ZVEI: Die Elektroindustrie

Failure Reasons for Insulations

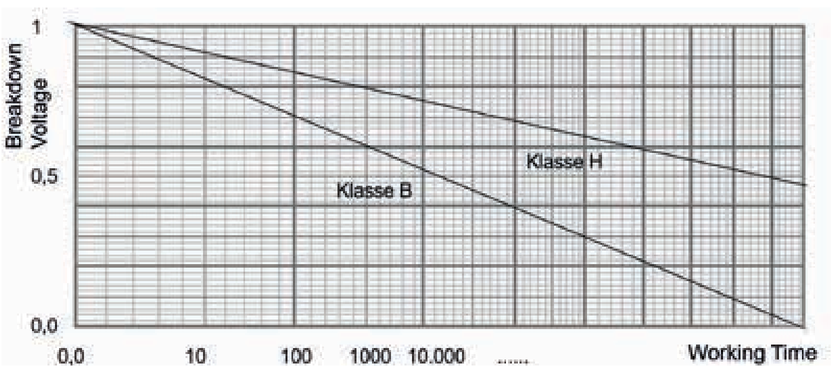
February 2016

The breakdown voltage in technical data sheets shows the engineer at which voltage the insulation material fails. Tacitly knowledge is assumed that this value is valid only in "new condition".

For testing the break down voltage, or in other words the penetration through the insulation material a voltage increase of 500V/sec. is commonly used. The breakdown voltage is then indicated as e. g. kV/mm standardized to the thickness.

However insulation capability of a material decreases during the operation of the device due to a variety of negative influences. Generally depending on the application of the material, more than one of these factors have to be considered during engineering.

Focusing on the electrical insulation films, following description of influencing factors can be used as a guideline:



Half the breakdown voltage according to UL 746 at 130 °C (Quelle: CMC)

1. Temperature

By increasing temperature, also the corrosive and oxidative effects on the insulation are increased. The speed of these degradation processes is not linear to the temperature and follows the so-called Arrhenius plot.

A general and simplified rule used in the electronics industry describes a halving of the lifetime by increasing the operation temperature by 10 °C.

Insulation materials are categorized in thermal classes according to standards such as IEC 60085 (e. g. B = 130 °C, F = 155 °C, H = 180 °C). These classes specify the continuous operation temperature of the insulation materials assumed that still 50 percent of the initial breakdown voltage after 20,000 hours is retained.

In other words this means that a material has lost half of its protective function against an electric shock after only two and a half years at maximum temperature permitted.

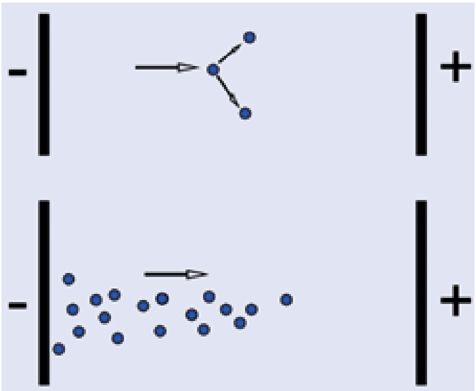
If a longer lifetime has to be achieved at a given operating temperature, insulation materials of a higher thermal class have to be used. The usual end-of-life criterion of "half the breakdown voltage" is reached much later in this way.

Regarding the maximum thermal exposure additional thermal influences as, for instance, heat accumulation within windings, highest possible ambient temperature and possibly occasionally appear-ing malfunctions have to be considered.

Other materials such as moulding compounds, coatings and impregnating resins which are used as insulation can become brittle due to heat, shrink or get stress cracks. Also weathering together with heat leads to an earlier failure of these materials.

2. Voltage (stress, partial discharge)

Starting from 400 V corona discharge occurs. By the resulting field strength free electrons are accelerated to an extent that they throw more charge carriers from their stable position. A charge carrier avalanche develops which then leads to a partial discharge (Corona or sliding discharge).



Charge carrier avalange by impact ionization (Source: CMC)

In circuits of modern devices such as power supply units, filter components and power module drives, repeating high-energy pulses (switching pulses) occur. They have short rise times and peak voltages significantly above the nominal value of the supply voltage.

