WHITEPAPER

CHARACTERISTIC PROPERTIES OF A LOW-VOLTAGE DIRECT CURRENT CABLE

LAPP

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CONTENTS

1 REDUCED NUMBER OF CONDUCTORS

In contrast to three-phase DC systems (AC systems) with three current-carrying phases L1, L2 and L3, DC cables in DC systems consist of only 2 phases in the low-voltage level, namely L+ and L-. Common to both systems is the carrying of the protective earth PE. While AC often carries a neutral conductor N depending on the grid shape, DC may require a centre conductor M. Unlike AC cables, which are run with three or five conductors, DC cables may have three or four conductors[1] .

2 SPECIAL COLOUR CODE

In order to clearly distinguish DC cables from AC cables, the colour code for cables and wires in the field is determined as follows according to DIN EN 60445: red for L+ and white for L-. The colour of the protective earth PE is not different and is green-yellow. The optional centre conductor is blue. **Figure 1** shows a comparison of a typical 5-core AC cable and 3-core and 4-core DC cables from LAPP.

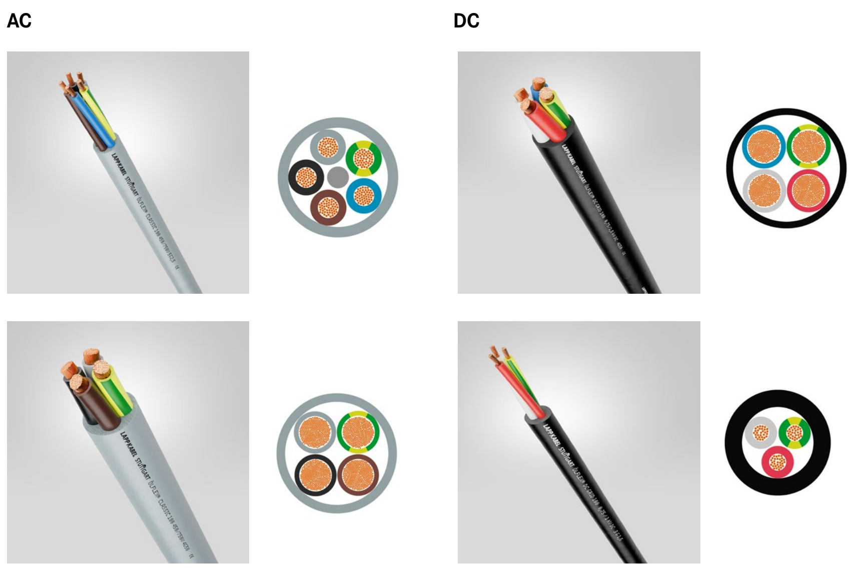

Figure 1: Exemplary comparison of 5-core AC cable (left) and 3-core resp. 4-core DC cables (right)

1 Whitepaper: "Comparison of copper cross-section and transmission losses for cables and wires in AC and DC systems", LAPP

3 REQUIREMENTS FOR THE INSULATING MATERIAL OF CABLES AND WIRES

3.1 Theoretical principles for the electrical stress of conductor insulation materials

Plastics such as PVC (polyvinylchloride), PE (polyethylene), PP (polypropylene), halogen-free insulation materials or thermoplastic elastomers are usually used as conductor insulation material (or insulation material, hereinafter simplified as insulation material) for low-voltage cables.

In addition to sufficient mechanical[2] and thermal[3] properties, the main requirement for an insulating material is to fulfil the electrical insulation between two different potentials, e.g., neighbouring conductors in a multi-core cable. The electrical insulation is characterised by the electrical dielectric strength (pass-through voltage or electrical pass-through field strength).

Electrical dielectric strength is a property that depends on the material, the temperature, frequency, duration of the stress and the type of electrical field (depending on the voltage form, e.g., AC or DC). Depending on these influencing factors, the application of an alternating or direct voltage results in a different formation of very small loss currents (e.g., in the peak to nano-ampere range) in the insulating material. If these loss currents increase sharply, they lead to a failure of the insulating material – a breakthrough occurs.

