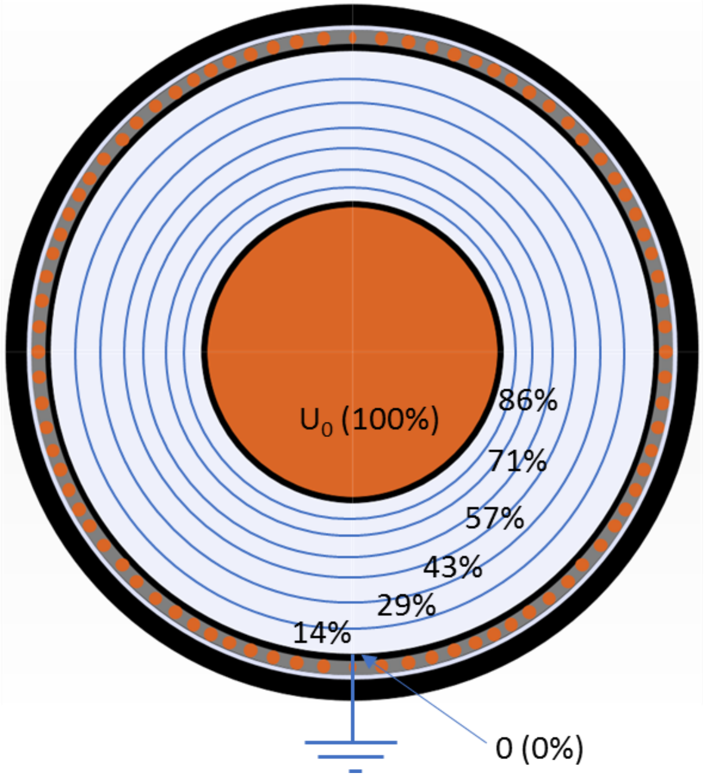
NKT

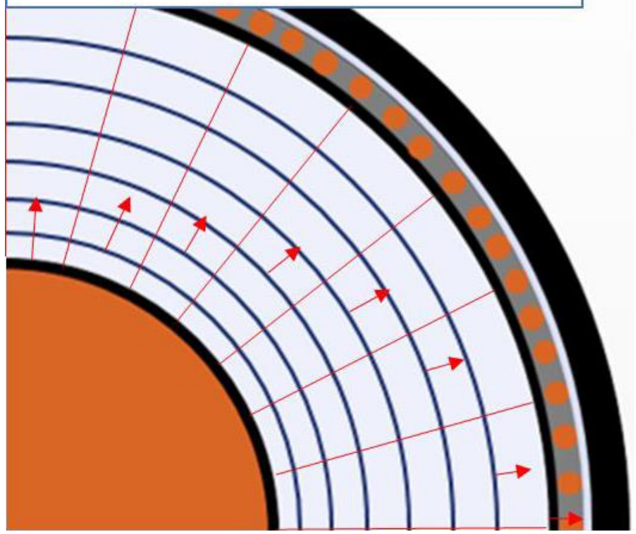
Importance of Field Control in Renewable Settings

Electric potential V and electric field E

145 kV (U0 = 76 kV) cable with 400 mm2 conductor and 15 mm insulation



$$V_2 - V_1 = -\int_{P_1}^{P_2} \boldsymbol{E} \cdot d\boldsymbol{l} \rightarrow \mathrm{E} = -\frac{dV}{dr}$$



$$E(r) = \frac{U_0}{r \cdot \ln\left({}^{r_0}/{}_{r_i}\right)}$$

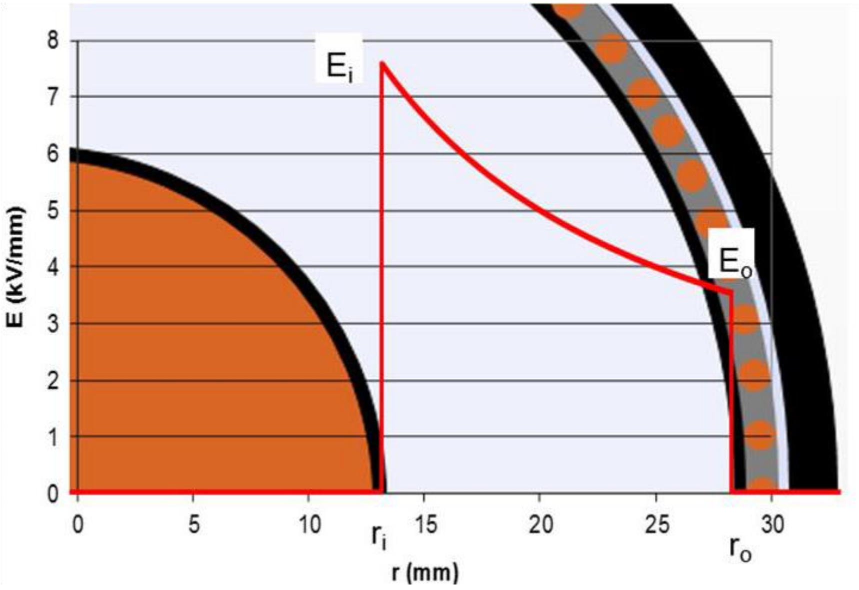


Illustration of equipotential lines (surfaces)

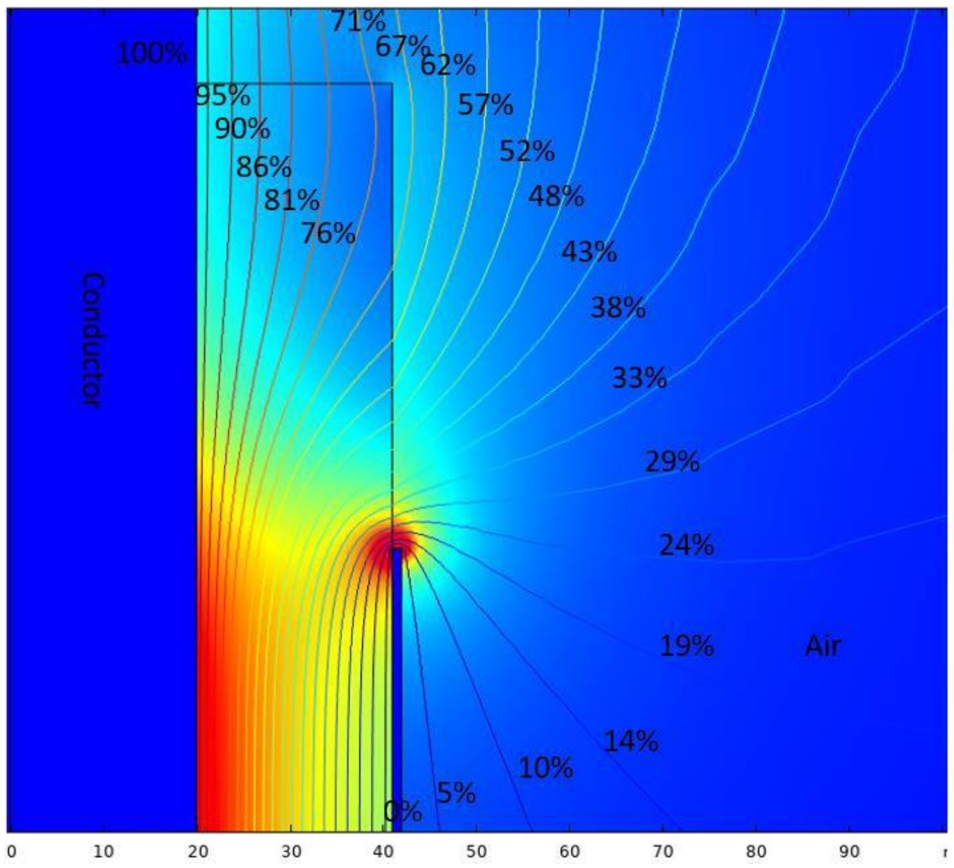
No electrical field control

- The conductor is at full voltage (100%).
- The insulation screen is at ground zero voltage (0%).

