Failure reasons for insulations
(a selection)

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 examining the penetration through the insulation material mostly a voltage increase of 500V/sec. is used. The breakdown voltage is then indicated as e.g. kV/mm standardized to the thickness.

However, this value decreases more and more during the operation time. A variety of factors are involved that have a negative effect on the insulation capability of a material. Therefore, depending on the application it is not enough to view the individual influencing factor. You have to consider rather the sum of all loads summarized in their effects in the specific case.

With the emphasis on insulation foils and based on the most common types of loads you should get an idea in the following of what to look for:

1. **Temperature**

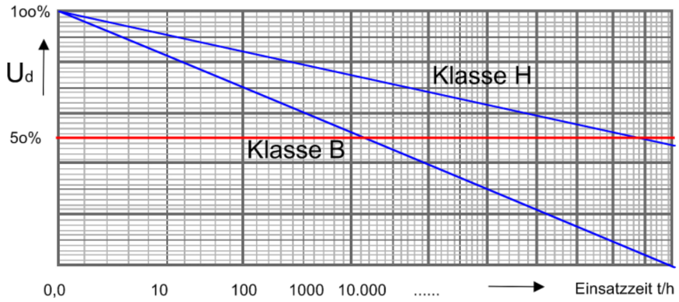
In general can be stated: the higher the temperature, the stronger are the corrosive and oxidative effects of the ambient air. Or even more generally speaking, with rising temperature the rate of aging is increasing whereby most processes obey the so-called Arrhenius plot.

As a general rule from electronics you simplified estimate with a halving of lifetime per 10°C increase in temperature.

Insulaton materials are devided into thermal classes by means of standards such as IEC 60085 (e.g. B=130°C, F=155°C, H=180°C). These classes specify at which continuous operation temperature the insulation materials still have 50% of the breakdown voltage after 20.000 hours which they had when new.

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.

So if you want to achieve a longer lifetime at a given operating temperature you have to use an insulation material of a higher thermal class. The usual end-of-life criterion of “half the breakdown voltage” is reached much later in this way.



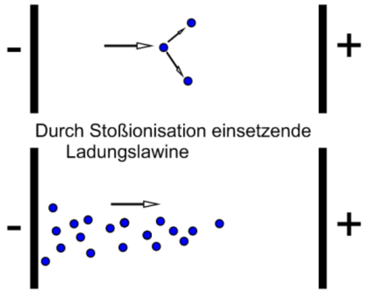
Achievement of half the breakdown voltage according to UL 746 (Source: CMC)

Regarding the heat maximum occurring you should also take into consideration heat accumulation within windings, highest possible ambient temperature and possibly occasionally appearing malfunctions.

Other materials such as molding compounds, coatings and impregnating agents 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 400V Corona discharge occurs. By the resulting field strength free elctrons 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).



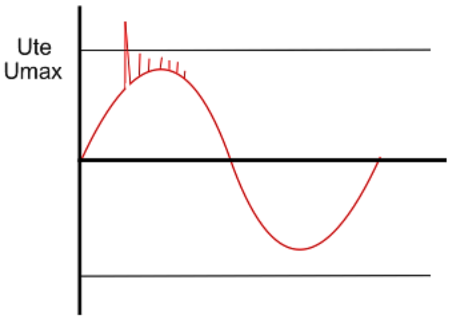
Charge carrier avalange by impact ionization
(Source: CMC)

In circuits of modern devices such as power supply units, filter components and power module drives it comes increasingly to repeating, high-energy pulses (switching pulses).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 because of 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, pulse shape, - polarity and - repetition rate affect significantly the degradation speed of the materials.



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

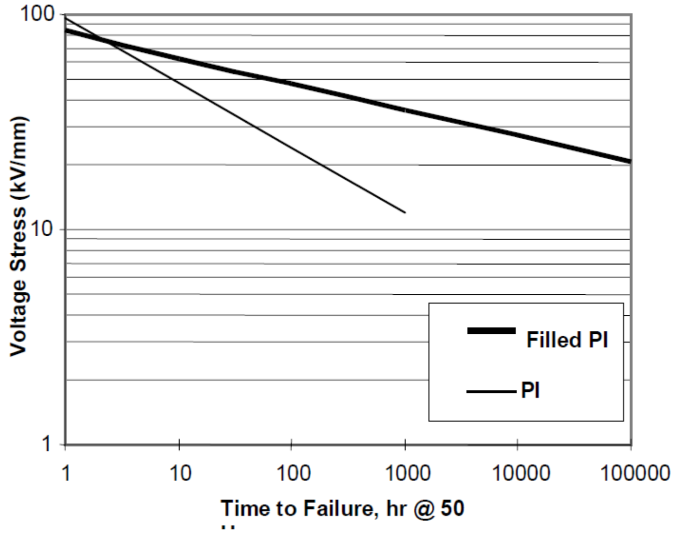
An adequate distance to the partial discharge extinction voltage is therefore always adviseable. This can be achieved - in addition to constructive measures - by the use of sufficient high-voltage, that is to say “thick” insulations.

