Materials for HVDC Cables

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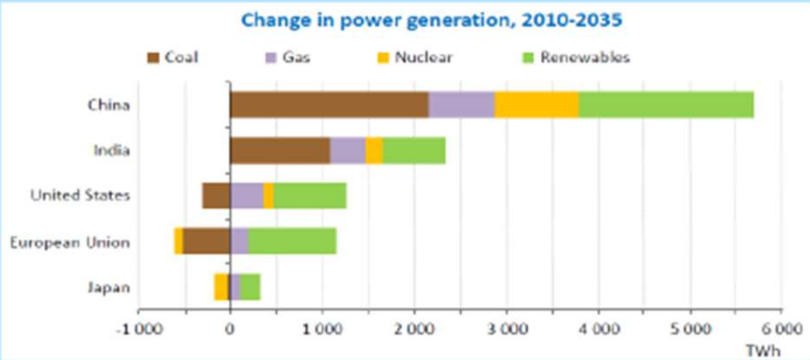
Increasing need to transport more energy over longer distances – more cables are needed

Renewable energy deployment



Source: EIA 2012

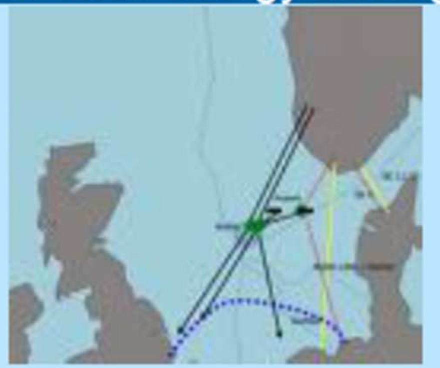
Bigger power stations

Solar energy for Europe

Within 6 hours deserts receive more energy from the sun than humankind consumes within a year

Source : Desertec

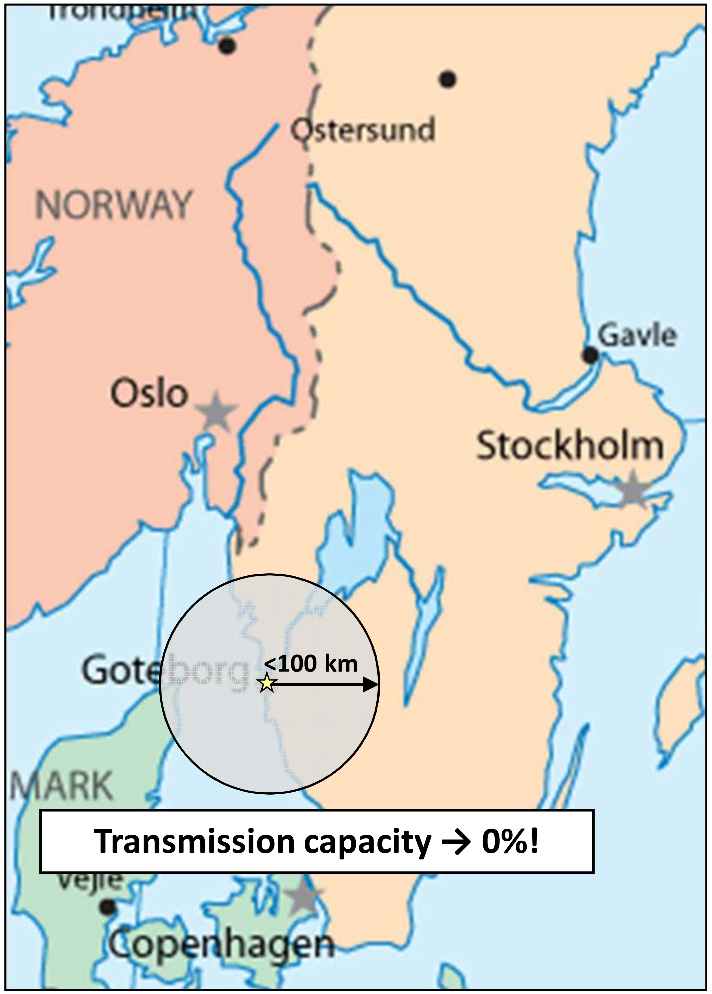
Increase energy trading



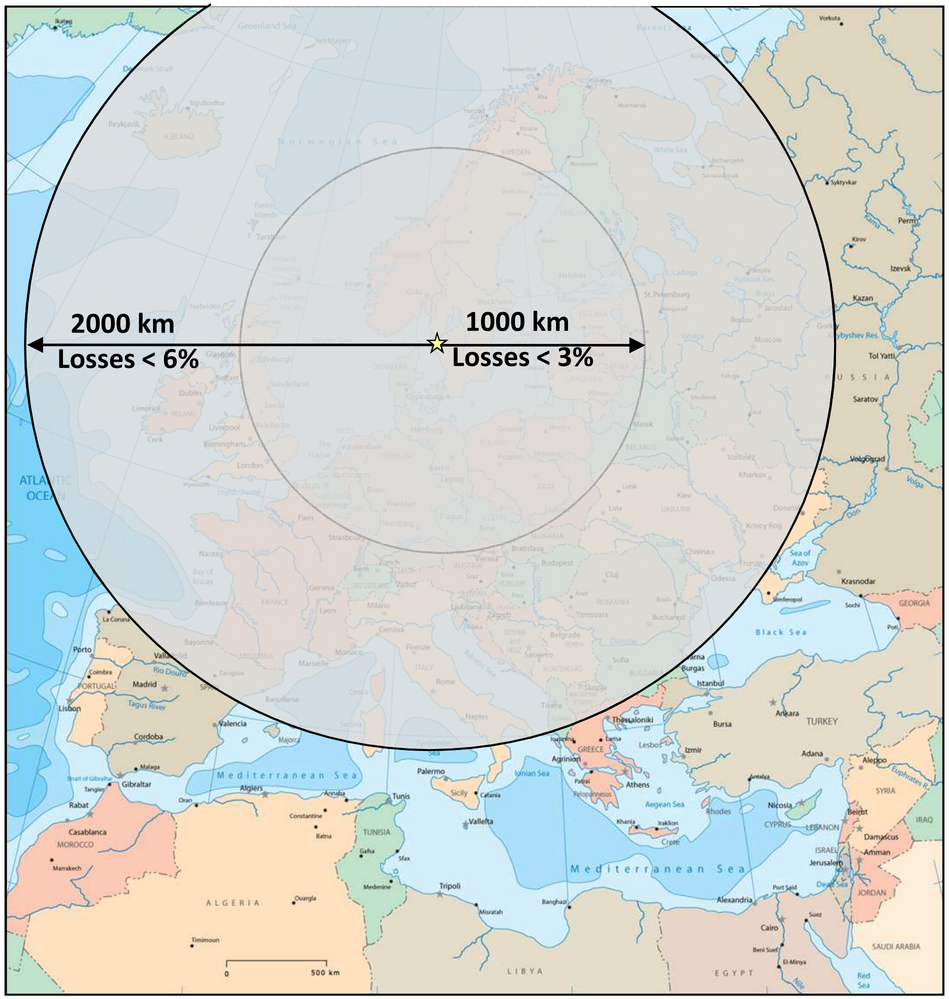
Why HVDC cables?

