# WHITE PAPER

Using connectors on DC / AC /impulse

High voltage

Electrical arc, due to the flow of electric current through the air gap between two conductors, causing plasma.

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## ISSUES about AC and impulse voltage / Partial discharges

Although the full extent of the complex physics involved may be beyond the scope of this white paper, it is important for device manufacturers to at least have a basic knowledge of the threats facing high voltage and connecting equipment in use.

Reliability and stability of electric power systems are of prime concern. The high voltage equipment such as power transformers, generators, connectors, and surge arresters should be correctly operated. The performance of high voltage equipment might steadily degrade with the age, usage, maintenance, and operating environment. The dielectric isolation of conductors including solids, liquids, or gas must be assessed, verified, and maintained to avoid any failures. Thus, the inspection and maintenance for the high voltage equipment must be properly performed to detect the problems as early as possible.

In general, the threats for electrical breakdown fall into two categories of arcs and discharges (partial & coronas). An arc is basically a spark that forms and jumps between two pieces of metal or other conductive materials. This is due to a breakdown of the dielectric resulting from voltages above the design voltage and/or degradation of the insulator from voltage stress or environment. Arcs are the most common failure mode within industry applications. The arc across the surface of an insulator produces a semi-conductive carbon track resulting from the arc energy's impact on the material surface. This erodes the dielectric strength of the insulator. With the breakdown voltage threshold now significantly lower, any subsequent flow of electricity will likely cause immediate product failure.

Partial discharge (PD) can be a major problem occurring in such high voltage equipment. This is a localized electrical discharge resulting from a flaw such a gas bubble in the insulation. This flaw will reduce the local dielectric strength within the insulation. A higher potential can develop on one side of the flaw. If the voltage difference is sufficient, it can arc across the flaw. This partial discharge acts to degrade the insulation performance causing ionization of the internal gas or carbonization of the surface of the flaw. Partial discharge often includes internal discharge, surface discharge, and air corona. A corona discharge is a phenomenon that occurs when electricity at a high voltage density flows from the components and into the surrounding gas, especially under conditions of high frequency. As the gas becomes ionized, it heats up, creating a blue glow (plasma), often with an audible buzz and an ozone smell. This plasma causes damage or failure due to dielectric deterioration and voltage breakdown over time, particularly in organic based insulation materials. This results in insulation breakdown and subsequently the failure of the equipment including the possibility of fire or explosion. It is necessary to detect the partial discharge, analyze discharge patterns and their criticality.

Figure 1 - High voltage LEMO connectors in use

## ABOUT DC / AC / PULSED VOLTAGE STRESS

**DC (Direct Current) Voltage Stress :**

Many technical applications are associated with high DC voltage stresses. Examples of these include devices for the DC supply of X-ray tubes, in monitors, charging devices, copiers, impulse circuits, lacquering and coating devices. This is also seen in test equipment with high electric DC fields, especially in the barrier junction of the rectifier components and in the dielectrics of smoothing and energy storage capacitors, that can be found in almost every power supply device. These stresses are frequently not a matter of pure steady-state DC voltage, often there are mixed voltage stresses: Grading capacitors and rectifier components are additionally stressed by a superimposed AC voltage. The voltage of smoothing capacitors contains a certain “ripple” and energy storage capacitors (“surge capacitors”) are discharged abruptly.

**AC (Alternating Current) Voltage Stress :**

Energy transmission with three phase AC systems require the application of high voltages to limit the losses. Therefore, insulation systems are stressed by high AC voltages with frequencies of f = 50 Hz or f = 60 Hz. Quasi-static (quasi-stationary) displacement fields can normally be assumed in the insulation of power apparatus. This means that the permittivity determines the distribution of the electric fields for the common insulating materials with low conductivities.

**Switching Impulse Voltage Stress :**

Pulse-shaped overvoltage can be caused by switching operations in the electrical grid, e.g. by interruption of a current during the opening of inductive circuits. As the origin is in the grid itself, the switching impulses are called “internal overvoltage”. For equipment, the electric strength against switching impulse overvoltage is normally proven during a type test. The peak value of the standardized “rated switching impulse withstand voltage” is defined in relation to operating voltage. Normally the peak time Tp (time to crest) is 250 µs and the time to half value (tail time) is 2500 µs. Recent biomedical applications also use pulsed voltage for treating atrial fibrillation, cancers, or undesired cells using a minimal intrusive process.  Second generation ablation uses a 15kV+ DC with a frequency of 1kHz.**Fast-rising Impulse Stresses (“Fast Transients”):**

There are many examples of fast rising impulses in different technical applications including gas-insulated switchgear (GIS) discharge processes which are caused by flashovers or by switching of disconnectors. Highly stressed insulations (e.g. in transformers and bushings) are endangered by significant transient over voltages. In unfavorable situations, the excitation of self-resonances (e.g., in the transformer windings) can result in further voltage overshooting. Wave propagation on the outside of the shielding can cause unwanted electromagnetic interferences in the secondary systems of the plant. Specific measures must be taken to guarantee “electromagnetic compatibility” (EMC).