However, this contradicts the requirements for as few as possible insulation material inside of transformers and generators. For only the “iron” and copper components in a transformer are electrically effective. Moreover, the situation of capacitive and inductive coupling will change significantly.

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 the natural substance Glimmer (Mica). They are not damaged by Corona discharges. An increased Corona resistance at combined flexible material such as e.g. NOMEX aramide paper T 418 is achieved by the insertion 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 at frequency converters (inverters).

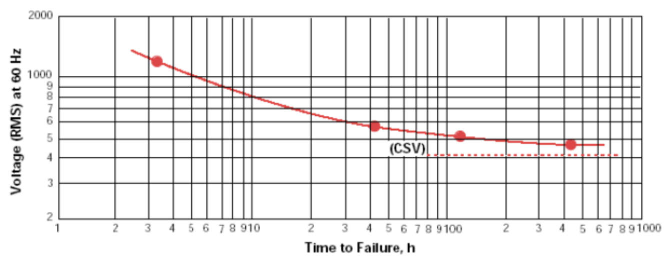
In large systems (motors, generators, distribution transformers) you can use semiconductive materials to avoid this sliding and Corona discharge as much as possible. Furthermore, the electrical field may be formed in this way to the extent that no electric flux line concentrations can arise.

For smaller sizes we recommend the use of Kapton® CR or fluoropoymers such as e.g. FEP. With Kapton® CR the PD-resistance is drastically increased by adding 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)

Comparable to the examinations of the influence of temperature here 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 50µm instead of 25µm foil thickness) significantly shifts the time of destruction. The dielectric strength remains longer above the voltage during continuous operation where partial discharges apply.



Corona Starting Voltage (CSV) = 425 V

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

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 happens between 100 hours and 1000 hours. From the results you can then extrapolate the time before 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 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.

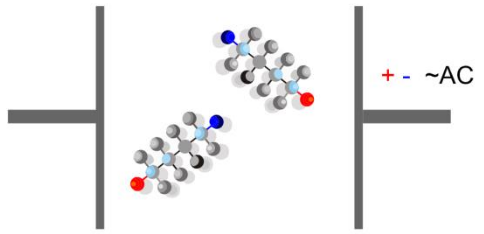
Note 2: Positive or negative DC voltage stresses insulation materials in different ways. No losses occur by the alternating field. Nevertheless partial discharges may occur. Furthermore, a material migration is possible.

3. Frequency

In a large number of "electric" basic standards usually measurements are done with a sinusoidal voltage at 50Hz. 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 inserted more and more frequently in 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.



Re-polarization losses in insulation materials (Source:CMC)

In the high-frequency welding technology these polarity reversal losses in the material are utilized for melting the plastic (dipole-plastics 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.

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	Dielektr. Verlustfaktor; (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 (luftfeucht)	3900	1300

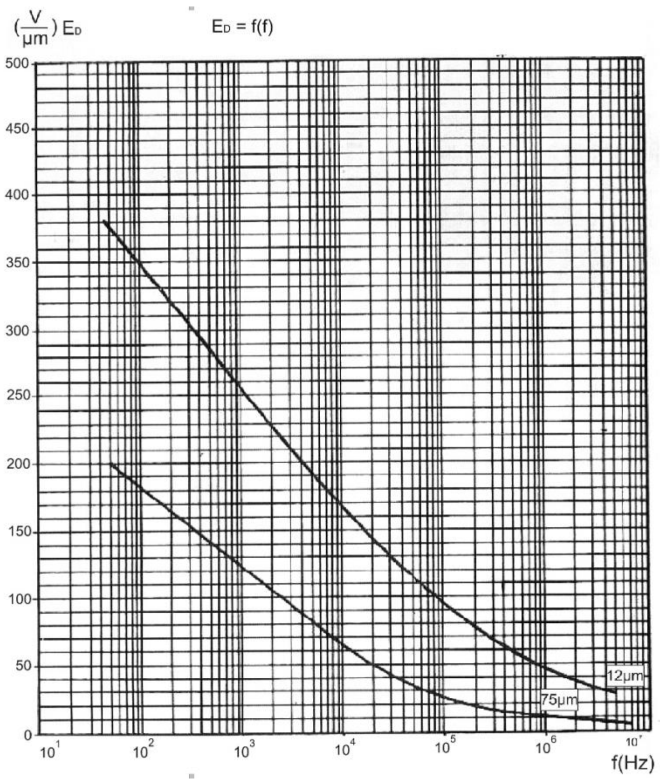
Overview of some insulation substances and their losses in the electrical alternating field related to two different operating frequencies

Today, frequency converter and switch power supplies stress insulations more than before since motor controls or e.g. computer power supplies are using pulse-width controlled voltages in the range of 20 kHz and more.

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 occur.

