High voltage cable insulation systems

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Paper insulation is still common, especially for land UG cables. However, there is an increasing application of polymer cables (XLPE and EPR), especially for in DC and submarine installations.

The insulation material is either paper impregnated with oil, or polymers such as polyethylene. The presence of contaminants, protrusions or voids (CPVs) in the insulation can lead to insulation overstress and eventual cable failure after time in service. In practice, modifications are made to the basic cable structure to ensure that the electric stress is uniformly distributed to avoid CPV induced discharges and other failure mechanisms. Stress design considerations are particularly important in HV and EHV cable insulation systems.

Cable types

There are about four main types of power cables, usually categorised on the basis of insulation systems. These are:

Polymeric (Fig. 1)

- Low density polyethylene (LDPE)
- High density polyethylene (HDPE)
- Cross linked polyethylene (XLPE)
- Ethylene propylene rubber (EPR)

Self contained fluid filled (FF or LPOF)

Paper or paper propylene laminated (PPL) insulated with individual metal sheaths and impregnated with low pressure oil (Fig. 2).

Mass impregnated non draining (MIND or solid)

Paper insulated with individual metal sheaths and impregnated with a low viscosity polybutene compound. Usually applied in MV and submarine DC installations.

High pressure fluid filled (HPOF or pipe type)

Paper insulated and installed in trefoil in steel pressure pipes, impregnated with high pressure non-degradable fluid. The fluid is usually compressed gas (N_2 or SF_6) at typical pressures of 15 bar (Fig. 3).

Electrical parameters

Electric Stress

A cable is usually modelled as a coaxial cylinder system (Fig. 4).

The electric stress at any point in the insulation material is given by equation (1).

$$E(x) = \frac{U}{x \ln \frac{r_o}{r_i}} \qquad (1)$$

where

U = Applied voltage

r_i = Conductor radius

r_o = Sheath radius

x = radial distance to any point in the insulation.

From Eqn. 1 it can be seen that:

$$E_{\max} = \frac{U}{r_i \ln \frac{r_o}{r_i}} = \text{maximum stress}$$

It occurs on the surface of the conductor which is the most probable location for instantaneous failure. This is more likely to occur if serious insulation defects are near the conductor surface.

$$E_{\min} = \frac{U}{r_o \ln \frac{r_o}{r_i}} = \text{minimum stress.}$$

The minimum stress occurs at the outer sheath and it becomes a critical factor if insulation defects are in the vicinity of the outer sheath. The mean stress (i.e. E_{mean}) across the insulation is critical if insulation defects are uniformly located throughout the bulk of the material.

Typical maximum stress levels for different types of cables are shown in Table 1 [1].

Capacitance

The capacitance of a single core cable is expressed as:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln \frac{r_o}{r_i}} \text{ F/m} \qquad (2)$$

It depends on the dimensions of the cable and the permittivity of the insulation system. The capacitance is essential for determining the charging current of the cable, which is given as:

$$I_{ch} = 2\pi f C U \qquad (3)$$

where

C = Cable capacitance

U = Voltage across the insulation

f = power supply frequency

Cable insulation systems

Cable insulation systems are required to have

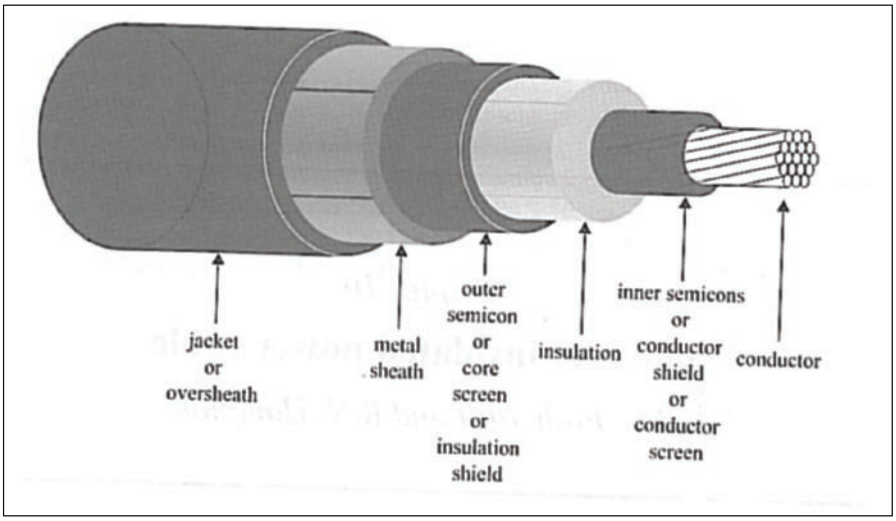

Fig. 1: Typical polymer power cable [1].

