

Challenging Defects of High Voltage Insulation Systems

Erling Ildstad

Norwegian University of Technology and Science (NTNU)
Department of Electric Power Engineering
NO-7491 Trondheim, Norway

Abstract- The primary function of high voltage insulators is to insulate, i.e., prevent the flow of electric current and to keep oppositely charged conductors mechanically separated during all service conditions. This means that the insulation of a power apparatus is designed to withstand any electrical, thermal, and mechanical stress likely to occur during manufacturing, testing, and the long-expected service lifetime of 30 years or more. Typical insulation systems, therefore, constitute combinations of different insulating gasses, oils, and solids. Experience shows that important characteristic properties, as electric breakdown strength, electric conduction, dielectric loss, and long-term endurance, are limited by minute amounts of additives, voids, particles, and other impurities, embedded in the insulation or at electrode interfaces. Such composite systems are difficult to describe in terms of the characteristics of each individual component, and efforts to improve manufacturing and refine the quality of insulating materials are therefore often based upon an empirical approach.

In this paper, a more theoretical approach is taken, aiming at predicting how important properties are affected by different types of impurities and additives. In the case of defects evenly distributed within the insulation, electric breakdown strength becomes the weakest link mechanism described by extreme value statistics. In practice, electrical conduction current originates from many different moving charge carriers, i.e., moving ions, particles, and electrons. At moderate and high electric stress, these charge carriers result in a different and highly non-linear increase in current versus applied voltage. The value of permittivity and dielectric loss may increase, even at power frequencies, due to interface charging and increased conductivity of the insulating materials. Voids and particle inclusions act as starting points for partial discharge and electrical treeing, resulting in a premature electric breakdown. Absorption and condensation of water lead to slow water tree degradation and reduced serviceability of polymer insulated cables.

It is concluded that in order to advance the science of high voltage insulation engineering, a fundamental approach is needed to understand and utilize the complex physical mechanisms governing and limiting the insulating properties.

The term “insulating material” has no meaning unless its molecular microstructure, crystallinity, content of byproduct from the manufacturing process and other additives are clearly defined.

I. INTRODUCTION

As a young researcher, I remember being very puzzled by the statement: “High voltage insulation does not exist—only insulation systems with defects,” presented by late prof H.F. Kreuger at a conference in 1992 [1]. Over the years I have realized the truth of this statement because it addresses that in

engineering the term “materials” is just used as a notion to describe the “building blocks” of “insulation systems.” A system which typically constitutes combinations of many different conducting and insulating materials and is designed to prevent the flow of electrical current between oppositely energized conductors. In other words: Electrical insulation works fine as long as it does not do anything. In practice, non-ideal behavior is caused by impurities or defects contained in the “building block” materials or introduced as by-products during the manufacturing process. Examples of such typical defects are schematically summarized in Fig .1. i.e., i) inclusions of particles and voids, ii) sharp irregularities at the electrodes or iii) interfaces between different types of materials and structures. In some cases, iv) additives are also necessary for the manufacturing process or to enhance particular material properties, i.e., to provide sufficient oxidation stability and mechanical strength at expected service temperatures.

In principle, some additives and impurities, therefore, need to be considered building blocks rather than insulation defects.

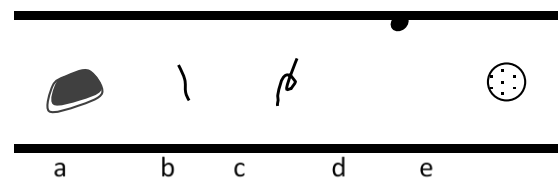


Fig. 1. Examples of inclusions in high voltage insulation systems, based upon [1]. a) partly embedded particle, b) conductive- and c) fiber inclusion, d) electrode protrusion, e) additives, amorphous or low-density regions, etc.

During the last decades, considerable improvements in high voltage insulation systems are made possible by [2]:

- A better understanding of the mechanisms of electrical conduction, permittivity, and breakdown.
- Improved knowledge of the properties of the various materials under extreme thermal, mechanical, and electrical stress condition.
- Development of standardized test methods for quality assurance and simulation tools for electric field calculation of high voltage insulation systems.
- Efforts to improve manufacturing and refine the quality of insulating materials, including both purification and addition of selected micro- and nano-sized fillers.

In the science of electronics and communication technology, there is a strong relation between fundamental researches in solid-state physics to the rapid development of compact

electronic devices. In the power industry, such a clear line of development is not that obvious, probably due to some of the following main reasons:

- Compared to modern electronic equipment, power apparatus is large in size, expensive to manufacture and install.
- Develop and market introduction of a new component for application in a power apparatus takes a very long time. Extensive testing is, for example, needed to verify sufficient endurance and expected long-term service performance of more than 30 to 40 years.
- To successfully introduce a new product, the benefits of new materials and components need to be higher than the costs regarding the risk of reduced service performance.

Considering both technical and economic reasons, a designer of large electric power equipment is therefore often left with a very limited number of choices between materials; all contain selected additives or imperfections that are very costly to get rid of. It is, therefore, necessary to both theoretically and experimentally determine how such inclusions affect the property in question.

This paper takes a theoretical approach, aiming at presenting the fundamental theory of how different type of additives and defects may affect and limit the characteristic electric properties of high voltage insulation systems. The physical mechanisms governing important physical phenomena of electrical breakdown, conduction, permittivity, dielectric loss, and ageing of solid and liquid dielectrics will be discussed. - These are properties, the electrical engineers and scientists dealing with dielectrics, need to understand in order to advance the science of high voltage insulation.

II. STATISTICAL DESCRIPTION OF BREAKDOWN PHENOMENA

A. Weakest link mechanism

When the applied electric field or the voltage stress across an insulation reaches a certain critical value, an electric breakdown will occur. In the case of a specific type of insulation system, the value of this breakdown voltage varies strongly with size and production process and can therefore not be considered a material constant. The most important reasons for this are the many different factors affecting the breakdown strength, of which the type of stress, defects, and interface irregularities play an important role:

- Shape and duration of the applied voltage
- Shape of electrodes and insulation
- Temperature
- Impurity content
- Mechanical stresses
- Pressure and humidity effects

Thus, even when care is taken to keep all parameters constant, the dielectric strength shows a rather large statistical variation.

When designing an insulation system, it is therefore important to emphasize that the breakdown strengths are statistical variables governed by the “weakest link” mechanism. This means that if there is a minute point, which cannot carry the electric field, this point will initiate a complete breakdown. Therefore, the statistical distribution of the measured breakdown values reflects the strength of the weakest points in the insulation system.

B. Statistical description

In the following, it will be shown that in the case of a “weakest link” mechanism, the number of distribution functions that can be applied is limited to a few extreme value distributions. The main advantage of applying extreme value statistics is that it provides a better estimate of the low probabilities for failure, at the tail of the distribution functions, compared to the Gauss distribution function which gives a good estimate of the mean values.

For simplicity, a parallel plate condenser, with insulation made up of many small elements, each of volume dV as indicated in Fig. 2, is considered:

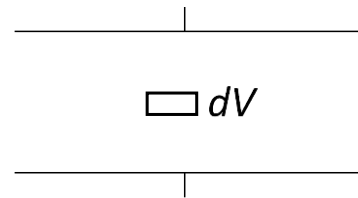


Fig. 2. Parallel plate condenser with a total volume V made up of $n=V/dV$ equal elements.