**Steady high frequency Voltage :**

In contrast to transient impulse stresses, high frequency stresses are long-lasting. With increasing frequency up to 1 MHz, the breakdown strength of air at standard atmospheric conditions decreases down to 80 % of the 50 Hz strength. The breakdown strength increases again above 3 MHz. Then, the electrons cannot follow the fast-changing field without decelerating and the field distortion by residual positive ions no longer occurs. Additionally, the statistical discharge delay has a strength-increasing effect. At 100 MHz the strength is 1.5 to 1.6 times higher than at 50 Hz. As the result, one understands that using $\sqrt{2}$ to get the AC BV from DC BV is not accurate enough depending on conditions explained previously.

**Micro/nano second pulsed electric fields:**

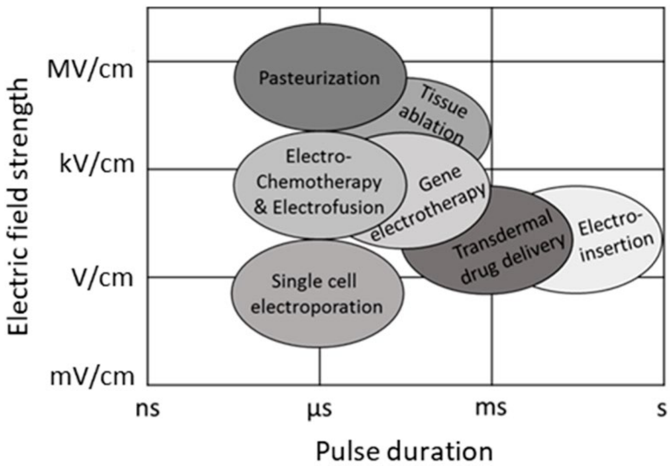



**Figure 2 – Applications of Pulsed Electric Fields**

Considering medical field, recent developments in Pulsed field ablation (PFA), Pulsed electric fields (PFE) and electroporation applications show that in the recent years the number of projects focusing shorter (nanosecond) pulses have increased significantly. The reason lies in the limitations of conventional microsecond range methodologies such as bioimpedance-dependent field distribution, Joule heating, muscle contractions, electrical breakdown and oxidative stress. Nanosecond pulses cannot solve all the problems completely; however, in many cases the negative factors are diminished. However, state-of-art pulsed power electronics are required for generators to form pulses up to tens of kV and hundreds of amperes in the nanosecond range. The price and engineering complexity of such generators is high, nevertheless, the trends in applications of nanosecond PEF make it viable.

