Signal Processing and Renewable Energy
December 2019, (pp. 49-70)
ISSN: 2588-7327
eISSN: 2588-7335

Homogenizing Electric Field of Lightning in L.P.S. XLPE Descending Conductor

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Received: 24-Apr-2019, Revised: 15-Jun-2019, Accepted: 22-Jun-2019.

Abstract

In this paper, behavior of MV cross-linked polyethylene insulation and homogenization of its electric field against the current flow, resulting from lightning stroke to arrest, is studied. In addition, it is shown that using two conductors with different structures field distribution can be homogenized and smoothed in the cable. A theoretical model is proposed for field distribution in the cable and the proposed cable. There is only a radial field (along x) inside a coaxial cable which its external conductor is grounded and varies with distance. That is, Schwager coefficient inside the coaxial cable is a function of this radius, and purpose of this study is to increase insulation breakdown voltage. For instance, if Schwager coefficient reaches 1, no insulation is required, and cable has a maximum breakdown voltage between middle conductor and external conductor. Therefore, by increasing Schwager coefficient, less insulation can be used. By reaching a Schwager coefficient of 58%, field inside the cable becomes homogenized and uniform; insulation can be used for the remained 42%. Now, if this insulation is made of refractory material, cable would provide high insulation strength. Among other advantages of refractory material, high melting point can be mentioned as a result of which they become pasty under critical and boundary conditions. One of the best insulations is XLPE or polyethylene with cross connections between its layers (cross-linked). In this study, critical and boundary condition for coaxial cable are applying lightning stroke of 1.2/50μsec. That is, wave front is 1.2ms and half wave front is 50μs. This current induces a voltage in devices including descending conductor between the aerial terminal of the arrester and ground connection of the arrester which might be several million volts. After obtaining field equations in the studied cable, characteristics of waveforms and creation of these waveforms are described in Simulink.

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Keywords: Coaxial Cable, Homogenization, Electric Field, HV Insulation, Lightning Stroke Wave, Schwager Coefficient, Cross-Linked Polyethylene, XLPE.

1. INTRODUCTION

Many studies have been conducted on insulation breakdown and partial discharge (PD) of various insulations in coaxial cables [1]. The most significant part of these studies has been devoted to various methods used to detect insulation breakdown voltage in cable and identify quality of insulation using nondestructive PD experiments [2]. Furthermore, the effect of using standard cable head to descend conductor of arrester and its connection to other parts of the system has also been studied [3]. In addition, uniform distribution of electric field in environments of different shape and different material have been investigated [4]. The International Electro Technical Commission (IEC) defines the IEC 62305 standards for lightning protection. Before this document, the lighting protection was following an older standard IEC 61024 Protection of structures against lightning, or other local national specific approaches as described in Refs [5].

Considering NFC 17-102, BS 6651, IEC 60230 and NFPA 780 standards, coaxial cable has been used for transmission of lightning current between aerial and ground terminals. Using HV coax cable with XLPE insulation reduce costs due to elimination of cohesiveness of descending conductor with metal equipment along its path. Employing the mentioned cable and insulation reduce the number of descending conductors under a specific condition where more than one conductor is required. Measuring lightning current inside internal conductor and buried MV coax shield cables are performed by the International Center for Lightning Research and Testing (ICLRT) and it is shown that voltage drops significantly at the end of the cable which is mainly due to high Schwager coefficient between two coaxial cylinders, cable length, two parallel paths for passage of lightning potential [6].

The electric field created between two coaxial cylinders of radius r1& r2 where r2>r1, is a non-uniform electric field. If the radius of the external conductor r2 is assumed to be constant, the maximum electric field intensity for a specific voltage is a function of (r1) and maximum electric field intensity occurs at r2=r1 which is created on the surface of the internal cylinder. In order to minimize this field intensity, maximum field intensity E-max, which is on the surface of the internal cylinder, should be differentiated with respect to r1. This calculation results in Npryn number e=2.718. This ratio is very important for designing HV cables or biasing coaxial loads with SF6. In this case, E-max on surface of the internal cylinder is minimized, and it is selected as r=2.5~3 for HV coax cables. For a value of r2/r1, value of E-max on surface of the internal surface is minimum, thus maximum voltage difference can be applied between two cylinders and a specific volume of insulation is used optimally. Ionization and partial discharge start at one point of the field in which field intensity is higher than other points. Thus, it is tried to homogenize electric field along surface of the insulation. As schwager, previous professor of Karler Ruhe University

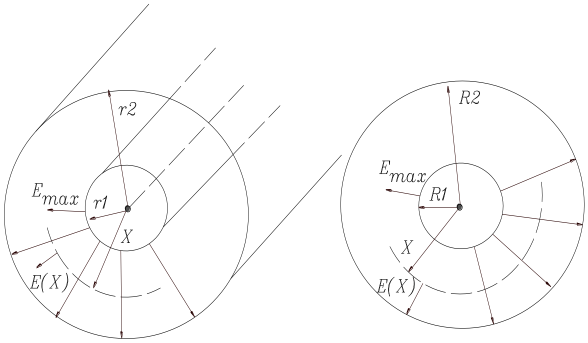


Fig. 1. Two coaxial cylinders.

of Germany has suggested, ratio of homogenous electric field to maximum field intensity is called homogenization coefficient or Schwager coefficient. For two coaxial cylinders with r2/r1=e (Figure 1), Schwager coefficient is 0.58 and for two coaxial spheres it is 0.5. On the other hand, a coaxial cable field, which its external conductor is grounded, only exists in radial orientation. This varies with distance. That is, Schwager coefficient inside a coaxial cable is a function of these radiuses. The purpose of this study is to increase Schwager coefficient to achieve higher insulation breakdown voltage [1].

Electric charge +Q is distributed uniformly on the internal cylinder of length L and -Q is distributed uniformly on the external cylinder, thus, electric field inside the insulation between these two cylinders with dielectric constant of £ can be calculated simply at a point between r1<r<r2. Gauss closed surface is a cylinder of length L and radius of r which is coax with two other cylinders. By getting far from the surface of the internal cylinder, the value of r increases and E decreases. Maximum electric field intensity is on the surface of the internal surface. In order to calculate potential difference between two cylinders, linear integral of electric field intensity between two cylinders along the field direction is used. Now, applications of coaxial cylinders in the electricity industry are mentioned. In such a condition, grounded walls of the laboratory, external cylinder and external sphere comprise coaxial cylinders and coaxial spheres, and, approximately, effect of electric fields of cylinders and sphere on each other can be neglected. If it is required to have the same E-max of the cylinder on the surface of the sphere, E-max of the cylinder should be set equal to E-max of the sphere. First application: a cylindrical conductor is used to connect circuits in HV labs. The radius of the cylindrical conductor (r1) should be selected such that the local electric discharge does not occur. This cylindrical conductor should be connected to a spherical electrode due to its limited length and in order to prevent local electric discharge at its end. In this condition, grounded walls of the lab, external cylinder and sphere constitute coax cylinders and spheres. Effect of electric fields of cylinders and sphere on each other can be neglected approximately. If it is required to have the same E-max of the cylinder on the surface of the sphere, E-max of the cylinder should be set equal to E-max of the sphere [4].

