ageing of the insulator. The droplet elongation is due, among other factors, to the different permittivities of the materials involved and this is a phenomenon by no means confined only to materials studied in the present investigation [20].

The fact that self-contamination, to a greater or lesser extent, cannot be avoided in the case of all three aforementioned switchgear technologies means that some parallel exists between indoor and outdoor ageing, especially if the 'early stage of ageing' phenomena are taken into account. This suggests again the importance of such mechanisms and their timely detection in order to diagnose defects and to take corrective action.

A model of surface ageing under multi-factor stressing thus emerges. Although the above give a more or less detailed picture of the mechanisms involved, more work has to be put into the influence of the volume conductivity on the 'early stage of ageing', the role of droplet volume as well as the intensity of PD between droplets being at various distances from each other.

5. Experimental Approach

Condensation on an insulating surface is a transient phenomenon depending on the thermal characteristic of the relevant solid component and the rate of temperature change of the surrounding gas. Such a phenomenon has to be simulated as reliably as possible in laboratory conditions. The conventional way is the use of a climatic chamber being able to run thermal and moisture cycles. This procedure, however, has been criticized because condensation occurs only during a small portion of the cycle time [21]. Therefore, a special

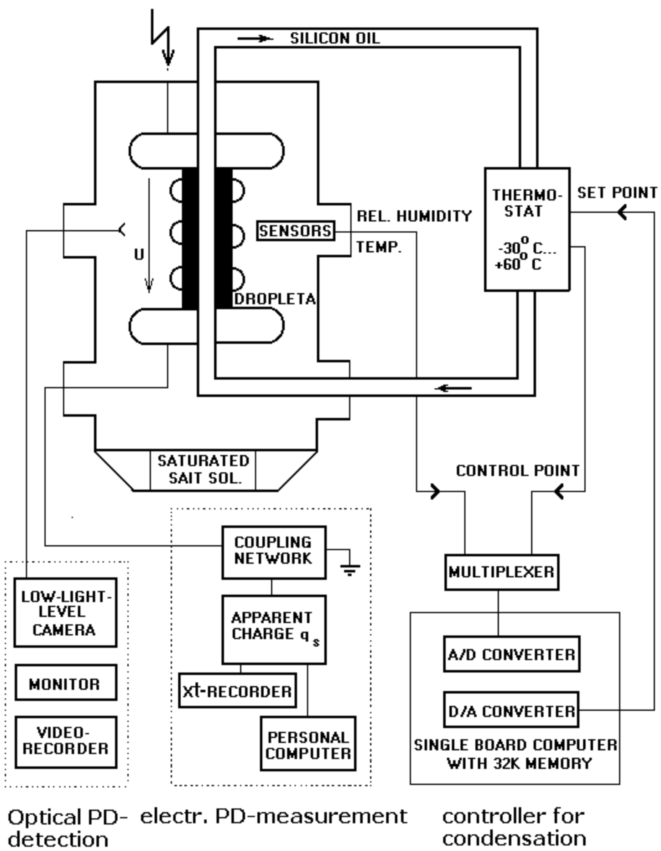


Fig. 3 Test setup 'inverse' climatic chamber (after [4])

test arrangement, termed 'inverse' climatic chamber, has been developed (Fig. 3) [4]. In this arrangement, the insulator surface is cooled down below the dew point of the surrounding air. Depending on the dew point distance, a well controlled and stable for longer periods condensation can take place [4], [21], [22]. A multitude of such 'inverse' climatic chambers has been used for comparative longtime tests [23].

Another test arrangement was the so-called salt-fog chamber, where an atomizer sprays with water of a defined adjustable quantity the insulator surface. The cold-fog droplets collide with the insulator surface, where droplet layers are formed (Fig. 4) [4]. Yet another test setup that that has been used was the so-called 'modified rotating-wheel-dip-test' [24].

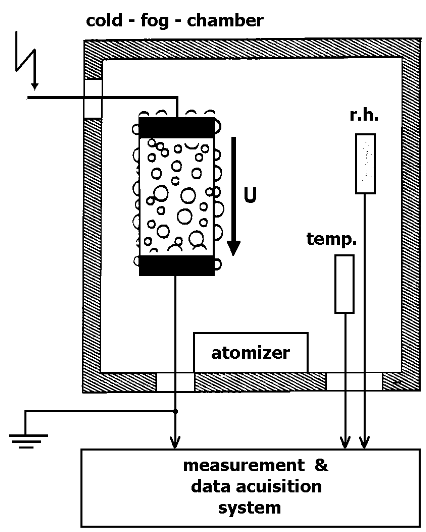


Fig. 4 Test setup cold-fog chamber (after [4])

In the above mentioned test setups, not only moisture layers of distilled water can be investigated but also layers of liquids with controlled increased volume conductivity [4]. Moreover, test samples should not present undue field concentrations where the electrode meets the insulating material for obvious reasons. Cylindrical test specimens have been used for the test arrangements described above since they are much closer to the real insulators.