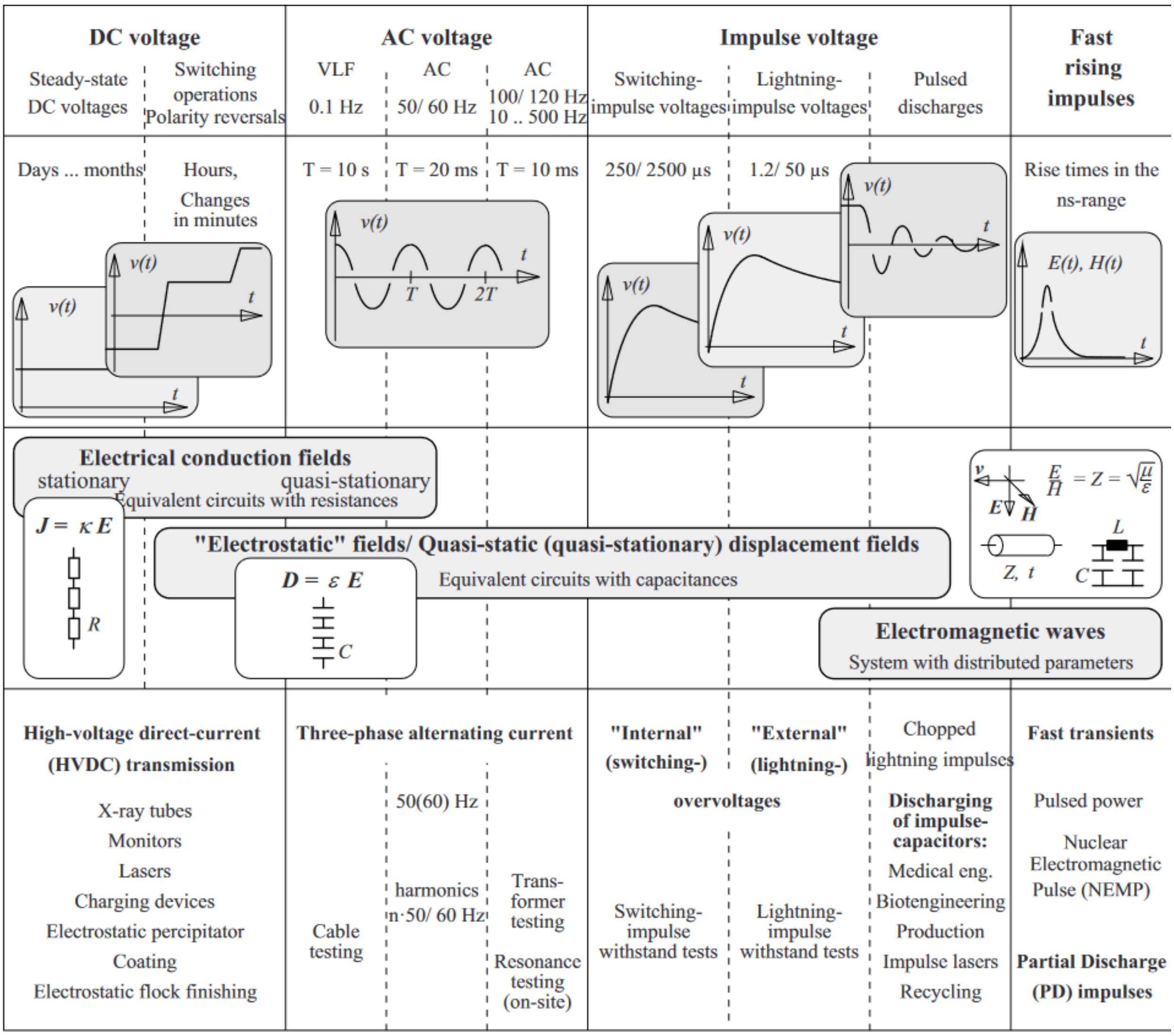



Figure 3 - Frequency dependency applications

## Partial Discharges (PD)

Partial discharges (PD) are discharges that affect only a part of the insulation distance and that do not immediately lead to breakdown. They take place in all types of insulation systems. Often, partial discharges do not affect short-term electric strength. In the case of organic insulating materials, erosion due to partial discharges, mainly in case of frequent and repetitive discharge impulses at AC voltage and repetitive impulse voltages, lead to a drastically reduced service life. The occurrence of partial discharges is an important criterion for the evaluation of insulation quality also for DC voltage.

Internal discharges occur in dielectrics with several cavities of various sizes inserted between two carbon or metal electrodes as presented in Fig. 4. The discharge occurs when the supply voltage is higher than the inception voltage of cavities.

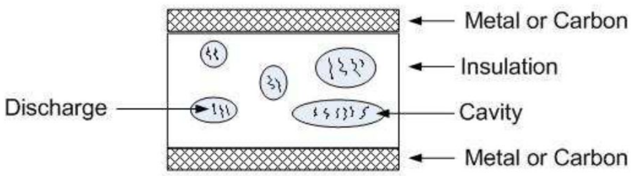



Figure 4 – Internal Partial Discharge

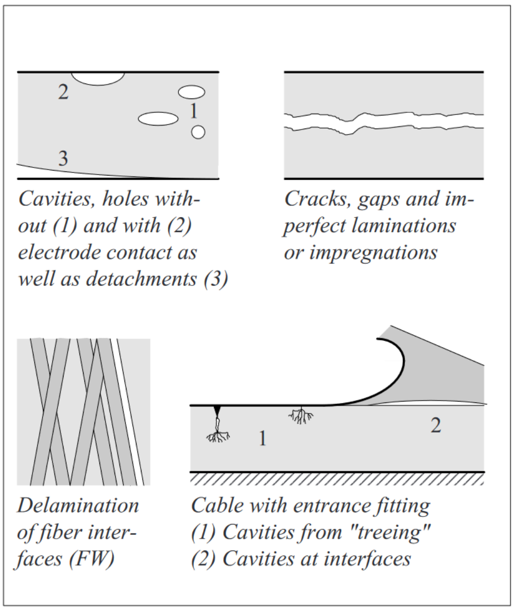
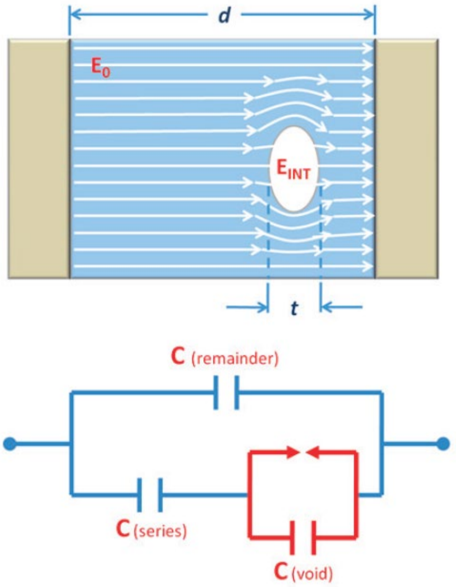