2. APPLICATION AND HISTORY

Recent studies have aimed to investigate the effect of thermal stress and electric field on tolerance of insulations. In addition, destructive mechanisms of insulation have been investigated under heat and aging [7]. In another study, effects of aging on insulation characteristics has been studied [8]. These studies are costly and time-consuming and require several years to provide sufficient database for solving economic problems of energy. Therefore, researchers try to find an efficient way to solve this problem. Recently, various smart systems have been proposed which help scientists to obtain database of the insulation system effectively. Among these smart methods, artificial neural networks (ANN) and fuzzy logic (FL) are robust tools for prediction and detection of HV insulation. In recent years, many applications of ANN have been proposed in HV context [3,4]. Furthermore, this method has been used for predicting properties of cable insulation [9]. But a few studies have employed fuzzy logic [1,2].

In recent years, application of XLPE cables in electric industry has increased due to its high robustness against voltage. Application of these cables in generators and transformers create a new type of generator and transformer called Power Former and Dry Former which are directly connected to transmission lines. Dry Former transformer converts voltage from transmission level to distribution level and its direct connection too, transmission lines creates a transient response in the network. In [10], different transient states with maximum amplitude at voltage terminals of a transformer, including transient response of lightning and switching which has been studied by proposing a transformer model with XLPE cable winding. Simulation results show a significant difference between a former dry transformer and transformer with conventional winding. When lightning strikes the ground or a building, electronic devices in buildings up to 1.5 kilo meters away from striking point and in a range of the created electromagnetic field are at risk.

Each air terminal is assigned an attractive radius, which is calculated as a function of its height, radius of curvature, location on the structure, structure dimensions, and a set of sight, atmospheric and curvature, location on the structure, structure dimensions, a set of sight, atmospheric and lightning-related parameters. In a similar manner, an attractive radius is assigned to all competing features on the structure which can also capture a lightning strike, e.g., building edges, corners, parapets, flagpoles, lift motor rooms, etc. The calculations of the attractive radii also depend on the upward leader inception criterion employed. In the present case, a critical breakdown field of~3 MV/mover an effective space charge or corona radius of~0.3 m, both are taken from laboratory experiments of previous investigations [11].

These air terminal placement methods typically fall into one of four categories:

(a) Pure geometrical constructions, such as the “Cone of Protection” or Protective Angela method, which is commonly found in national and international standards [11].

(b) Faraday Cage concepts, in which a “meshwork” of conductors or air terminations is placed at set intervals over a structure [11].

(c) Electro geometric models (EGMs), in which empirical relationships for striking distance and lightning peak current are invoked. The most common example is the “Rolling Sphere Method”, which is also partly a geometric construction [11].

(d) Physical models, where air breakdown mechanisms are applied to the lightning scale; these models have been derived from laboratory investigations of long sparks and, to a lesser extent, field studies of natural lightning [11].

The optimized placement of air terminals ensures that the most efficient lightning protection system (LPS) is installed on the structure. We define a LPS to be "efficient" if it achieves the desired level of protection and safety at the lowest possible cost for the end user [11].

Effective protection of these devices against induced voltage is possible when all internal and external protection systems are installed simultaneously [10].

Using cable at the point where transmission lines connect to the transformer, amplitude and waveform of excess voltages reaching terminals of the transformer are balanced significantly. In addition, due to the characteristic impedance of the cable and transmission line, lightning strike which moves towards the transformer along the cable is reduced significantly. The tolerable overvoltage level of power systems is determined in standards which are satisfied with insulation design. This parameter is called basic lightning impulse level (BIL) which is a measure of strength of the devices against overvoltage [12].

Overvoltage's are generated in the building directly hit by lightning, not only by the shunted lightning current but also by electromagnetic fields induced by the lightning current which flows into bonded conductors. IEC 62305-1 recommends equi-potential bonding for the grounding system of a building so that dangerous voltage may not stress electrical apparatuses. To achieve equipotential bonding, all conductors need to be connected directly or through surge protective devices (SPD). When the SPD is activated by overvoltage's generated by lightning which directly hits the building, fraction of lightning current will flow into the electrical wirings through the activated SPD[13].

Considering current development of wind farms in the world and their vulnerability to lightning strikes, it is necessary to study lightning electromagnetic obstacles in wind farms [14]. Underground cables are one of the necessary components of wind farms which connects turbines to the electricity network. Characteristics of these cables vary by changing type, thickness and length. Therefore, this overvoltage is a function of these factors. In addition, when lightning strikes the cable indirectly, maximum slope and overvoltage changes induced in the conductor are affected by lightning parameters significantly. These parameters include: a) return stroke current amplitude b) rise time, settling time to half of the final value, c) return stroke speed, d) cloud height [14]. Has investigated ground conductance and relative permittivity, being subject to wind tower and increase in lightning current in electromagnetic fields unsheathes the underground cable.

Lightning over voltages can be also transferred to the building electrical system from the multi conductor transmission line through the distribution power transformer. Experimental investigations of efficiency of lightning protection systems of small structures have been carried out for couple of years at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, and at the Rzeszow

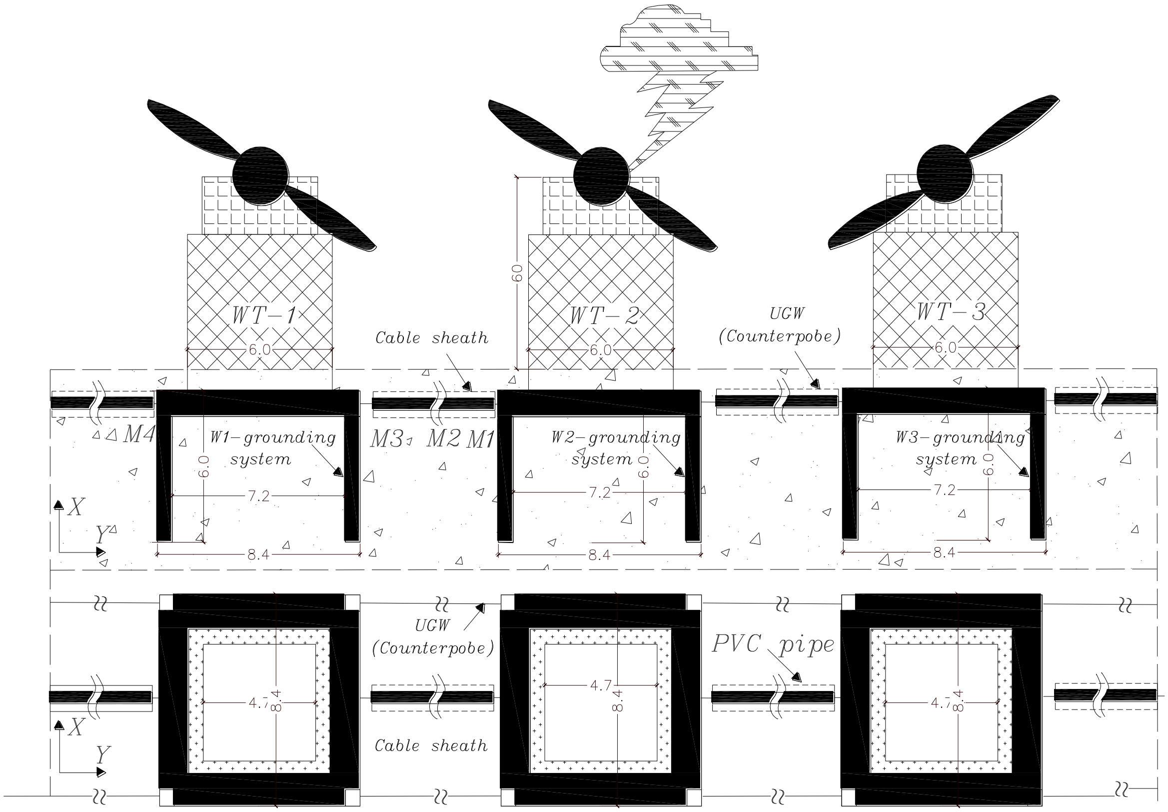


Fig. 2. Geometric definition of solution space in Cartesian system [14].