6. Diagnostic Tools and Test Results

A number of non-destructive and destructive diagnostic tools have been used in order to study and assess the surface ageing effects in indoor and outdoor insulators. Non-destructive diagnostic tools such as PD measurements and leakage current measurements were employed. Destructive diagnostic tools such as flashover voltage measurements and investigation of the microstructure of the insulator surface (which assumes interruption of the test) have also been employed. The microstructure examination is necessary in order to measure contact angle and surface tension and to compare such quantities between non-aged, aged or slightly aged samples. In what follows, test results obtained with various diagnostic tools are discussed.

6.1 Partial discharge measurements

PD measurements consist a higly important diagnostic tool for many types of insulation [25, 26]. The advent of the combination of the amplitude of PD with their corresponding phase, count number and other relevant quantities together with the development of software offer nowdays a more complete estimate of the state of an insulation [27].

Epoxy resin insulators stressed under electric field and humidity showed a rapid increase of PD activity when the amount of relative air humidity surpassed 90 % [8]. The presence of even small PD activity is related to lightly conductive condensed water droplets on the surface of the insulator. A basic tendency is that increased conductivity of the droplets leads to a PD-inception voltage decrease [28]. Such small PD are related to the 'early stage of ageing'. Increase of the volume conductivity of the surface layer reduces the duration of the 'early stage of ageing'. A tendency of increased PD activity on rough surfaces was also noted. Moreover, with wet aromatic epoxy resin specimens, whereas at the beginning of a test PD may be small, with the progression of time they become larger (as much as two orders of magnitude larger). The latter means the end of the 'early stage of ageing', the beginning of the formation of dry zones with the occasional high energy discharge and the starting of the 'late stage of ageing' [29]. This shows that PD measurement is a reliable tool to diagnose not only the state of the insulator but also the discrimination between the two ageing stages.

6.2 Leakage current measurements

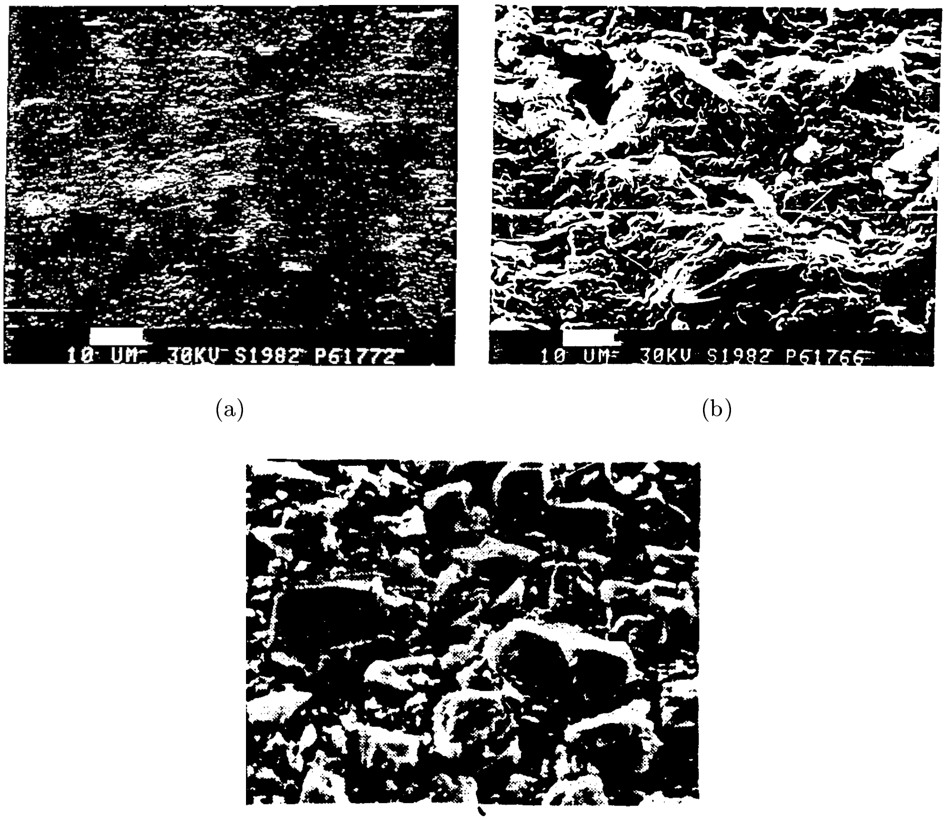
In case of ageing the leakage current increases with time for both rough and non- aged surfaces [8]. The leakage current increases also with relative air humidity [8]. This correlates very well with the results of PD measurements mentioned above. Furthemore, leakage current measurements correlate well with the type of the material under test, i.e. with the type of the filler material used (alumina, quartz powder, dolomite, with or without silane treatment) [30]. In [30], it was shown that if untreated or silane treated quartz powder is used as filler material with epoxy resin, the leakage current remains stable which in turn shows that no essential ageing occurred. The significance of leakage current measurements has also been shown under real ageing conditions for outdoor insulation [11]. In the latter paper, it was shown that insulators with strongly reduced leakage distances manifest dry band formation and intensive arcing. This correlates well with the findings for indoor insulation [30], [31].