Figure 5 – Examples of Partial Discharge Inducing Discontinuities

With the presence of a bubble or discontinuity, the localized voltage stress is increased. The higher level of voltage stress raises the probability of partial discharge across the discontinuity. Voids and cavities introduce a parallel capacitive path. This new circuit through the dielectric results in a significant decrease in the breakdown voltage for the insulator.

Figure 6 - Example of calculation of decreased Breakdown Voltage at the Void




| | |
|---|---|
| **Relative permittivity** | |
| Air | 1.0 |
| Polyurethane | 4.0 |
| **Breakdown strength kV/mm** | |
| Air | 3.0 |
| Polyurethane | 10 |

$$V_{(void)} = V \frac{C_{(series)}}{C_{(series)} + C_{(void)}} = V \frac{1}{1 + \frac{1}{\varepsilon r}\left(\frac{d}{t} - 1\right)}$$

In the example above, the breakdown voltage of a Polyurethane 20mm gap, would be 200 kV and the breakdown voltage of an air gap of 20mm would be 60 kV. The result of the local capacitive effect and the increase in voltage stress means that the impact of the air void is to reduce the breakdown voltage at the void to 17.25 kV !

Surface discharge takes place externally along the insulation surface between two conductive electrodes as shown in Fig. 7.

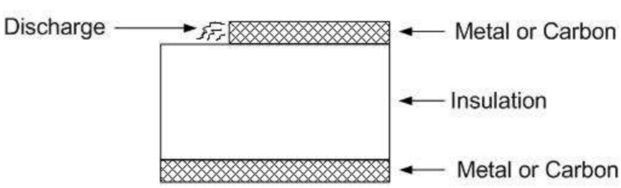



Figure 7 – Surface Discharge

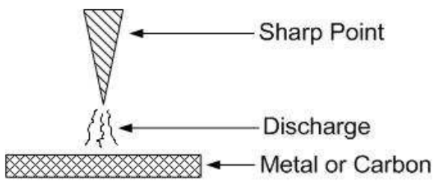



Figure 8 – External Corona Discharge

External corona discharge occurring at a sharp metal point or edge is shown in Fig. 7. If the discharges occur on the negative half cycle of the sinusoidal test waveform, the location of sharp edge is at high voltage side. On the other hand, if the discharges occur on the positive half cycle of the sinusoidal test waveform, the location of sharp edge is at the earth potential.

In the case of DC voltage, discharge frequency and erosion efficiency are enormously reduced, and the question can be raised whether PD at DC voltage is still a danger for the insulation system? The answer is: “That depends”. For example, charge displacements on interfaces or the charging of surfaces by corona discharges can lead to field distortions and flashovers. Hence, the occurrence of partial discharges is an important criterion for the evaluation of insulation quality also at DC voltage. The interpretation of PD at DC voltage is much more difficult than the interpretation of PD at AC voltage. The intensities of partial discharges as well as a few other parameters (e.g. PD inception and PD extinction voltages) are generally measured while testing the withstand voltage of a device. Thus, the criterion for passing a high voltage test is not only the short-term strength. It also involves the partial-discharge behavior (intensity limits, inception and extinction voltages) that has been recommended in the standards for specific categories of devices (e.g., high voltage transformers, high-voltage cables and connectors !), or which has been individually agreed upon between the manufacturer and the customer.

**Frequency dependency :**

Graph (Fig. 9) below shows a comparison of short-time breakdown field strength (Eb), among various solid dielectrics. For any given solid dielectric (assuming again that Eb at 60 Hz is unity), this value is about one- tenth at 1 MHz. With phenolic resin, for example, Eb is reduced to about 22% at 1 MHz, and to about 6% at 100 MHz. Once again, the likelihood of breakdown increases with the increase in frequency. It is also worth noting that the bottom (worst-case) is not yet observed.