University of Technology (RUT), Poland [15].

An arbitrary amplitude-time-infinite 3D method is implemented for this study. Lightning current through cable sheath and the corresponding electric field can beeffectively used as a counterpoise through connecting ground connection of wind towers using underground bare wires.

Current waveforms in elements of the test house are different regarding the amplitude and the rise time. These differences are caused by frequency dependent parameters of the system. Experimental examinations of input impedances of distributing transformer overhead lines and underground cable, electrical installation with household appliances, and the LPS have shown strong influence of frequency on both their modules and phases [15].

Accordingly, effect of division, reduction on lightning strike through the sheath and its corresponding electric field is investigated. Results show that lightning conductance current through cable sheath and its electric field is lower than ground conductance. In addition, it can be seen that tailor ground effect and location of wind tower on electric field and crust current depend on ground conductance. Using cable reduces amplitude and increase rate of transient voltage (dv/dt).

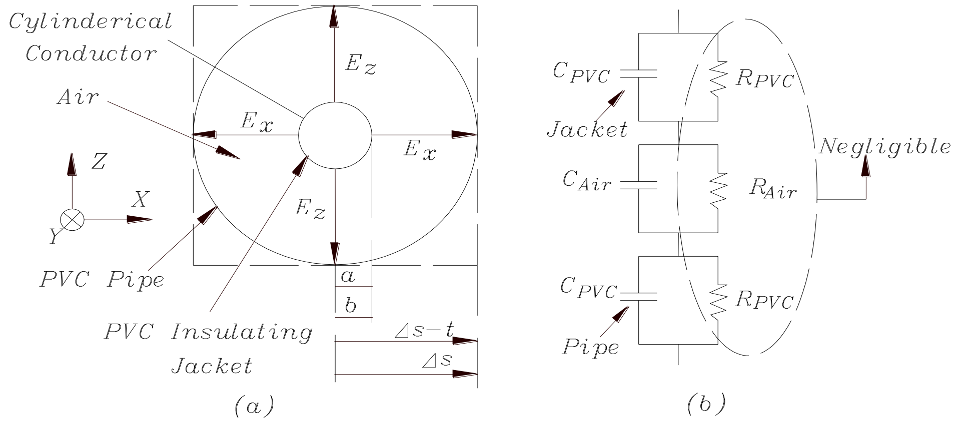
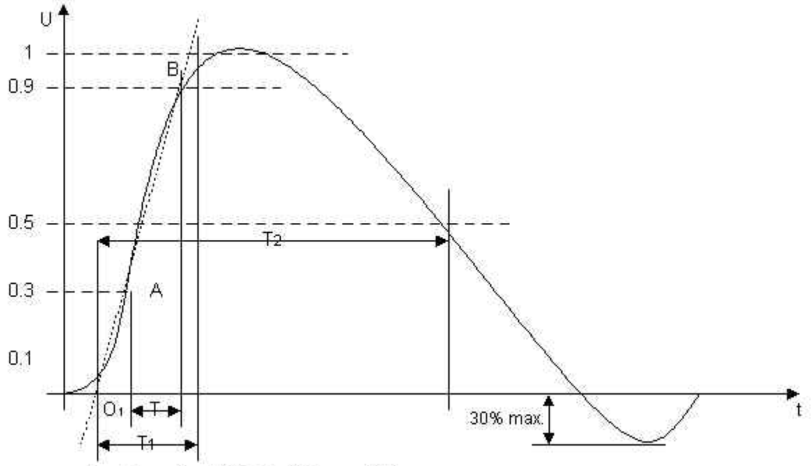


Fig. 3. Underground cabling (a) cross section of the cable sheath (b) equivalent circuit of the shunt capacitance and leakage resistance of the cable sheath [14].



Front time: $T_1 = 1.67 \times T = 1.2$ us +- 30%
Time to half-value: $T_2 = 50$ us +- 20%
Note: The front time T_1 of a surge voltage is a virtual parameter defined as 1.67 times the interval T beteen the instants when the impulse is 30% and 90% of the peak value.

Waveform of open-circuit voltage (1.2/50 us)

Fig.4. Lightning current waveform.

Attenuation of high frequencies of shielded power cables is affected by three factors, including: a) crust loss of the conductor b) dielectric loss of the insulation c) dielectric loss of the semiconductor. Crust loss can be ignored using thick cables. Cables which have XLPE isolation have a low dielectric loss, thus the dominant low frequency loss is the result of dielectric loss of semiconductor. Geometric definition of the solution space in Cartesian system is shown in Figure (2).

Figure (3) (a) shows an underground cable which its crust is shielded with a PVC and it is developed inside a PVC pipe. The penetration depth of the electromagnetic wave propagating in the sheath layer is less than the thickness of the crust. Therefore, cable is considered as a cylindrical conductor with the same radius as the crust. Lightning current waveforms used in this paper are shown in Figure (7). Electromagnetic fields

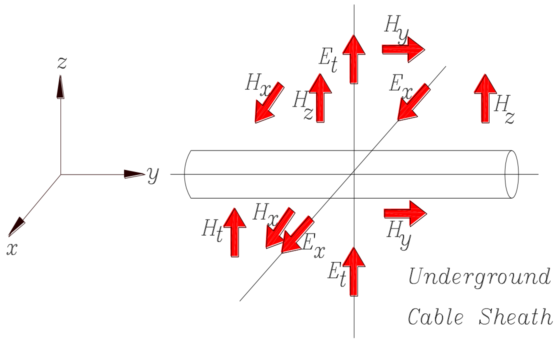


Fig. 5. Lightning electromagnetic fields in the underground cable [14].

around the underground cable are shown in Figure (8) [14].

When measuring current, magnetic field around the cable was also measured and it was observed that field around the cable coax with the multi-layer insulation is reduced significantly, compared to bare wire. In this study, internal conductor and shielded are connected together at the end and ground. If the insulation does not stand or it is not grounded, insulation breakdown occurs. Field induction in the shield and internal conductor of the cable, main insulation between core and shield is stressed.

Electromagnetic calculation methods (ECMs) are widely used in analysis of lightning electromagnetic pulses and lightning waves resulting from different systems. One advantage of ECMs compared to circuit simulation methods is that they allow a complete solution represent two transient current distributions in a 3D conductor system with electromagnetic background, therefore, despite being costly, they are used widely (Figure 5). Among ECMs, finite difference time domain (FDTD) method is mostly used to solve Maxwell equation in LEMP and simulation [14]. In [4], applications of FDTD in LEMP and simulations including 1) lightning electromagnetic fields in close and far distances 2) lighting on transmission line conductors and transmission of potential force 3) distribution and communication networks 4) lightning electromagnetic environment in electricity stations 5) lightning in towers of wind generator turbine 6) lightning in PV arrays 7) lightning electromagnetic environments in electric vehicles 8) lightning electromagnetic environment in airplanes 9) lightning and electromagnetic environments in buildings and 10) ground electrodes are investigated. Different types of conductors and lightning closing paths towards ground are shown in Figure (6) [14].

As the downward leader from the cloud approaches a structure, the electric field around the structure increases to the point where corona streamers are produced from the geometrically “sharp” features of the structure, e.g., edges, corners, etc. One or more of these streamers may develop into a stable, propagating upward leader that intercepts the downward leader. The inception criteria for conversion from a streamer into a leader are quite complex, but are described fully in Ref [11].