These pulses lead to another way of ageing of insulation systems than under conventional line frequency alternating voltage:

- Partial discharges destroy the insulation by aggressive degradation products, UV radiation and ozone.
- Electro-mechanical fatigue due to the current pulse.
- The electrical heating caused by the high frequency components of the voltage pulses.

Even if the nominal voltage is below the PD inception voltage such superimposed pulses can ignite partial discharges. In this case temperature, air humidity, as well as the shape, polarity and repetition rate of the pulse affect significantly the degradation speed of the materials.

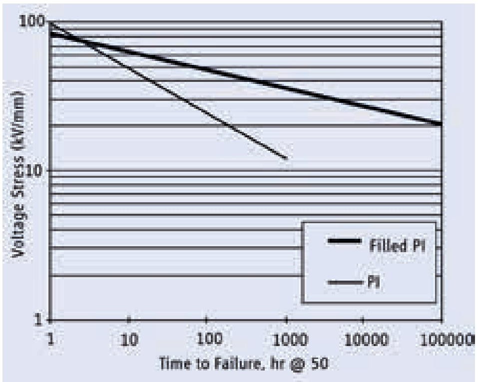
An adequate distance to the partial discharge extinction voltage is therefore always advisable. This can be achieved – in addition to constructive measures – by the use of sufficiently high voltage-resistant insulations (e. g. higher dti [distance through insulation]).

Triggered PD even below PD inception voltage operation conditions (Source: CMC)

If the risk of partial discharges cannot be excluded, materials that are particularly PD-resistant are used. This includes all inorganic insulation materials such as glass, ceramic or natural mica mineral. These materials are not damaged by corona discharges. An increased corona resistance in composite flexible materials such as e. g. Nomex® aramid paper type 818 is achieved by the addition of fine mica platelets. With manufacturer-specific solutions the corona resistance of high voltage machines (generators, motors) can be improved. Of course, this also applies for the insulation assembly of motors which are operated with frequency converters (inverters).

In large systems (motors, generators and distribution transformers) you can use semi conductive materials to avoid this sliding and Corona discharge as much as possible. Furthermore, the electrical field may be formed in this way to the extent that no electric flux line concentrations can arise.

For smaller sizes it is recommend the use of Kapton® CR or fluoropoymers such as e. g. FEP. With Kapton® CR the PD resistance is drastically increased by the addition of inorganic materials to the polymer mass. Fluoropolymers impress with their low reactivity, however, they have other disadvantages (ductility, cold flow).



Lifetime difference between Kapton® HN and Kapton® CR with exposure to partial discharges (Source: DuPont)

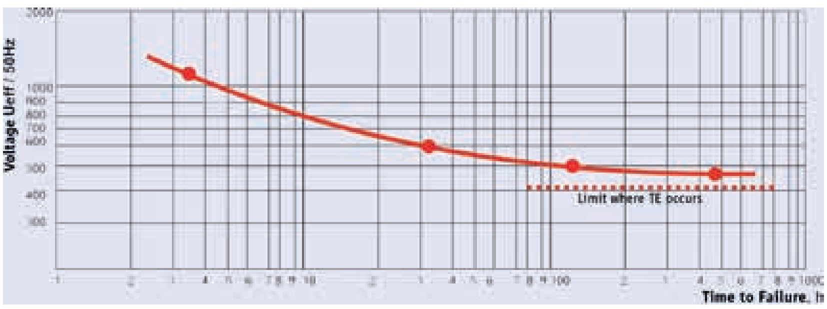
Just like in the previously outlined effect of temperature, in this case as well the use of a higher quality foil (e. g. a class F foil instead of class B, Kapton® CR instead of Kapton® HN or 50 µm instead of 25 µm foil thickness) significantly improves the time to failure. The dielectric strength remains above the voltage during continuous operation under partial discharge regime, for an extended time.

In IEC 60343 (Recommended test methods for determining the relative resistance of insulating materials to break-down by surface discharges; similar but not identical to ASTM 2275) the test set-up is chosen in a way that a failure of the samples happen between 100 hours and 1,000 hours. From the results you can then extrapolate the time to failure at a lower voltage stress. Another important standard on this subject is DIN IEC / TS 61934 (Electrical measurement of partial discharges (PD) at repeating voltage pulses with short rise time).