If the applied stress in one of these elements exceeds its breakdown strength, a process will start causing the electric breakdown of the entire capacitor. Since each volume unit has a certain probability for breakdown, the probability of breakdown to occur will increase with increasing numbers of elements. Thus, the probability of having a breakdown will increase with increasing size of the insulation system.

The following statistical deduction is based upon the assumption that:

- The field distribution within the insulation system is homogeneous and that
- the “weak” points are evenly distributed within the insulation system

If each element dV is assigned a certain breakdown probability αdV , its probability for not having a breakdown is $1 - \alpha dV$. Here, the intensity factor α typically is a function of the applied stress; voltage, time, and temperature. Generally, if the probability for the breakdown of a volume V is $F(V)$, where $V = ndV$, the probability of not having a breakdown of the entire capacitor becomes:

$$1 - F(V) = (1 - \alpha dV)^n = (1 - \alpha dV)^{V/dV} . \quad (1)$$

By adding an extra element dV to the insulation, the probability for not having a breakdown is modified to:

$$1 - F(V + dV) = (1 - \alpha dV)(1 - F(V)). \quad (2)$$

This gives the following differential equation:

$$\begin{aligned} \frac{F(V + dV) - F(V)}{dV} + \alpha F(V) &= \alpha, \\ \frac{dF(V)}{dV} + \alpha F(V) &= \alpha. \end{aligned} \quad (3)$$

Thus, the probability for breakdown will vary with the insulation volume V according to the exponential relation:

$$F(V) = 1 - \exp(-\alpha V). \quad (4)$$

This deduction shows that if the parameter $\alpha > 0$, a breakdown will certainly occur, provided that the volume of the insulation be sufficiently large. As indicated in Fig. 3, $F(V)$ approaches unity with increasing volume.

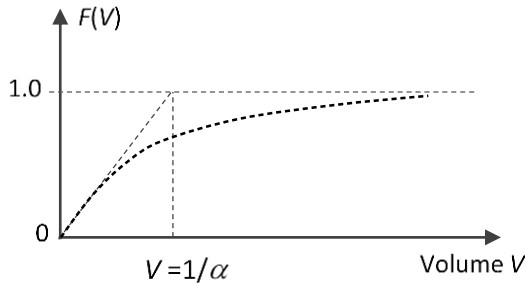


Fig. 3. Probability of breakdown exponentially increasing with insulation volume.

In practice, one may find that the breakdown processes are initiated due to protrusions, voids, or other irregularities at the electrodes rather than in the volume of the insulation system. In such cases, the volume element considered above must be replaced by an area element dA . For an electrode area A , the probability for a breakdown then becomes:

$$F(A) = 1 - \exp(-\alpha A). \quad (5)$$

Considering a test object where the insulation volume V (or the electrode area A) is kept constant, the information about the functional relationship between the probability function $F(V)$ and the magnitude and duration of the applied electric field E , is contained in the intensity factor α :

$$F(V, E, t) = 1 - \exp(-\alpha(E, t)V). \quad (6)$$

In general, this type of exponential distribution function is characterized by extreme values statistics. Gumbel [3] has described two types of intensity factors, applicable for such

extreme value distribution functions, namely the so-called Gumbel and Weibull [4] distribution functions:

$$\begin{aligned} \alpha &= \exp(-\alpha_n(E - E_n)) && \text{Gumbel,} \\ a &= \frac{E - E_a}{E_0 - E_a} && \text{for } E > E_a \quad \text{Weibull,} \\ a &= 0 && \text{for } E < E_a, \end{aligned} \quad (7)$$

where the Gumbel parameters α_n , E_n and the Weibull parameters E_0 , β are determined by experimental data, whereas the third Weibull parameter E_a indicates minimum breakdown stress. It has become common to use the latter Weibull distribution function, as it is found to easily fit measured data of electric breakdown strength, even by assuming $E_a = 0$. It was introduced by Weibull [4] to deal with the failure of mechanical components owing to mechanical stress and wear.

Considering the volume of each test object constant, the characteristic value $E_0 - E_a$ for each volume can be modified such that every volume V (or area A) has a probability for electric breakdown given by:

$$F(E, V) = 1 - \exp\left(-\left(\frac{E - E_a}{E_{0v} - E_a}\right)^\beta\right), \quad (8)$$

where E_a and β are constants independent of the volume V , and E_{0v} is an experimentally determined parameter which depends upon the volume of the test object. By assuming that the weak points are evenly distributed in the volume (or at the electrode interface), this relation can be used to estimate the probability of breakdown of a large configuration, based upon the measured values of a smaller test object.

III. ELECTRICAL CONDUCTIVITY

A. Importance of electric conduction

Although the electrical conductivity of dielectric materials is usually extremely low, there are several reasons why its value is of great importance:

- i. In insulation systems for high voltage DC (HVDC), the conductivity determines the final electric field distribution within the insulation. As the magnitude of the conductivity varies with local temperature and electric stress, knowledge about these effects are of crucial importance for proper design and operation of HVDC insulation systems.
- ii. A different mechanism of conduction may apply at low and high electric stress. Understanding the mechanisms causing increased conductivity at high electric stress may also form a basis for factors limiting the electric breakdown strength. In strong inhomogeneous electric fields, for examples at the tip of a conductive inclusion, the magnitude of the electric conductivity can become so high that it will affect the electric field distribution even during application of AC voltage.

iii. Measurement of conductivity, for example, in insulating oil, is a good indication of insulation quality and can be used as a part of a condition assessment procedure.

In general, the magnitude of electric conduction current is determined by the contribution from several different factors, determined by the ability of ions, electrons, or charged particles to move in the applied electric field:

$$j = n q v = n q \mu E = \rho v = \sigma E, \quad (9)$$

where the parameter:

n is the number of charge carriers present, i.e., the concentration of electrons, ions or charged particles,

q is the amount of charge carried by each carrier,

v is the average velocity of the charge carriers,

E is the applied electric stress,

$\mu = v/E$ is the mobility of the charge carriers,

ρ is the charge density, and

σ is the conductivity, defined as $\sigma = n q \mu$.

At relatively low E -stresses (below approximately 10–20 kV/mm), conduction currents are typically created by positive and negative ions, whereas electrons and holes may play a more dominant role at higher stresses, particularly close to electric breakdown [5]. In the case of liquids and gasses, contributions from the movement of charged particles may need to be considered.

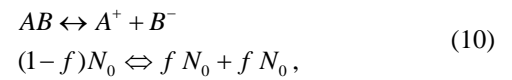
In the following sections, the challenging task of how to distinguish between the different physical conduction mechanisms will be addressed.

B. Ionic conduction

In general, extremely low concentrations of ionic impurities are needed to cause a significant leakage current. If, for example, ionic conduction is considered the dominant conduction mechanism of a polymer, an ion concentration of $n = 6.3 \cdot 10^{12} [1/m^3]$ will result in a typical conductivity of $\sigma = 10^{-15} \Omega^{-1}m^{-1}$, provided the ions carry a single electronic charge, and the ionic mobility is $\mu = 1 \cdot 10^{-9} [m^2 V^{-1} s^{-1}]$. This is a very low concentration compared to the molecular density of, for example, a polymer with a density of $1 \cdot 10^3 [kg/m^3]$. In case the molecular weight of each repeat unit is 100, such conductivity value is caused by just one moving ion per 1.10^7 repeat units [6].