- Imagine that you could measure the voltage anywhere with a volt meter. Any line (surface) having the same voltage potential is called an equipotential line.

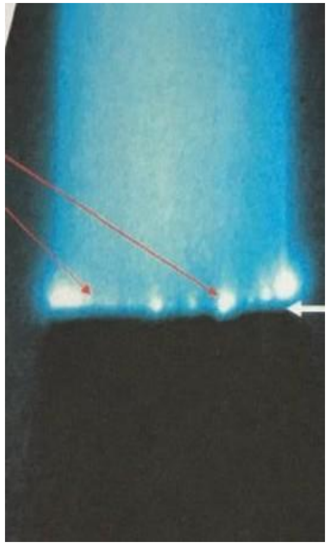
- The closer these lines, the higher the electric field. Basically the electric field is the potential difference (V) per distance (m), i.e. E=V/d.

- The electric field magnitude can be visualized by color, e.g. red is high and blue is low value.
- Note the high electric field at the triple point.



The triple point

- The triple point is a ”sharp” edge.
- It is at high electric field.
- Any air at this point will result in air to break down, first with partial discharges likely leading to breakdown of the cable insulation.
- It is the first job of the accessory to avoid air at the triple point and offer stress relief and control of the electric field to safe levels (at all places inside and outside the accessory).



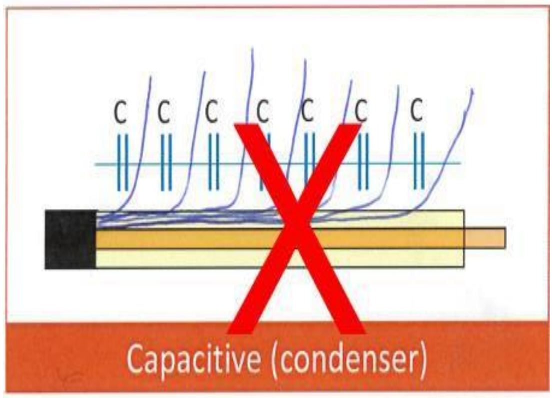
PD at triple point with voltage present

Traces of PD

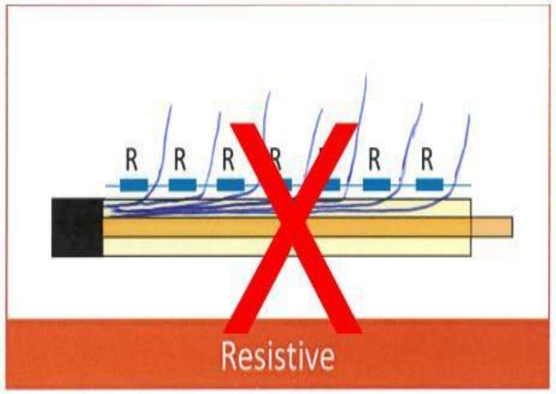
PD in service. Break Down in cable insulation

Electric field control methods

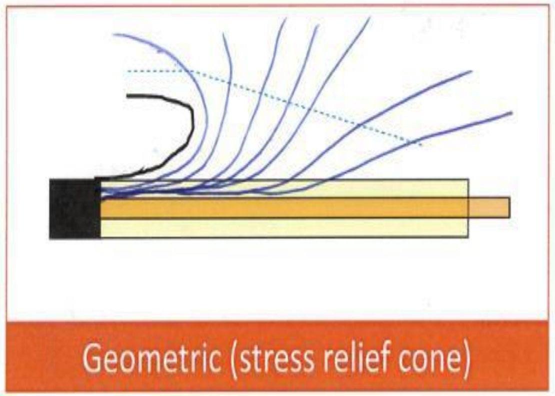
There are four types of the electric field control



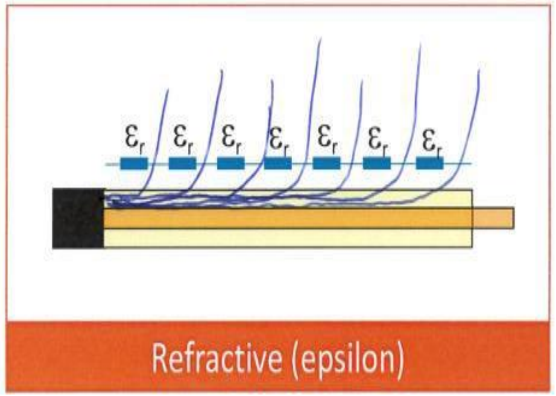
With metallic layers/foils, condenser



Linear or non-linear resistive materials



Geometric shape; semi-conducting stress relief electrodes deflector/cone



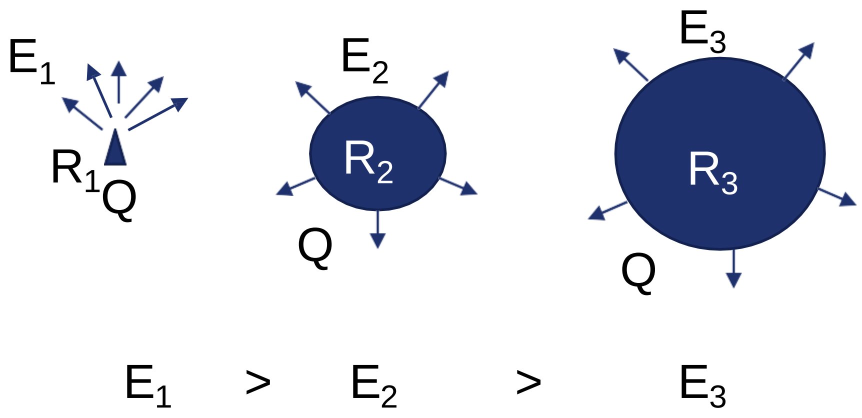
Epsilon; high relative permittivity, $_r$ /K materials

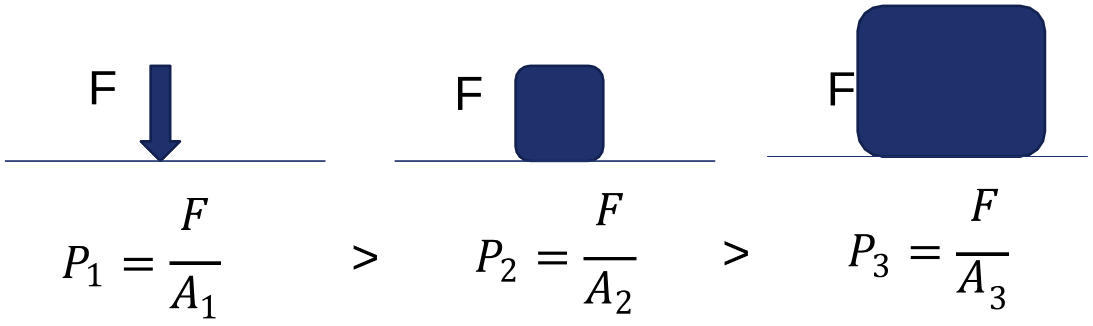
- These methods are somewhat overlapping and can be used in combinations.
- In prefabricated accessories for AC only geometric and refractive control methods are really used.

Geometric field control

How does it work?

- Electric charges Q (electrons) tend to accumulate at sharp edges with small radius (R) on conductors. This leads to a high charge density and high electric fields.
- Sharp edges must be prevented or screened/controlled, e.g. geometric round shapes. The larger shape, the lower the electric field.
- It may be helpful to consider the analogy with pressure and force. The pressure P is given by the force F per area A. A small area such as a sharp tip creates a high pressure.