A bipolar load transmission model is used to simulate the formation of charge space in XLPE plaques under a thermal gradient [16]. This model is used to evaluate the relative importance of charge migration and blocked extraction for three possible effects of thermal gradients. Simulation is performed for samples with different thicknesses and results are validated through comparison with experiment. Thus, it is shown that a thermal gradient not only affects different

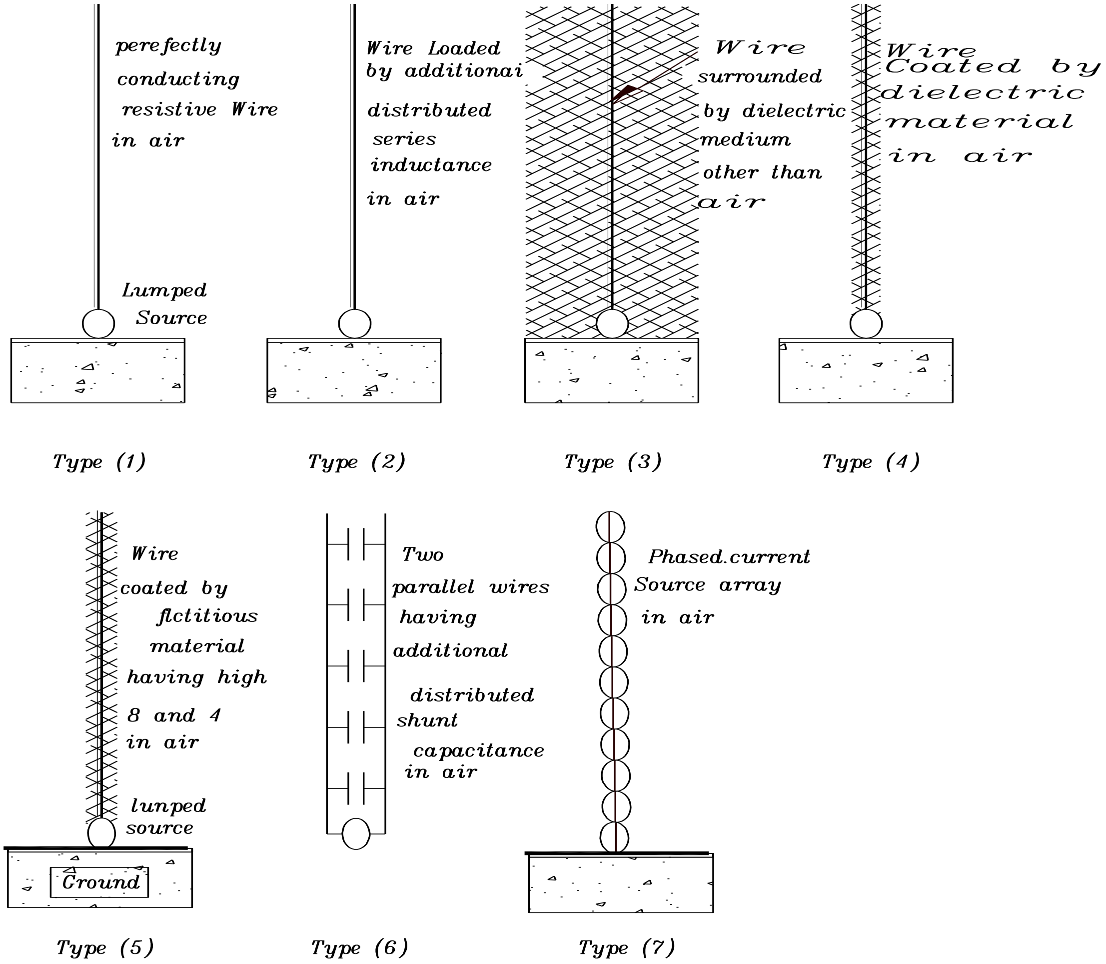


Fig. 6. Lightning opening channel in various descending conductors [16].

temperature electrodes through accumulation of spatial charge using a conductance gradient but also through difference in injection and extraction procedures. The reason that contact voltage is not transmitted and no field is induced from the proposed cable to the building. The main reason is the isolated conductors or coaxial conductors due to the existence of multiple insulation layers in the cable structure. It is well-known that corners, edges, etc. of structures are the most likely locations to be struck by lightning because of the electric field intensification they create. It is a structure using the field intensification factor as a fundamental parameter. This is the real-world situation. This assumption also ensures that there is inherent safety in the technique [11].

2.1. Using Cable with Cross-Link Polyethylene Insulation (XLPE)

This insulation is used due to its robustness against an increase in frequency of insulation of capacitances. Its robustness against moisture allows replacement of the lead shield of cables with Polyethylene, thus, weight of cables is reduced significantly.

Despite outstanding insulation properties of PE, its low robustness against heat is an obstacle for using this insulation in HV engineering. With the establishment of length connection of Polyethylene chemical bond in width, chain structure of the polymer becomes more stable. Therefore, polyethylene loses its thermoplastic property and cannot be melted. Such a change in structure of polyethylene is called cross-link polyethylene (XLPE) and this material has thermal and electric robustness, and it is neutral against chemical effects [10].

Underground HV cables are used for transmission and distribution of electric energy in urban and suburban areas of large cities [10]. In recent years, cables were insulated using oil impregnated papers which have been gradually replaced by polymer material like polyethylene (PE), XLPE and PVC [5,9]. Artificial insulated cables and plastic have many advantages both technically and economically. Among its advantages, simple implementation of cable, small volume, simple operation and not requiring maintenance can be mentioned. In addition, these insulations have good mechanical and electrical properties. This change in insulation technology has increased service operating condition from 15 kV/mm to 40 kV/mm and reduced energy loss [7].

Since one of the main problems of regional electricity companies is destructive effects of strike waves of their devices, and cables are one of the most important components of these underlying devices in the network, effect of lightning strike on cables has been studied and results of various experiments are presented.

2.2. Shielded Cable (coax) with XLPE and its Characteristics

Polyethylene is of polymer families with linear molecular structure; since the CH2 group is not polar, inter-molecular force of polyethylene is not strong. Its melting point and stiffness is low (about 115 degrees of centigrade for melting point) . Among good insulation properties of PE, low loss factor (about 0…. 3) relative insulation, number of 2/3 and good electric robustness of 300kV/cm can be mentioned. Loss factor, and relative insulation, do not fluctuate significantly with changes in temperature and frequency. Thus, this insulation is widely used in the cable industry and it has become a good alternative for HV cables which used oil impregnated paper in recent years. The one is used in insulation of capacitances due to their good robustness against the frequency increase. Its robustness against moisture allows replacement of the lead shield of cables with polyethylene; thus, weight of cables is reduced significantly. Despite outstanding insulation properties of PE and its low robustness against heat is an obstacle against using this insulation in HV engineering. With the establishment of length connection of Polyethylene chemical bond in width, chain structure of the polymer becomes more stable. Hence, polyethylene loses its thermoplastic property and cannot be melted. Such a change in structure of polyethylene is called cross-link polyethylene (XLPE) and this material has thermal and electric robustness and it is neutral against chemical effects. The cable used in experiments has the following characteristics; these cables are single phase