6.3 Scanning electron microscope results

Scanning Electron Microscope (SEM) photographs seem to be a good diagnostic tool for the evaluation of insulator surfaces. Photographs 5(a) and 5(b) on the Figure 5 show examples of epoxy resin surfaces before and after stressing respectively [8]. Photograph 5(b) shows the changes on the surface which, although damaged, still retains its resin matrix covering quartz crystals of the filler. Photograph 5(c), on the other hand, shows not covered quartz crystals of an aged epoxy resin surface [12]. The destruction of the resin matrix is the main cause for the hydrophillic properties of aged epoxy resin surfaces [12]. Self- pollution implies chemical attack of the surface and this in turn means a decrease of surface resistivity. Evidence from SEM photographs correlates well with PD measurements, i.e. aged samples with rougher surfaces show also a more intensive PD activity [28], Such evidence correlates also well with the behaviour of water droplets on the insulator surface, i.e. water droplets tend to spread more on an aged (rougher) surface due to its hydrophillic behaviour [29].

6.4 Contact angle considerations

By examining and comparing different types of quartz powder filled aromatic epoxy resin surfaces (unaged, first stage of 'early stage of ageing', advanced stage of 'early stage of ageing, 'late stage of ageing'), it has been found that the contact angle of water droplets changes progressively from the value of $> 90°$ (for unaged samples) to clearly much less than $90°$ for the 'late stage of ageing' surface [32]. Such data correlate well with the increasing roughness of the aged surface, i.e. rougher (more aged) surfaces present smaller contact angles than smoother (unaged or slightly aged) surfaces. This droplet behaviour with the progression of ageing has also been reported in [33].



(a) (b)

(c)

Fig. 5 (a) Photografph of new surface (epoxi resin) taken with SEM (969 x) (after [8])
(b) Photograph of pre-stressed surface (epoxi resin) taken with SEM (960 x) (after [8])
(c) Photograf of SEM-photograph of an aged epoxy resin surface (400 x) (after [12])

7. Influence of the Casting Resin System on Ageing

Based on the experimental procedures described previously, various epoxy resin (EP) and polyurethan (PUR) compounding systems filled with inorganic fillers were tested. The inorganic fillers were alumina, quartz powder with and without silane treatment, and dolomite. In case of longtime tests, systems filled with dolomite failed much earlier than other systems whereas EP systems filled with the quartz powder with or without silane treatment presented no remarkable differences up to 8000 h of ageing. On the contrary, the inclined plane tests [34] showed that systems with dolomite presented higher withstand voltages than the systems with quartz powder [33]. In the 'modified-rotating-dip-wheel-test', however, samples with silane treatment manifested a lower leakage current than samples without silane treatment [35, 36]. Different tests classify the various materials differently, probably because of different ageing mechanisms at work. Salt-fog tests, e.g., with different layer conductivities ($< 10\ \mu$S/cm and 100 μS/cm) lead to different classifications of the systems [36].

8. Discussion

The lifetime of an insulating material system, such as described above, can be prolonged if the surface layer deterioration progresses more slowly. This can be partly achieved if localized high electric field enhancements are avoided. Due attention should be given to smoothed electrodes [4]. Electrodes with surface inhomogeneities may cause excess field, local gas breakdown and therefore small PD which eventually will lead to the production of reactive radicals which in turn are the prerequisite of the 'early stage of ageing' [7]. Depending on the electrode configuration, the degree of field enhancement in the vicinity of the electrodes can widely vary [4].

Another vital parameter as to the 'early stage of ageing' is the volume conductivity of the droplet layer. Increase of the volume conductivity of the surface layer reduces drastically the duration of the aforementioned stage. Fig. 6 shows that as the layer conductivity κ_F increases the flashover voltage decreases. Therefore, the effects of self-contamination generated by low energy surface discharges are experimentally proved [4].