Fig. 2: Paper insulated oil filled cable with oil channels [2].

high dielectric strength (for minimal cable size and cost) so as to provide the necessary withstand against normal operating and impulse voltages. There are two main types of cable insulating materials, namely impregnated paper and polymer. Paper remains the most popular, especially for land installations in the HV and EHV ranges. However, polymer cables are increasingly being used in new installations, especially for DC and submarine systems. It is estimated that about 83% of HV cables in existing systems are paper insulated [1]. XLPE cables constitute about 2 - 5% of installed HV cable capacity in the 115-161 kV range, and make up about 50 - 70% of new cable installations in the HV range [1].

Solid paper insulated cables are suitable for application up to the MV range. At higher voltages they present operational problems due to high dielectric losses and presence of voids. At higher system voltages, oil filled and pressurised cables are used to overcome the effects of voids as well as minimise the losses. In oil filled cables, the formation of voids is prevented by maintaining a flow of oil under pressure. In pressurised gas cables, the dielectric strength of the gas in the void is increased through the external gas pressure, usually transmitted through a membrane. The impregnation improves the dielectric properties, as shown in Table 2.

In polymer insulation the insulating XLPE compounds must act as thermoplastic materials, be immune to thermal degradation and must not be prone to defects such as voids, protrusions or contaminants [1]. Compared to paper insulation systems, polymers have no risk of oil leakage or fire, are simple in design and have lower dielectric losses (e.g. 5,1 mA/m compared to 14,7 mA/m for paper 1000 mm^2 cable at 132 kV)[1].

Insulation failure mechanisms

Partial discharges (PDs)

Partial discharges occur in voids or at protrusions that occur in the insulation due to manufacturing systems flaws and contamination. Voids can also occur due to expansion and contraction of the insulation, caused by changes in the loading cycles of the cable. The gas in the void has a lower permittivity and dielectric strength compared to the surrounding solid insulation. The electric stress in the void is enhanced by a factor equal to the relative permittivity of the insulation and this could cause a discharge if the breakdown strength of the gas in the void is exceeded (Fig. 5).

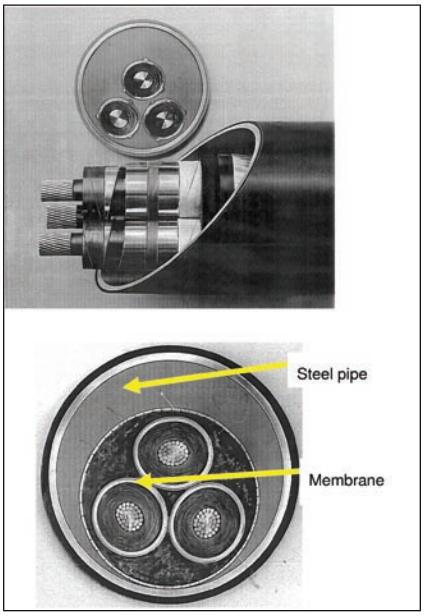

Fig. 3: High pressure gas cable [2].

Sustained discharges lead to void enlargement due to electrons bombarding the cavity walls and chemical reactions by discharge byproducts such as ozone and acidic compounds. The process can take several months or years resulting into cable failure eventually due to the weakening of the insulation.

Electrical trees

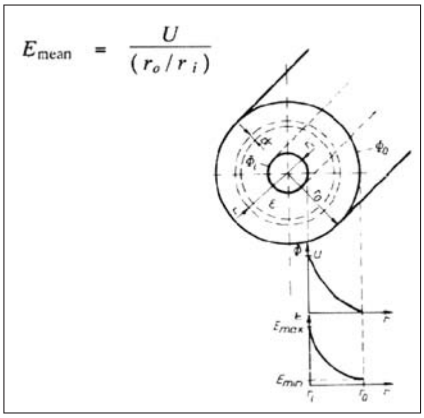

Fig. 4: Model of a single core cable [3].