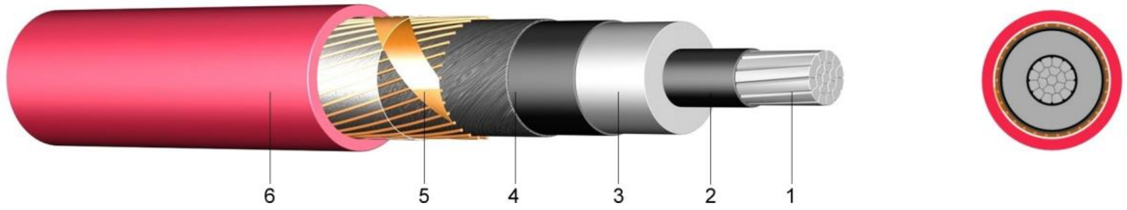


Fig.7. Xlpe Cable Cross Section & Detail Construction.

and manufactured based on an IEC60502-2 standard:

- Thickness of XLPE on the conductor: 3 mm
- Thickness of graphite layer: ½ mm
- Thickness of the crust: 1/85 mm
- Shield thickness: 0.55 mm
- Capacitance: 0/233 µF/km
- Nominal voltage of the single-phase cable: 13/8kV
- Nominal voltage of the network: 20kV
- Insulation type: XLPE/PVC
- Conductor cross section: 70 mm^2
- External diameter: 30 mm
- Conductor diameter: 11 mm
- Cable length: 40 m

Construction:

1 .Stranded (RM) aluminium wires
2 .Inner layer of semi-conducting material
3 .Core insulation of cross-linked polyethylene
4 .Outer layer of semi-conducting material
5 .Screen of copper wires
6 .Outer sheath of polyvinylchloride (PVC), red

Standards:

- DIN VDE0276-620
- HD 620 S1: 1996
- DIN EN 60228 class 2 (construction)

Research Objectives:

- Uniform distribution of electric field between two coaxial cylinders
- Increasing the insulation strength of the coaxial cable using non-melting material
- Using HV coaxial cables for the lightning descending conductor
- Optimizing implementation of the arrester descending conductor
- Homogenization of high voltage electric field in coaxial cable by using the theory of coaxial cylinders and increasing the Schweizer coefficient.

3. EXPERIMENTAL METHODS

First, it is required to investigate papers, books, standards and other references in the context of homogenizing electric field intensity in coaxial cable. Studies about the insulation strength of different material, which can be used as HV coaxial cable or even multiple-insulations, seems useful. Finally, by presenting theoretic model calculations and its comparison with simulation results and validation of the obtained results in HV lab and potential difference between two ends of bare wire

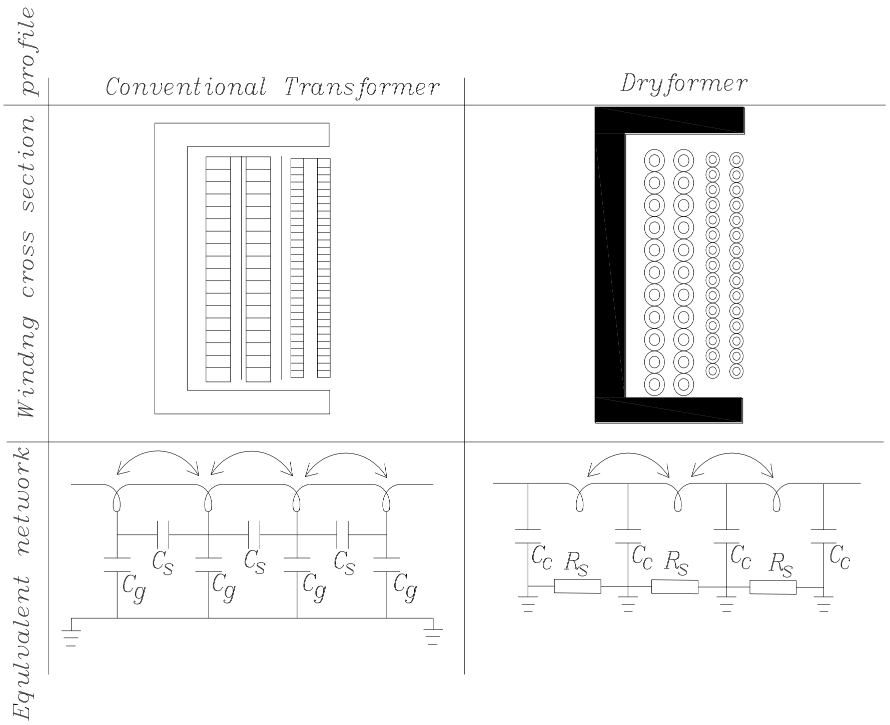


Fig. 8. Winding of the transformer with conventional insulation (Left) and XPLE insulation (Right) [16].

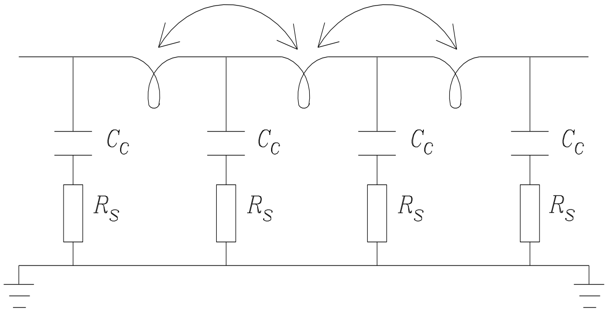


Fig. 9. Structure of the studied cable (left) and its equivalent circuit (right) [16].

compared to 20kV-XLPE Shield Cable are provided.

In order to perform field calculations, theoretic relationships and Maxwell equations are implemented in MATLAB. In this code, first, the geometric structure of the cable and input current of the circuit are designed; then, relationship and theories, mentioned in the following, are used to calculate magnetic flux density. In this program, magnetic flux density of each conductor is investigated separately and then the total magnetic flux density is obtained using superposition theorem. In the third section, where the outputs are given, various diagrams are plotted.

4. DISCUSSION AND RESULTS

A. Theoretic Model

In [10], a model has been proposed for transformer with XPLE insulation. Figure (8) compares winding of the transformer with conventional insulation and XPLE insulation.

The structure of the studied cable is shown in Figure (8). The structure of the cable, studied in this research, is similar in the structure of the cable used in Dry Former due to using two coaxial conductors and existence of a dielectric between these two conductors. It has been shown in this study that by using two different conductors, field distribution in the cable can be homogenized. Equivalent circuit of the cable system is shown in Figure (9) [10].

Having an equivalent circuit of the transformer and cable, it has been analyzed and simulated. Using Figure (11), boundary conditions and field relationships at the interface of the dielectric and metal are described. Index ‘d’ indicated dielectric, index ‘m’ indicated metal, E Electric field, H field intensity. Using boundary conditions, we have:

$$\begin{cases} \varepsilon_m E_{zm} = \varepsilon_d E_{zd} \\ E_{xm} = E_{xd} \\ H_{ym} = H_{yd} \end{cases} \begin{cases} \varepsilon_m E_{zm} = \varepsilon_d E_{zd} \\ E_{xm} = E_{xd} \\ H_{ym} = H_{yd} \end{cases} \tag{1}$$

thus, it can be concluded that:

$$k_{xm} = k_{xd} \; k_{xm} = k_{xd} \tag{2}$$

on the other hand, using Maxwell equations, we have:

$$\begin{pmatrix} \partial_x \\ \partial_y \\ \partial_z \end{pmatrix} \times \begin{pmatrix} 0 \\ H_y \\ 0 \end{pmatrix} = \varepsilon \frac{1}{c} \partial_t \begin{pmatrix} E_x \\ 0 \\ E_z \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} -\partial_z H_y \\ 0 \\ \partial_x H_y \end{pmatrix} = -\varepsilon \frac{\omega}{c} \begin{pmatrix} E_x \\ 0 \\ E_z \end{pmatrix} \tag{3}$$

$$\frac{k_{zm}}{k_{zd}} \frac{H_{ym}}{H_{yd}} = -\frac{\varepsilon_m}{\varepsilon_d} \frac{E_{xm}}{E_{xd}} \; \frac{k_{zm}}{k_{zd}} \frac{H_{ym}}{H_{yd}} = -\frac{\varepsilon_m}{\varepsilon_d} \frac{E_{xm}}{E_{xd}} \tag{4}$$

and since $E_{xm}=E_{xd}$ and $H_{ym}=H_{yd}$, we have:

$$\frac{k_{zd}}{\varepsilon_d} + \frac{k_{zm}}{\varepsilon_m} = 0 \; \frac{k_{zd}}{\varepsilon_d} + \frac{k_{zm}}{\varepsilon_m} = 0 \tag{5}$$

