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THE MODELLING OF NON-HOMOGENOUS STRUCTURE OF POWER CABLES INSULATION SYSTEMS

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Abstract: Among exploitation stresses of power cables are electrical stresses, created by electric field strength in an insulation system. Insulation system of power cables typically has a non homogenous distribution of the electric field strength, where its maximum value is critical. Local defects in a structure of power cables influence the field distribution. Its value around defects can exceed the working electric field strength and initial field of partial discharge inception. The electric field strength in medium voltage cables with ethylene-propylene insulation are analyzed in the paper. Local defects similar to the exploitation ones were assumed as potential sources of partial discharges. The presented patterns of electric field strength illustrate the impact of the defect type and its localization in the insulation system on changes of field distribution and local field strength increase.

Key words: medium voltage cables, electric field distribution, failure, partial discharges, insulation degradation

1. INTRODUCTION

In exploitation power cables are subjected to complex stresses impacting the insulation system. Apart from thermal and mechanical stresses, the electrical ones, created by electric field strength, have a key influence. The spectrum of power cables applications in medium voltage (MV) networks is determined by the voltage level. In the case of most typical ratings 15 kV and 20 kV occurring in MV networks, the polyethylene (XLPE) and ethylene-propylene rubber (EPR) are used, typically as one phase cables. The EPR cables are not typical on our domestic market, however they have been broadly used since many years in the USA and in Western Europe. Higher nominal voltage level and thicker insulation leads to the increase of working electric field strength. Figure 1 shows typical values of working electric field strength in medium (MV), high (HV) and ultra high voltage (UHV) power cables [1].

Local defects occurring in the cable structure have impact on the electric field distribution. Its value around defects can exceed the working electric field strength and initial field of partial discharges (PD) [2].

The above mentioned problem is presented on an exemplary case of 22 kV in EPR insulation. The local defect in the form of shield defect on the conductor, microsharpening on the semi-conducting shield and gaseous voids in the insulation system are presented.

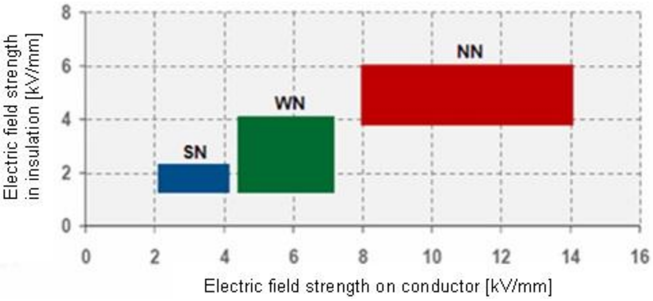

Fig. 1. Comparison of typical ranges of working electric field strength for MV, HV and UHV cables [1]

2. THE ROOTCAUSES OF POWER CABLES DEFECTS AND FAILURES

The reasons of power cables failures can be both external and internal. The typical external failures are mechanical and due to random events. The internal failures can be caused by:

- design errors,
- technological defects not detected during factory test and commissioning,
- incorrect positioning and assembly faults,
- partial discharges (Fig. 2),
- aging and corrosion,
- improper overvoltage protection, due to both lightning and switching [6].

Creation of defects is a non deterministic process, very often caused by several sequential or simultaneously occurring reasons. The highest impact on the failures of the

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cable lines have the electrical causes, approximately 40% of all failures[4].

3. DEGRADATION PROCESSES OF POLYMER INSULATION

The polymer insulation system is deteriorated mainly due to the following three processes: physical, chemical and electrical degradation. Just after manufacturing, the polymers do not have a crystalline structure. The final vulcanization of the insulation structure is a slow process and may last for a long time. Due to this fact, gaseous micro-inclusions and local spaces of higher density may be formed inside the insulation. The non-homogenous insulation structure subjected to electric field can extend, while the insulation breakdown is increasing. The polymer insulation is prone even to low intensity partial discharges. The chemical degradation is leading to changes in mechanical properties of the insulation. The chemical decomposition can result in breaking down of long polymer chains in depolymerization process. The reaction follows due to active free radicals formed during oxidation. The formation speed is determined by: temperature, oxygen content and radiation. However, the biggest challenge for polymer insulation is the electrical degradation, especially partial discharges, both electrical treeing and water treeing [2, 5].