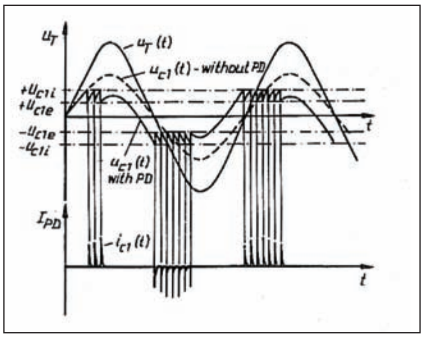

Fig. 5: Partial discharges and current pulses in a void [3].

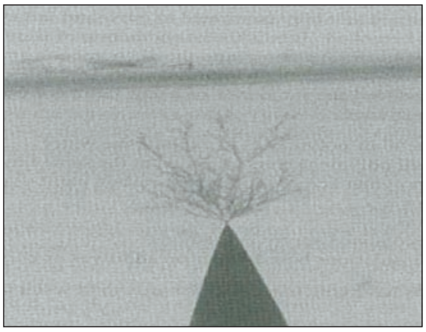

Fig. 6: An electrical tree in epoxy resin [1].

Protrusions and contaminants can also cause localised high electric stresses which lead to discharges known as electrical trees, which occur in polymer insulation. The tree has a branched structure with the channels growing along the field lines. The channels have diameters of 1 - 20 µm and can be as long as 5 - 25 µm before branching (Fig. 6) [1]. Once an electrical Tree is initiated it cannot be stopped and the cable will eventually fail. The formation of the trees can only be prevented by avoiding CPVs during manufacturing and installation processes.

Water trees

The processes leading to the formation of water trees are not well understood.

However, they are thought to depend on voltage, frequency, temperature and presence of water [4,5]. There are two types of water trees: the vented trees which originate from the surface of the insulation and the bow tie trees which develop from contaminants or voids in the insulation [1]. The branches of water trees comprise a high density of water filled voids of diameters of 1 - 10 µm (Fig. 7). Water trees grow more slowly than electrical

Insulating material	**Dielectric strength [kV/mm] AC**	**Loss tangent(tanδ) 20° C**	**Loss tangent (tanδ) 100°C**
Dry paper	10,6	2 x 10^{-3}	3,5 x 10^{-3}
Impregnating oil	24	0,8 x 10^{-3}	3,3 x 10^{-3}
Impregnated paper	57,5	2,6 x 10^{-3}	8,5 x 10^{-3}

Table 2: Dielectric properties of dry and impregnated paper.

Cable type	**EHV**	**HV**	**MV**
Dielectric	**E_{max} [kV/mm]**	**E_{max} [kV/mm]**	**E_{max} [kV/mm]**
Fluid filled	17	14	10
EPR	8	5	3
XLPE	11	6	3

Table 1: Typical maximum electric stress levels for selected cable types.

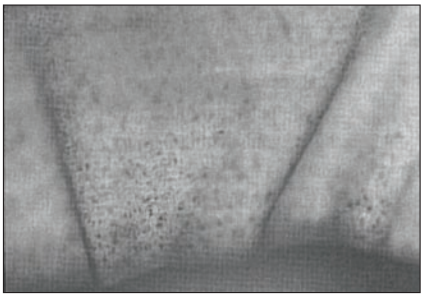

Fig. 7: Water trees and breakdown paths in an EPR cable. The black streaks are breakdown paths starting to cross the cable. The black dots, which are intense around these breakdown paths, are stained water trees. EPR is more resistant to water trees than XLPE, but this cable had been taken from service where it had been saturated in water with no metal sheath [Fig. 10.8 Reference 1].