Maximum transmission distance:

HVAC power cables



HVDC power cables



Present HVDC cable technologies

	Single core mass impregnated cables	Extruded XLPE cables
		
Present level:	**+/- 500 kV at 2000 MW**	**+/- 320 kV at 1000 MW**

Advantages with extruded cables:

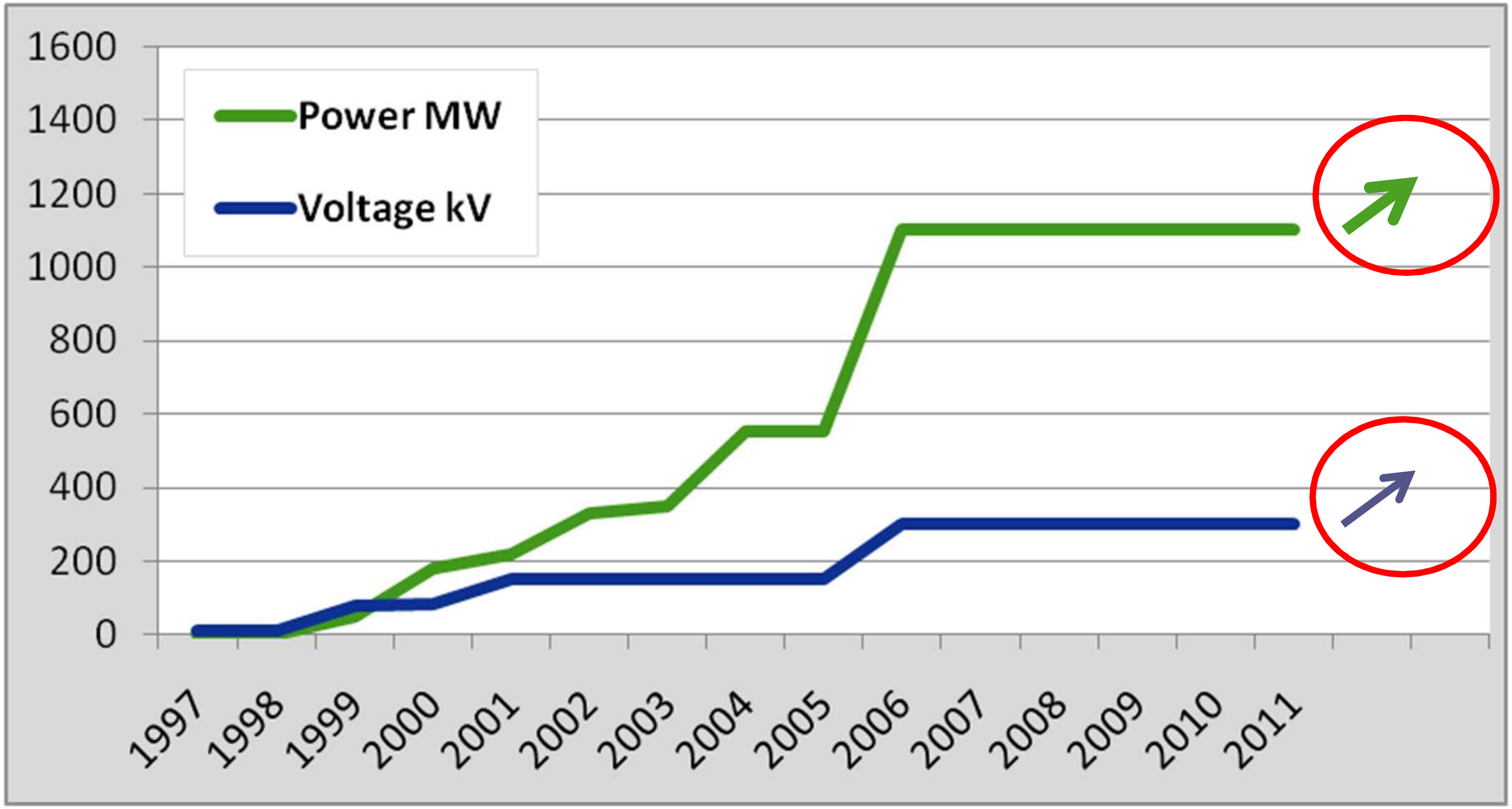
- Easier production
- No risk for oil leakage

Examples of projects with extruded cables

Project Name	Power (MW)	Voltage (kV)	Cable Length (km)	Entered in service
Gotland, Sweden	60	80	140	1998
Tjoerborg, Denmark	8	9	9	2000
Direct link, Australia	180	84	390	2000
Cross Sound, USA	330	150	84	2002
Murraylink, Australia	200	150	360	2002
Troll A, Norway	80	60	68	2004
Estlink, Finland-Estonia	350	150	105	2006
Borkum2, Germany	400	150	390	2009
Trans-Bay, USA	400	200	85	2010
Eigrid, Ireland-UK	500	200	512	2012
Helwin 1, Germany	576	250	260	2014
Borwin 2, Germany	800	300	400	2013/14
Dolwin 1, Germany	800	320	330	2014
Sylwin 1, Germany	864	320	410	2014
France-Spain	1000	320	264	2014
Helwin 2, Germany	690	320	260	2015
South-West link, Sweden	720	320	600	2014

