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Numerical Investigation of Electrical Characteristics in Cross-Linked Polyethylene for PV Applications

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This study presents a detailed numerical analysis of the electric field distribution in cross-linked polyethylene (XLPE) dielectric insulators used in photovoltaic (PV) power transmission systems. The modeling was carried out in Mathcad using stationary electromagnetic field equations, with the geometric parameters of the cable structure explicitly considered: a conductor cross-section of 6 mm^2, a first XLPE insulation layer thickness of 0.7 mm, and a second dielectric layer of 0.8 mm. The investigation focused on evaluating how variations in the relative permittivity ratio between adjacent insulation layers ($\varepsilon_1 > \varepsilon_2$ and $\varepsilon_1 < \varepsilon_2$) influence the electric potential distribution and local electric field intensity. For the case $\varepsilon_1 > \varepsilon_2$, the potential at the interface reached 817 V, while the maximum electric field intensity was 1207 kV/m, exhibiting an almost uniform field distribution across both layers. This configuration ensured high dielectric strength and minimized localized stress regions. Conversely, when $\varepsilon_1 < \varepsilon_2$, the interlayer potential decreased to 518 V, but the peak electric field intensity increased to 1735 kV/m, producing distinct field concentrations associated with reduced dielectric strength and a higher likelihood of partial discharge or breakdown. The results confirm that multilayer XLPE-based insulation promotes electric field leveling, and that optimizing the thickness and dielectric properties of each layer can substantially enhance dielectric robustness while reducing material consumption. The developed numerical model provides a reliable tool for assessing the electrical characteristics of multilayer XLPE insulation systems and offers practical guidance for the design and optimization of high-reliability photovoltaic cables and transmission components. These findings are particularly relevant for improving the safety, efficiency, and long-term durability of PV installations across both low- and high-voltage operating environments.

Keywords: XLPE, Energy efficiency, Dielectric insulators, Photovoltaic lines, Electric Field Characteristics, Numerical modeling

1. INTRODUCTION

Modern photovoltaic (PV) systems require highly reliable power transmission lines, where dielectric insulation determines safety and efficiency. Cross-linked polyethylene (XLPE) is one of the most common materials for multilayer insulators due to its high dielectric strength, thermal stability, and aging resistance [1-4]. Optimization of the geometry and dielectric properties of the insulation layers allows for equalizing the electric field, reducing local stress concentrations, and increasing the service life of transmission lines.

The integration of renewable energy sources and storage systems into modern networks increases their efficiency, energy independence and sustainability [5, 6]. Combining photoconverters in series-parallel configurations forms PV batteries that perform the function of an electricity generator. The transmission of electricity to the grid or hybrid inverter is carried out through PV lines, where the electromagnetic field is the energy carrier. The insulation system of such lines must provide high electrical strength, which allows to reduce the thickness of the layers, increase the permissible current, reduce material consumption and increase the flexibility of structures.

In modern transmission technologies, preference is given to thermosetting polymer dielectrics, in particular XLPE, which combines heat resistance [7], mechanical strength [8], water resistance and ease of installation [9,10]. The disadvantages of such materials are high cost, limited processing capabilities, and sensitivity to moisture[11].

It is relevant to study the spatial distribution of potential and electric field strength in transmission lines with multilayer XLPE insulation, taking into account the dielectric properties of each layer, which determine the shape and intensity of the field. Recommended parameters

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of PV lines include [12]: for modular connections – 4–6 mm², 1–2 kV DC, XLPE, copper; for combining battery strings – 10–25 mm², 1–1.5 kV DC, XLPE, copper or aluminum; for AC cables to the inverter and the grid – 16–50 mm², 0.6/1 kV AC or 6–35 kV for high-voltage lines, XLPE, stranded.

Numerical simulation of electric fields is an effective tool for predicting the behavior of multilayer insulators [13-15]. It allows us to evaluate the influence of the ratio of dielectric constants and layer thickness on the potential distribution and local stresses, which contributes to the optimization of PV line designs and increasing their efficiency in multi-voltage systems.