However, avoiding partial discharges in the insulation system remains the first priority in the design of electrical equipment despite improved insulation materials. The UV light resulting from such Corona discharges, the aggressive degradation products as well as the reactive ozone affect the surrounding materials in general and not only the directly concerned foil.

Note 1: Measuring the level of PD in an electrical component is a common method of production monitoring today.

Note 2: Positive or negative DC voltage stresses insulation materials in different ways. No losses occur by the alternating field. Nevertheless partial discharges may occur. Furthermore, a material migration is possible.



Time until Kapton® achieves the PD inception voltage under voltage stress (Source: DuPont)

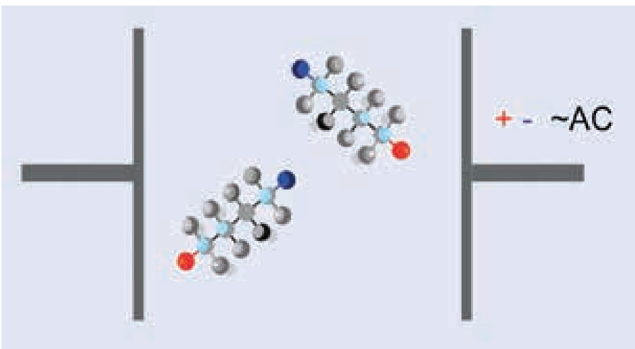
3. Frequenz

In a large number of "electric" basic standards usually measurements are done with a sinusoidal voltage at 50 Hz. However, modern switch power supplies operate with significantly higher frequencies. Thus the stress on the insulation material increases.

Excursion: The electrical variable "voltage" makes a statement about the power which is necessary to move a unit of electric charge. And this "work" is applied more and more frequently to the insulation materials at increasing alternating frequency. The result is a mechanical stress and "frictional heat". Non-polar materials such as ceramics or glass are only slightly affected. The organic insulation foils such as PE, PP, PET, PA, PI etc. are however more or less polar.

The complex polymer chains form dipoles which try to align themselves with the external electric field. This results in a mechanical stress and "frictional heat" inside the material. The consequence is a decreasing dielectric strength.

In the high-frequency welding technology these polarity reversal losses in the material are utilized for melting the plastic (dipoleplastics such as PVC, PA and acetates; high dielectric losses). Roughly one can say that the higher the applied electric field and the higher the frequency, the more thermal energy is entered into the material.



Repolarization losses in insulation materials (Source:CMC)

What is desired in welding is damaging an insulation foil in continuous operation; Because this "internal" heating often remains unnoticed on ageing considerations and is not covered by conventional standard measurements (e. g. UL 746).

Material	Dielectric dissipation factor; (x10e-4)	
	50 Hz	1 MHz
PTFE	0,5	0,7
PP	2,5	3,5
PI	3	11
PET	20	210
PVC	120	300
PA (humid)	3900	1300

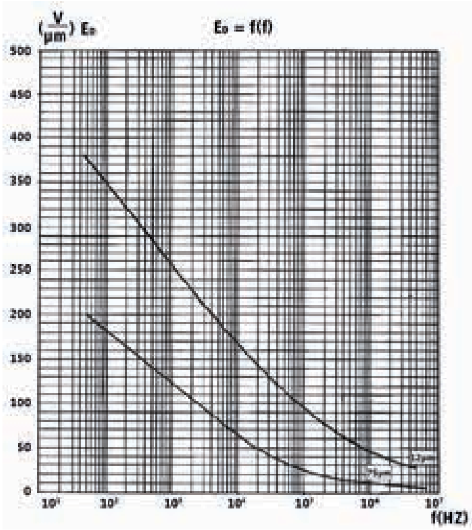
Overview of some insulation substances and their dissipation factor in the electrical alternating field at two different operating frequencies

Today, the use of frequency converter and switch power supplies stresses insulations increasingly, since motor controls or e. g. computer power supplies are using pulse-width controlled voltages in the range of 20 kHz and above.