Next generation transmission system requires improved materials

Development of extruded HVDC cables



Important properties of the insulation material

General material properties

- Mechanical properties
  - stiffness/modulus
  - heat deformation
- Rheology
  - Good processability
  - Low sagging
  - Good scorch performance
- Long life time
- Proven reliability

Electrical properties

- Impulse and DC breakdown strength
- Low space charge accumulation
- Low conductivity

Mechanical properties

Stiffness - important for handling of the cable

The relatively low crystallinity of LDPE gives a convenient modulus

Heat deformation – at full load part of the crystals will be melted

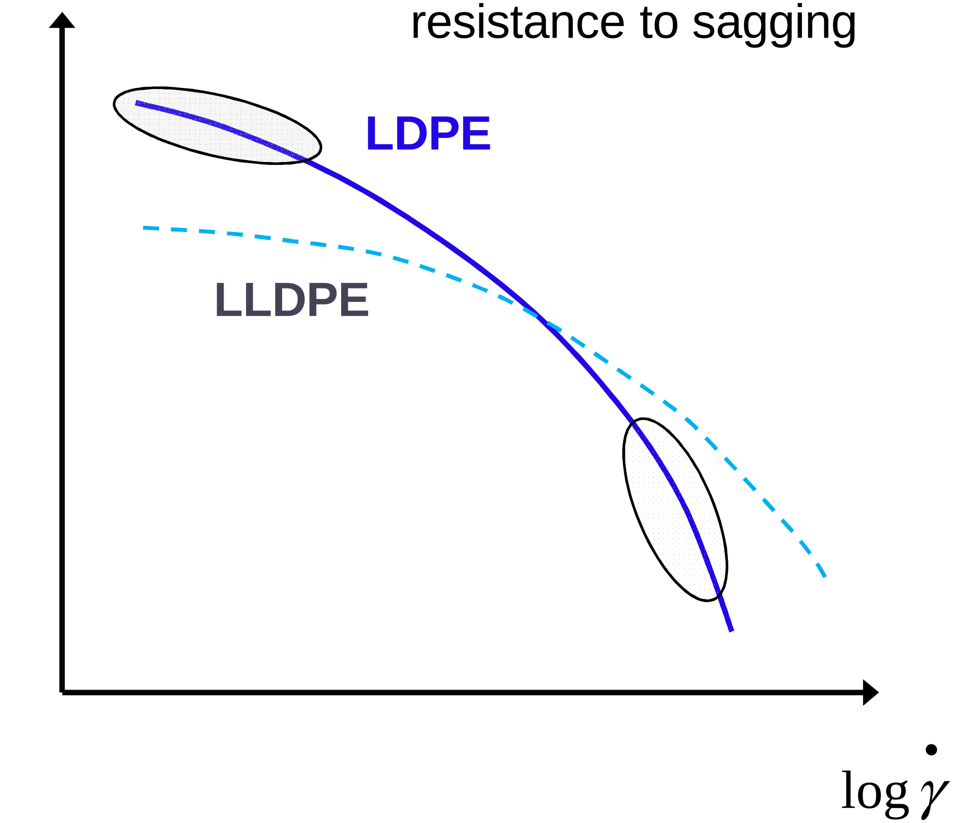
LDPE is therefore crosslinked using peroxides. This gives:

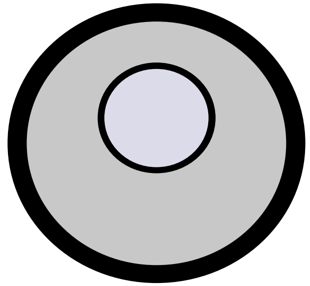
- good heat deformation
- stress cracking resistance

Rhelogical properties

Higher melt viscosity at zero rate → higher resistance to sagging

$\log \eta$



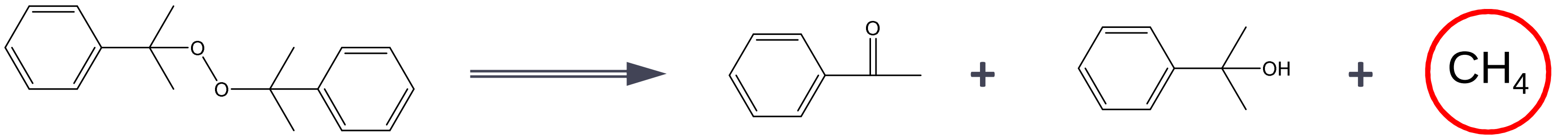


A material with too low zero rate viscosity may lead to an unsymmetrical result in a CCV line.

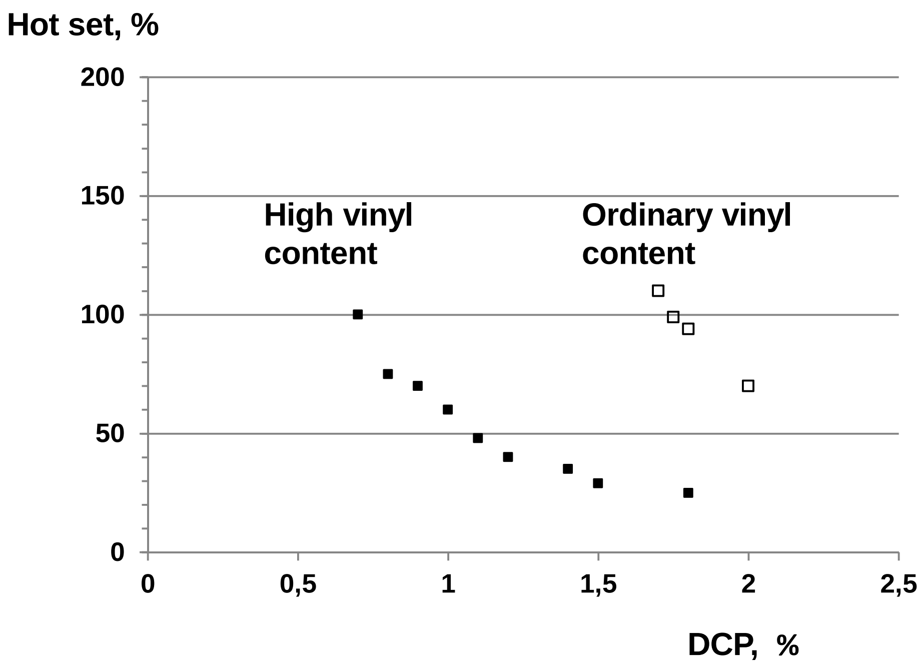
Lower melt viscosity at processing speeds → higher extrusion speed

Crosslinking

Crosslinking of LDPE is done with peroxide, e.g. dicumyl peroxide leading to decomposition products:



The formation of methane calls for degassing.