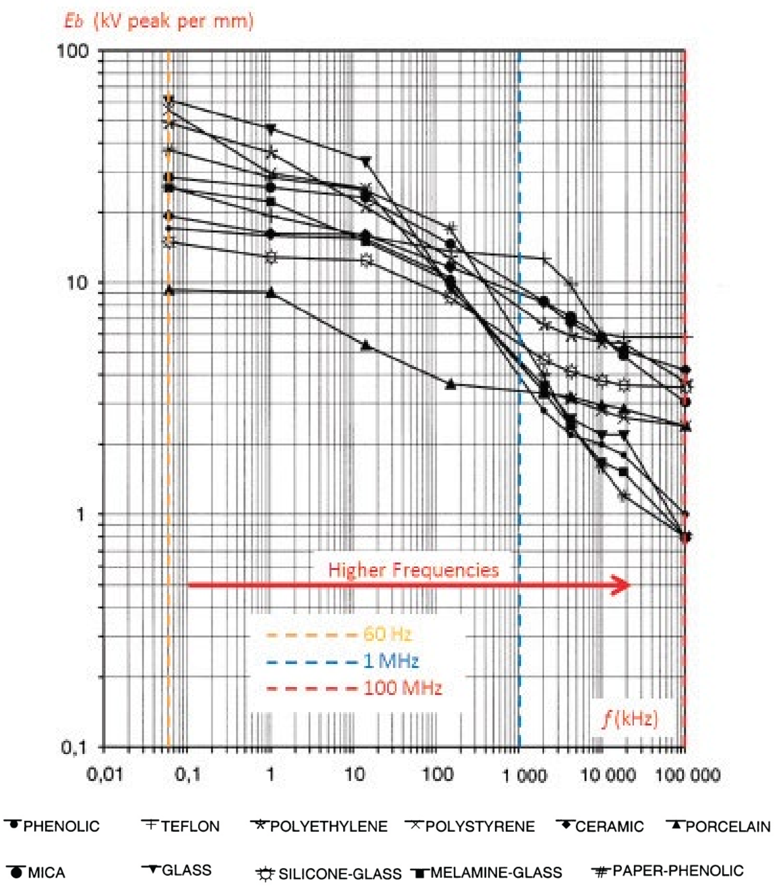



Figure 9 - Breakdown at high frequency, solid insulation; d = 0.75 mm. Reproduced from Figure C.3 of IEC 60664-4 ed.2.0 (2005). Copyright © 2005 IEC Geneva, Switzerland. www.iec.ch

## Detection and tests :

Partial discharge detection technique according to IEC 60270 standard [3], known as conventional method, is widely accepted for providing reasonable accuracy. This technique can describe the phenomena of internal discharge, surface discharge, and air corona.

Figure 10 - Cable termination and connector high voltage testing in LEMO’s laboratory. The test is performed in a faraday cage to ensure safety / security working with high voltages.

There are various causes of partial discharge driven by material characteristics, design criteria, and manufacturing methods. As a result, the type and location of the defect can be presumed in many cases. Definition of the exact root cause for a partial discharge issue can be difficult due to the multitude of probable sources of partial discharges, to the complexity of insulation systems and to the superimposition of partial discharges from different defect sources. The measured intensity of partial discharges may not be helpful for error diagnosis, since only the “apparent charge” at the connections of the test object and not the "actual charge" of a partial discharge impulse itself can be recorded.

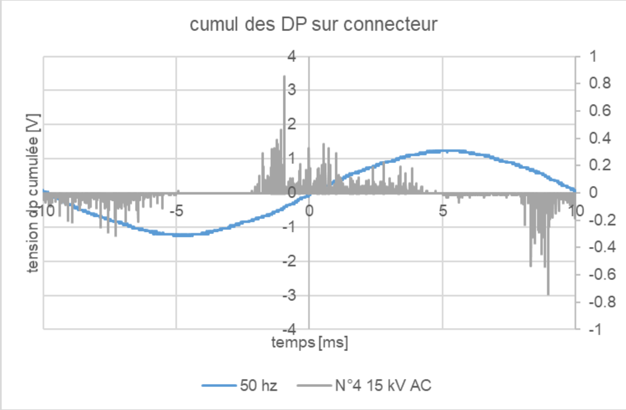



Figure 11 - Measured partial discharges in LEMO's test lab.