The aim of the work is to develop and test a mathematical model for determining the potential distribution and stationary electric field strength in a two-layer XLPE insulator of a PV line based on traditional electromagnetic field equations. Additionally, a comparison of electrical parameters in layers of insulation made of halogen-free polymers in cases of inhomogeneities caused by the difference in dielectric constants is provided.

2. EXPERIMENTAL DETAILS

The mathematical model of the stationary electric field of a two-layer XLPE insulator of a PV line is based on Maxwell's equations and implemented in the Mathcad environment. The modeling allows to determine the potential distribution and electric field strength. The visual programming environment provides the ability to change the radius of the conductive core, the thickness of the first and second layers of insulation, as well as the dielectric constants of both layers, which allows to simulate dynamic processes and material options.

To determine the minimum insulation thickness, basic expressions derived from the electric field equations are used. The field is considered stationary, since solar panels generate a direct current. The local characteristics of the field are determined from the complete system of electrodynamics equations, provided that only conduction currents are present, without taking into account electromagnetic induction. The electric field inside and outside the conductors is potential (vortex-free). For a homogeneous isotropic medium, the distribution of the electric potential is determined by the Laplace equation.

In the case of a sudden change in the conductivity of the medium, it is necessary to take into account the boundary conditions at the interface of the two media, which are established as follows [13-15]: equality of the tangential components of the electric field intensity fields at the interface of media; greater value of the normal component of tension in a medium with a lower dielectric constant; equality of the normal components of the electric displacement vectors at the interface of media; continuity of the potential at the interface of media.

The model of multilayer cylindrical insulation is described by the parameters: R_1 — radius of the cable core; R_i — radius of the boundary of the i-th layer; ε_i — dielectric constant of the i-th layer; U_{op} — operating voltage; $d_i =$

$R_{i+1} - R_i$ — thickness of the i-th layer; n — number of layers.

For perfect electric field alignment $R_i \cdot \varepsilon_i$ = const. Since it is difficult to change the permeability smoothly, multilayer insulation is used, where ε_i = const within the layer. The value of the maximum permissible electric field strength of the i-th layer of insulation:

$$E_{i\max} = \frac{U_{op}}{R_i \varepsilon_i \sum_{i=1}^{i=n} \frac{1}{\varepsilon_i} \ln\left(\frac{R_{i+1}}{R_i}\right)}. \tag{1}$$

The parameters of a single-core flexible PV transmission line H1Z2Z2-K 1×6 mm² EN 50618 were used for the simulation. The central core is made of stranded tinned copper wires with a nominal cross-section of 6 mm². The outer diameter of the cable is 6.1 mm. The thickness of the XLPE insulation layers is 0.7 mm (layer 1) and 0.8 mm (layer 2). The nominal voltage is 1000 V for alternating current and 1500 V for direct current. The electrical resistance of the core is 3.39 Ohm/km. The dielectric constant of the first layer of insulation is 2.3 at 60 Hz, the second layer is 1.53. The permissible electric field strength is 1207 kV/m.

3. DISCUSSION

Fig. 1 shows the distribution of the electric field intensity in a two-layer XLPE insulator of a PV line under the. condition $\varepsilon_1 < \varepsilon_2$. If the dielectric constant of the first layer is less than that of the second, the electric field strength increases to 1735 kV/m, which leads to an increase in the maximum voltage near the conductive core and a decrease in the electrical strength of the insulation, increasing the risk of breakdown.

Fig. 2 and Fig. 3 respectively show the electric field potential gradient and electric field intensity distribution in a two-layer XLPE insulator of the PV line with Bi-XLPE insulation (PV-DuoXLPEInsulatedLine). Numerical simulation showed that with a higher dielectric constant of the first layer, the potential between the layers is 817 V (Fig. 4), and the permissible electric field strength is 1207 kV/m. The electric field intensity remains practically constant in both layers of insulation, which indicates effective field equalization due to multilayering.

For the case $(\varepsilon_1 < \varepsilon_2)$ the distribution of the electric field strength becomes inhomogeneous, and the potential between the layers decreases to 518 V (Fig. 5).

Multilayer insulation effectively evens out the distribution of electric field strength in PV lines. The use of multiple XLPE layers with different dielectric constants reduces local voltage peaks, increases the allowable voltage and electrical strength of the insulation, while optimizing the material thickness.