Such low ionic concentrations can originate from impurities or additives, which may act either as dissociable or loosely bound ions.

1) *Dissociable ions*: If the insulation in question has a concentration N_0 of dissociable impurities, a fraction f of these is at thermal equilibrium dissociated according to the reaction:



where the degree of dissociation, is governed by the law of mass action and the Coulomb energy, ΔW required to separate the ions. The low degree of dissociation ($f \ll 1$) is expressed as:

$$f \approx \left(\frac{K}{N_0} \right)^{\frac{1}{2}} = \left(\frac{K_0 \exp\left(-\frac{\Delta W}{\epsilon k T}\right)}{N_0} \right)^{\frac{1}{2}}, \quad (11)$$

where K_0 is an entropy material constant, ϵ is the permittivity of the insulation, T is the temperature, and k is the Boltzmann constant.

If AB is the only ionizable species present, the conductivity can be expressed by:

$$\sigma = q(K_0 N_0)^{\frac{1}{2}} (\mu_+ + \mu_-) \exp\left(-\frac{\Delta W}{2\epsilon k T}\right), \quad (12)$$

where μ_+ and μ_- is the mobility of the positive and negative ions, A and B , respectively.

The square root dependence of the impurity concentration N_0 stems from the degree of ionic dissociation and can be used as a strong indication of ionic conduction. In addition, the relation shows increasing dissociation with increasing permittivity ϵ of the material. This agrees with the observed increase of conductivity of a polymer due to absorption of water ($\epsilon_r \approx 80$) [6], a conduction mechanism applied for example in so-called antistatic surface agents.

In the case of gas and oil insulation, ionic dissociation of impurities is usually considered fast enough to replace the ions drifting with the E-field towards the electrodes. This means that thermal equilibrium and the law of mass action are fulfilled throughout the insulation gap. When increasing the applied stress, this assumption may not be valid, resulting in typical current-voltage characteristics, as shown in Fig. 1.

Above a certain applied voltage, the current may reach a region of saturation, illustrated by the range $E_1 < E < E_2$ in Fig. 4. This can be explained as the situation when ions are moving to the electrodes faster than new ones are generated. The number of generated charge carriers then becomes the limiting factor, resulting in a nearly constant current at a value determined by the rate of dissociation. The high field region is characterized by a strong increase in current with the applied voltage, due to field emission and a large increase in the number of charge carriers contributing to the current.

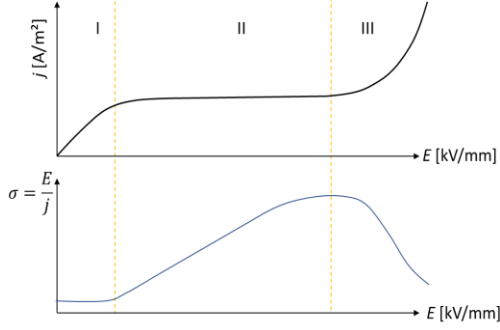


Fig. 4. Typical current and conductivity as a function of the electric field in gas and liquid dielectrics.

2) *Loosely bound ions*: Glass is a typical example of an amorphous material where ionic conduction is caused by loosely bound Na-ions, originating from the alkali oxides, i.e., Na_2O , added to break the crystal structure of quartz forming an amorphous glass. As a result, some Na ions will be loosely bound within the structure and free to move from one position to another, even at normal service temperatures. Considering a contribution to conduction, each ion position is assumed to be surrounded by energy barriers, over which the ions must pass or jump in order to move from position to position. This can, as a first approximation, be illustrated by the 1-dimensional model shown in Fig. 5. Here possible ion positions are supposed to be separated by a distance d and surrounded by a potential energy barrier with a height of ϕ [eV].

At thermal equilibrium, the probability for the agitation energy of the lattice to be larger than the barrier ϕ is given by **Boltzmann-statistics**. Thus, the number of jumps ξ per time unit will be proportional to:

$$\xi \sim \nu \exp(-\phi / kT), \quad (13)$$

where k is Boltzmann's constant, T is the absolute temperature, and ν is a parameter proportional to the natural frequency of the ion vibrations in the potential well.

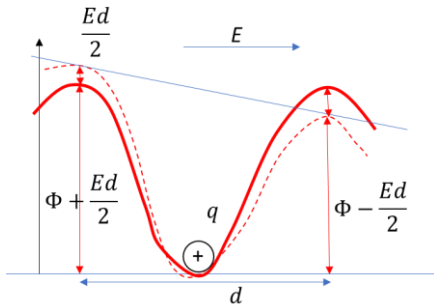


Fig. 5. 1-dimensional diagram showing the deformation of the energy barrier around a loosely bound ion by an applied electric field.

In the case of no electric field applied, the frequency of jumps will be the same in all directions, and the net flow of current will be zero. If an electric field is applied, the potential barrier will be modified as indicated in Fig. 5, lowering the barrier in

the direction of the electric field by $\Delta\phi = Edq/2$, and increase it by the same amount in the opposite direction. The average jumping frequency of the ion will then be higher in the direction of the applied field resulting in a net average drift velocity v , and current density j in the direction of the field expressed as:

$$j = \nu N q d \exp\left(-\frac{\phi}{kT}\right) \sinh\left(\frac{Edq}{2kT}\right). \quad (14)$$

At moderate fields, i.e., $Edq/2kT \ll 1$, this expression gives approximately an ohmic current, proportional to the applied electric field, and an exponential E-field dependence at high electric stress. If the current density values, measured at high stress and constant temperature, are plotted as $\log j$ versus applied stress E , one should expect to obtain straight lines with slopes determined by $qd/2kT$. This means that if the charge q is known, for example, equal to the electron charge, the average jump distance d can be determined. In this way, the average jumping distance has been found to be in the range of $d = 5 - 20 \text{ \AA}$, depending upon the type of glass [7].

Electrical conduction in several polymers is typically of ionic nature, due to many different types of by-products, fragments of polymerization catalysts, degradation and additive used in polymeric insulation systems. In the case of PVC (Poly Vinyl Chloride) it is found that below the glass transition temperature of $T_g = 87 \text{ }^\circ\text{C}$, the apparent jump distance is about 12 \AA , a value in good agreement with typical molecular spacing [6].

In addition, Polyamides, cellulose and its derivatives, also show pronounced effects of ionic conduction at elevated temperatures. The conductivity of Nylon - 6,6 exceeds $10^{-8} \Omega^{-1}\text{m}^{-1}$ above $100 \text{ }^\circ\text{C}$, evidently because of the dissociation of amide groups [8]. Experimental observation of conductivity in paper-oil systems shows the same type of temperature and E-field dependence. It is, however, questionable to apply the 1-dimensional model above for a fibrous material, which tends to conduct current along the fibers where the electric field stress is unknown. In most cases, the logarithmic of the current density, $\log j$, is seen to be a linearly decreasing function with the inverse of the temperature. Such Arrhenius type of temperature dependence stems from the Boltzmann statistics and is typical for almost all dielectric materials.