The resulting harmonics have frequencies up to far above 15 MHz and due to e. g. resonances and inductive or capacitive coupling peak voltages far above the operating voltage occurs.

The high switching speeds dv/dt considerably stress the insulation materials used (power dissipation within the material: $P_{diel} = U^2 \times \omega \times C \times \tan \delta$). Additionally, wave reflection, standing waves and retroactive effects from the energized device can cause further stress for the insulation. In addition, the stress is increased by the capacitive coupling, e. g. from phase to ground or phase to phase.

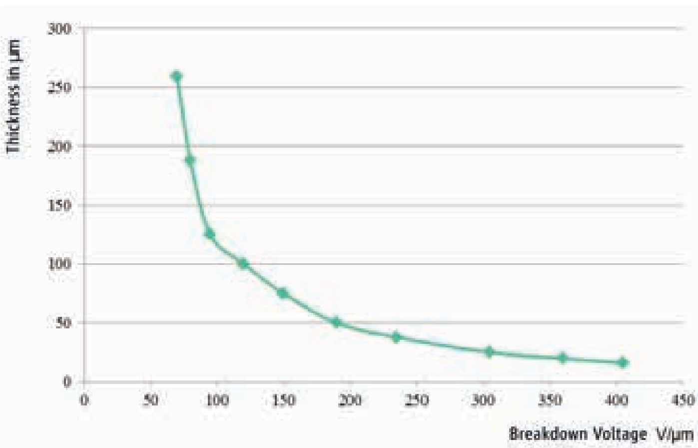
The following diagram shows this relation for polyester films:



Dependency of the breakdown voltage vs. frequency
(Source: Hoechst)

The breakdown voltage for electrical insulation materials is specified in many data sheet based on an operating frequency of 50/60 Hz sinusoidal AC current. As shown above, many of the standard insulation films show a reduced breakdown voltage at higher frequencies. It should be noted furthermore that the standardized breakdown voltage doesn't grow linearly with increasing thickness of the foil. Instead, the break-down voltage in V/µm is significantly lower at a greater thickness due to the losses within the material.

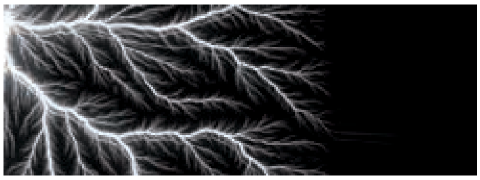
Conclusion: Besides the ageing due to temperature and the weakening of the material by partial discharges the applied frequency significantly determines the considerations for designing an electrical device.



Breakdown voltage vs. material thickness of polyester foil (Bsp.: PET, Source: CMC)

4. Soiling (Environment)

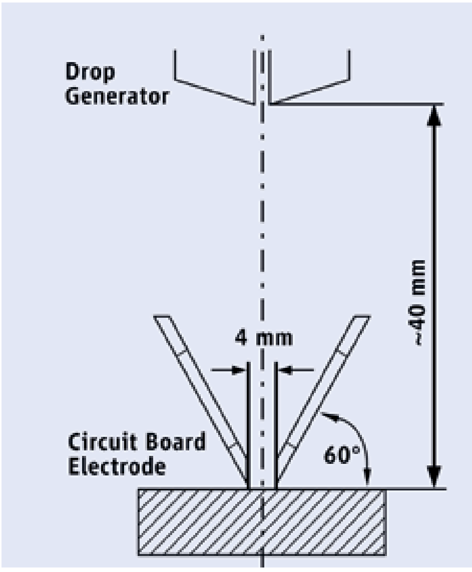
If surfaces of insulation materials are soiled by humidity and dust conductive pathways occur slowly but surely with incipient sliding discharges. They consist of carbonated remains of the soiling and the destroyed insulation substance. These conductive pathways are spreading further mostly in ramifications (treeing) and in the end they can lead to failure of the insulation.



Formation of a conductive path on or in insulation materials
(Source: CMC)

An important aspect is the potential water absorption of the insulation material, as it accelerates the destruction even within the material. Certain products which are produced by means of polycondensation (e. g. polyester foils) can even be damaged relatively quickly by hydrolysis in case of existing humidity and temperatures above 80 °C.