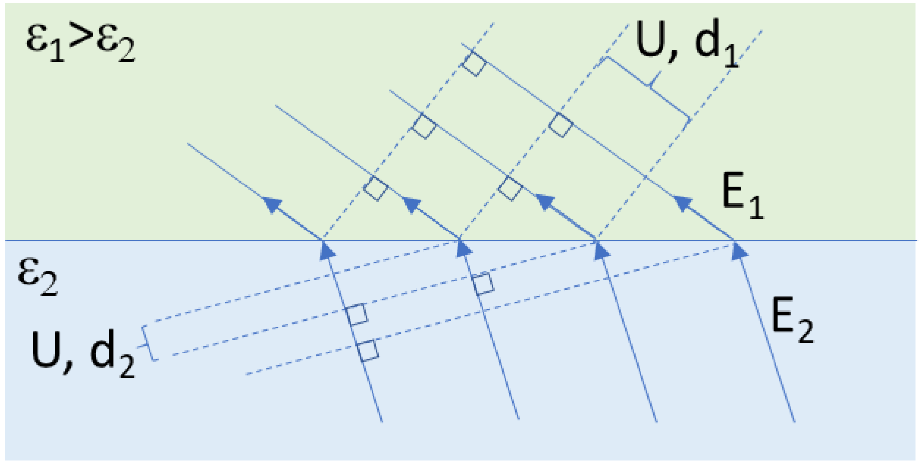


Refractive (high $_r$ / K) field control

How does it work?

$\varepsilon 1 * E1n = \varepsilon 2 * E2n$

- The permittivity of the material will bend (refract) and scale the electric field.
- The higher the permittivity, the lower the electric field and more separated (spread out) the equipotential lines.
- The electric field and equipotential lines are perpendicular (at right angle 90°).



Dashed line = equipotential line
Solid line = electric field line

$$E = \frac{U}{d} \Rightarrow E_1 = \frac{U}{d_1} < E_2 = \frac{U}{d_2}$$

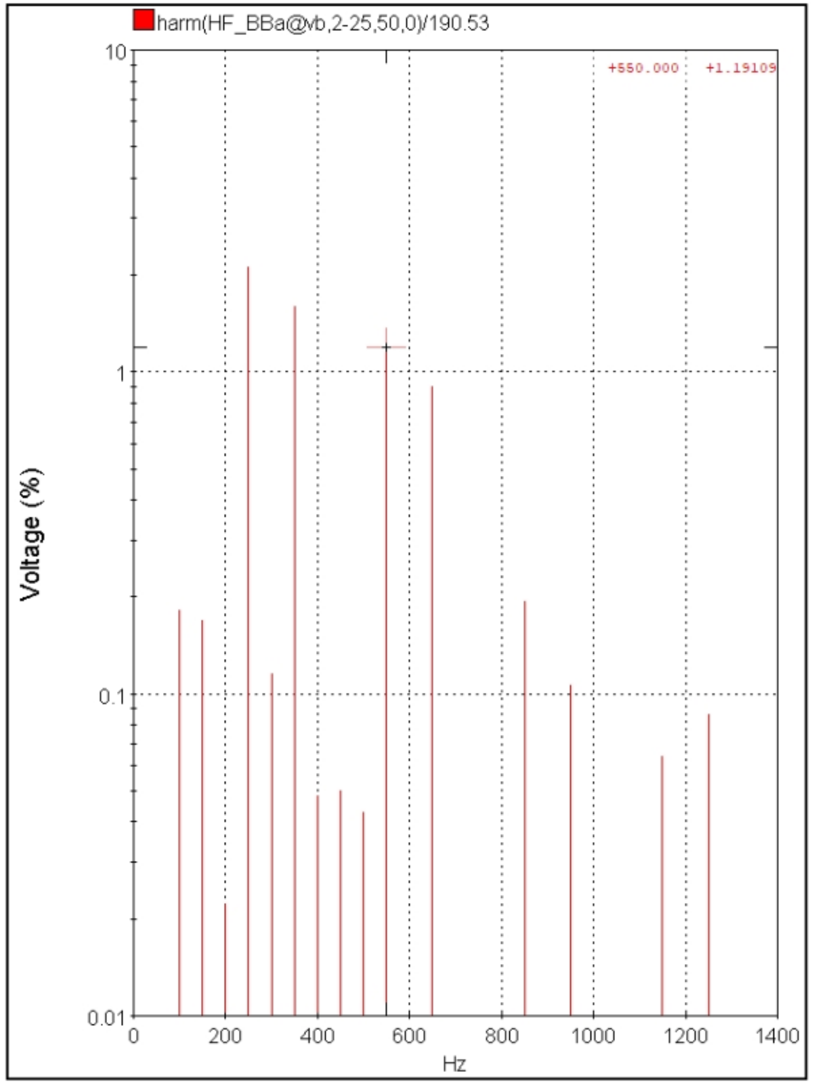
Harmonics

Ideally the voltages and currents are pure sinusoidal functions of one fundamental frequency (f), e.g. 50/60 Hz.

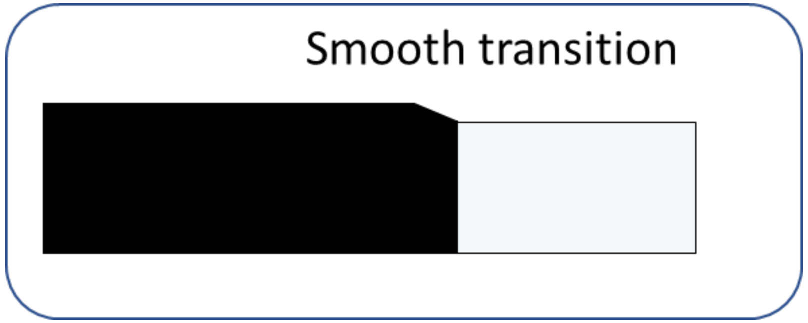
However, non-linear loads, e.g. electric arc furnace and power electronics, creates harmonics.

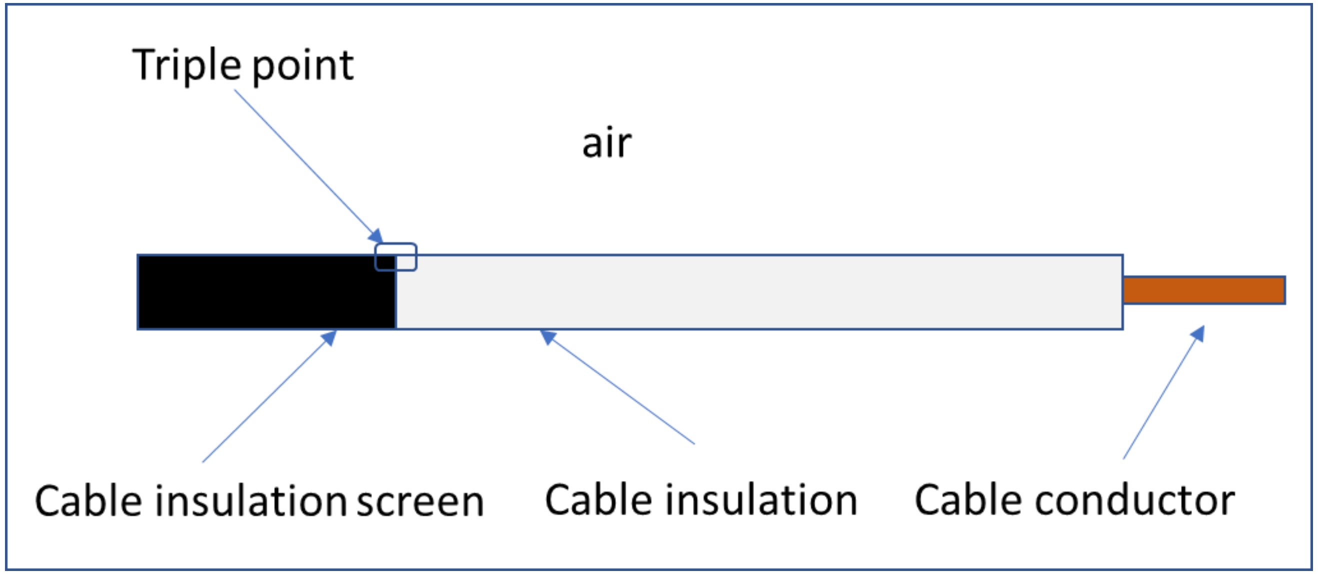
Harmonics are multiples (n) of the fundamental frequency, e.g. 100, 150, 200, ..Hz.