The amount of peroxide and thus decomposition products can be decreased by using LDPE with high content of vinyl groups.

A. Smedberg et.al., Polymer, 1997, vol 38, 4127-4138

Electrical properties

In the quest for insulation materials for higher voltages the electrical properties are crucial, in particular:

- Impulse and DC breakdown strength
- Low space charge accumulation
- Low conductivity

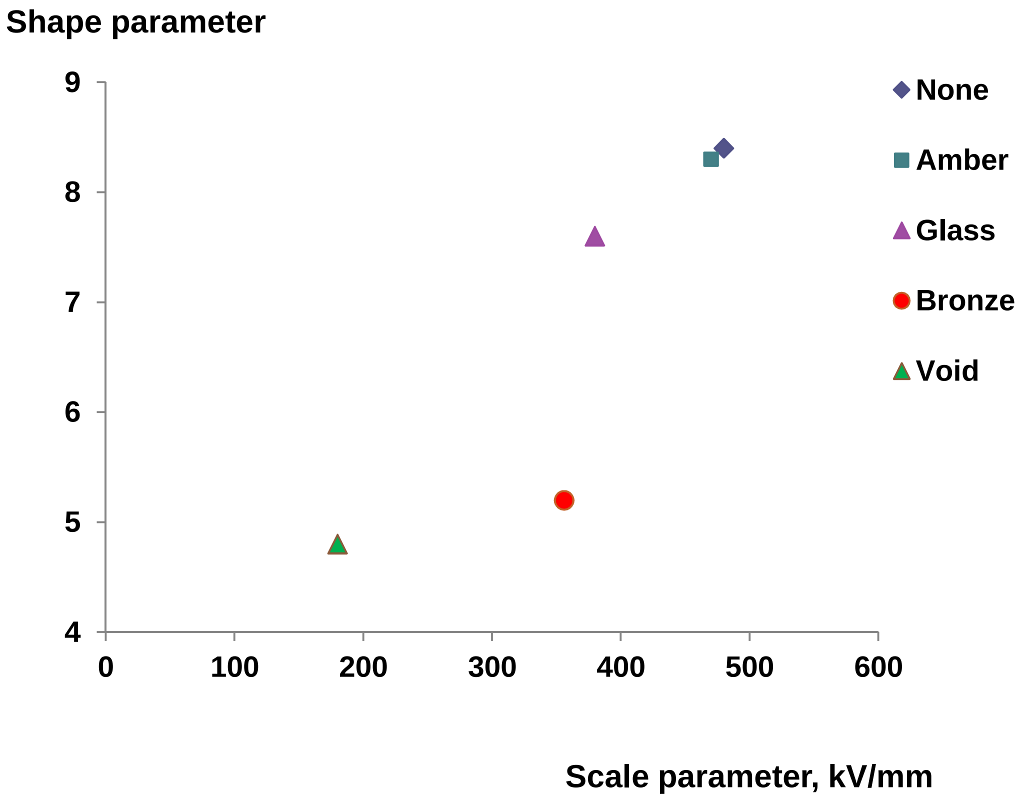
To meet these demands it is essential to have:

- **Physical cleanliness**
- **Chemical cleanliness**

As a starting point LDPE should be a good material as it does not contain catalyst residues etc. The long experience obtained with HVAC cables have indeed contributed to the fact that XLPE has developed to the material of choice also for HVDC cables.

Breakdown strength and physical cleanliness

The effect of added contaminants (50 – 60 µm) on the Weibull breakdown parameters of LDPE discs with a Rogowski profile and tested under DC.



Important aspects:

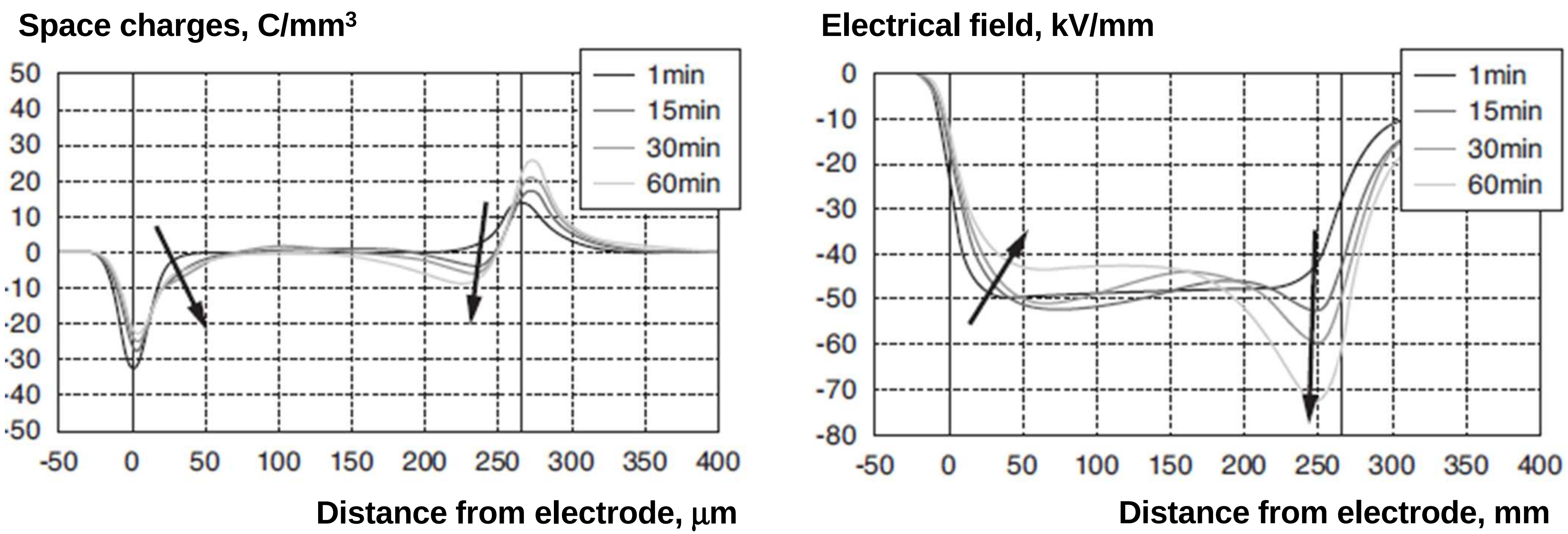
- Size and shape
- Dielectric properties
- Matrix contact

J-O. Boström et.al., 2003, Jicable, 111-117

Accumulation of space charges

If a typical **AC-XLPE** material is tested under DC condition it is common to observe accumulation of space charges leading to distortion of the electrical field distribution.