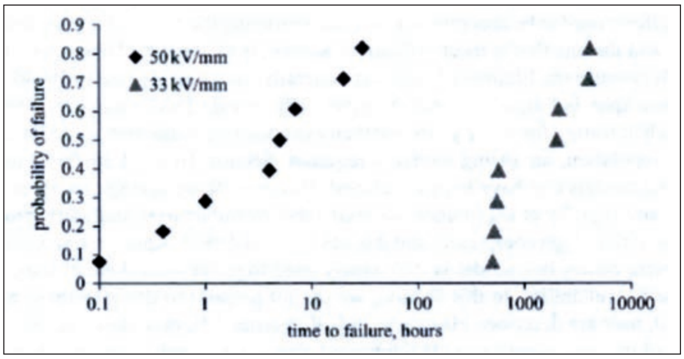

Fig. 10: Variation of loss tangent with voltage.

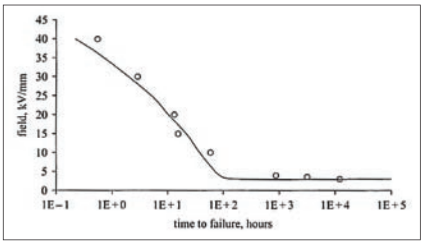

Fig. 8: Effect of electric stress on insulation life time [1].

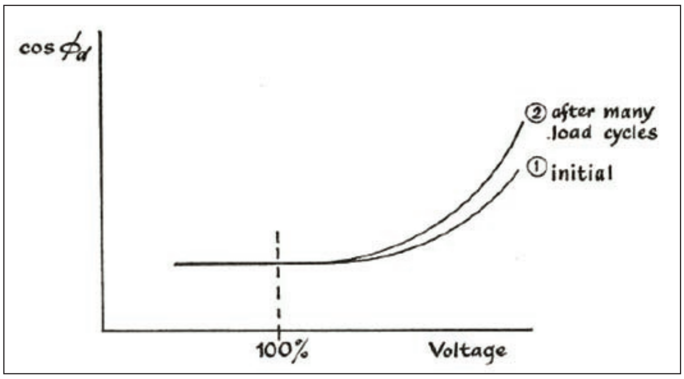

Fig. 9: Effect of electric stress on time to failure of XLPE cables [1].

trees and it may take several years before they are observed. It also possible for vented trees to cross the insulation without necessarily leading to a breakdown. However, they greatly weaken the insulation which could eventually fail due to electrical trees.

Water treeing does not appear to be a problem in LV cables. However, polymer insulated cables operating at HV and EHV require water barriers to prevent ingress of moisture which could lead to water treeing.

Thermoelectric ageing

Environmental considerations are forcing more high power cable transmissions.The tendency is, therefore, to push the push the operating electric stress limits of XLPE cables towards 16 kV/mm from the normal 5 - 7 kV/mm. XLPE cables are also operating at higher temperatures (about 900°C) due to improved cross linking processes. However, both high operating temperatures and electric stresses have an impact on the life time of the cable (Fig. 8)[1]. Further studies need to be carried out to understand the ageing processes in the insulation systems and how improvements can be made in the manufacturing processes to increase both the life time and reliability of polymer insulation systems.

Design considerations

The operating electric stresses of cables are in the range of 3-11 kV/mm, which is much lower than the withstand capacity of insulating materials used. The electric stress in practical cables is reduced by the following factors:

- Increased operating temperatures
- Length of operation
- Length and thickness of insulation (high probability flawed insulation)

The above factors need to be taken into account at the design stage. It is not easy to take into account the length of operation due to the long lifetimes of cables. This is usually accommodated by extrapolating data obtained over a limited test period. Test data show that electric stress has a big influence on the ageing rate (Fig. 9). The allowance made for ageing has an influence on the eventual size of the cable. Other design considerations include:

- Semi-conducting cylinders in polymer cables for stress control
- Filling voids with oil in oil filled cables
- Increasing of pressure of gas in voids in pressurised cables

Condition monitoring

The condition of the cable insulation is usually monitored through the following two main methods:

- Loss tangent measurements in which the variation of tan δ with temperature and voltage is measured periodically. In a good material, tan δ should be small and constant over the operating voltage range. A different characteristic is an indication of faulty insulation (Fig. 10).
- Partial discharge (PD) measurements in which the health of the insulation is indicated by the patterns of the pulses recorded. PD measurements require specially shielded laboratory facilities and equipment to ensure that the results are free of any external interference.

Acknowledgement

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