C. Conduction due to charged particles

Considering electrical conduction of gases and liquids contribution from the movement of charged macroscopic impurities need to be considered; as for example minute metal particles, water droplets, and paper or textile fibers. If such a particle touches an energized electrode, it becomes charged at the same polarity as the electrode, repelled and then contribute to current when drifting towards the opposite electrode. The magnitude of the charge is increasing proportionally with the size of the particle and the applied electric stress. At steady-state conditions, a spherical particle with radius r will move at an average speed v determined by the Coulomb force $Fe = qE$

being equal to the friction force $F\eta = 6\pi\eta r v$ acting on the particle. In the case of uniform concentration of N particles per unit volume, the conductivity then becomes:

$$\sigma = \frac{j}{E} = A \frac{Nr^3 \epsilon_r^2 E^2}{\eta}, \quad (15)$$

where A is a constant determined by the dimensions of the moving particle and η is the viscosity of the oil.

Several experiments confirm such strong non-linear electric field dependence of oil [9]. The conductivity of oil σ , typically increases with increasing temperature, due to reduced oil viscosity at higher temperatures.

D. Electronic conduction

Conduction due to electrons is generally considered more complex, as the theoretical approach needs to be based upon the quantum mechanical energy band theory. In addition, electrons contributing to conduction may originate from several sources, making it necessary to combine energy band, intramolecular conduction, and intermolecular hopping conduction. It is, however, common to distinguish between so-called electrode- and bulk-limited conduction. Here, some selected theoretical models, used to evaluate electronic conduction with respect to the possible electric field and temperature dependence are presented [5,6,10].

1) *Modeling of energy band structure:* According to quantum physics, electrons can only be kept at specified energy states within certain energy bands. Within the valence band, electrons occupy all available levels. This means that electrons of a full valence band do not contribute to electrical conductivity, and an external electric field cannot change their energy and cause any net movement of electrons.

Above the top of the valence band, there is a region in which no free electrons can exist. This forbidden energy gap has a width of $\Delta W = W_{conduction} - W_{valence}$, that relate to the strength of the chemical bonds in the solid. It is as illustrated in Fig. 6, typically larger in insulators, 5–10 eV, than in so-called semi-conducting materials as Si, 1.1 eV, and Ge, 0.7 eV.

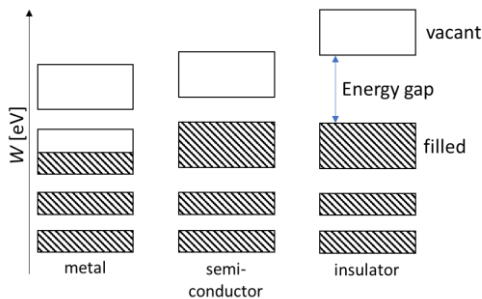


Fig. 6. Characteristic band structure of different materials.

In the case of metals, electronic conduction is dominated by the abundance of electrons free to move even at low temperatures, because nearly no excitation is required to bring electrons into vacant levels within the conduction band. Metals experiences, however, decreasing conductivity with increasing temperature. An effect caused by lattice vibrations and electron collisions with impurities. Semiconductors and insulators act very differently, as the numbers of electrons excited to the conduction band strongly increase at increasing temperature.

The excitation results in holes or empty electron states in the lower energy level (the valence band). Then electrons moving between these empty states, also contribute to the conduction current. The electronic conductivity of an insulating material can, thus, be written as a sum of contributions from both electrons and holes:

$$\sigma = n_0 q \mu_e + p_0 q \mu_h, \quad (16)$$

where n_0 and p_0 is the number of electrons and holes, q is the electronic charge, and μ_e and μ_h is the mobility of electrons and holes, respectively.

The equilibrium densities n_0 of electrons and p_0 of holes are governed by **Fermi-Dirac statistics**, which defines the occupation probability $f(E)$ of a level at energy E by the distribution function:

$$f(E) = \frac{1}{1 + \exp[(E - E_F) / kT]}, \quad (17)$$

where E_F is the Fermi Level, which corresponds to the energy level at which the probability of occupation by an electron is 50%. This expression shows that the occupation probability falls off exponentially for energy levels higher than E_F . Likewise, the probability of finding a hole, $p(E) = 1 - f(E)$, falls off exponentially as the energy E decreases below E_F , indicating that all electronic states are almost fully occupied.

From semiconducting technology, it is known that deliberate doping with impurity elements, can produce a large increase of conduction electrons or holes at any given temperature. There are, however, several characteristic differences between insulators and semiconductors:

- a) Practical insulators usually contain a higher number of different impurities, usually at unspecified concentration levels. One should, therefore, expect to have many energy states, including both donors and acceptors and traps in the forbidden gap.
- b) Insulating materials are partly, or completely, amorphous. The periodic lattice approach leading to the energy band theory, which has turned out to be very effective in the case of semiconductors, may not be directly applicable in case of amorphous materials.

Closer examinations show, however, that the energy band structure is mainly determined by the type of short-distance

order and binding mechanisms. In materials where the short distance order is not significantly changed in crystalline and amorphous regions, it is a good approximation to assume that the energy band theory is applicable even for amorphous materials [5.6]. It is therefore very likely that impurities and additives of insulators can act as donors or acceptors, resulting in several donor, acceptor or trap energy levels located within the forbidden gap.

2) *Modeling of electrode interface charging*: When contact is made between two different materials, there will always be movement and redistribution of electrons across the interface. This process of contact charging is governed by the energy levels of the different materials and runs until the difference in Fermi levels is balanced, and a contact potential is established -Thus electrons can also be injected to the conduction level from the metal electrodes kept in contact with the insulation.

It is common to distinguish between three different types of contacts [11]:

i) In the case of so-called *blocking contacts* all the donor levels close to the interface will be emptied up to a distance x_0 , resulting in a positively charged depleted layer, preventing electrons from leaving the metal if a negative voltage is applied to the metal, unless the electric field becomes so high that tunneling may occur across the depleted region.

ii) *Injection type* of contact is established if the work function of the metal is smaller than that of the insulator. At contact electrons will move from the metal to the insulator to reach equilibrium, establishing a layer of accumulated negative charge at the interface. In this case, there is no potential barrier from whichever side of the junction, and the current flow does not depend on the polarity of the applied voltage.

iii) The third, *Ohmic type* of contact, may be established if the Fermi levels are at the same potential with respect to the vacuum level. Then, there will be no degree of band bending, as illustrated in Fig. 7.

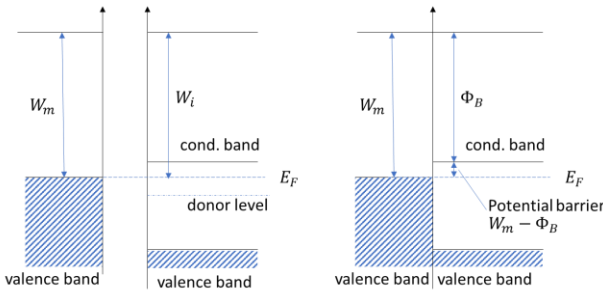


Fig. 7. Energy level diagram for a metal and an insulator with donor type impurities: a) before contact, and b) after contact. => Ohmic type of junction.