Thus, multilayering is a key factor in increasing the reliability and safety of transmission lines in photovoltaic systems.
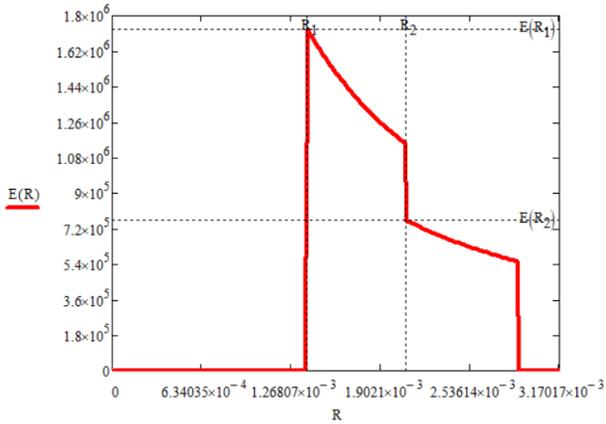
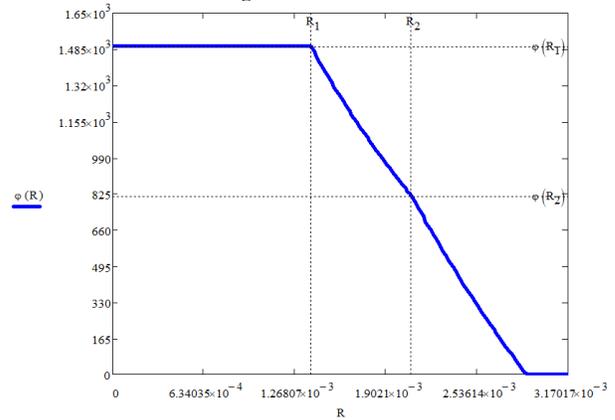characteristics of waveguide structures.

Fig. 1 – Electric field strength distribution in a two-layer XLPE insulator of a PV line under the condition $\varepsilon_1 < \varepsilon_2$
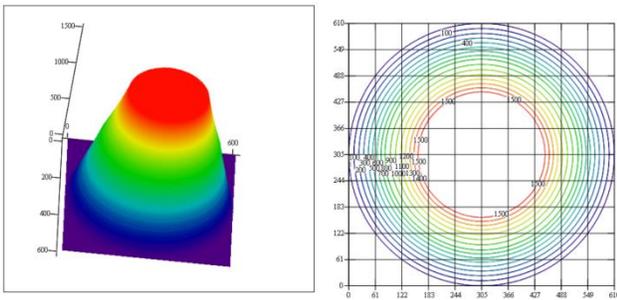

Fig. 2 – Electric field potential gradient in a two-layer XLPE insulator of a PV line ($\varepsilon_1 > \varepsilon_2$) 3D simulation (left) and 2D simulation (right) Mathcad
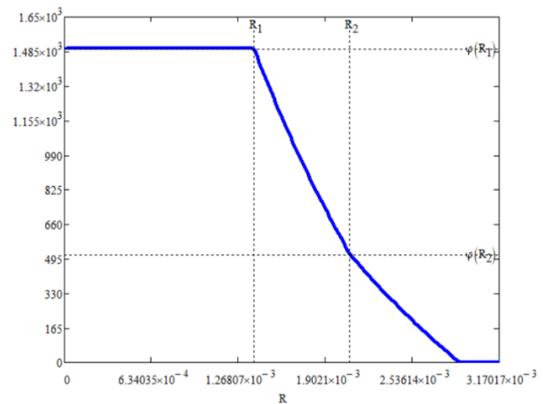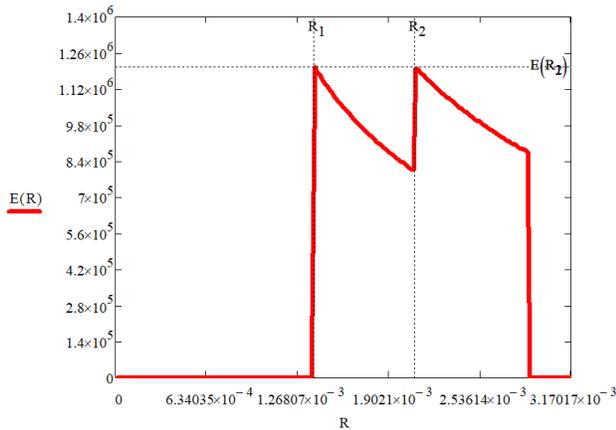