To be able to indicate how easily a material tends to form conductive pathways on the surface you use the so-called CTI value. The comparative tracking index is measured as follows: Two electrodes are placed on the surface to be measured. A conductive saline solution is added dropwise in between and a voltage is applied. That voltage at which the surface of the material is being damaged by flashover then classifies it into one of six stages.



Measuring the CTI value on insulating materials (Source: UL 746)

This particular combination of sliding discharge and soiled surface leads to an even faster destruction of the insulation material compared to dry partial discharges. Especially for electrical devices used in the outdoor area with the risk of water condensation, increased distances have to be observed (see e. g. IEC 61558).

5. Constructive measures

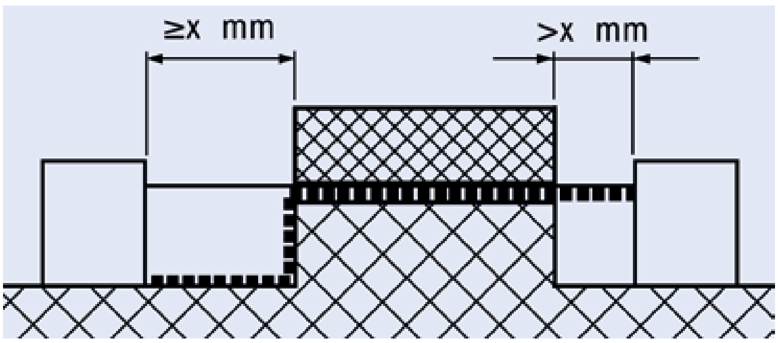
There are several ways to ensure the electrical safety even after thousands of hours of operation.

The increase of air and creepage distances contributes as an essential protection that even with aged insulation materials and accordingly reduced dielectric strength nothing happens. The required air and creepage distance is all in all a function of CTI, soiling degree, overvoltage category, frequency and area of use (domestic, industrial, medical).

In addition, you can for example make the design more fault tolerant. Relatively simple but highly effective often is the use of an insulation material of the next higher insulation or CTI class. The time to failure can normally be increased by at least twice by doing this.

Moreover, the quality of the materials used is a determining factor for the performance over the entire operating time. For example, the thermal stability of a polyimide foil clearly depends on the production process. The same chemical designation does not automatically mean the same characteristics.

Finally, of course also the mechanical stresses during processing and possible preliminary damages by test methods for production verification (e. g. high-voltage test) determine the lifetime.



Increase of air and creepage distances to avoid age-related breakdowns (Source: EN 61558)

6. Other potential causes

Temperature, voltage stress, unfavourable material properties and partial discharges are certainly the strongest degradation mechanisms of polymers. However, there are other factors that may play a role depending on the application.

Nearly all plastics can be damaged by radiation (UV-light, radioactivity). The high-energy radiation destroys the polymer chains and leads e. g. to a lower mechanical strength.

Something similar can happen with plastics such as polyester, polyamide and polyimide by the so-called hydrolysis. In this case the bonds of the polymer chain are split by the dipole H_2O at a sufficiently high energy (e. g. water vapour at 90 °C).Tests with 50 µm thick polyester foils have shown that even after 1,500 hours at 85 °C/85 percent relH the mechanical strength is almost lost. The foil breaks in a buckling test (IEC 61234, Method of test for the hydrolytic stability of electrical insulating materials).

The so-called "motorette test" (e. g. UL 1446) considers in the evaluation of insulation materials also their resistance to mechanical vibration as they occur in rotating machines. This is to check if the plastic tends to erosion under the influence of friction and thus reduced dielectric strength.

Repeated temperature changes (e. g. only temporary operation) particularly stresses composites of insulating and core material or enamelled wires. The expansion coefficients of plastics are usually far above those of metals. This may lead to stress cracks, especially in moulded systems.

Another reason for a reduced service life of an electrical insulation may be due to the wrong choice of curing conditions (casting- or coating materials). A too rapid cross-linking process is inevitably leading to an incomplete and therefore inadequate reticulation causing a reduced service life.