The creation of an electric field with both alternating and direct voltage results in a shift of fixed positive and negative charge carriers (atoms, ions, molecules) to dipoles. This behaviour occurs in most solid insulating materials (plastics) in the crystalline areas and is referred to as displacement polarisation[4]. Depending on the type and nature of these insulating materials, other different types of sub-polarisation are distinguished.

Note on material structure: Plastics have amorphous and crystalline ranges depending on the degree of polymerisation (number of monomer molecules connected to a macromolecule). Amorphic areas are characterised by glassy, brittle and non-crystalline (non-ordered) structures due to incomplete cross-linking. Charge carriers can move freely here. In contrast, ordered crystalline structures exist in the crystalline areas (complete cross-linking) (crystalline structure, see illustration on the left in Figure 2). This means that the charge carriers are predominantly bound and the number of freely moving charge carriers is low compared to those in amorphous areas.
The formation of the loss currents depending on the voltage type is described below:

2 E.g., tensile and bending strength, elasticity module and hardness
3 E.g., maximum permissible and continuous temperature, thermal conductivity, thermal expansion coefficient, thermal capacitance, flammability, stress current resistance, temperature dependence on material parameters
4 E.g., A. Küchler: "Hochspannungstechnik: Grundlagen – Technologie – Anwendungen" (High-voltage technology: basics – technology – applications), Springer Verlag Berlin Heidelberg, 2017

3.2 Stress with alternating voltage

Due to the temporal (and periodic) change in the voltage signal u(t), a dielectric displacement field builds up under alternating voltage stress, under the influence of which the formed dipoles are constantly reformed (repolarisation; see **Figure 2**). This creates undesirable small loss currents in the insulation material. On the other hand, there are barely any or no directed movements of free charge carriers (electrons or ions).

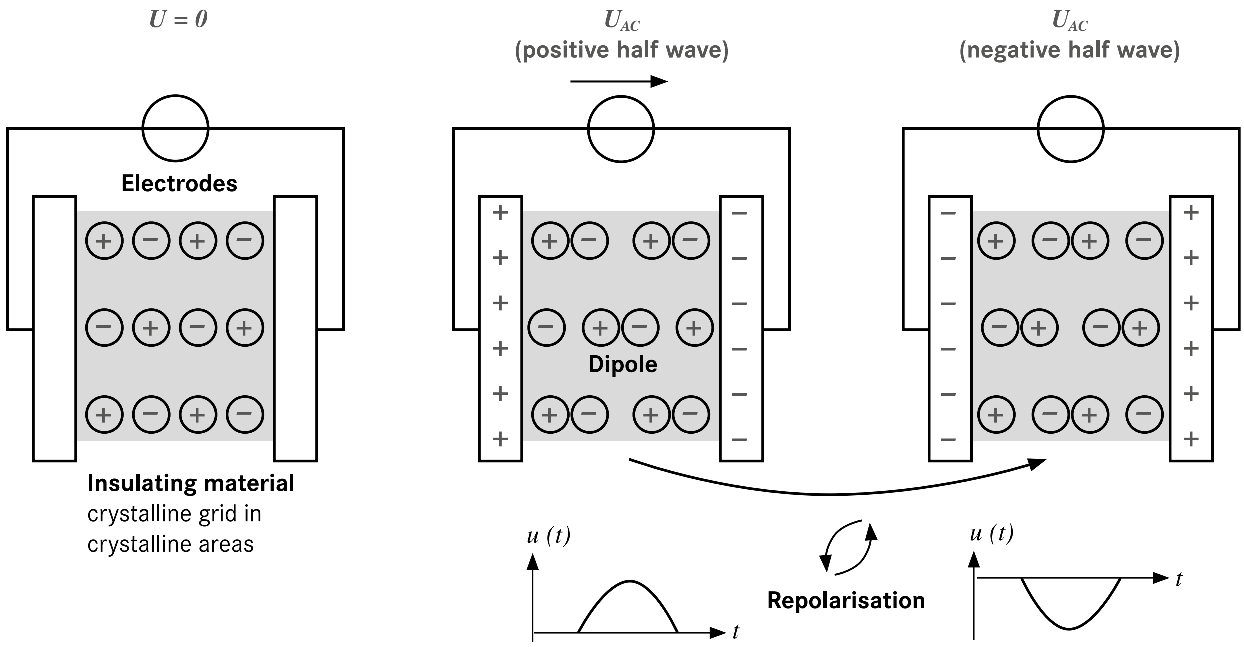

Figure 2: Polarisation and repolarisation in solids under AC stress

3.3 Stress with direct voltage

In a direct comparison with a load with alternating voltage, the physical effects inside the insulating material differ with a load with direct voltage. Basically, a stationary current field (with no change in time) builds up when stress is exerted with direct voltage, which initially leads to polarisation in the crystalline areas and direct movements of freely moving charge carriers.