THD (total harmonic distortion) is a measure of the amount of harmonics.



The prepared cable & triple point





Triple point at cable insulation screen

Step at transition

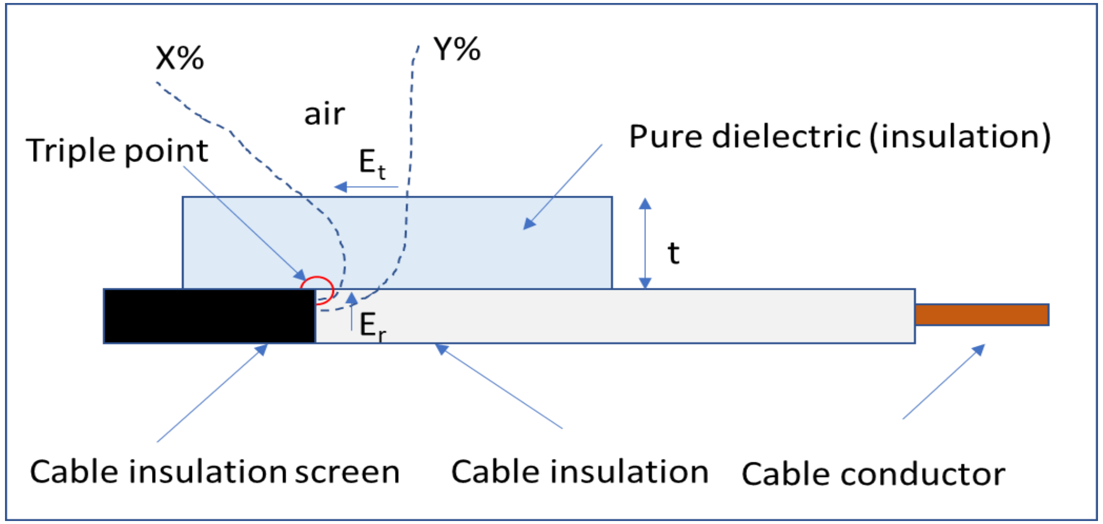
Risk for air gap

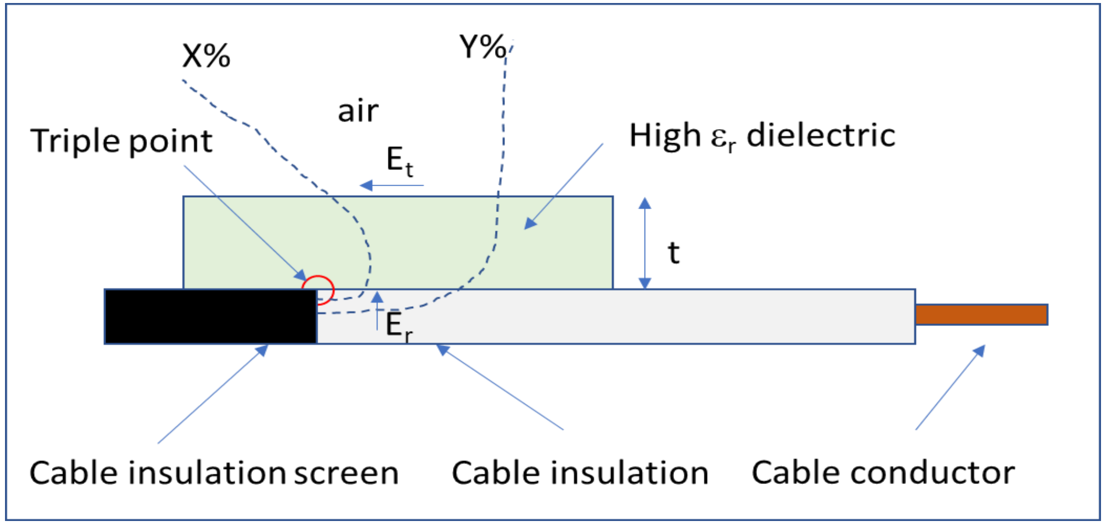
Smooth transition

No risk for air gap

Pure dielectric (insulation) or High ε_r (K) refractive field control only

- The electric field in the air may be OK depending on thickness t.
- There is no air at the triple point.
- The electric field concentration at the triple point is controlled with refractive control.
- However, there is still a **sharp edge** (electric field concentration) at the triple point in the pure insulation.

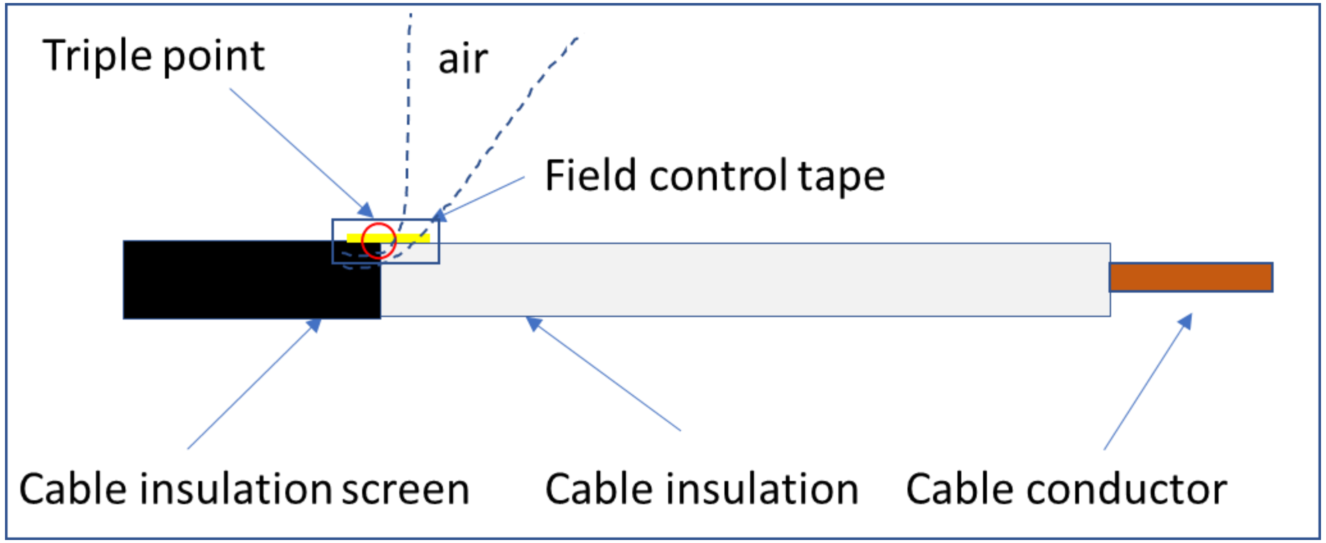


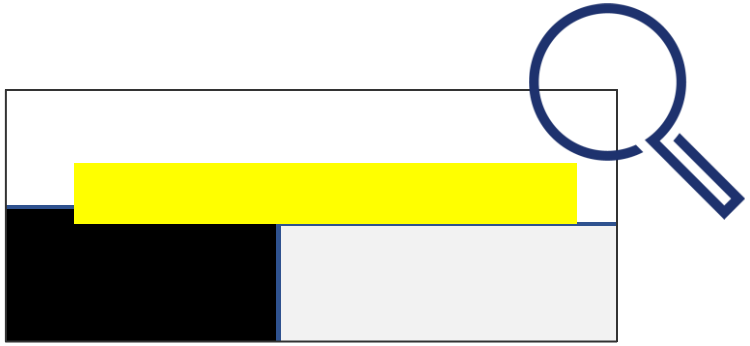


High $_r$ (K) refractive field control (or void filling) tape

Strippable insulation screen – step at triple point

- The electric field in the air is high.
- No air at the triple point.
- The electric field concentration at the triple point is controlled.