Space charge and electric field distributions in AC-XLPE at 50 kV/mm, 30° C

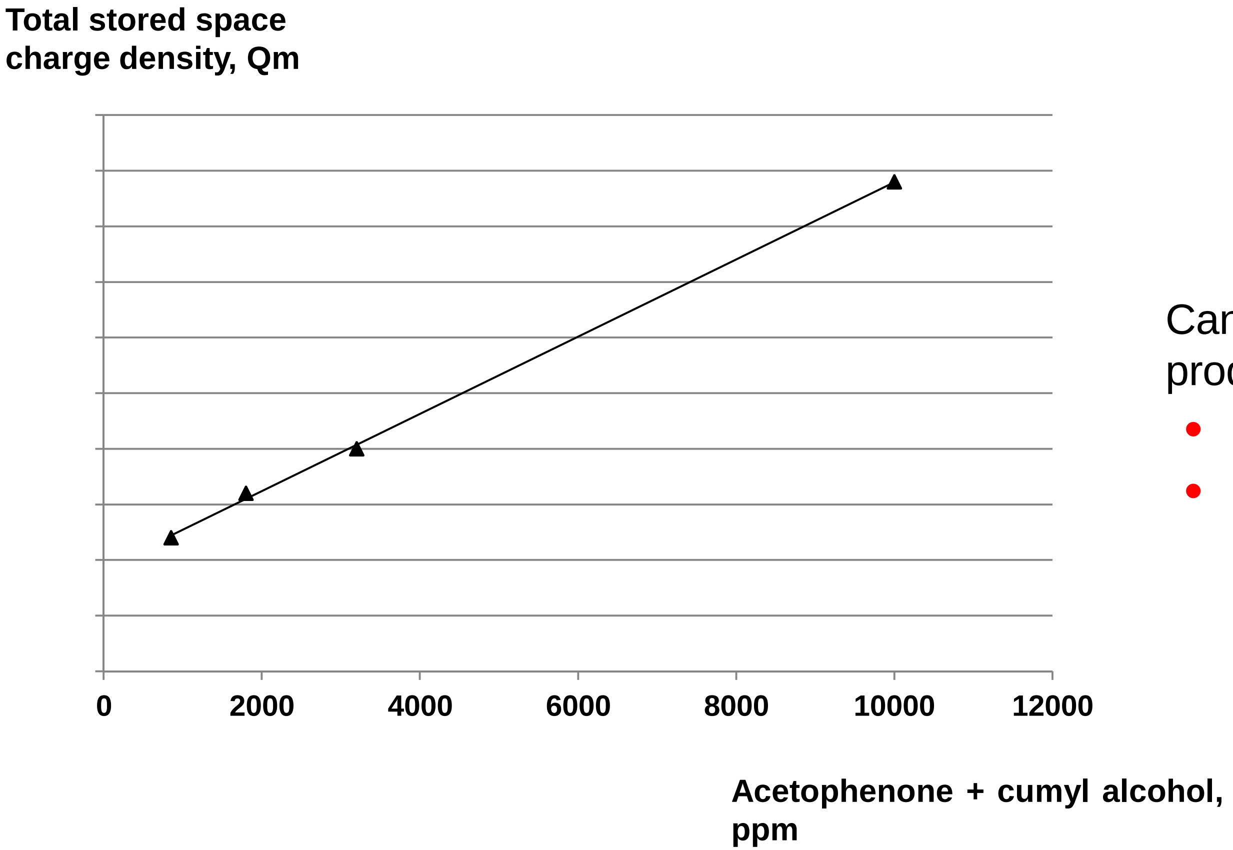


The distortion of the electrical field distribution leads to enhancement of the electrical field. This is of extra concern in Line Commutated Converter (LCC) systems using polarity reversal while Voltage Sourced Converter (VSC) systems are less sensitive.

Y. Murata et.al., SEI Technical Reveiw,76, April 2013, 55-62

Chemical cleanliness and space charges

The effect of the decomposition products from DCP on the accumulation of space charges.



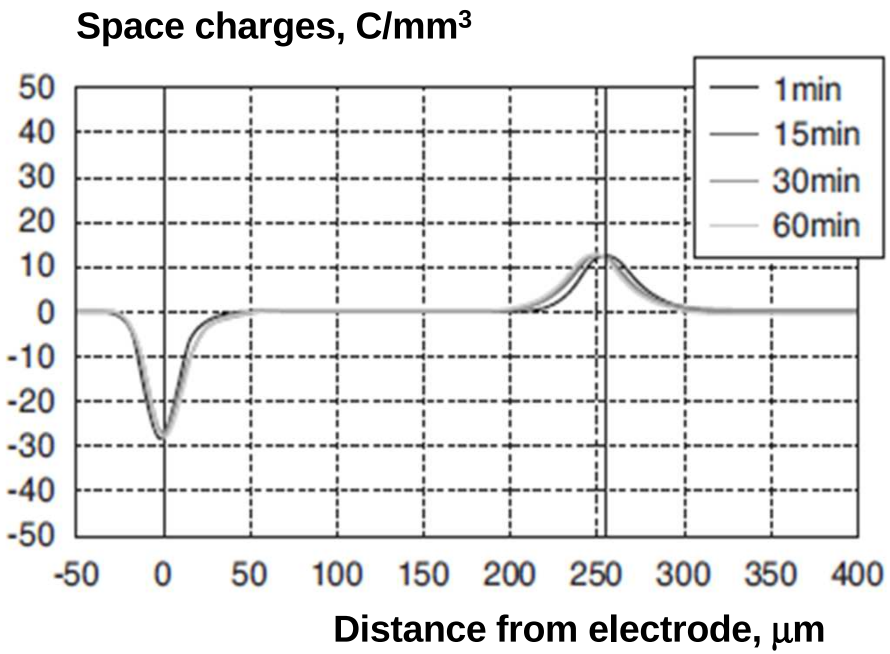
Can the effect of the decomposition products be reduced:

- increased degassing (?)
- reduced peroxide content

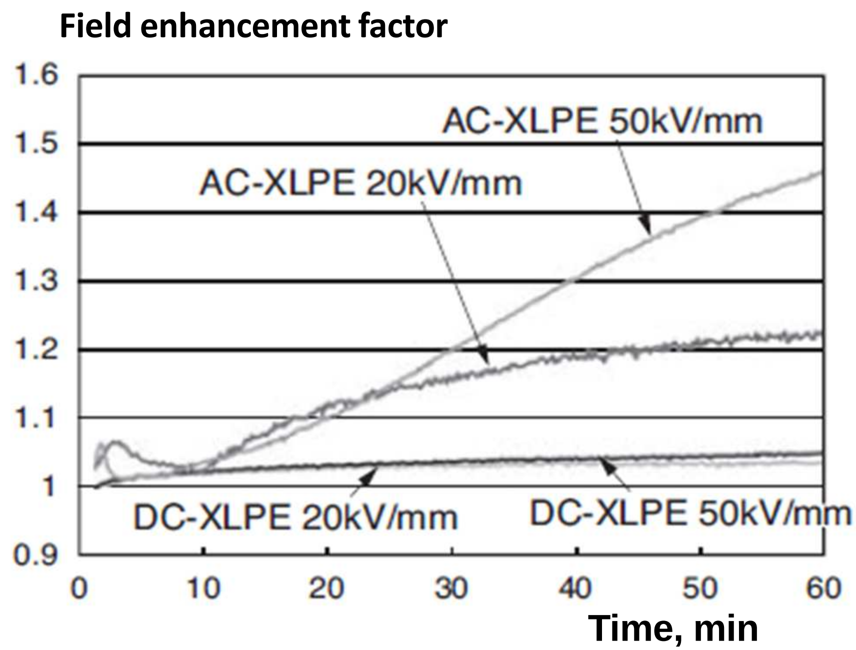
Reduction of space charges

Several approaches have been presented with the aim to reduce the accumulation of space charges. One includes the addition of low amounts of nanofillers, in particular MgO.

Space charge in DC-XLPE at 50 kV/mm, 30 °C



Comparison between DC-XLPE and AC-XLPE materials



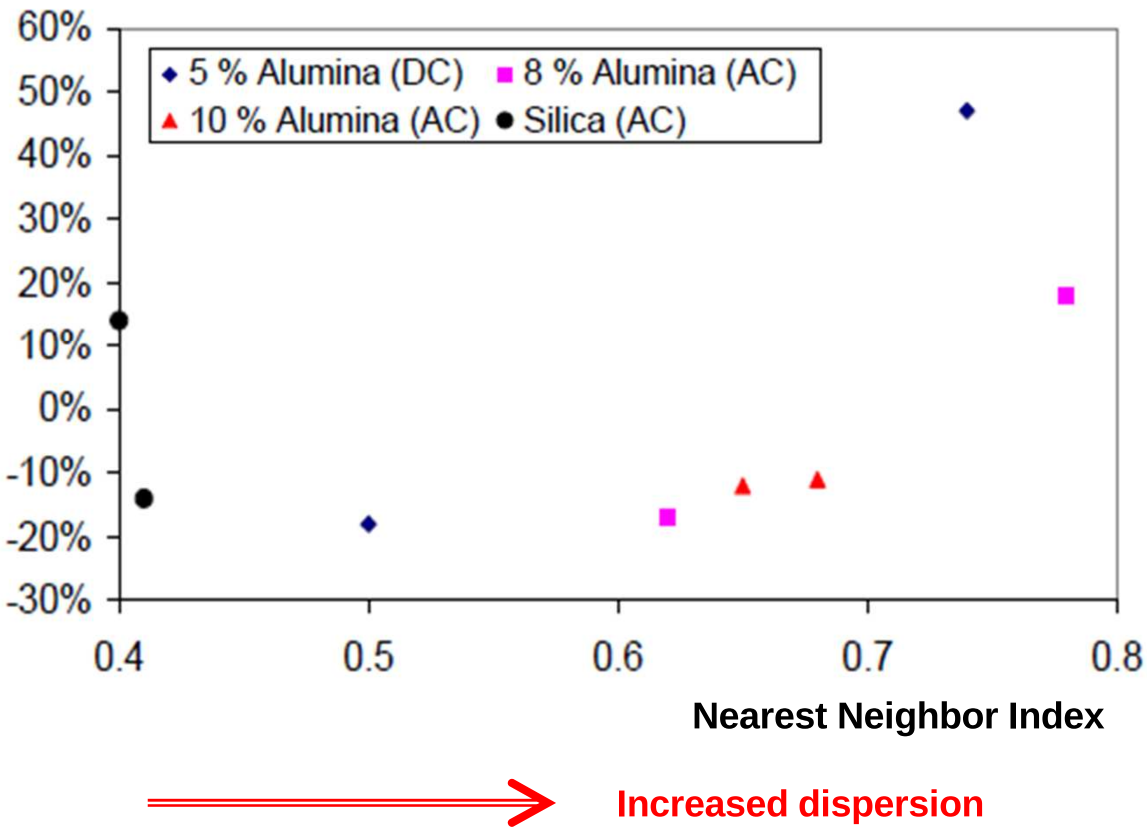
Y. Murata et.al. , SEI Technical Reveiw,76, April 2013, 55-62

Close and Return

Nanofillers and breakdown strength

When nanofillers are used it is essential that the dispersion of the particles is perfect. In particular it is important to avoid large aggregates which will work as physical contaminants.