3) *Current due to “interface” – Schottky effect*: If the electronic current is limited by injection of electrons from the electrode, the so-called Schottky effect may dominate, particularly so at

high electric stress. This mechanism was described by Schottky [11] considering a section of a perfect insulator, kept between two equal metal electrodes with ohmic contacts. Because of the laws of electrostatics, an electron leaving a highly conducting metal surface will experience a mirror force trying to pull it back into the metal:

$$F = q^2 / 4\pi\epsilon_r\epsilon_0 (2x)^2. \quad (18)$$

According to the usual convention of electrostatics, the potential energy is zero far away from the surface, at $x = \infty$. Using this, the potential energy due to the mirror force F then modifies the energy diagram, using a linear extrapolation towards the Fermi level E_F at distances $x < 1 \text{ \AA}$. In case of a constant applied electric field, E , the total potential energy at a distance x will be modified accordingly, and the potential barrier will be at its maximum be reduced by a factor $\Delta\phi$:

$$\Delta\phi = |W(x_0)| = \frac{q^{3/2}}{(4\pi\epsilon_0\epsilon_r)^{1/2}} E^{1/2} = \beta_s E^{1/2}, \quad (19)$$

where β_s is called the Schottky coefficient.

Using the expression for thermal emission, the current density can be written as:

$$j = AT^2 \exp\left(-(\phi - \beta_s E^{1/2}) / kT\right), \quad (20)$$

where $A = 120 \text{ cm}^{-2}\text{K}^{-2}$ is the Richardson–Duchmans constant. Generally, this Schottky effect is lower in solids than in vacuum or gas, simply due to the higher permittivity ϵ_r of a solid. In case of $\epsilon_r = 4$, an applied stress E of 10 kV/mm (10^7 V/m) will give $x_0 = 30 \text{ \AA}$ and $\Delta\phi = 0.06 \text{ eV}$.

By plotting observed current values $\log j$ against the square root of the applied E-field, $E^{1/2}$, one should according to this get a straight, so-called Schottky line, from which the value of the Schottky coefficient and thus the permittivity ϵ_r of the material can be determined. In principle, it is also possible to experimentally determine the potential barrier ϕ by plotting $\log(j/T^2)$ as a function of $1/T$ at constant E-field.

4) *Current due to “bulk” – Poole-Frenkel effect*: In this case, it is assumed that at high E-fields the electronic current is limited by the amount of thermally excited conduction band electrons from donors. As in the above Schottky case, the potential barrier around the donors is lowered by the applied electric field, and the Coulombic force established between the electron and the ionized donor is in this case given by:

$$F = \frac{q^2}{4\pi\epsilon_0\epsilon_r x^2}, \quad (21)$$

where x is the distance of separation between the electron and the donor, as illustrated in Fig. 8.

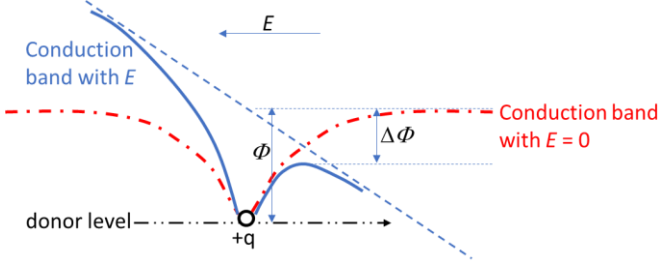


Fig. 8. Poole Frenkel effect: the modified shape of the potential barrier around a donor, with and without electric stress E applied.

The resulting current will, however, strongly depend upon the applied energy band structure. For simplification, an idealized case is here considered, where it is assumed that:

- i) The insulator has a wide forbidden energy gap containing donors only.
- ii) The donor states are located several eV below the conduction band.

Thus, the maximum height of the barrier, in the direction of the electric field, is reduced by:

$$\Delta\phi = \frac{q^{3/2}}{(\pi\epsilon_0\epsilon_r)^{1/2}} E^{1/2} = \beta_{PF} E^{1/2}, \quad (22)$$

where β_{PF} is called the Poole-Frenkel coefficient, and we see that: $\beta_{PF} = 2\beta_S$.

In order to determine the current ($j = n_c \cdot q \cdot v$), we need first to determine the number of electrons in the conduction band, n_c . A value, which is determined by the potential barrier and the position of the Fermi level. In case nearly all donor levels are filled with electrons (i.e., the Fermi level is higher than the donor level) the low number of electrons in the conduction band is equal to the number of empty donor states:

$$n_c = N_d - n_d, \quad (23)$$

where N_d is the total number density of donors, and n_d is the number of donor states occupied by electrons. This latter number is given by Fermi-Dirac statistics, and the expression obtained can be used to determine the position of the Fermi level E_F :

$$\frac{E_F}{kT} = 1/2 \ln \frac{N_d}{N_c} + \left(\frac{E_d + E_c}{2kT} \right). \quad (24)$$

Using the assumption of a large energy gap between the conduction band and the fermi level, $E_c - E_F \gg kT$, the number of electrons in the conduction band, without electric field applied, becomes:

$$n_{c0} = N_c \exp\left(-\frac{E_c + E_F}{kT}\right). \quad (25)$$

Inserting the above expression for the Fermi level gives:

$$n_{c0} = \sqrt{N_c N_d} \exp\left(-\frac{E_c + E_d}{2kT}\right) = \sqrt{N_c N_d} \exp\left(-\frac{\phi}{2kT}\right). \quad (26)$$

According to the above Poole-Frenkel deduction, the effect of applying an electric field is to modify the potential barrier according to:

$$\Phi_{eff} = E_c - E_F = \phi - \beta_{PF} E^{1/2}. \quad (27)$$

Thus, the number of electrons in the conduction band will increase with increasing applied electric field E according to:

$$n_c = \sqrt{N_c N_d} \exp\left(-\frac{\phi - \beta_{PF} E^{1/2}}{2kT}\right). \quad (28)$$

If we assume that these electrons all move a specified distance d , independent of the applied electric field, before being trapped by ionized donors, the drift velocity becomes constant. In this case, the current can be expressed as:

$$I = I_0 \exp\left(\frac{\beta_{PF} E^{1/2}}{2kT}\right). \quad (29)$$

Due to scale factor 2 in the denominator and the fact that $\beta_{PF} = 2\beta_S$, the slope of a $\log I = f(E^{1/2})$ plot will, in this case, be the same as that of the Schottky mechanism.

However, situations might occur where the slope and the E-field dependence is expected to become twice that of the Schottky effect. This applies, for example, in case of an energy model shown in Fig. 9.

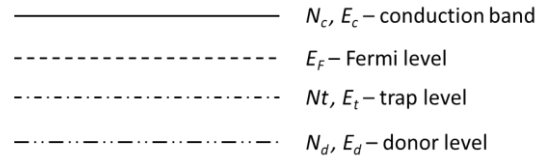


Fig 9. The energy model of an insulator containing both donors and nearly filled trap levels.