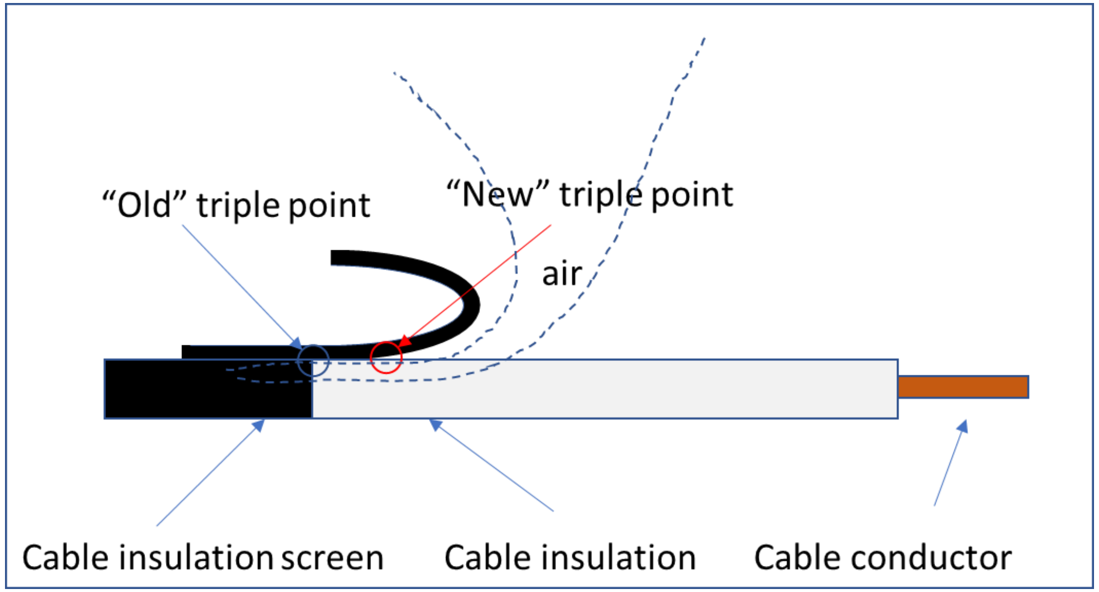


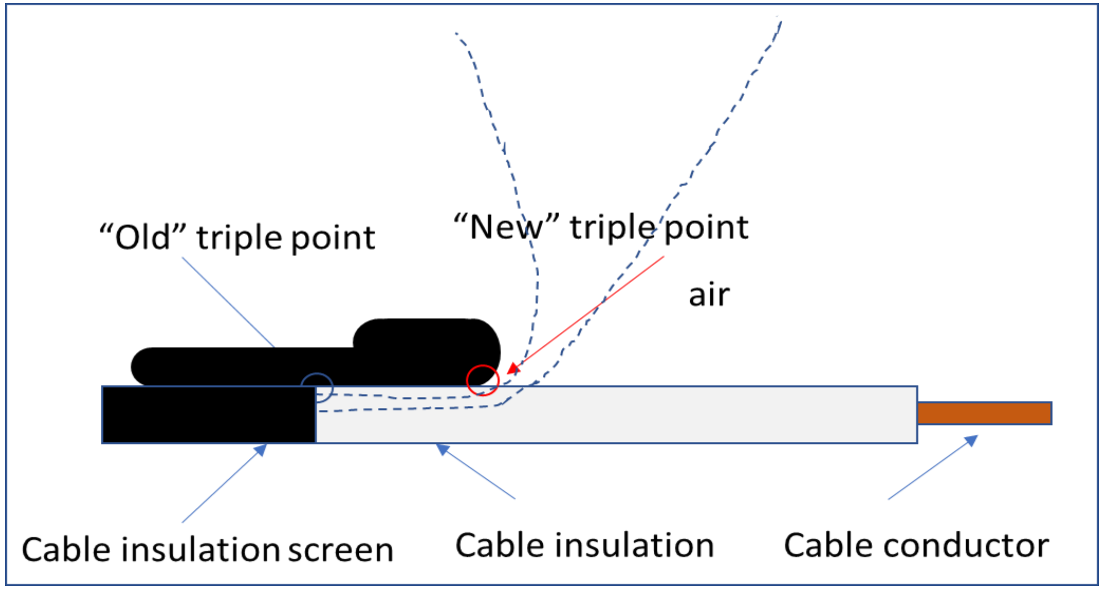


Geometric field control – stress relief cone / deflector only

The electric field at the ”old” triple point is controlled.

However, there is now a new triple point to air with high field.





Combination of dielectrics

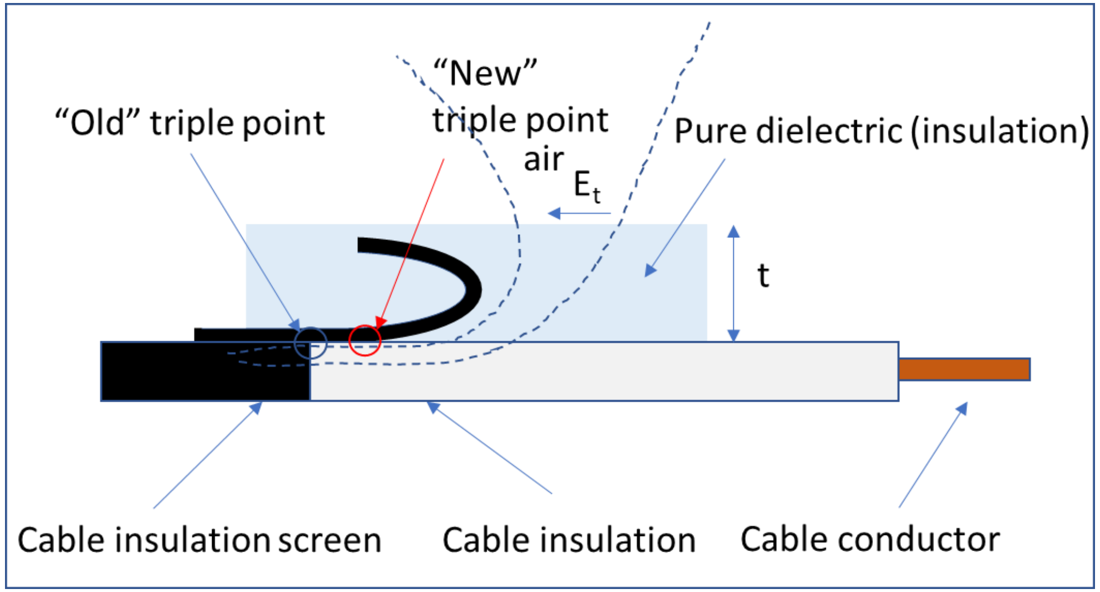
The electric field at the ”old” and ”new” triple points are controlled