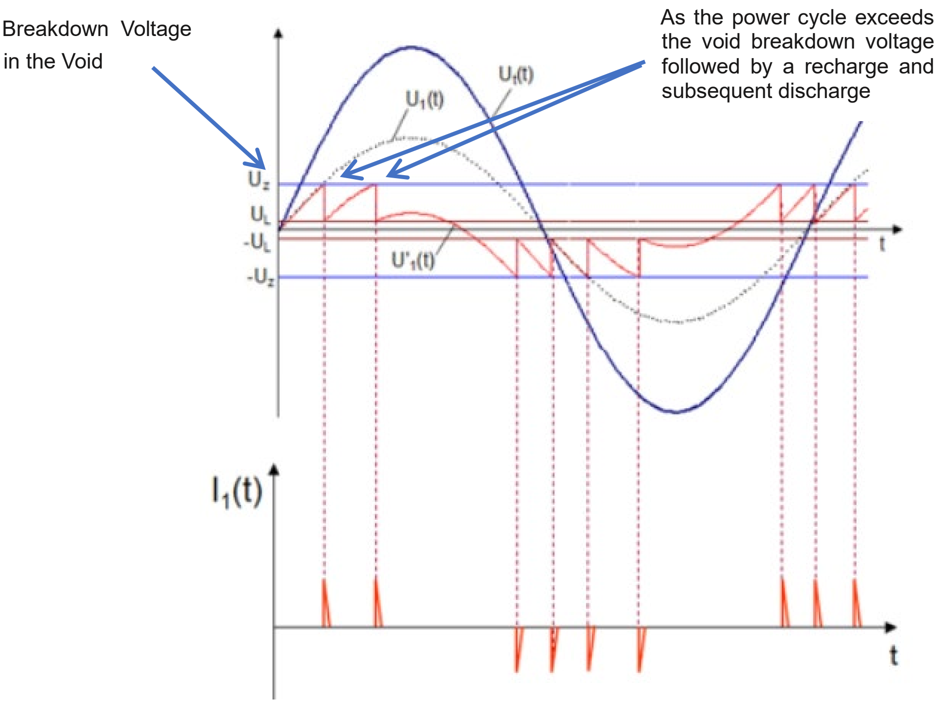



Figure 12 - Typical pattern of partial discharges using sinusoidal test voltage

Unfortunately, the development of a phase-resolved partial discharge pattern is intensely dependent on the voltage shape. That is, a voltage highly distorted by harmonics no longer gives the partial discharge images known from sinusoidal voltages. It is therefore essential to use an undistorted sinusoidal test voltage profile for the interpretation.

**Frequent damage modes due to partial discharges :**

Figure 13 below illustrates the void-to-tree transition. Conduction carriers (electrons) can penetrate the void, either through the ionization of gas in the void, or by separating loose molecular chain ends. Electron production is accelerated by the intensive electric field within the void following the development of electron avalanche. The electric field further divides electrons and positive ions, and the electron cloud strikes the wall of the void. In the meantime, positive ions drift to the opposite side. The wall is eventually damaged because of either carbonization, or ohmic heating, or both. After an elapse of time, the carbonized area shapes a 'new' void. As the new void is considerably smaller than the original, the electric field within the new void is stronger than before (higher voltage density), ultimately giving birth to electrical treeing.

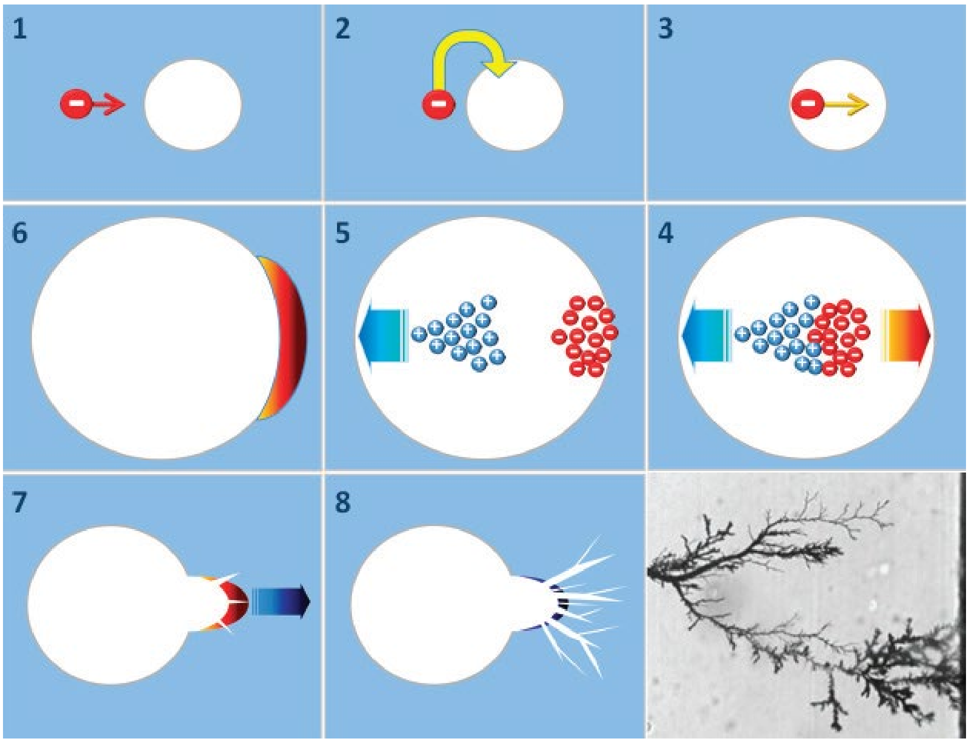



Figure 13 - Electrical trees are the main mechanism of failure in solid polymeric insulation. Their growth is associated to partial discharge (PD) activity.