On the other hand, in general, for the propagation constant we have:

$$k_x^2 + k_y^2 + k_z^2 = k^2 \; k_x^2 + k_y^2 + k_z^2 = k^2 \tag{6}$$

$$H_z = \frac{\beta}{\omega\mu_0} E_y \tag{7}$$

Now, we focus on EM waves inside several layers including thin dielectric and metal layers. In this system, each interface can propagate limited EM waves. When the distance between the two interfaces is comparable or smaller than decay length, interactions between EM waves of the two surfaces create coupling modes. In order to make general properties of coupled EM waves, clearly, we focus on two 3-layer systems. First layer is a thin metal (I) between two thick dielectric layers (II, III); in other words, the heterogeneous structure of insulation/metal/insulation (IMI) and the second is a layer close to the dielectric core (I) between two metal shields (II, III); that is, it is the heterogeneous structure of the metal / insulation/metal (MIM). We begin with a general description of TM modes which oscillate along Z which is orthogonal to interface. For z>a

$$E_z = -B \frac{\beta}{\omega\varepsilon_0\varepsilon_2} e^{i\beta x} e^{k_2 z} \tag{8}$$

Therefore, fields in shields (II) and (III) are attenuated exponentially. Note that, for simplicity, wave vector orthogonal to interface is represented by $k_i \equiv k_{zai}$

In –a<z<a, the following relationships are obtained as a result of coupling between top and bottom interfaces:

Solving this linear system gives the following equation for scattering:

$$e^{-4k_1 a} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2} \qquad \frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3} \tag{9}$$

$$\begin{array}{ll} N_D^+ = N_{D0}^+ + \delta N_D^+ & N_D^+ = N_{D0}^+ + \delta N_D^+ \\ N = N_0 + \delta N & N = N_0 + \delta N \\ J_e = J_{e0} + \delta J_e & J_e = J_{e0} + \delta J_e \\ E_{sc} = E_0 + \delta E_{sc} & E_{sc} = E_0 + \delta E_{sc} \\ I = I_0 + \delta I & I = I_0 + \delta I \end{array} \tag{10}$$

Finally, electric field for two symmetric and asymmetric modes are as follows:

$$E = (E_{xa} + E_{xs})\hat{e}_x + (E_{za} + E_{zs})\hat{e}_z \tag{11}$$

MV shielded conductors might be comprised of 1, 2 or 3 insulation layers. Usually, insulation is comprised of XPLE or HDPE (High Density Poly Ethylene). Sometimes, semiconductors are used in the third layer. A layer of semiconductor surrounds the central core of the cable which reduces potential points of electric charge accumulation and partial discharge at these points and it is shielded by a layer of polyethylene. PVC layer is used for external layer which is suitable for open environments. The main advantage of using multi-layer insulation is that due to the double-sided connection of the semiconductor to the core and shield when lightning current flows, electric potential on both sides of the semiconductor is uniform; in fact, a semiconductor is located between two coaxial cylinders which has the maximum Schwager factor (uniformity factor) and minimum PD and insulation destruction are observed. Actually, semiconductor between core and shield plays the role of a dielectric between two plates of a capacitor; when lightning current passes the cable, core and shield become charged and they are connected to each other and total length of the cable becomes equipotential. At the end of the cable which is grounded, this task is done by the spark gap isolator. Besides, at the beginning of the cable which is connected to the aerial terminal of the arrester, it is done by the cable head of the semiconductor. Separation distances for different materials are currently defined by standard IEC 62305-3: 2010[5]. Cable head of the semiconductor to reduce contact voltage and prevent surrounding sparkles. Cable head of the semiconductor operates as a Zener diode and when a particular voltage is applied, avalanche breakdown occurs and opens a path for transmission of lightning current from arrester's side to ground (one-sided).

Among other factors which reduce lightning voltage amplitude is cable length. As the cable length increases, amplitude and voltage gradient reduce significantly. The effect of this parameter for two cables with EPR and XLPE insulations is given in Table (1).

As expected, reducing the amplitude and voltage gradient, especially incremental gradient, which results in most destructions,

Table 1. ***Relationship of overvoltage and cable length [10].***

Cable Length (m)	**Maximum Overvoltage Domain (kV)**			
	XLPE Cable		**EPR Cable**	
	Open Circuit	**Connected to Transformer**	**Open Circuit**	**Connected to Transformer**
Without Cable	1068	1064	1068	1064
30	1060	1026	1037	1002
50	984.9	958.6	954	925
70	930	897	899.5	875
100	874	855	839	818
200	755	743	707	689
500	593	581	530	513
1000	472	465	393	376
1500	389	385	312	294
2000	351	345	255	236.5

Table 2. ***Relationship of overvoltage and radius of XLPE cable [10].***

XLPE			
Cable Length (m)	**Cable Radius(mm)**	**Maximum Voltage (kV)**	
		Open Circuit	**Connected to Transformer**
70	6.2	930	879
	6.8	911	885
	7.4	859	868
1500	6.2	389	385
	6.8	371	362
	7.4	350	342

is higher in EPR cables compared to XLPE cables for all longs. On the other hand, at longer lengths, using EPR cable is more effective such that at 30m, amplitude and gradient of voltage for EPR is about 97% of the corresponding values for XLPE. While at 2000m, this ratio is reduced to less than 70%. Therefore, in order to use shielded cable as descending conductor of the arrester system, cable with XLPE shield is more suitable than cable with EPR shield considering the above technical issues and press [12].

Tables (2) and (3) show the relationship of overvoltage and radius of EPR and XLPE cables. It can be seen from the following tables that although increasing radius of cables reduces amplitude of overvoltage, but its effect is not considerable. For instance, by a 20 % increase in radius of XLPE cable, at 70m and 1500m, voltage amplitude is

Table 3. ***Relationship of overvoltage and radius of EPR cable [10].***

EPR			
Cable Length (m)	**Cable Radius(mm)**	**Maximum Voltage (kV)**	
		Open Circuit	Connected to Transformer
70	6.6	899.5	875
	7.2	888	864
	7.8	870	848
1500	6.6	312	294
	7.2	303	287
	7.8	294	278

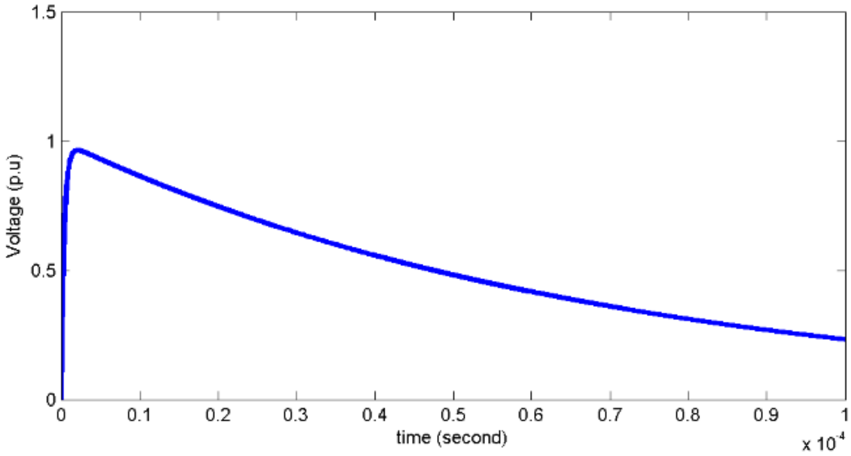


Fig. 10. Completely standard voltage impulse waveform.

reduced 3% and 10%; for EPR, voltage amplitude reduces 3% and 5% at 70m and 1500m. Despite low impact of cable radius, using XLPE cable at short distances is more logical.