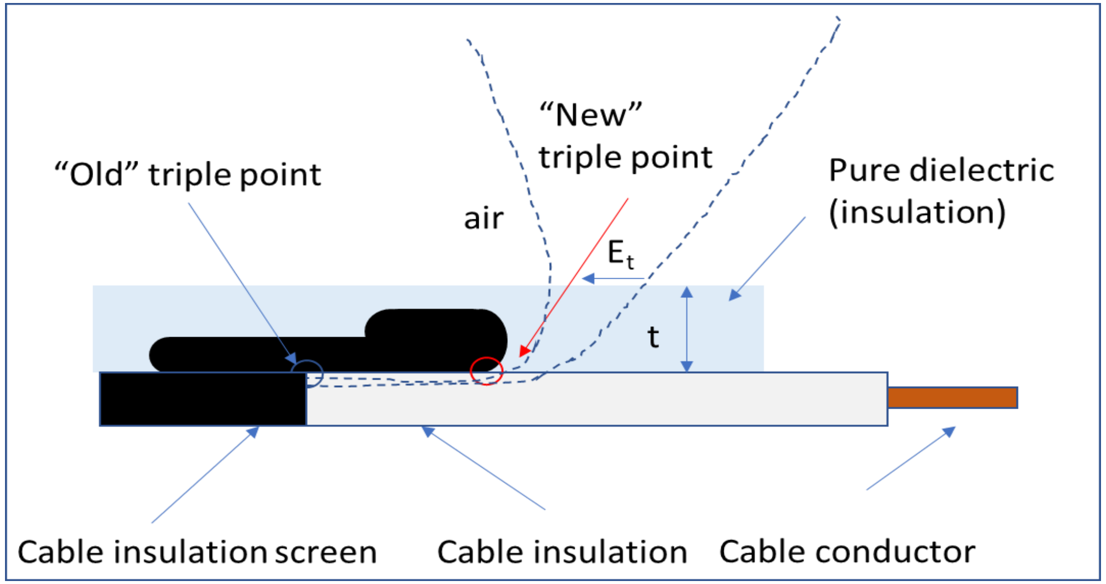
There is no air or high field at the new triple point.

No sharp edges due to rounded deflector.

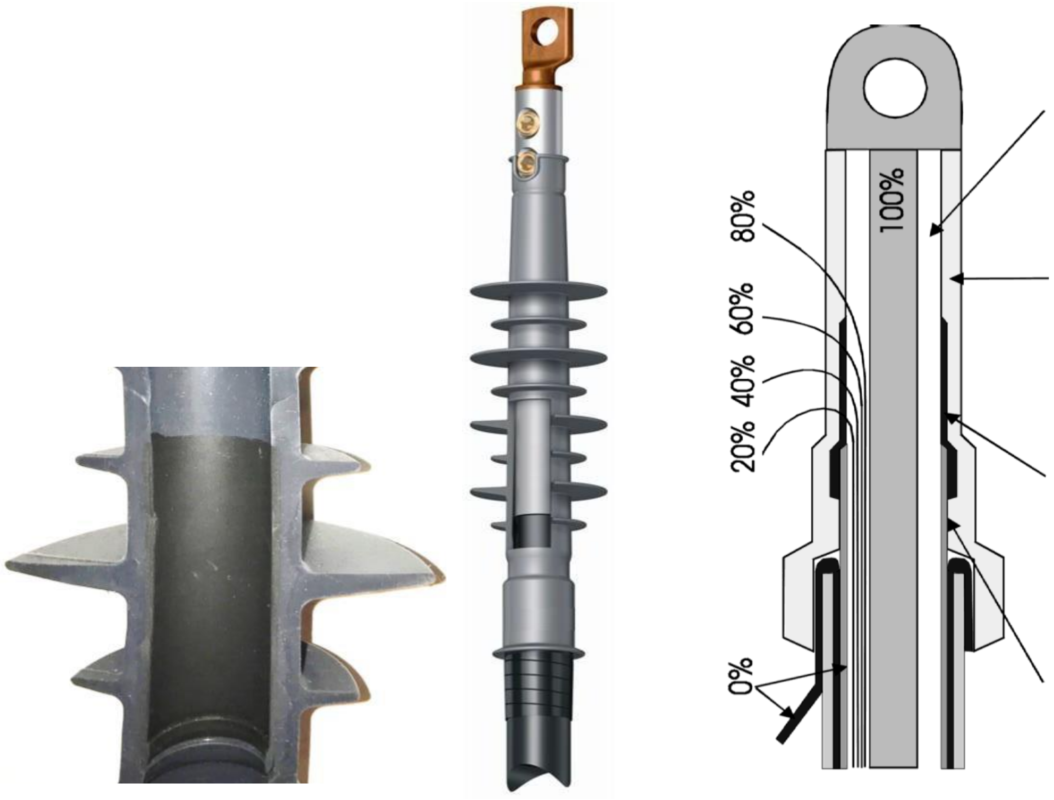
Perfect solution for premoulded components

The geometric electric field control “component” is made of a semi- conducting material combined with insulation. Depending on the shape it can be referred to as a stress relief cone or deflector.

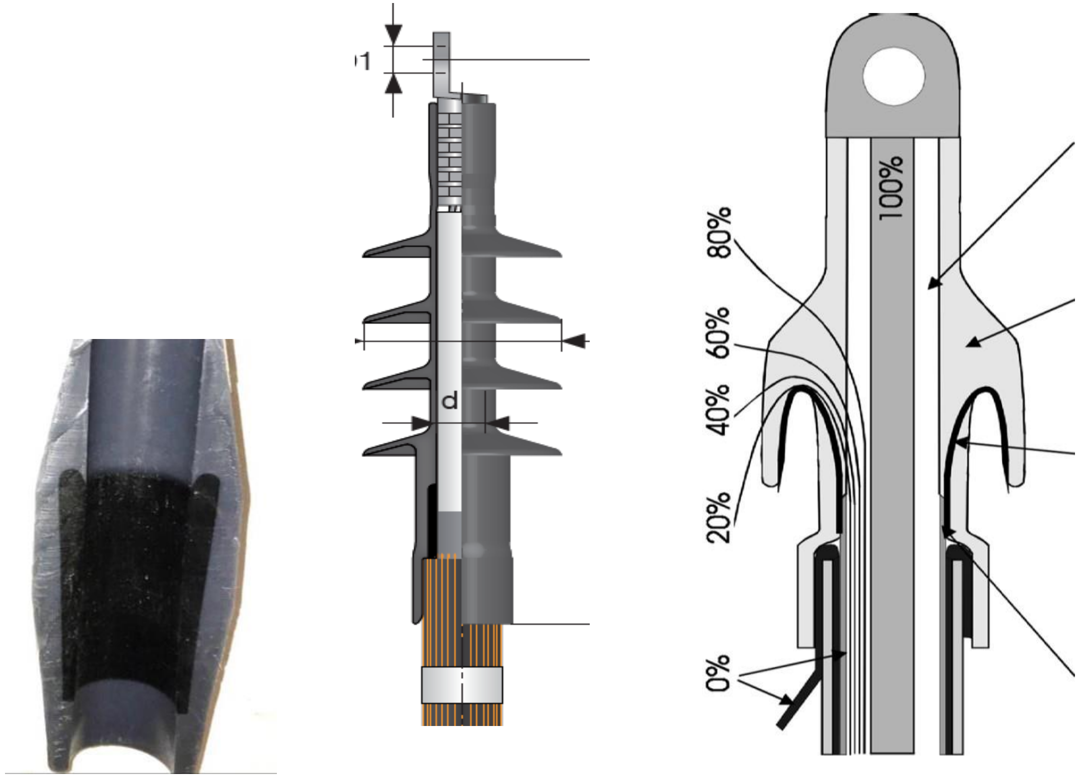




NKT examples of terminations SOT vs TO



SOT – with refractive electric field control



TO – with geometrical electric field control

Electrical Field Control in Renewables

Old network strategy / thoughts at the TSOs & DNOs:

„Oil paper cables are great!
Very old and still working“

N+1 Concept
Every system is installed twice,
each system loaded with 50%

Conductor temperatures of 25°C
were not seldom

Like an idle run of an engine

Today's differences

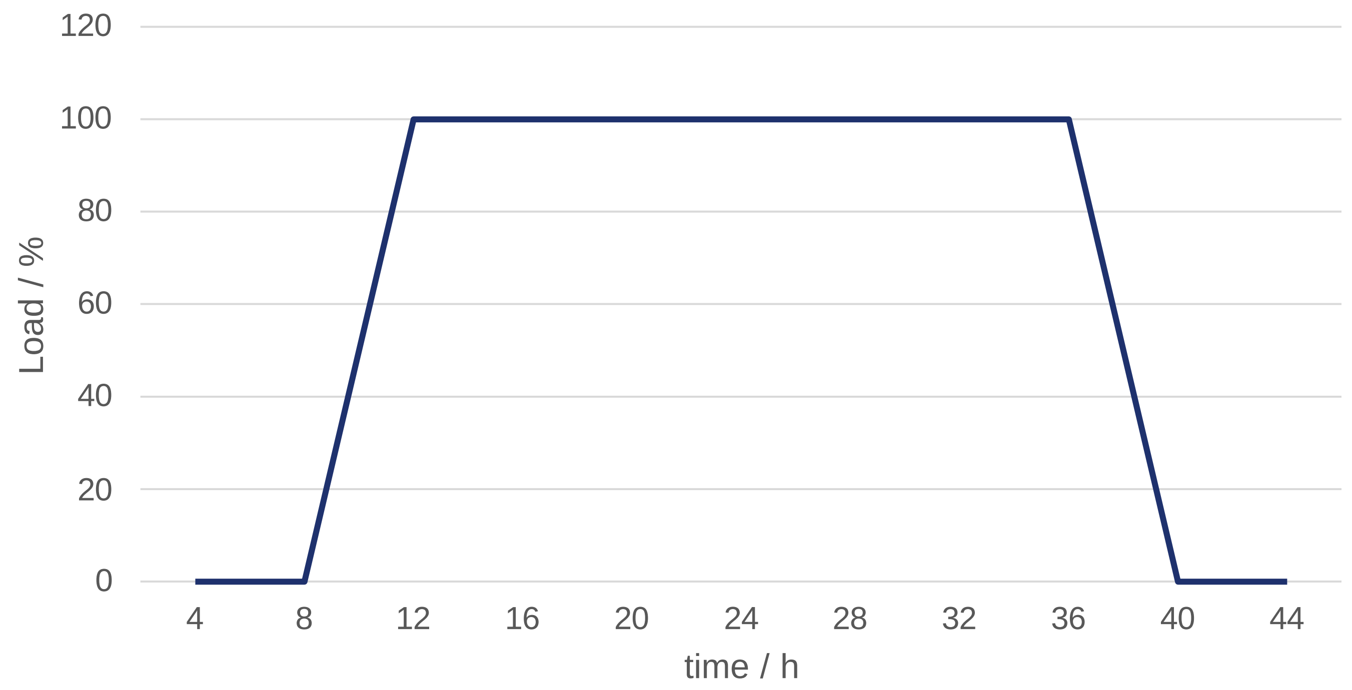
Wind- and Solarparks have different requirements

100% loaded, but volatile

Inverters create a non sinusoidal current and voltage

Renewables need also renewed cable accessories

Wind park load curve (ideally)



Conductor temp. XLPE: 90°C

Δϑ: 70K

Soil temp.: 20°C

Load of the wind park connection is digital: on-off

Thermal expansion of aluminium

$$\Delta L = \alpha \cdot \Delta T \cdot L_0$$

Where
- ΔL =extension (mm)
- α $=24 \cdot 10^{-6}$ °C^{-1} = expansion coefficient of aluminium
- L_0 =initial length of the sample (mm)
- ΔT =temperature increase (°C)

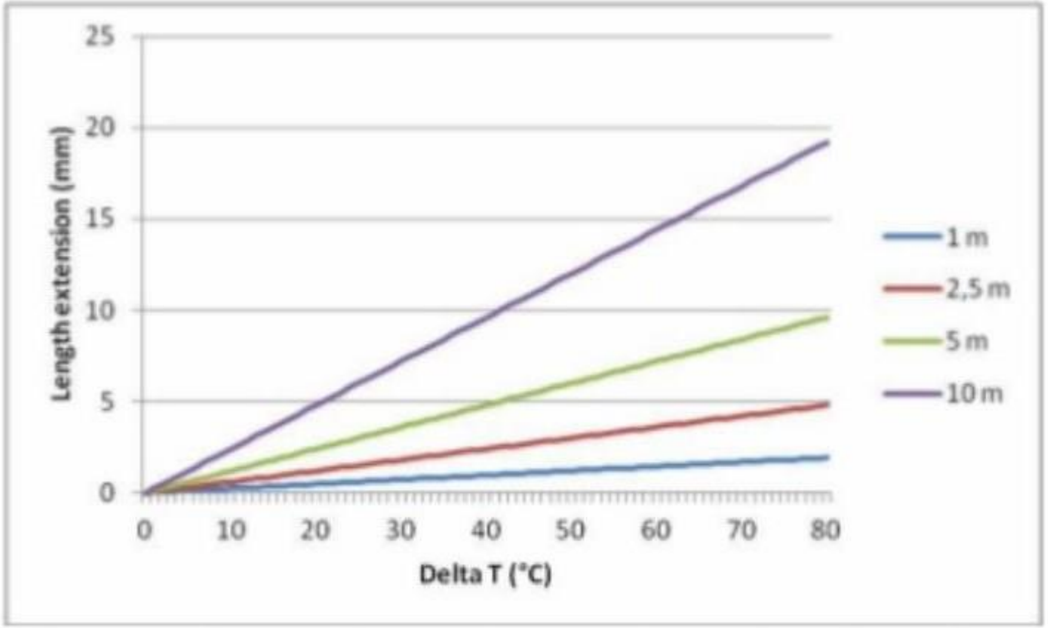


Figure 2: Theoretical length extension in function of the temperature increase for an aluminium conductor

Current causes higher temperature and with that, metal expansion

Source: Paper 0128 CIRED 2013

Force of aluminium conductors

Example 630sqmm: 50.000N (5t)

$$F_{tot} = F_t = E \cdot A \cdot \alpha \cdot \Delta T$$

Where

- α $= 24 \cdot 10^{-6}$ °C^{-1} = expansion coefficient of aluminium
- E $= 7 \cdot 10^{10}$ N/m^2 = Young's modulus of aluminium
- A =conductor cross-section (m^2)
- ΔT =temperature increase (°C)

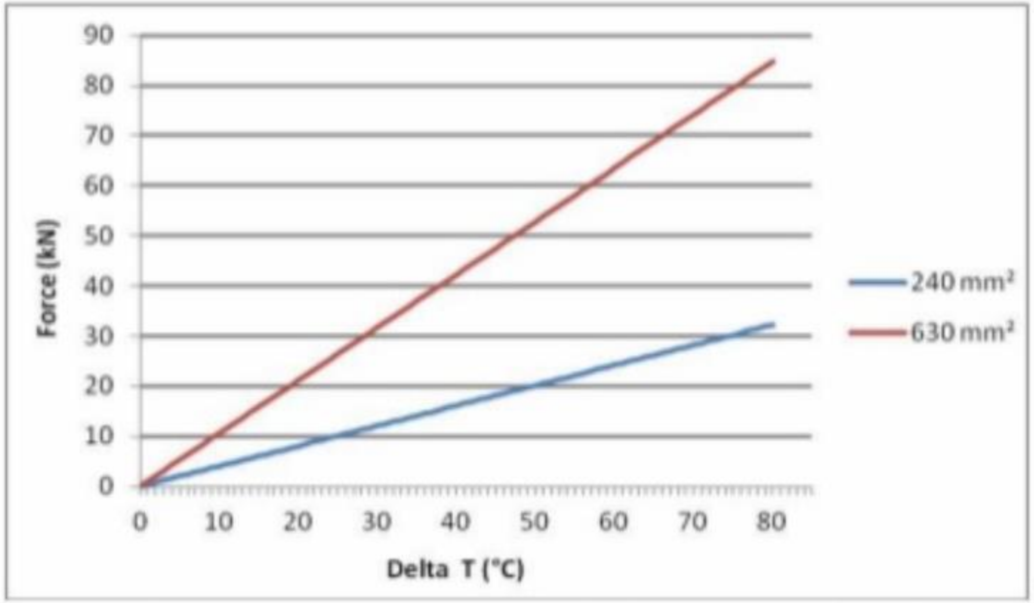


Figure 1: Theoretical forces exerted by a 240 and 630 mm² aluminium conductor in function of the temperature increase

Current causes higher temperature and with that, mechanical forces

Source: Paper 0128 CIRED 2013

What is covered by CENELEC 629?