4. CONDITIONS FOR OCCURENCE OF PARTIAL DISCHARGES

The high value of working electric field strength and long exploitation time are common reasons for initiation of degradation processes in cable insulation systems. Such processes usually have local character; they are not present along the whole cable length, but lead locally to the breakdown. In polymer power cables the defect can assume a form of (Fig. 2):

- conductive or non-conductive micro-inclusions and micro-impurities as a residue of the manufacturing process,
- failure of the shields on the conductor or insulation, often in a shape of the microblades,
- gaseous voids, adjoin to the shields or localized inside the insulation, formed for example during pressure variation in extrusion process or during cooling phase.

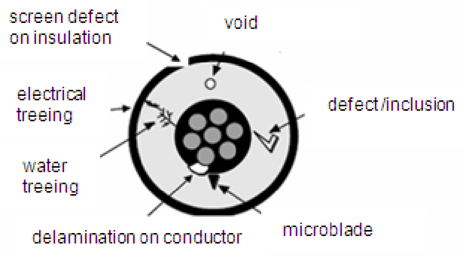

Fig. 2. Typical defects in extruded cables leading to partial discharges [2]

It is important to underline, that the current conditions and control of the manufacturing process more and more eliminate possibilities of occurrence of such defects. However, simultaneously are growing the requirements for electric field stress, which necessitate detection of low intensity PD. The above mentioned defects are localized in the cylindrical insulation system of the cable, where the electric field strength has a value from a single up to tens of kV/mm. The discharge charge in the void depends on their radial localization in the cable insulation.

5. THE COMPUTER ANALYSIS OF ELECTRICAL FIELD IN CABLE

The analysis refers to concentric electrical fields found in screened core MV power cables, which form majority of installed cable population.

The cross-section of a typical single-core XLPE or EPR cable is depicted in Figure 3. The cable consists of the following layers:

- conductor: aluminum or copper conductor with radius *r*,
- conductor screen: semiconducting layer extruded around conductor with thickness *e*,
- insulation: XLPE or EPR in MV cables,
- insulation screen: semiconducting layer around insulation,
- outer layers: swelling types wrapped around the insulation screen and earth screen,
- outer sheath: usually polyethylene layer.

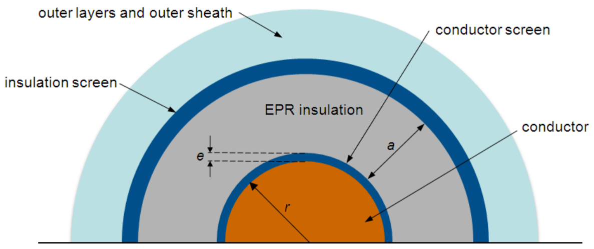

Fig. 3. Schematic drawing of a typical single–core EPR cable, *e* – thickness of semiconducting layer, *a* – thickness of insulation

The insulation wall thickness a of cables traditionally is designed in accordance with the criteria of impulse stress and operating stress. For example that is:

$$a = r\left[\exp\frac{V}{r \cdot E} - 1\right] \tag{1}$$

where: a – insulation thickness (mm), r – conductor radius (mm), V – applied operating voltage (kV), E – maximum stress (kV/mm) at the inner insulation wall corresponded to V.

6. SIMULATION METHOD

Computations have been performed by use of COMSOL Multiphysics software. The modeling process usually consists of a few stages, mainly:

- choosing an appropriate mode,
- drawing geometry of simulated object,
- defining boundary conditions and material constants,
- meshing and solvers choosing.

In this case, "Quasi-Static, Electric" mode available in the COMSOL Multiphysics model navigator was chosen. In this mode the following equation is being solved for the electric potential *V* in every point in space:

$$-\nabla \cdot \left((\gamma + j\omega\varepsilon_0\varepsilon_r)\nabla V - J^e\right) = 0 \tag{2}$$

where: γ – electrical conductivity, V – electric potential, ε_0, ε_r – absolute and relative permittivity respectively and J^e – external current density.