**What about real life ?**

Voids and cavities can be found usually in junctions between materials, insulation, conductive parts within connectors and cables. Thus, cable termination is a critical area where it can be difficult to avoid partial discharges and therefore failure after a while.

Following pictures show the damage induced by either breakdown or partial discharges on insulations: carbon tracks along the insulation, ageing and embrittlement of organic materials, and electrical tree generation due to partial discharges along insulator.

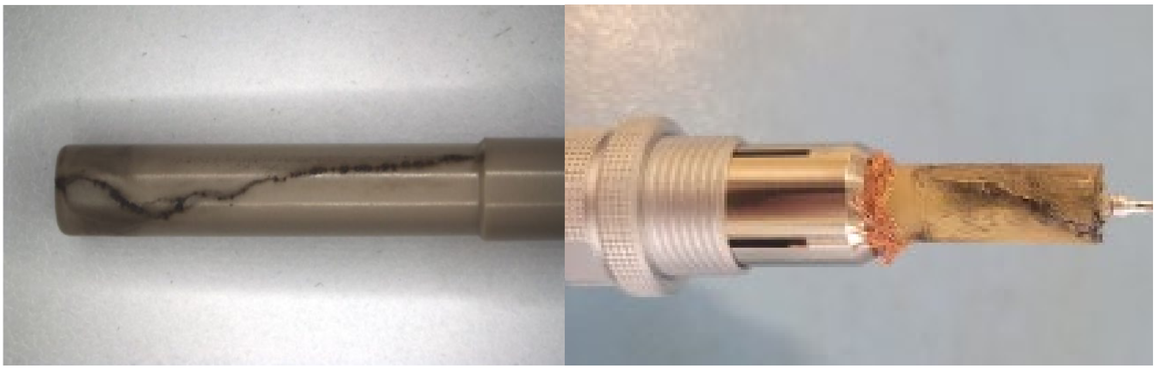


Figure 14 - The carbon track is developed between the isolated conductors resulting in an arc along the conductive carbon path.

Figure 15 - Ageing in a silicone insulator due to ozone production during PD process.

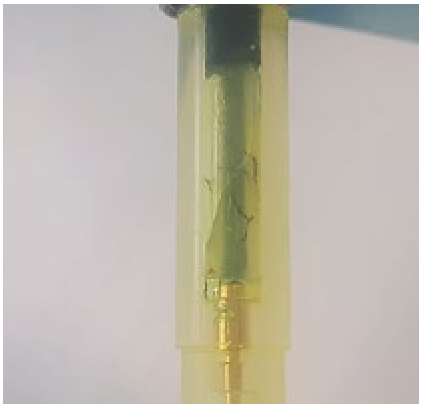


Figure 16 - Electrical tree on a silicone insulator

## About testing lifetime :

Repetitive voltage stresses with a constant peak value, give rise to lower breakdown voltages than stepwise increased individual stresses (step test). This shows that repetitive stresses above the inception threshold for micro discharges lead to the erosion of insulation and/or the progression of the electrical tree towards the conductor.

In the following picture test (figure 17), the shape and length of the electrical tree is a function of lifetime and voltage applied. The higher the voltage, the shorter the lifetime of the XLDE insulation in the cable.