Length of the test loop: 6-8m (low thermal expansion)

- DC Voltage
- AC Voltage 50Hz
- Impact test
- Impulse voltage
- Aging in air with current
- Aging in water with current

- Voltage
- Short circuit screen
- Short circuit conductor
- Impulse voltage
- AC Voltage 50Hz

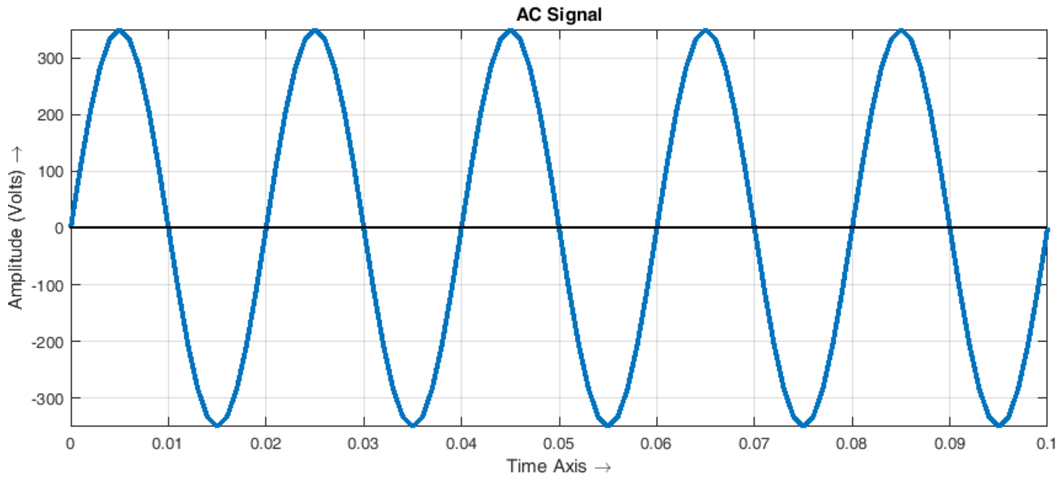
Table 4 – Joints and transition joints for impregnated paper insulated cables (see Figure 2)

Test		Test clause of EN 61442	Test sequences Type of joints (1)			Test requirements
			I B1	II B1	III B2	
1	DC voltage dry	5	x	x	x	15 min at 6 U_0, no breakdown
2	AC voltage dry	4	x	x	x	5 min at 4,5 U_0, no breakdown
3	Impact at ambient temperature	14		x		Insulation resistance - Conductor to screen 10^3 MΩ minimum - Screen to water 50 MΩ minimum (5)
4	Impulse voltage at elevated temperature	6	x	x		10 impulses of each polarity, no breakdown
5	Electrical heat cycling in air	9	x	x		63 cycles at 1,5 U_0, no breakdown
6	Electrical heat cycling in water	9	x	x		63 cycles at 1,5 U_0, no breakdown
7	A. C. voltage dry	4	x	x		4 h at 3 U_0, no breakdown
8	Thermal short circuit (screen) (2)	10			x	2 short circuits at I_{sc}, no breakdown
9	Thermal short circuit (conductor)	11			x	2 short circuits to raise conductor to θ_{sc} of the cable, no breakdown
10	Dynamic short circuit	12			x	1 short circuit at I_d (3), no breakdown
11	Impulse voltage at ambient temperature	6	x	x	x	10 impulses of each polarity, no breakdown
12	AC voltage dry	4	x	x	x	15 min at 2,5 U_0, no breakdown
13	Examination	-	x	x	x	For information only (4)

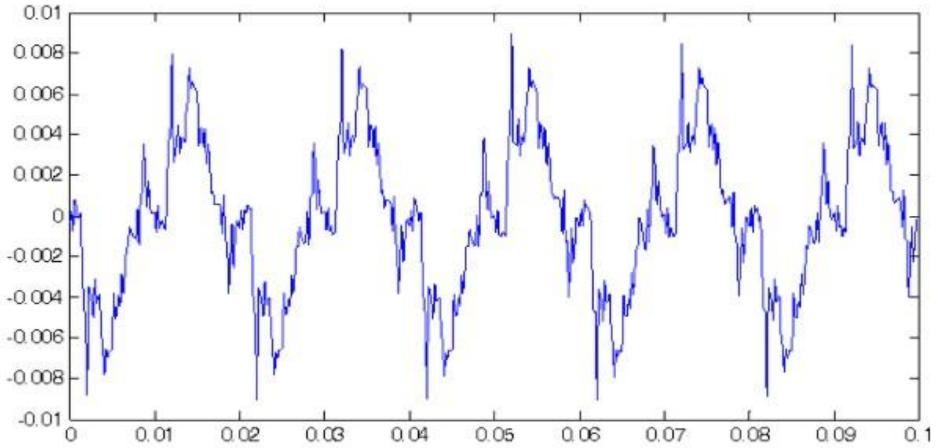
Standard reflects the load and laying conditions before renewables

Harmonics and switching impulses are coming from inverter technology

Ideal



Real



50 Hz signal with lots of harmonics

Power quality

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NKT cable accessories with geometric stress control are **not sensitive to harmonics and switching impulses**. Also, the thermodynamic effects are less sensitive to NKT joints as they are more flexible than other products in the market.

Summary of various electric field control methods

- **No control** – not applicable in accessories above 12 kV, high fields in air leading to breakdown.
- **Capacitive (condenser):** This is the case with conducting layers (usually of metal, e.g. aluminum sheets) interspersed in the insulation. The electric field control is very good. However, it does not really work practically in prefabricated accessories. It is often used for bushings, e.g. KFEV 300.
- **Resistive:** works good for DC, but is less common in AC due to high losses and lower breakdown strength. Not suitable for cold shrink as it is very stiff.
- **Refractive / high $_r$ (K):** the electric field control is very good, but the materials are "sensitive" to high frequencies due to relatively higher losses and lower breakdown strength. Worse shrink back properties. Not suitable for cold shrink.
- **Geometric:** Field control is very good. The main advantage is that the losses are low and the breakdown strength is high. Thus, it is insensitive to harmonics and transients. It can be produced with high flexible LSR. Ideal for cold shrink.

Combination of methods

- Geometric electric field control can be used in combination with high $_r$ (K) tapes, e.g. using void filling tapes at triple point.
  COMBINATION METHOD USED BY NKT AUSTRLAIA

Conclusion – why geometrical field control is a safer choice

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- The high electric fields in the cable need to be controlled by the accessory, both inside as well as outside.
- The two major electric field control techniques are A) geometrical control and B) refractive & non-linear resistive control.
- In case of geometrical electric field control, only low loss and high breakdown strength insulation materials are used. The field is controlled by a conducting properly rounded or shaped electrode (deflector/stress relief cone). The controlling member geometry is fixed and does not depend on voltage or frequency. The insulation material has a low loss which is also not dependent on voltage or frequency.
- Refractive & non-linear resistive control is achieved by adding "fillers" to an insulation material in order to achieve certain dielectric constant and non-linear resistivity. The controlling member in this case is thus the material itself. The material has dielectric losses that depend on the voltage (electric field), frequency (switching frequencies, harmonics) and tand. The losses also depend on the temperature. The material properties may be sensitive to fast transients, e.g., from frequent switching operations and power electronics.
- For most situations at voltages up to 52 kV cable accessories using refractive & non-linear resistive control work just fine (provided they are correctly designed). However, in cases of high harmonic content, high occurrence of switching operations, fast transients, and power electronics, refractive & non-linear resistive control can be prone to heat losses and ageing effects which may be problematic.

Stay Safe - Go with Geometrical Electric Field Control.

Thank you for your attention!