Change in Breakdown Strength



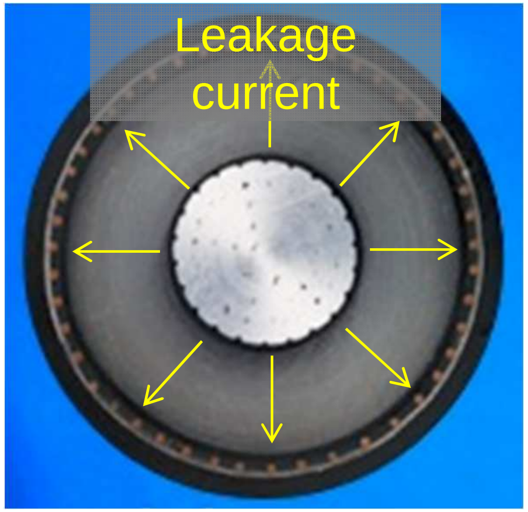
The degree of dispersion will depend on several factors:

- amount of filler
- processing conditions
- surface treatment

Due to these factors a nanofilled system may be less robust giving different results depending on the specific conditions.

C. Calebrese, L. Hui, L.S. Schadleer, J.K. Nelson, 2011, IEEE Trans. Dielectr. Electr. Insul., vol. 18, 938-945

The significance of electrical conductivity



The leakage current generates **heat** in the insulation:

$$Heat = insulation\ conductivity \times electric\ field^2$$

The heat leads to a **temperature rise**, *ΔT*:

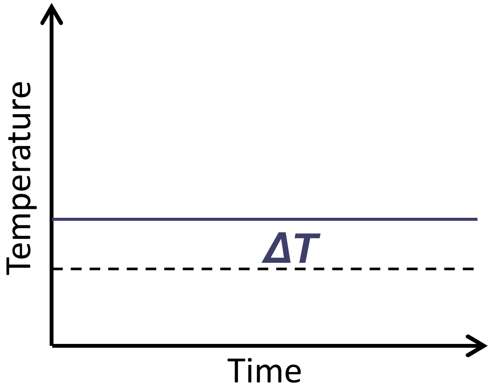
$$\Delta T = Heat \times \left(\frac{d^2}{2k} + \frac{d}{h}\right)$$

$d = insulation\ thickness$

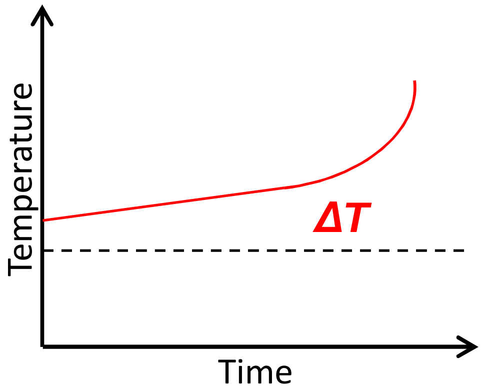
$k = heat\ conductivity\ of\ insul.$

$h = heat\ transfer\ coefficient$

Scenario 1 – Steady state



Scenario 2 – Thermal runaway



How to reach low conductivity

$$Conductivity = \sum_i n_i \cdot q_i \cdot \mu_i$$

n = number of charge carriers

- LDPE
- process chemicals
- POX decomposition products
- antioxidants and other additives

q = charge of charge carrier

μ = mobility of charge carrier

- low – high MW
- crystallinity
- traps, e.g. nanofiller

Two approaches

1. Decrease the conductivity by using traps, e.g. nanofillers.
2. Decrease the inherent conductivity of the insulation material, i.e. work with the chemical cleanliness.

Toolbox for decreased inherent conductivity

If you choose to decrease the inherent conductivity of the insulation material there are several factors that are important. For the material itself the following issues could be considered:

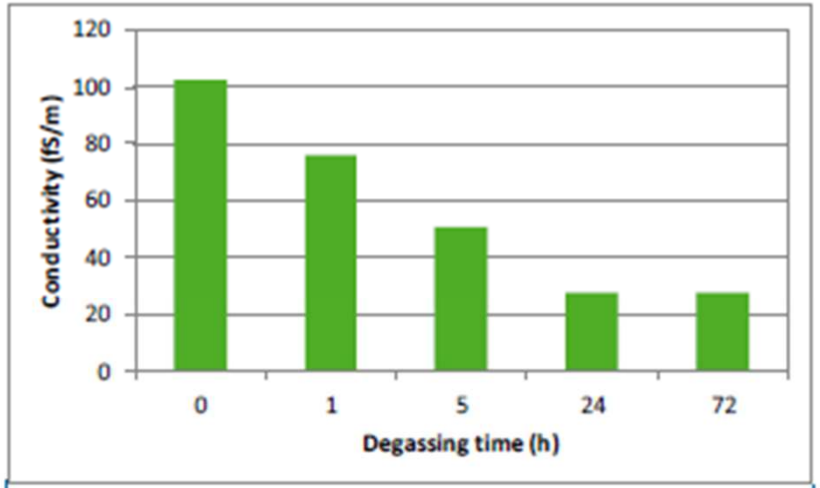
- the effect of process chemicals on the base resin
- minimize the amount of peroxide decomposition products
- careful selection and optimization of antioxidants and other additives

Then it is important that the full production cycle is considered:

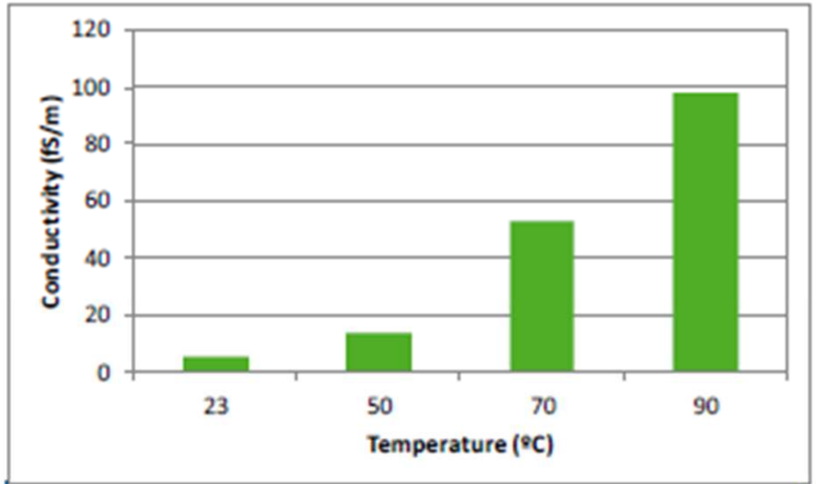
base resin → compound → cable production

POX decomposition products and conductivity

Degassing clearly leads to lower levels and controlled conductivity at higher temperatures:



Degassing study at 70 °C for different time periods: 0, 1, 5, 24 and 72 h



Partially degassed : at 70 °C during 4 h

Measurements were performed on 1 mm plaques at 70 ºC using a stress of 30 kV/mm. Reported conductivity values are taken after a measurement time of 24 h.