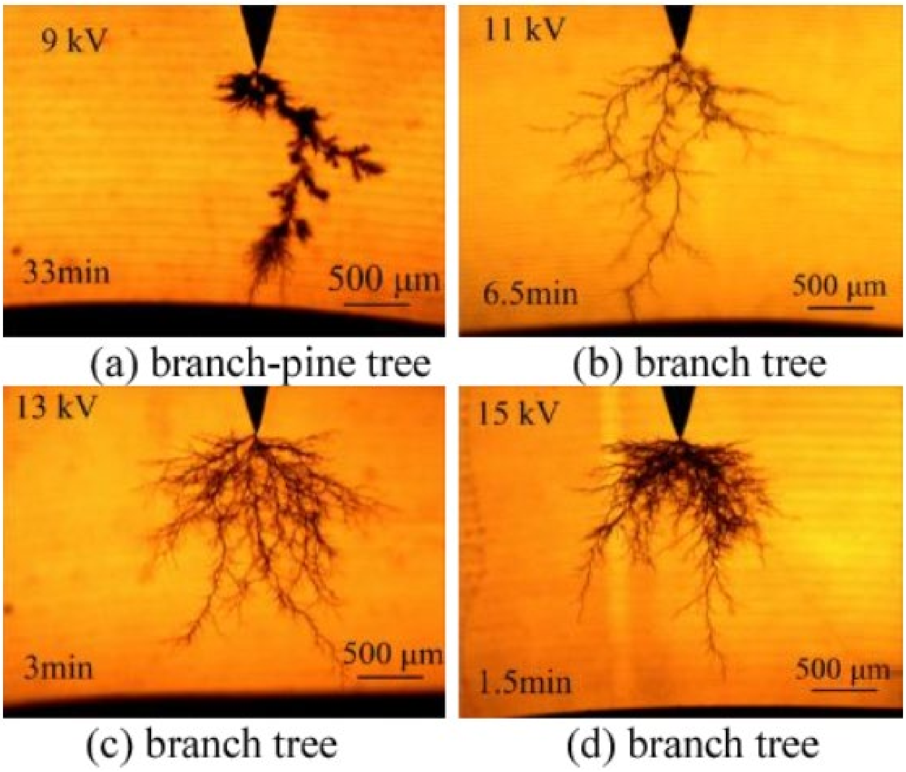



Figure 17 - Lifetime in a XLPE cable insulation depending on the voltage level.

The failure mode always ends by complete breakdown of the electrical insulation. Lifetime depends strongly on all the parameters raised before: voltage level, shape, frequency, insulation material, temperature, shape, and media (air or other gases). The consequence is that the design must consider all the application parameters to offer the best lifetime over high voltage with a particular emphasis on cable termination.

## About cable termination:

Connector design for high voltage addresses only part of the total system. Cable termination and harness designs for high voltage are also critical since they are a major source for partial discharges. DC cables have creepage surfaces at their ends if they are not terminated by cable joints, or by cable entrance fittings. After the inception of corona discharges at the edge of the partially removed cable sheath, streamer discharges and leader discharges, which can be observed under AC voltage stress, cannot develop as there is no displacement current that can feed high-current surface discharges. Nevertheless, accumulated space charges and surface charges cause flashover at comparatively low voltages, so that field grading is necessary.

Today, traditional cable technologies with long-term application life expectancy are challenged also for DC applications driven by extruded cables that have lower costs in production, laying and operation. Field grading technologies are also used for DC voltage cable accessories:

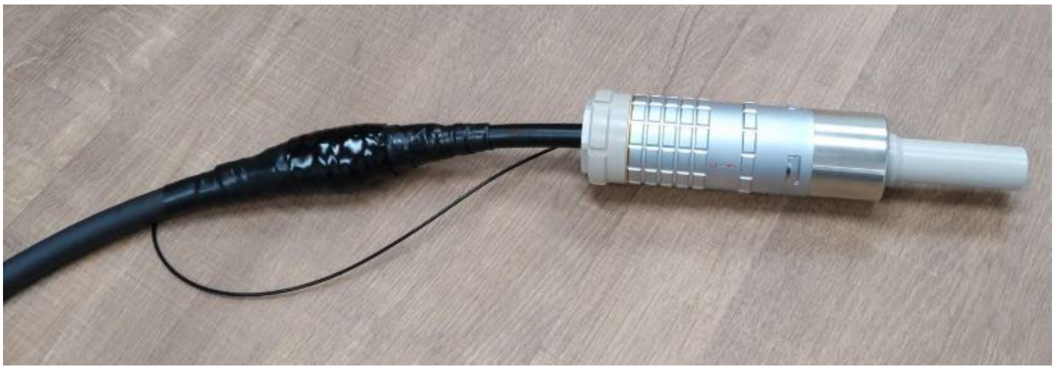


Figure 18 - LEMO connectors example of grading cone with deflector for high voltage application

## Summary:

As shown in this overview of connector and harnesses development, it is very complex with a large number of challenges to obtaining a high reliability system that meets the performance objectives. To develop a well-designed interconnect system (both cable and connector), focus on requirement communication, subject matter expertise to define and manage the key parameters is essential. It also demands specialization in execution and manufacturing that is not common with many connector manufacturers. By selecting an experienced and proven high voltage interconnection partner and working together with detailed application information every step of the way, system manufacturers can ensure that their devices and equipment will operate effectively and safely from day one—and for many years to come.

LEMO is the acknowledged leader in the design and manufacture of precision custom connection and cable solutions.
LEMO's high quality Push-Pull connectors are found in a variety of challenging application environments including medical, industrial control, test and measurement, audio-video and telecommunications.

LEMO has been designing precision connectors for seven decades. Offering more than 75,000 combinations of product that continue to grow through custom specific designs, LEMO and its affiliated sister companies REDEL, NORTHWIRE and COELVER currently serve more than 100,000 customers in over 80 countries around the world.

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