A. Simulation Results

Here, characteristics of the waveforms of interest are described and their formation in Simulink is also explained.

B.1. Completely Standard Voltage Impulse Waveform:

Main characteristics of this waveform are given in IEC-60060-1 standard. Its peak is created at 1.2µs and its tail is reduced to 50% of the peak in 50µs. Figure 10 shows an example such waveform.

B.2. Interrupted voltage impulse waveform: This type of voltage impulse has the shape of a standard voltage impulse which might have interruptions at tail, front or peak. In this study, voltage impulses with interruptions at 3µs (Figure 11) and 15µs (Figure 12) are studied.

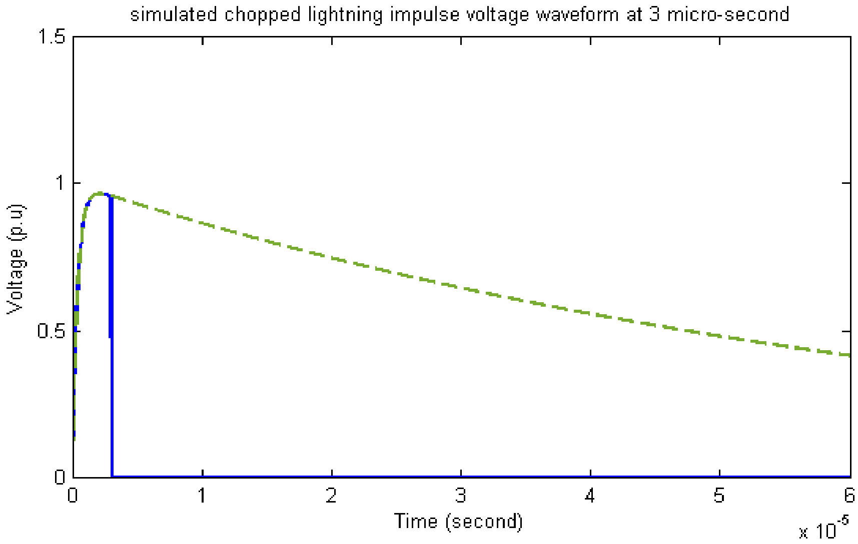


Fig. 11. Interrupted voltage impulse waveform at micro-second.

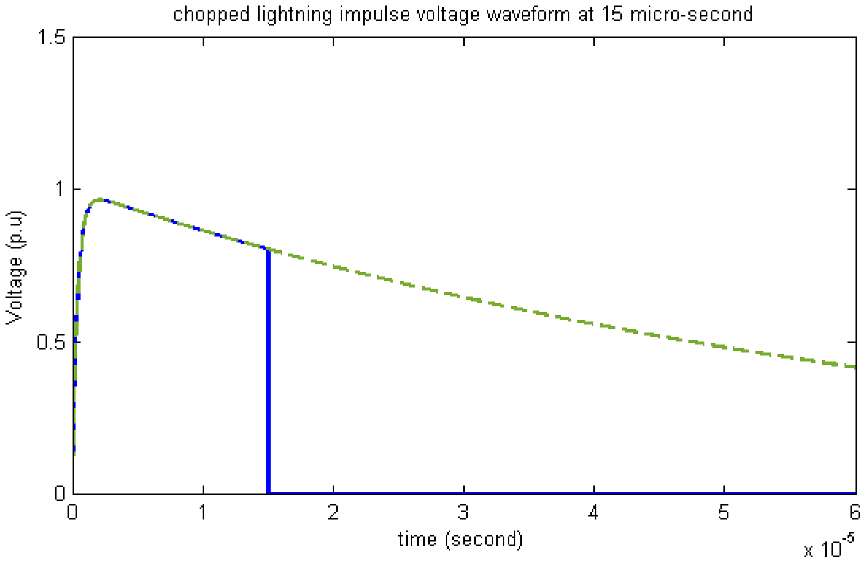


Fig. 12. Interrupted voltage impulse waveform at 15 micro-second.

B.3. Non-standard single pulse voltage impulse:

Non-standard single pulse voltage impulse is used to study voltage response of windings to non-standard non-oscillating lightning voltage pulses. These waveforms have a sharper front compared to standard waveforms and their tail is also shorter and non-oscillating. Front of the impulse is 0.8µs and its tail is reduced to 50% of its peak in 2.8µs. Figure 13 shows simulation results of this waveform.

B.4. Non-standard damping oscillating voltage impulse:

Oscillations of impulse waveforms might occur due to series and parallel resonances and incompatibility of parameters in

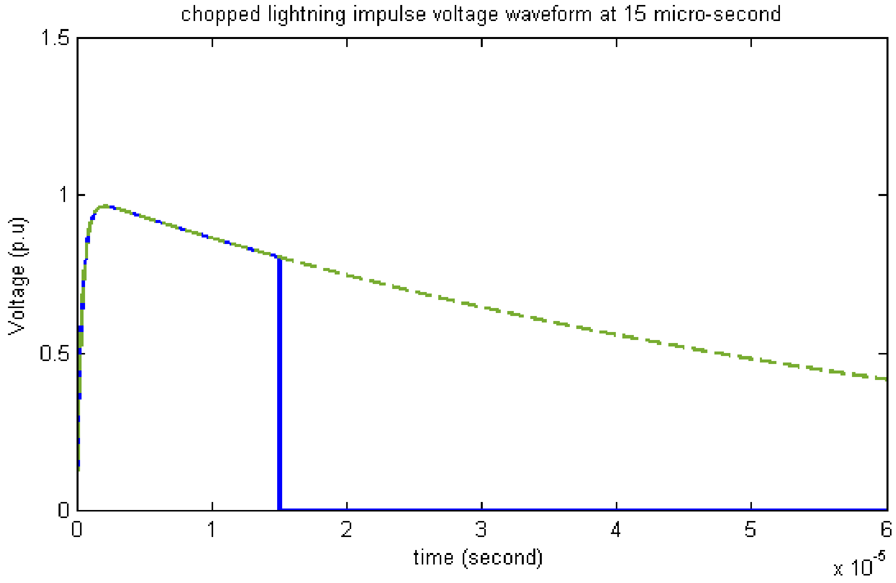


Fig. 13. Non-oscillating single pulse voltage impulse.