Removal of cumyl alcohol and acetophenone by degassing is time consuming. An alternative is to use an LDPE with increased content of vinyl groups (Supercure) which allows a lower amount of peroxide.

Simplified equation for temperature increase

The equation for temperature increase due to the leakage current:

$$\Delta T = \sigma \times E^2 \times \left(\frac{d^2}{2k} + \frac{d}{h} \right)$$

σ = insulation conductivity
E = electrical field
d = insulation thickness
k = heat conductivity of insulation
h = heat transfer coefficient

With typical values of d (15-30 mm), k (0.2 W/mK) and h (4 W/m^{2}K) it is found that the ***d²*** term in the parenthesis is ca 10 % of the ***d*** term. The parenthesis is thus essentially depending on ***d***, i.e.:

$$\Delta T_{rel} \propto \sigma \times E^2 \times d = \sigma \times \frac{U^2}{d^2} \times d = \sigma \times \frac{U^2}{d}$$

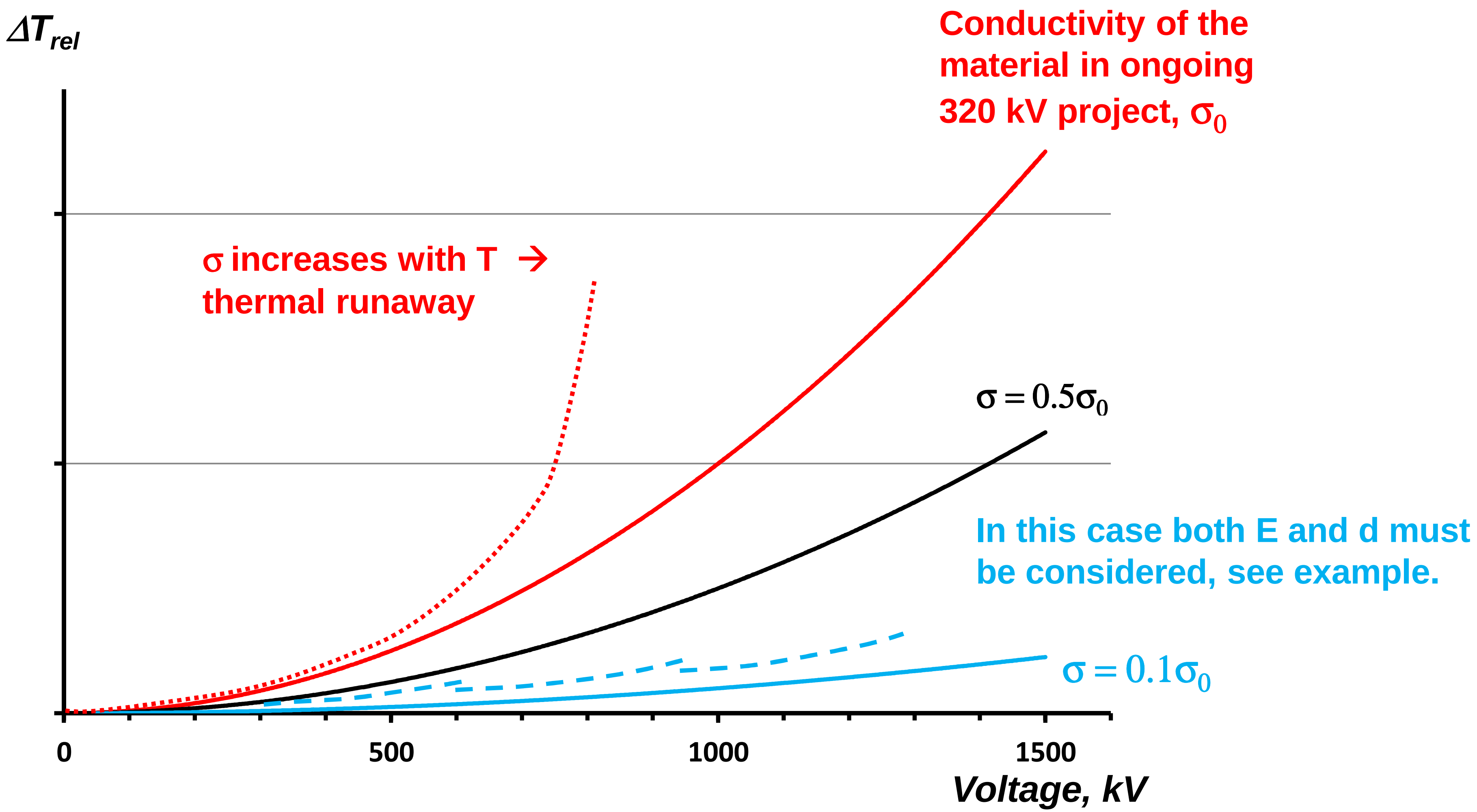
U = applied voltage

Remembering that the variations in ***d*** is not too large one can as a first approximation write:

$$\Delta T_{rel} \propto \sigma \times U^2$$

What is needed to reach higher voltages?

$$\Delta T_{rel} \propto \sigma \times U^2$$



Conclusions

- The general material properties of LDPE/XLPE make it a good choice for extruded cables
- There are now XLPE materials that meet the demands for 320 kV HVDC cables
- For materials intended for higher voltages both the physical and chemical cleanliness is of outmost importance
- The temperature rise due to leakage current in the insulation is a critical aspect
- The DC conductivity must be decreased significantly compared to that of the present commercial materials.
- Internal tests have proven that we have a XLPE compound solution which will meet future HVDC market needs