As the polarisation has disappeared very quickly (t ~ picoseconds to nanoseconds), the electrical field strength in the stationary state is determined by the number of freely moving charge carriers (mainly in the amorphous areas) in the insulating material: these charge carriers produce an electrical conductivity κ and are a measure of the undesirable loss currents in the insulating material. The number of charge carriers is significantly influenced by the purity and composition of the insulating material, as well as by the electrode material.

The release and movement (charge carrier drift) of these charge carriers with a so-called average drift speed is exponentially dependent on the temperature and the electrical field strength.

Depending on the electrical field strength, either ions or electrons dominate as freely moving charge carriers in the cable processes (see **Figure 3**):
For smaller electrical field strengths (e.g., for voltages in the low-voltage range), the ions predominate; for higher field strengths (high-voltage range), electrons dominate. Ions are formed through dissociation processes, e.g., from cross-linking residues, impurities, foreign molecules or additives (such as antioxidants or stabilisers). Dissociation is the split of molecules or ions into smaller components (ions, electrons) when substances are dissolved in water or solvents or through the supply of energy, e.g,. from electromagnetic fields or high temperatures. Electronic wiring processes (through electrons and holes) are also due to the activation (energetic stimulation) of electrons from physical and chemical defects. Due to the material structure, electrons can also be locally bound over a certain period of time, so that so-called space charges form and influence the electrical field strength.