Fig. 3 – Electric field strength distribution in a two-layer XLPE insulator of a PV line under the condition $\varepsilon_1 > \varepsilon_2$

4. CONCLUSION

Numerical simulations have shown that the potential distribution and electric field strength in the multilayer dielectric XLPE insulation of the PV line depend on the ratio of the dielectric constants of the layers, and have also confirmed the robustness and validity of the proposed mathematical model for estimating the electrical

Fig. 4 – Electric field potential distribution in a two-layer XLPE insulator of a PV line under the condition $\varepsilon_1 > \varepsilon_2$

Fig. 5 – Electric field potential distribution in a two-layer XLPE insulator of a PV line under the condition $\varepsilon_1 < \varepsilon_2$

In the case when the dielectric constant of the first XLPE layer is greater than that of the second ($\varepsilon_1 > \varepsilon_2$), the potential between the layers is 817 V, and the permissible electric field strength is 1207 kV/m, which is in good agreement with the known data [12] for the corresponding transmission lines. The field voltage is distributed almost evenly, which provides increased electrical strength of the insulation. If the dielectric constant of the first XLPE layer is less than the permeability of the second ($\varepsilon_1 < \varepsilon_2$), the potential between the layers decreases to 518 V, and the maximum electric field strength increases to 1735 kV/m. In this case, there is a local increase in electric field intensity near the conductive core and a non-uniform field distribution, which reduces the electrical strength of the insulation and increases the risk of breakdown.

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Чисельне дослідження електричних характеристик перехресно-зшитого поліетилену для фотогальванічних застосувань

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У даному дослідженні проведений детальний чисельний аналіз розподілу електричного поля в діелектричних ізоляторах із зшитого поліетилену (XLPE), що використовуються в лініях електропередач фотоелектричних систем. Моделювання виконано в Mathcad із застосуванням стаціонарних рівнянь електромагнітного поля, з урахуванням геометричних параметрів конструкції провідника: площа поперечного перерізу провідника – 6 мм², товщина першого шару XLPE – 0,7 мм, другого шару – 0,8 мм. Досліджено вплив співвідношення відносної діелектричної проникності між шарами ($\varepsilon_1 > \varepsilon_2$та $\varepsilon_1 < \varepsilon_2$) на розподіл потенціалу та інтенсивність електричного поля. Для випадку $\varepsilon_1 > \varepsilon_2$потенціал на межі шарів досягав 817 В, а максимальна напруженість електричного поля – 1207 кВ/м, при цьому поле було майже рівномірним по обох шарах. Така конфігурація забезпечує високу діелектричну міцність та мінімізацію локальних напружень. Навпаки, при $\varepsilon_1 < \varepsilon_2$потенціал між шарами зменшувався до 518 В, а максимальна інтенсивність поля зростала до 1735 кВ/м, створюючи локальні піки, що знижують діелектричну міцність та підвищують ризик пробою. Результати підтверджують, що багатошарова ізоляція на основі XLPE ефективно вирівнює електричне поле, а оптимізація товщини та діелектричних властивостей кожного шару дозволяє підвищити діелектричну надійність та зменшити витрати матеріалу. Розроблена чисельна модель є надійним інструментом для оцінки електричних характеристик багатошарових діелектричних ізоляторів та надає практичні рекомендації щодо проєктування та оптимізації висоонадійних фотоелектричних кабелів і систем передачі електроенергії. Ці результати особливо актуальні для підвищення безпеки, ефективності та довговічності фотоелектричних установок у низько- та високовольтних умовах експлуатації.

Ключові слова: XLPE, Енергоефективність, Діелектричні ізолятори, Характеристики електричного поля, Фотоелектричні лінії, Чисельне моделювання