The assumption of both donors and traps (N_d and N_t) being present at energy levels below the Fermi level imply that nearly all donors and traps are filled with electrons. If the density of donors is much higher than that of traps ($N_d \gg N_t$), it is reasonable to assume that nearly all the traps are filled by the electrons excited from the donor level. Thus, the position of the Fermi level is determined according to:

$$N_d - n_d \approx n_t \approx N_t. \quad (30)$$

The number of electrons in the conduction band, without applied electric field, is then determined according to Fermi Dirac statistics, and the current becomes:

$$I = I_0 \exp\left(\frac{\beta_{PF} E^{1/2}}{kT}\right). \quad (31)$$

In this case, the slope of a $\log I = f(E^{1/2})$ plot becomes twice of that deduced in case of no traps. Thus, it should, in principle, be possible to distinguish between a Schottky and a Poole Frenkel mechanism. It is, however, generally difficult to distinguish between these two mechanisms in practice as the experimental data may fit both mechanisms. The best is, therefore, to examine whether the current appears to be bulk or electrode limited, by systematically varying the insulation thickness or the electrode area.

5) *Space charge limited conduction*: Space charge limited current is typically found in thin insulating films, in good (injection type) of contact with the electrodes. This means that when a voltage is applied, a reservoir of electrons may build up in the insulation. The electric field set up by this space charge may then become the limiting factor controlling the current between the electrodes. Whether this happens or not, will depend on the density of charge, type of charge, its mobility, the injection properties of the electrodes, and the trapping properties of the insulation.

An **ideal insulator** will by definition be without both donors and traps, and at low applied voltage, there is an only little amount of free electrons in the conduction band. At the cathode, electrons are easily injected into the conduction band, forming a cloud of space charge close to the electrode. This process will continue until the effective electric field at the cathode equals zero. Thus, assuming a parallel plate electrode arrangement, the charge total Q is given by:

$$Q \approx C \cdot V = \varepsilon_r \varepsilon_0 V/d, \quad (32)$$

where C is the capacitance per unit area, and ε_r is the relative permittivity of the insulation, and d is the insulation thickness.

The current density, $j = n_c q \cdot v = \rho \cdot v$, can alternatively be expressed as $J = Q/t$, where Q is the total injected free charge per unit area, and t is the transit time needed for an electron to pass from the cathode to the anode:

$$t = \frac{d}{v} = \frac{d}{\mu E} = \frac{d^2}{\mu V}, \quad (33)$$

where $E = V/d$ is the electric field stress and μ is the mobility of the electrons in the conduction band.

The current density J is then found by combining these relations:

$$J = \varepsilon_0 \varepsilon_r \mu \frac{V^2}{d^3}. \quad (34)$$

The space charge will be distributed within the insulation. If this is considered, the current density needs to be multiplied by a correction factor of 9/8. Thus, it is a good approximation to assume that most of the injected charge is located close to the cathode. These expressions clearly demonstrate that the Space Charge Limited (SCL)—current is increasing with the square of the applied voltage and may strongly contribute in case of testing thin insulating films at high voltage. -Thus, care must be taken when comparing data of conduction values obtained using thin laboratory samples to that of thicker high voltage insulation systems.

In a somewhat more realistic model, also the thermally excited electrons from the bulk of the insulation should be considered. These electrons are excited directly to the conduction band from donor levels located just under the conduction band. They are free to move and will, therefore, not contribute to the space charge of the insulation. The current contribution from these thermally generated electrons, assuming a density n_c , can be expressed as:

$$J = n_c q \mu E = n_c q \mu (V/d). \quad (35)$$

These electrons will result in an ohmic current, which will dominate at voltages below:

$$V < \frac{n q d^2}{\varepsilon_r \varepsilon_0}. \quad (36)$$

If the donor is replaced by traps (or acceptor) levels located below the conduction band, some of the electrons injected from the cathode will become captured in these traps and unable to contribute to the current.

The total injected space charge Q_t , per unit area, will then constitute a mobile charge Q_c and an immobile trapped charge Q_t :

$$Q_t = Q_c + Q_t \approx C \cdot V = \varepsilon_r \varepsilon_0 \frac{V}{d}, \quad (37)$$

while the current density is given by the mobile charge $J = Q_c/t$ only. The challenge is then to determine the magnitude and ratio $\theta = Q_c/Q_t$ of the mobile versus the trapped charge.

Several models, considering both so-called shallow and deep traps are usually considered. Traps are considered shallow if their energy bands E_t are located above the Fermi level E_F and deep in the case of $E_t < E_F$. - This means that shallow traps are only partly filled by electrons at low applied voltage. The effect of increasing the applied electric stress is to increase the number of injected electrons in the insulation, subsequently filling the traps. The traps then become deep, characterized by an energy level below the Fermi-level.

The schematic graphs shown in Fig. 10 indicate that the current is expected to increase abruptly with voltage when such trap filling occurs.

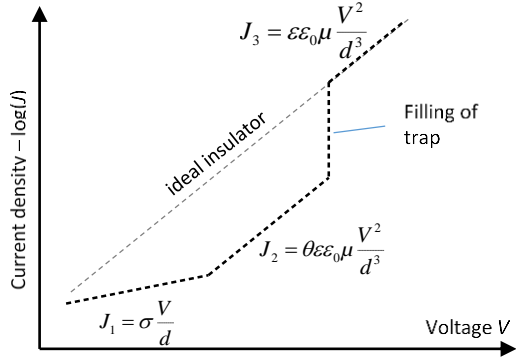


Fig. 10. Current density versus voltage in case of space charge limited current, in case of (a) an ideal insulator and (b) an insulator with shallow traps.

IV. PERMITTIVITY AND DIELECTRIC LOSS

In the design of high voltage AC insulation systems, low permittivity and the dielectric loss are usually the most important parameters.

Low permittivity is usually preferable, as the capacitive load current of, for example, a long cable, should be kept as low as possible. In other cases, high permittivity is desirable, for example, when a compact condenser is to be designed. In mixed insulation systems, as oil-impregnated insulation, the ratio of the permittivities are selected in such a way that optimum AC electric field distribution is obtained.

In addition, it is desirable to use insulation with low dielectric loss, to ensure that the heat generated in the insulation is kept below critical limits. This is particularly important at the highest system voltages, where the insulation thickness is large, and the transport of heat may become a limiting factor as the heat generated by the current load of the conductor also need to be transported through the insulation.

1) *Polarization and loss mechanisms*: The polarization of a dielectric is generally determined by several time-dependent and sometimes also by electric-field-dependent phenomena; making it a frequency and voltage-dependent quantity. Electronic and ionic polarization takes place at high frequencies and will not result in a permittivity larger than about 2.5.

Orientation polarization arises if molecules with permanent dipoles can rotate to align with the applied electric field. This mechanism particularly contributes to polarization in gases and liquids and sometimes also in solids.

The so-called space charge or interface polarization is a mechanism of most practical relevance at power frequencies. This type of polarization occurs due to movement of ions and other charge carriers, causing the buildup of space charge in the bulk of the insulation or at interfaces. Thus, this mechanism particularly contributes to the polarization of mixed insulation systems at the power and even at low frequencies. Filled epoxy and paper-oil insulated systems are examples of practical insulation systems, where this polarization mechanism plays an active role at AC 50 Hz service stresses.