The insulating resins used today are almost exclusively chemically cured. During this process, many physical properties of the resins change. Among others a dramatic increase in viscosity and an increase in density occur. This results in a volume shrinkage, which can be minimized, but not eliminated. Consequences can be for example cavities, cracks or delamination. Curing with slow speed and at low temperatures (thermal expansion coefficient) reduce the risk of such consequences.

Another reason especially in hermetically closed equipment is trapped moisture in the insulating materials, by-products of the curing reaction and degradation products during the ageing. The designer of a device should provide countermeasures to ensure that these substances can leave the machine or condense in places where they do not cause damage.

Finally, the chemical compatibility of all materials used in the insulation system (UL 1446, IEC 61858 and IEC 61857) is vital in the ageing resistance of the individual components. In long-term aging tests or shortened tests (Sealed Tube Test) the interaction of all insulation materials is checked. Incompatibilities are leading to a reduced voltage resistance.

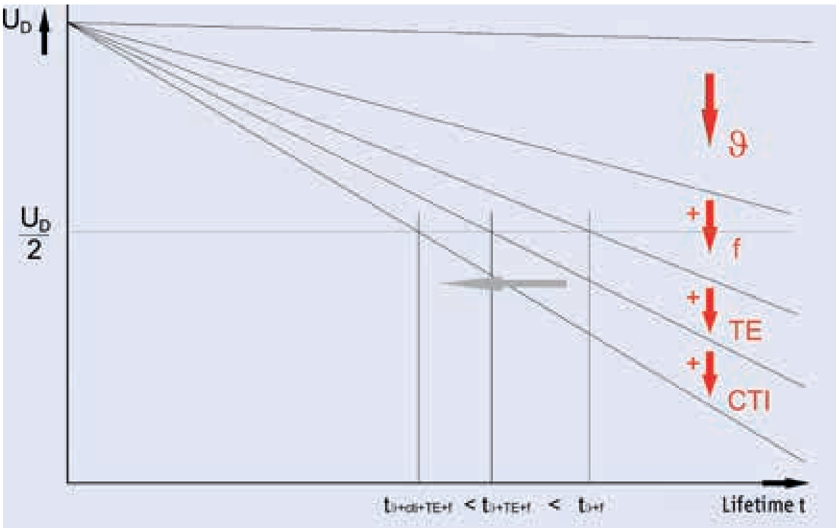
Material	expansion coefficients in (10^{-6} K^{-1})
Aluminum	23,1
Iron	11,8
Copper	16,5
PET – polyester	~80
PA – polyamide	~120
PI – polyimide	~56
PE – polyethylene	~200

7. Summary

Today's devices are constructed under the dictum "smaller, faster, and more efficient". Developers try to meet these requirements through the smallest possible insulation distances with more difficult heat management and through significantly higher frequencies.

The Ecodesign Directive 2009/125/EC (electric motors also 2009/640/EG) forces the manufacturers since at least the end of 2011 to a more energy-efficient design, which is usually synonymous with a higher energy density and the resulting consequences.

The data sheet specifications of insulation materials reflect the optimal value of the insulation capacity under standardized conditions at the beginning of the operating time.



Reduction of the potential operating time by reduction of the breakdown voltage due to temperature, frequency, partial discharge (electrical stress) and environmental conditions (Source: CMC)

During the operation, temperature affects the insulation foils through accelerated aging / embrittlement and, consequently, reduced dielectric strength. High voltage damages the material e. g. by sliding discharges and electrical stress. At higher frequencies, the dielectric strength breaks down strongly especially with polar materials. Soil and humidity can lead to the formation of conductive pathways on the surface. Chemical stresses, hydrolysis and mechanical pressure during the production is affecting the insulation material.

For the safe design of an electrical device it is therefore necessary to sum up all appearing influencing factors and their effect. With these considerations, it is worth to know the required dielectric strength at the end of the expected lifetime as it codetermines substantially which materials should be used with which initial characteristics.

However, since the sum of the influencing factors at a specific electrical component is neither mathematically determinable nor by tests, component standards such as IEC 611558, material standards such as UL 510 or IEC 60674 and measurement standards such as IEC 61934, IEC 60343, IEC 60034-27 or UL 746 help to find suitable as well as tried and tested solutions.

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