The electric potential that was obtained by equation (2) is then used to find out the electric field $E = -\nabla V$ [7].

7. RESULTS OF MODELLING

The study of the electrical field distribution in single-core EPR cable rated voltage 22 kV, when the different local defects exist in insulation, is presented in this article.

7.1. Single-core cable without defects in insulation structure

The cable is characterized by the following material parameters:

- EPR insulation thickness a = 5,5 mm,
- relative permittivity of EPR insulation ε_{EPR} = 3,8,
- conductor screen thickness e_{int}=0,5 mm, e_{ext} = 1,1 mm,
- relative permittivity of conductor screen ε_s = 33,
- electric conductivity of conductor screen $\sigma = 10^{-7}$ S/m.

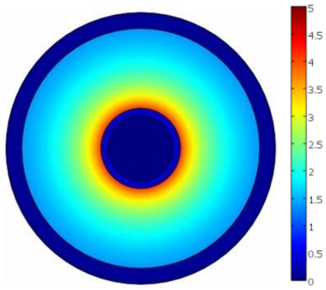

Fig. 4. Single-core cable cross-section (16mm^2). Color scale shows electric field in the cable

For an applied voltage V, the same insulating material, the electrical stress distribution in insulation depends on conductor diameter and its maximum value exists at the semiconducting layer extruded around conductor (conductor screen) (Fig. 4).

The comparison of electrical field distribution in insulation for the different conductor cross-sections is presented in Figure 5 and maximum electrical field at the inner insulation wall E_c in Table 1.

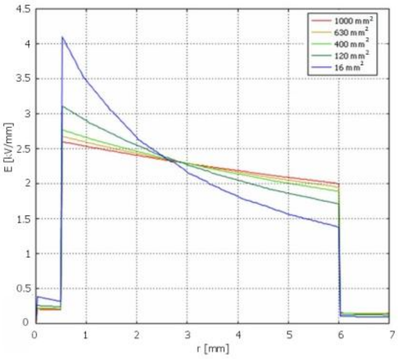

Fig. 5. Electric field distribution in single-core cable insulation for different cross-sections

Table 1. Comparison of maximum electric field values in cables with different cross-sections

Conductor cross-section [mm^2]	16	120	400	630	1000
Maximum E_c [kV/mm]	4,14	3,1	2,75	2,7	2,6

7.2. Single-core cable with defects in insulation structure

1) *Local lack of adhesion of semiconducting layer to conductor*

In such a case, under the screen can be formed a gaseous layer and radical increase of electric field strength. Characteristic depicted in Fig. 6 shows that electric field in defect increases by about 32%.

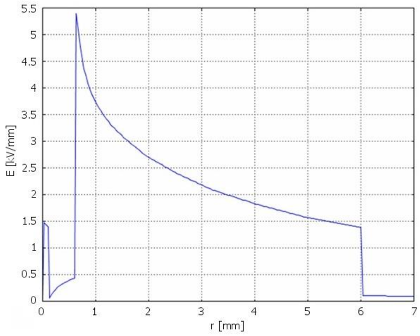

Fig. 6. Electric field distribution in cable insulation with defect at conductor screen

2) *Microblades on the conductor screen surface*

Such defect is a result of surface non-homogeneity of conductor screen (Fig. 7).

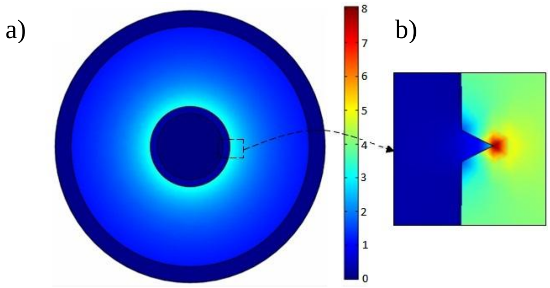

Fig. 7. Electric field patterns: a) in insulation with defect, b) at the conducting microblade (microblade height = 0.01 mm)

Figure 8 shows electric field distribution in the insulation of single-core cable with defect (microblade) on the conductor screen surface.