If a time-varying electric field, $E(t) = E_0 \cos(\omega t)$, is applied across a dielectric, the resulting polarization will lag behind the applied electric field. This phase shift can mathematically be expressed as a phase lag δ in the electric displacement:

$$\begin{aligned} D(t) &= D_0 \cos(\omega t - \delta) \\ &= D_0 \cos \delta \cos(\omega t) - D_0 \sin \delta \sin(\omega t). \end{aligned} \quad (38)$$

In complex vector form, selecting the applied electric field E along the real axis, this can be written as:

$$D = D_0 \cos \delta - j D_0 \sin \delta = \varepsilon^* \varepsilon_0 E = \varepsilon' \varepsilon_0 E - j \varepsilon'' \varepsilon_0 E \quad (39)$$

Leading to the definition of the real and imaginary part of the permittivity: $\varepsilon' = \frac{D_0 \cos \delta}{\varepsilon_0 E_0}$ and $\varepsilon'' = \frac{D_0 \sin \delta}{\varepsilon_0 E_0}$.

Relations linked by the loss angle δ : $\tan \delta = \frac{\varepsilon''}{\varepsilon'}$.

The complex permittivity ε^* can then be written as:

$$\varepsilon^* = \varepsilon' - j \varepsilon'' = \varepsilon' (1 - j \tan \delta). \quad (40)$$

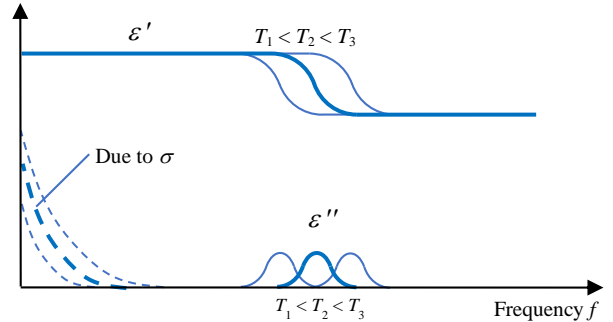


Fig. 11. Schematic illustration of relative permittivity and dissipation factor dependent on temperature, frequency, and conductivity.

2) *Dielectric loss due to conductivity*: An insulation can be regarded as a non-conducting (ideal) dielectric with resistance in parallel. The equation describing the resulting apparent complex permittivity, ε_a^* , of such a conducting dielectric, then becomes:

$$\begin{aligned} \vec{J} &= \frac{d\vec{D}}{dt} + \sigma \vec{E} = j\omega \varepsilon_0 \varepsilon_a^* \vec{E} + \sigma \vec{E}, \\ \varepsilon_a^* &= \varepsilon' - j \varepsilon'' = \varepsilon' + \frac{\sigma}{j\omega \varepsilon_0} = \varepsilon' - j \frac{\sigma}{\omega \varepsilon_0}. \end{aligned} \quad (41)$$

Due to the latter contribution from conduction, the dielectric loss factor is as indicated in Fig. 11, expected to strongly increase at low frequencies ($\omega \rightarrow 0$):

$$\tan \delta = \frac{\sigma}{\omega \varepsilon_0 \varepsilon'}. \quad (42)$$

3) *Dielectric loss due to interface polarization*: As addressed above, insulation systems very often consist of a mix of different dielectric materials. The example below considers a two-layer dielectric consisting of equally thick materials ($d_1 = d_2$) where ohmic conductivities are the only loss-mechanism involved. The complex permittivity of each layer then becomes:

$$\varepsilon_1^* = \varepsilon_1' - j \frac{\sigma_1}{\omega} \quad \text{and} \quad \varepsilon_2^* = \varepsilon_2' - j \frac{\sigma_2}{\omega}. \quad (43)$$

The resulting permittivity of the layered insulation will then vary with frequency according to:

$$\varepsilon' - j\varepsilon'' = \frac{\varepsilon_1' \cdot \varepsilon_2'}{\varepsilon_1' + \varepsilon_2'} + 2 \frac{\frac{\sigma_1 \varepsilon_2' + \sigma_2 \varepsilon_1'}{\sigma_1 + \sigma_2} - \frac{\varepsilon_1' \cdot \varepsilon_2'}{\varepsilon_1' + \varepsilon_2'}}{1 - j\omega \frac{\varepsilon_1' + \varepsilon_2'}{\sigma_1 + \sigma_2}}. \quad (44)$$

It is here assumed that σ_1/ω and σ_2/ω are small quantities compared to the real part of each permittivity, ε_1' and ε_2' .

This expression describes a single relaxation polarization process with a time constant:

$$\tau = \frac{\varepsilon_1' + \varepsilon_2'}{\sigma_1 + \sigma_2}. \quad (45)$$

This slow interface polarization mechanism was first presented by Maxwell in 1892. It shows that during the application of AC voltage, polarization will occur due to charges accumulation at the interfaces between the layers. It also shows that if the ratio of the conductivities is equal to that of the permittivity ($\varepsilon_1/\varepsilon_2 = \sigma_1/\sigma_2$) there will be no loss due to interface polarization.

In paper-oil insulation, for example, the ionic charge is expected to accumulate at the interface. If each insulating layer is thought of as very thin, down to the microscopic scale, the space charge can be considered as ions moving only a few atomic distances, or even as dipoles rotating in the field. In 1914, Wagner gave an approximate calculation of the resulting complex permittivity of insulation with inclusions of conductive impurities. In this approach, the impurities were considered as small spheres, with dielectric constant ε_2 and conductivity σ_2 , distributed by volume fraction f in the dielectric matrix with permittivity ε_1 .

The relations show that the relaxation time decrease as the conductivity of the impurities increases. For example, taking $\varepsilon_1' = \varepsilon_2' = 3$ and $\sigma_1 \ll \sigma_2 = 10^{-4} (\Omega\text{m})^{-1}$, the dielectric loss will show a peak at about 210 kHz. This means that the Maxwell-Wagner-interface effect can easily be mistaken for dipole orientation polarization. In the case of insulations consisting of several layers, with low conductivity, the maximum loss may occur at frequencies below 50 Hz, with measurable contributions at power frequency.

V. DEGRADATION AND AGEING

According to IEC TC63 ageing of high voltage insulation systems is defined as: "Irreversible deleterious change to the serviceability of insulation systems. Such changes are characterized by a failure rate that increases with time." This section gives a brief overview of some physical and chemical mechanisms, causing ageing during both dry and wet service condition.

A. Effects of voids and particles – electrical treeing

Under dry service conditions, inherent contaminants as voids, additives, and particle inclusions are the main factors causing gradual degradation and pre-breakdown phenomena [12]. High local field enhancement within voids, at the tip of conductive inclusions and electrode protrusions, can result in the initiation of partial discharges and growth of tiny, partly conductive, tubular channels, typically forming tree-like structures as shown in Fig. 12. During the growth process, which typically takes from seconds to several hours and days PD activity will vary with time, side branches will form, and the tree structure will widen to the shape of a bush, gradually increase in length and eventually lead to an electric breakdown.

During service at high temperatures, oxidation and other thermal degradation processes may occur. To prevent such ageing, antioxidants and stabilizers are usually added to the insulation systems. Anyway, such additives react and deplete during service, limiting the serviceability and lifetime of the insulation.

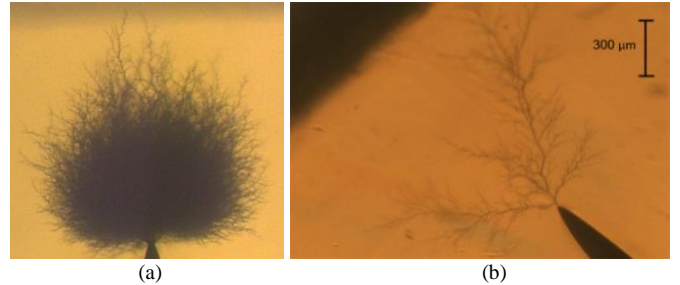


Fig. 12. AC electrical trees formed at the tip of needles enclosed in XLPE cable insulation: (a) at 50 Hz and (b) at 0.1 Hz.