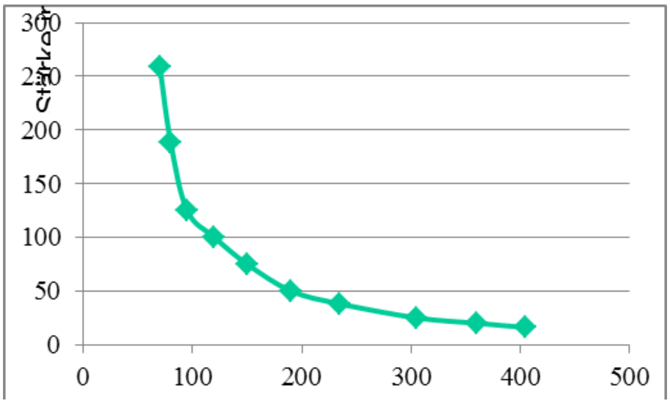
The high switching speeds dv / dt considerably stress the insulation materials used (power dissipation within the material: $Pdiel = U2 \times w \times C \times tan$ d). Additionally, wave reflection, standing waves and retroactive effects from the energized device can cause further stress for the insulation. 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 the frequently used polyester foils:



Dependence of the breakdown voltage from the frequency (Source: Hoechst)

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



Breakdown voltage versus material thickness with polyester foil (Source: CMC)

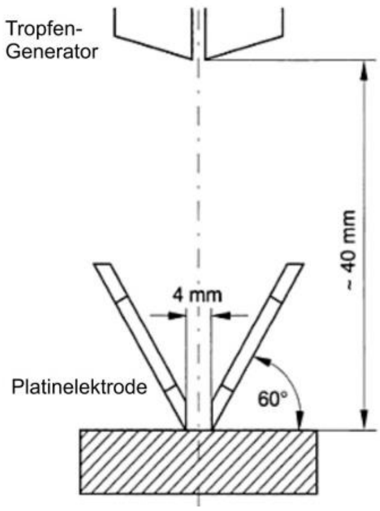
Besides the ageing due to temperature and the weakening of the material by partial discharges the frequency significantly determines the considerations for designing an electrical device.

4. Behaviour with 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 at the end they can lead to failure of the insulation.

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

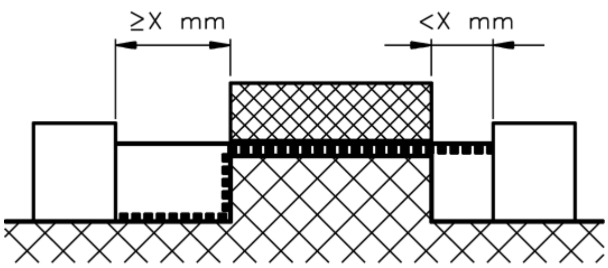
An important aspect is the potential water absorption of the insulation material, as it accelerates the destruction even within the material. Certain products which are produced by means of polycondensation (e.g. polyester foils) can even be damaged relatively quickly by hydrolysis in case of existing 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 even faster to the destruction of the insulation material as dry partial discharges. Especially for electrical devices used in the outdoor area with the ability of condensation, increased distances have to be observed (see e.g. IEC 61558).

5. Constructive measures



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

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.

6. Other potential causes

Temperature, voltage stress, unfavorable 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, radio activity). 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 vapor at 90°C).Tests with 50µm thick polyester foils have shown that even after 1,500 hours at 85°C/85%$_{rel}$H the mechanical strength is almost lost. The foil breaks in a buckling test.

The so-called "motorettes 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.

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

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

Finally, the chemical compatibility of all the materials used in the insulation system plays a role in the age-resistance of the individual components.

7. Summary

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

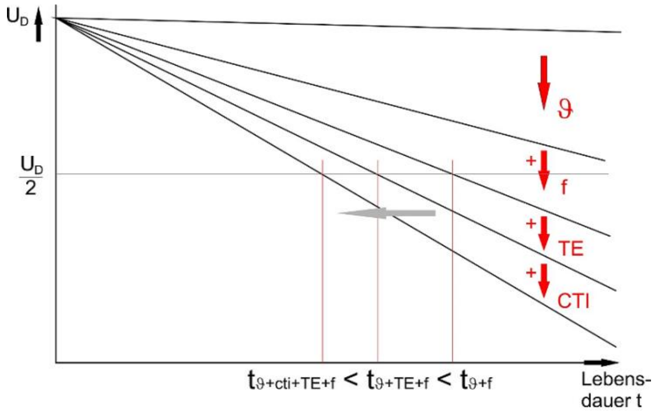
The Ecodesign Directive 2009/125/EC (electric motors also 2009/640/EG) forces the manufacturers since at least the end of 2011 to a more energy-efficient design, which is usually synonymous with a higher energy density and the resulting consequences.

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.

During the operation temperature effects the insulation foils by 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 bothering 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 co-determines 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 UL746 help to find suitable as well as tried and tested solutions.



Reduktion der möglichen Einsatzdauer durch Reduktion der Durchschlagspannung aufgrund von Temperatur, Frequenz, Teilentladung (elektrischer Stress) und Umweltbedingungen

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)

Autor: Gerald Friederici, friederici@cmc.de
Tel 06233/872 356