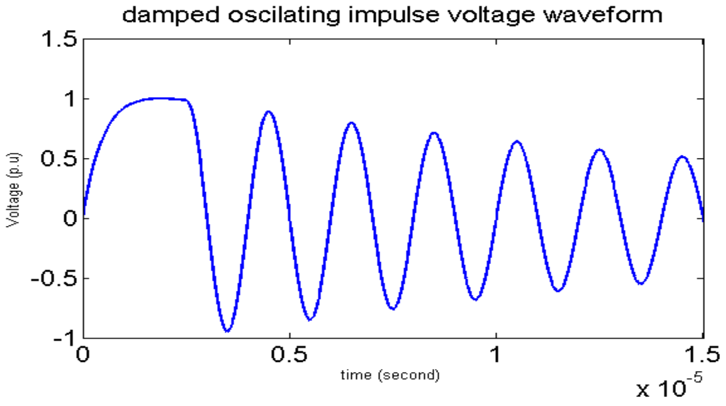


Fig. 14. Damping oscillating voltage impulse simulated in Simulink.

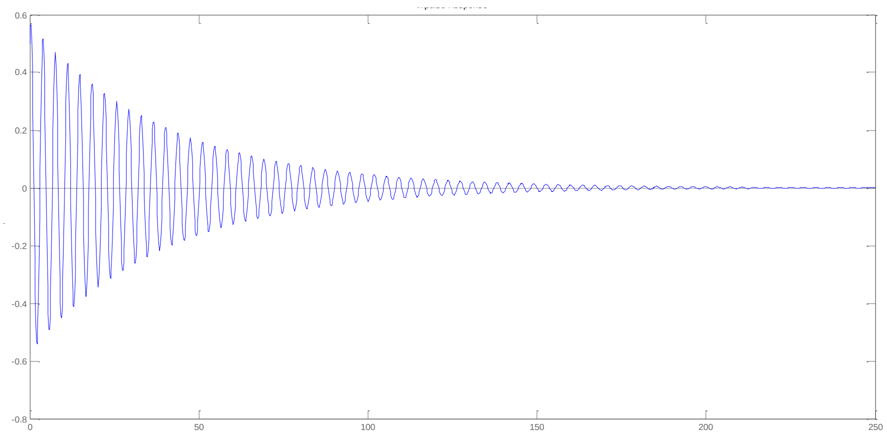


Fig. 15. Lightning oscillation in conventional cable.

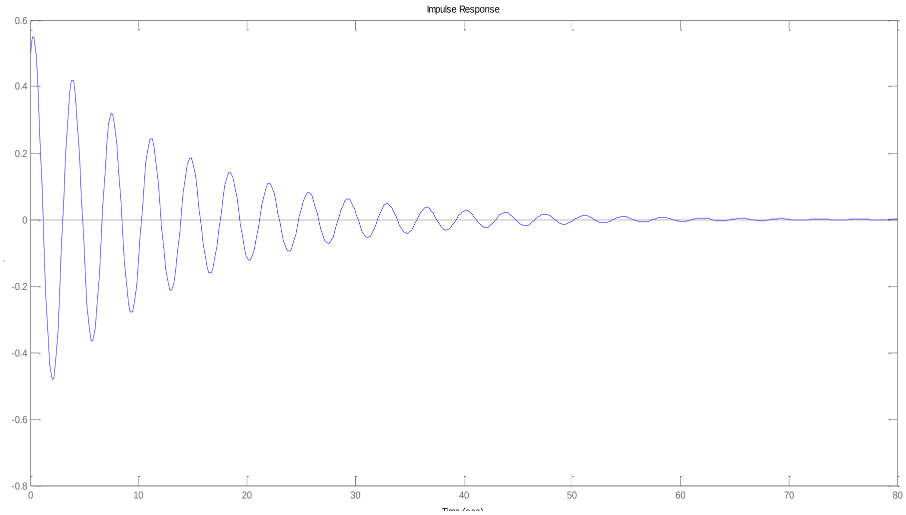


Fig. 16. Lightning oscillation in the proposed cable (bottom).

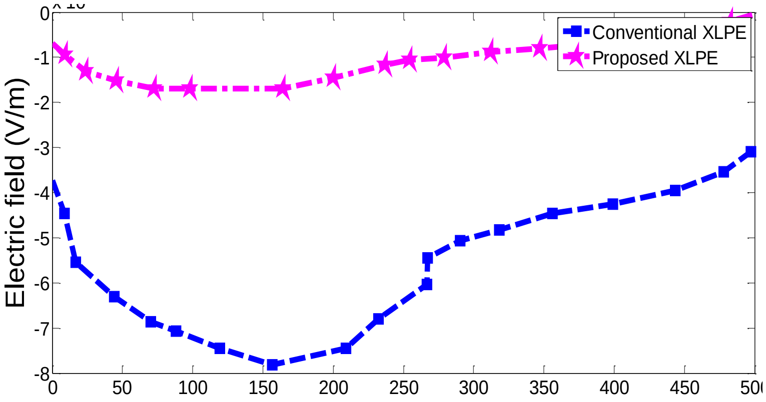


Fig. 17. Field distribution in conventional XLPE cable and the proposed XLPE cable.

generating voltage impulse. Rising time of this waveform is 1.9µs and the main feature of its tail is oscillating and damping with a frequency of 0.5MHz. Damping oscillations occur at 2.5µs. Simulation results are given in Figure 14.

Simulation results of applying lightning voltage impulse, its damping for conventional cable and the proposed cable are given in Figures 15 and 16. It can be seen that the proposed cable has more uniform oscillations.

Figure 17 shows field distribution in conventional XLPE cable and the proposed cable. It can be seen that field distribution of the proposed cable is more uniform.

B. Suggestions

Considering the details of the structure and performance of the proposed cable along with its specific stress terminal and verification of its performance of laboratory tests, following suggestions can be made about this study:

- Using the proposed cable for particular projects, including communication towers, data center, hospital, Petro chemistry due to its high security.

- Considering the reduction of voltage gradient at the end of the proposed cable, using cable is a proper option for designing protection system against lightning for all buildings.
- Considering financial justification presented in the next section, using this cable is cost-effective and reduces implementation time of the lightning arrester protection system which makes it suitable for contractors.
- Uniforming distribution of electric field between two coaxial cylinders.
- Increasing coaxial cable insulating resistance using laminate materials.

5. CONCLUSION

In this study, HV insulations and homogenization of their electric field, especially in XLPE cables is investigated. In addition, it is shown that using two different conductors with different materials, field distribution in the cable can be homogenized. A theoretic model is proposed for field distribution in the cable and the proposed cable. Computational results in homogenization theory verify 58% of the results in the proposed cable. On the other hand, simulation results are also close to computational results due to considering ideal condition line ground system, environment condition and conductor type. Important conclusions are made:

1. The proposed cable and XLPE insulation with the tolerable voltage level of 20kV has tolerated lightning stroke wave in transient state up to 1500kV without destruction. Cross-linked polyethylene is highly robust against harsh environmental condition and insulation breakdown.
2. Two coaxial cylinders (core conductor and cable shield) prevent point discharge due to high uniformity and this is one of the most important reasons why cable health is preserved after applying a voltage of 1500V.
3. Considering the voltage reduction at the beginning and the end of the cable, the superiority of the proposed cable compared to other non-coaxial cables or bare wire as descending conductor is obvious.
4. Since the proposed cable is shielded and no side-flash occurs, this cable is the best option for optimization of descending conductors of arresters in various structures including communication towers.
5. If the proposed cable is used, time and cost of implementing descending conductor of the arrester are reduced.
6. Using the cable head of the semiconductor results in on-time operation of the second channel for discharging lightning current from shield towards the ground.
7. Using polyethylene reduces charge accumulation points and increases lifetime of the cable through homogenization of electric field.
8. Polyethylene insulation performs better than PVC under hard condition, this lifetime of this cable is higher than the bare conductor of arrester system.
9. The multilayer insulation structure reduces partial discharge and increase lifetime of the cable

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