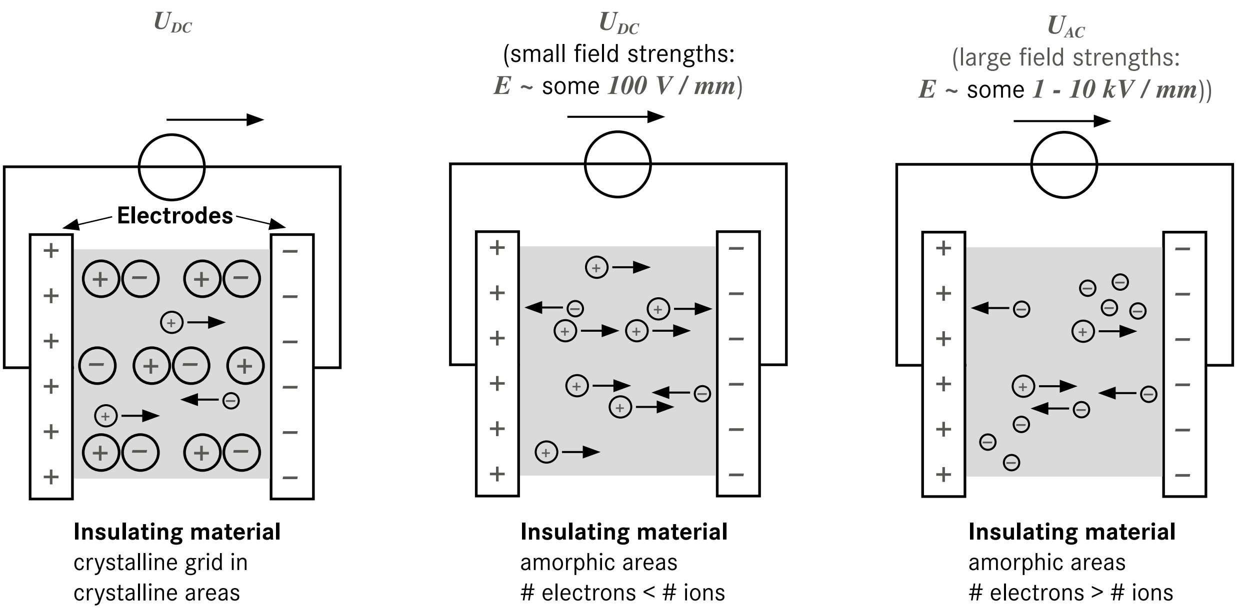

Figure 3: Polarization and conduction processes in solids under DC stress

3.4 Selection and electrical stress of insulating materials at low voltage

Typical insulation wall thicknesses of low-voltage (AC) cables and wires are in the range from a few 0.1 mm to approx. 1.6 mm according to AC nominal voltages U_0/U (standard up to $U_0/U = 0,6/1$). U_0 is the conductor-earthing voltage and U is the chained voltage between two potential-conducting conductors. An example of the conversion of these values to the corresponding operating field strength Eb results in:

$$E_b = \frac{U_0}{d} = \frac{0,6\ kV}{1,6\ mm} = 0,375\ \frac{kV}{mm}.$$

A comparison of E_b with the electrical field strength (AC) of plastics using $E_{d,\,AC} \sim 40...60\ \ kV / mm$ shows that the electrical stress of the plastic is very low. With DC, $E_{d,\,DC}$ for the respective plastics without taking into account ageing, long-term and space-charging effects (at higher electrical field intensities) tends to be 2 times higher than AC[5]:

$$E_{d,\,DC} \gtrsim 2 \cdot E_{d,\,AC}.$$

A further comparison of the operating field strength E_b calculated above with the electrical penetration field strength for air (with AC) with $E_b < E_{d,\,Luft} \approx 3\ kV / mm$[7] shows that no penetration occurs even over the insulation distance of 1,6 mm with the insulation medium air.

Both calculations and comparisons show the rather negligible electrical stress of the insulating material in the low-voltage range. The selection and requirements of insulation materials and their wall thicknesses are primarily determined by the thermal and mechanical stresses. Therefore, most of the polymeric insulating materials of AC can also be used equally for DC cables. A very good compromise of good electrical and mechanical properties taking into account the costs is the use of PVC. For higher requirements (e.g., higher mechanical bending or torsional stresses on cables or higher resistance to environmental influences), the use of higher-quality insulation materials such as polyethylene, polypropylene or thermoplastic elastomers is necessary.

LAPP was able to demonstrate further findings as a funded partner in the publicly funded DC Industry 2 project (footnote 7) (funded by the BMWK). In extensive metrological analyses, the basic correspondence between the failure behaviour of the core insulation material for AC and DC in the low-voltage range was established - if a material fails with AC, it also fails with DC and vice versa. However, there is an influence of additives on the long-term resistance of plastics and therefore also differences within a material group, such as PVC. The water bath storage carried

5 E.g., K. Fuchs: "Ein Beitrag zur Optimierung der elektrischen Feldstärkeverteilung in LDPE unter HGÜ-Beanspruchung" (A contribution to optimising the electrical field strength distribution in LDPE under HGÜ stress), University Publishing House Ilmenau, 2021

6 For an aerial distance of 1 mm, a voltage of 3 kV is required so that a breakthrough is created over this distance

7 System concept of the DC-Industrie 2 project, URL: https://dc-industrie.zvei.org/publications/system-concept-for-dc-industrie2

out as part of the project is the highest stress for insulation materials, regardless of the applied voltage. Thus, under the influence of moisture and water, some PVC and halogen-free compounds can develop breakdowns when subjected to voltage, which can be attributed to the simultaneous effect of water and electric field on the fillers and additives in the aforementioned compounds. Unfilled, i.e. pure insulating materials, on the other hand, withstand the stress.

3.5 Electrical stress of insulating materials at high voltage

As the nominal voltage increases, the insulation wall thickness increases from a few millimetres up to a few centimetres for some 100 kV. As a result, the electrical field strength of polymer high-voltage and peak-voltage cables extends to $E_b \sim 10 \ldots 20\ kV / mm$[8]., even though E_b is well below the electrical field strength of $E_{d,\,AC}$ and $E_{d,\,DC}$, respectively. Despite this circumstance, the insulating material (typically cross-linked polyethylene PU) is subject to a much higher electrical stress. The operating field strength is also above the electrical field strength of air. This means that a breakthrough would already occur with a comparable aerial distance. **Figure 4** illustrates the difference between the electrical field strength load at low and high voltage.