The diagnostic tools used to study the stage of ageing of the insulators for indoor use correlate reasonably well with each other. Such tools can also be used in the diagnosis of aged surfaces for outdoor composite insulators [37, 38, 39]. PD measurements, on the other hand, seem to be a reliable diagnostic tool since, with their aid, a discrimination between hydrophobic and hydrophillic surfaces is possible [4]. Intermittent periods, i.e. periods without detected PD, are also of great interest, since such periods are followed by PD activity [29]. Such periods are remimiscent of periods of extremely small, practically undetectable PD, which, contrary to the general belief, are not innocuous to the insulator [40].

Different test methods may give different classifications of the various insulating systems [36]. This may be due to the different salinities used. The way an insulating system is manufactured plays a dominant role for its sur-

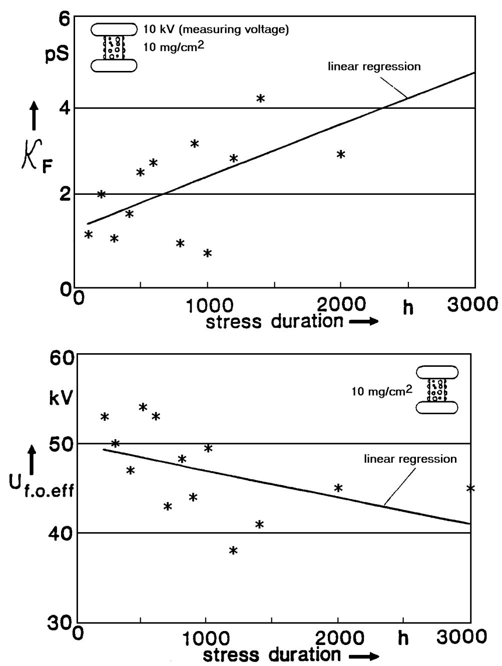


Fig. 6 Layer conductivity κ_F and flashover voltage $U_{f.o.}$ at different times of stress duration (after [4])

face hydrophobicity. Fillers, for example, and the way they are processed, may critically influence the hydrophobicity of the insulator [41]. Compound formulation is more important than the generic polymer types [42]. It seems that there is no unique test method which can be qualified as optimal for the evaluation of materials and systems for indoor applications [36]. A similar approach is adopted with regard to the outdoor insulating systems too [43], where it was stressed that short time tests with high electric stresses and high levels of pollution are not necessarily representative of the long term performance. A further point to be remembered is that, regarding test methods and ageing tests, the behaviour of a switchgear unit greatly depends on its individual components. Installed in different units, identical components may behave differently. In other words, operational conditions matter most [44].

A more detailed model describing the 'early stage of ageing' should include the study of single - as well as of adjacent - droplets and their performance under the influence of high electric field. The influence of the applied electric field on the shape of the droplets as well as the influence of the resulting droplet shape on the electric field (feedback action) are phenomena which define, among other factors, the rate of ageing of the insulator surface. An additional parameter to be taken into account is the droplet conductivity, especially since for indoor switchgear service conditions, more severe than mere 'occasional condensation' may occur from time to time [45, 46]. Moreover, the behaviour of droplets has to also be investigated on real high voltage insulators, i.e. surfaces which are inclined, and not only on laboratory samples [47].

Some common aspects between indoor and outdoor insulation have been emphasized in this paper. The 'early stage of ageing' seems to be of significance not only for indoor but also for outdoor insulation. Despite the differences regarding external influences between indoor and outdoor applications, there are strong indications that ageing starts from light contamination of the insulator surface and low energy discharges. This stage of ageing (characterized by layer conductivites of much less than 10 μS/cm [48], [49]) has been overlooked until now. It is believed that detailed study of this ageing stage may give the manufacturers of such equipment additional knowledge and an incentive to search for new diagnostic tools in order to recognize early enough future insulating system failures. Additional diagnostic tools for that purpose, such as Electron Spectroscopy for Chemical Analysis (ESCA), Energy Dispersive X-ray Analysis (EDX) and Fourier Transform Infrared Spectroscopy (FTIR), would be useful [50]. It is, however, reminded that the above mentioned diagnostic tools have already been successfully employed for outdoor insulation.

9. Conclusions

Several aspects of indoor insulation ageing have been investigated in this paper. Some common aspects of the aforementioned insulation ageing with the ageing of outdoor insulation have been emphasized. Particular emphasis has been given to the 'early stage of ageing'. 'Early stage of ageing' seems to be a stage of vital importance for both sorts of insulation. A model describing surface ageing under multi-factor stressing has been given. Concentrated efforts need to be undertaken in order tp better study this ageing stage and to acquire the necessary knowledge and diagnostic tools for its timely recognition.

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