B. Effects of water absorption – water treeing

In the 1970s, XLPE insulated cables in a wet environment started to fail prematurely after less than 10 years of service. Microscopy examination of failed cable samples revealed that water-filled tree structures, denoted water trees, had formed within the insulation. A prerequisite for the development of such water trees is that dissolved water is absorbed, above a certain critical concentration, in the energized polymeric insulation. Then, temperature variations in synergic effects with the applied electric stress enhance condensation forming liquid water within the insulation. Water trees typically grow in the direction of the electric field, and it has not been possible to detect partial discharges or emission of light during the

initiation and growth of the water tree. Water trees are usually classified into two types, determined by their initiation site, examples of which are shown in Fig. 13.

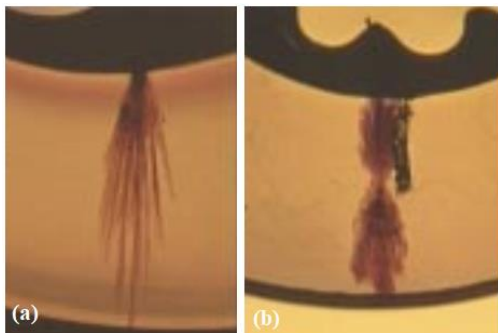


Fig. 13. Examples of water trees observed in service aged XLPE 12 kV cables: a) Vented water tree and b) bow-tie water tree.

Bow-tie trees start from a specific location such as contaminants voids etc. within the insulation while **vented trees** initiate at the interface between the insulation and semiconductor/electrode.

During condensation and formation of water droplets at nuclei impurities, mechanical pressure is exerted on the polymer surrounding the water-filled void. Theoretically, it has been shown that a saturation ratio of 1.06 is sufficient to cause crazing of the surrounding polymer [13]. Then, due to Maxwell mechanical forces, it is reasonable to expect enhanced growth of water-filled channels (crazing zones), directed parallel to the applied electric stress.

These low-density water-filled crazing zones mainly form within the mechanically weaker amorphous regions. Thus, any physical or chemical mechanisms increasing the mechanical endurance, or the crazing resistance of the insulation may also increase the water tree resistance of the polymer.

However, at 50 and 60 Hz, water trees have been found to grow in all types of polymeric insulation, even at low electric field stresses of about 1 kV/mm. Therefore, water treeing is considered one of the main ageing phenomena of polymeric insulation systems exposed to humidity. At steady-state high voltage DC stress it has, however, not been possible to detect water tree growth [14], an observation in accordance with the different electric field distribution and Maxwell force acting at the tip of a water-filled channel during DC stress.

At the final stage of degradation, electrical trees may initiate within the water-treed regions due to either service stress or transient overvoltage. Subsequently, an electric breakdown may follow shortly after such PD and electrical tree formation. Thus, during ageing in a wet environment, water-tree degradation reduces the withstand strength at a higher rate than in case of dry service conditions without partial discharge activity. At higher system or transient overvoltage, it is reasonable to assume that the transition from a water tree to an

electrical tree can take place even before water trees have bridged the insulation wall.

VI. CONCLUDING REMARKS

High voltage insulation systems, typically, constitute combinations of different insulating gasses, oils, and solids. Experience shows that important characteristic properties as electric breakdown strength, electric conduction, dielectric loss, and endurance are limited by minute amounts of additives, voids, particles, and other impurities, embedded in the insulation or at electrode interfaces. The term “insulating material” has no meaning unless its molecular microstructure, crystallinity, and content of byproduct from the manufacturing process and other additives are clearly defined.

The probability of electric breakdown of an insulator where weak defects are distributed evenly within the insulation is described by extreme value statistics. In practice, electrical conduction current is caused by contributions from moving ions, charged particles, and electrons. At moderate and high electric stresses, these charge carriers result in a different and highly non-linear increase in current versus applied voltage. In the case of thin insulating layers, contributions from electronic conduction strongly depend upon the quantum mechanical energy model of the interface between the electrodes and the insulation. Interface charging and conductivity may contribute to permittivity and dielectric loss, even at power frequencies. Voids and particle inclusions act as starting points for partial discharge and electrical treeing, resulting in a premature electric breakdown. Absorption and condensation of water may lead to slow water tree degradation and reduced serviceability of polymer insulated cables.

In order to advance the science of high voltage insulation engineering, a fundamental approach is needed to understand and utilize the complex physical mechanisms governing and limiting the insulating properties.

ACKNOWLEDGMENT

During the preparation of this paper, I received practical help and fruitful comments from supportive colleagues and PhD students. Appreciation is particularly extended to F. Mauseth, E. Kantar, T. G. Aakre, and G. Håkonseth.

REFERENCES

- [1] F.H. Kreuger, "Do materials exist?" Nordic Insulation Symposium, Vasterås, June 15-17, 1992.
- [2] H.Okubo, "Enhancement of Electrical Insulation Performance in Power Equipment Based on Dielectric Material Properties," IEEE Trans. Dielectr. Electr. Insul., vol. 19, no. 3; June 2012.
- [3] E.J. Gumbel, "The Maxima of the Mean Largest Value and of the Range," Ann. Math. Statist., vol. 25, no. 1, pp. 76–84, 1954.
- [4] W.A.Weibull: "Statistical Distribution Function of Wide Applicability," J. Appl. Mech. Vol. 18, pp. 293–297, 1951.
- [5] K.C. Kao, "Dielectric Phenomena in Solids," Elsevier Academic Press, 2004.
- [6] A.R.Blythe and D.Bloor, "Electrical Properties of polymers," Cambridge University Press, 2005.

- [7] A. Doi, "Review: Ionic conduction and conduction polarization in oxide glass," *J. Material Science*, vol. 22 , pp. 761–769, 1987.
- [8] G.R. Govinda Raju, "Electrical conduction in aromatic polyamides," *Proc. 19th Electrical Electronics Insulation Conf.* 1989.
- [9] M. Dong, L. P. Shen, H. Wang, H. B. Wang, and J. Miao, "Investigation on the Electrical Conductivity of Transformer Oil-Based AlN Nanofluid," *Hindawi- Journal of Nanomaterials*, Article ID 842963, 2013.
- [10] J.M-Vega, "Dielectric Materials for Electrical Engineering," John Wiley, 2010.
- [11] L.Solymar and D.Walsh, "Lectures on the electrical properties of materials," Oxford Univ. Press. 1985.
- [12] L. A. Dissado and J. C. Fothergill, "Electrical Degradation and Breakdown in Polymers," *IET*, 1992.
- [13] S. Hvidsten, E. Ildstad, J. Sletbak, and H. Faremo, "Understanding water treeing mechanisms in the development of diagnostic test methods," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 5, no. 5, pp. 754–760, 1998.
- [14] E.Ildstad, "High Voltage AC and DC Aging of an XLPE Distribution Cable in Wet Environment," *Nord-IS 1988*, Trondheim, Norway.