Due to the higher electrical field strength and the different physical effects when applying stress to insulating materials with AC or DC voltage (see 3.2 and 3.3), the same polymer insulating material compositions can no longer be used for AC and DC at the high voltage level. Particularly due to the formation of space charges (see chapter 3.3), a significantly higher amount of effort is required in the production of polymer insulating materials in DC.

On the one hand, a higher purity of the polymer can be achieved through, for example, a complex degassing of residues immediately after the production process. The type and proportion of fillers and additives also have an influence on the purity. This approach is predominantly used by European manufacturers for the installation of cable systems for high-voltage direct current transmission (HVDC) with a maximum voltage of ± 525 kV. In the Asian region, on the other hand, special compounds (basic polymer with certain fillers) are often produced to ensure sufficient DC resistance.

As a special feature in the high-voltage and peak-voltage levels, oil-paper insulation (or mass-impregnated paper) is still used for DC cables. Unlike polymers, these have a significantly higher electrical conductivity, but can avoid the formation of space charges at the required electrical operating field strengths. However, this insulation can only be claimed with a reduced permissible operating temperature range of 55 °C.

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8 U. Schichler, P. Ratheiser: “Mittelspannungs-Gleichstromübertragung – Übertragungskapazität und Wirtschaftlichkeit von Kabelstrecken” (Medium voltage direct current transmission – transmission capacity and economic efficiency of cable tracks),
URL: https://link.springer.com/content/pdf/10.1007/s00502-022-01039-8.pdf, 2022-03-22

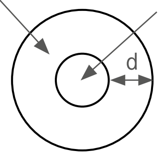
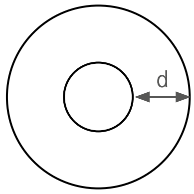
	Low voltage	High voltage
Typical cable geometry with associated parameters	Insulating material Inner-conductor  Nominal voltage $U_{DC} = 1{,}5\ kV$ Insulation wall thickness $d_1 = 0{,}6\ mm$ $d_2 = 1{,}2\ mm$	 Nominal voltage $U_{DC} = 320\ kV$ Insulation wall thickness $d \sim 3\ cm$
Breakthrough voltage at comparable air travel distance Assumption: $E_{d,\,Luft} \approx 3\ \frac{kV}{mm}$	$U_{d,\,Luft1} = E_{d,\,Luft} \cdot d_1 = 1{,}8\ kV$ $U_{d,\,Luft2} = E_{d,\,Luft} \cdot d_2 = 3{,}6\ kV$ $U_{d,\,Luft} > U_{DC}$ → No breakthrough at low voltage up to 1.5 kV in the solid for these geometries	$U_{d,\,Luft} = E_{d,\,Luft} \cdot 3\ cm$ $U_{d,\,Luft} = 90\ kV \ll U_{DC}$ → Breakthrough at high voltage in the cable (solid material) possible with such geometries

Figure 4: Comparison of the electrical throughput voltages air – solid for exemplary low-voltage and high-voltage stresses

The standardisation (UL 758) provides for identical tests for AC and DC cables (240 h at 70 °C).

LEGEND

- $U, u(t)$ - Voltage, alternatively, the linked voltage between two live conductors (in time) in $[V]$
- U_{AC} - Alternating voltage in $[V]$
- U_{DC} - DC voltage in $[V]$
- t - Time in $[s]$
- κ - Electrical conductivity in $[S/m]$
- E - Electrical field strength in $[V/m]$
- E_b - Electrical operating field strength in $[V/m]$
- $E_{d,\,AC}$ - Electrical breakthrough field strength (for AC) in $[V/mm]$
- $E_{d,\,DC}$ - Electrical breakthrough field strength (for DC) in $[V/mm]$
- $E_{d,\,Luft}$ - Electrical breakthrough field strength (for Luft) in $[V/mm]$
- ⊕→ - moving positive ions
- ⊖→ - free moving electrons
- ⊖ - fixed electrons (space charges)
- U_0 - Conductor-earthing voltage in $[V]$
- d - Insulating wall thickness in $[mm]$