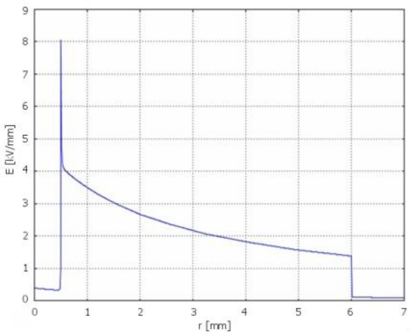

Fig. 8. Electric field distribution in cable insulation with defect at conductor screen

3) *Gas inclusion in EPR insulation*

The elliptical void near the conductor can be formed in the manufacturing process or due to thermal stresses in the insulation. The electric field patterns illustrate the influence of the voids on the distribution of the electric field along cable radius (Fig. 9,10)

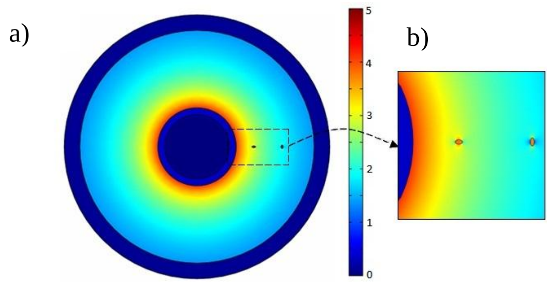

Fig. 9. Electric field patterns: a) in insulation with defect, b) in local defect (conductor cross-section – 16 mm^2)

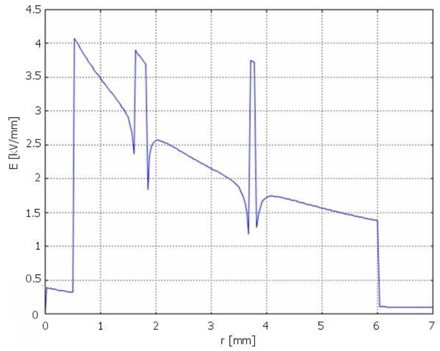

Fig. 10. Electric field distribution in cable insulation with defect at conductor screen (conductor cross-section – 16 mm^2)

8. CONCLUSIONS

The main goal of power cable development is high reliability of power distribution as well as assurance of high economical and environmental standards. The realization of these objectives is realized by:

- introduction of conductive and insulating materials with improved exploitation parameters,
- modernization and improvement of cable manufacturing lines and extrusion process, in order to eliminate the potential imperfections leading to the increase of local electric field strength,

The electric field strength in local defects can considerably exceed the working electric field conditions, which can lead to initiation and development of partial discharges (Table 2).

Table 2. Comparison of electric field strength values

Case	Screen delamination	Microblade	Void
Max. E_c [kV/mm]	5,4	8,0	4,14

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MODELOWANIE NIEJEDNORODNEJ STRUKTURY UKŁADU IZOLACYJNEGO KABLI ELEKTROENERGETYCZNYCH

Słowa kluczowe: kable średniego napięcia, pole elektryczne, awaryjność, wyładowania niezupełne, procesy degradacji

Do zespołu narażeń eksploatacyjnych kabli elektroenergetycznych należą narażenia elektryczne, jakie stanowi oddziaływanie pola elektrycznego w izolacji. Układ izolacyjny kabli charakteryzuje nierównomierny rozkład pola elektrycznego, którego wartość maksymalna oznacza robocze natężenia pola dla danej konstrukcji. Lokalne defekty w izolacji powodują, że jej struktura staje się niejednorodna, ulega zmianie rozkład pola elektrycznego. Jego wartość w otoczeniu defektów może przewyższyć natężenie robocze w kablu oraz natężenie początkowe wyładowań niezupełnych. W artykule przedstawiono analizę rozkładu pola elektrycznego w kablu średniego napięcia o izolacji etylenowo-propylenowej. Przyjęto warunki występowania w jego konstrukcji lokalnych defektów w izolacji, które w eksploatacji mogą stać się ośrodkami wyładowań niezupełnych. Przedstawiono obrazy pola elektrycznego ilustrujące wpływ rodzaju defektu i jego usytuowania w izolacji na zmiany rozkładu pola i lokalny wzrost jego wartości.