Optimal Voltage Waveform for Better Utilization of Existing AC Cable Systems

Master Thesis

Wanlin Li

TU Delft
Delft University of Technology

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Wanlin Li

Supervisors:

Prof.ir. P.T.M. Vaessen

Dr.ir. M.Ghaffarian Niasar

Thesis Committee Members:

Prof.ir. P.T.M. Vaessen

Dr.ir. M.Ghaffarian Niasar

Dr.Simon Tindemans

DC systems, Energy conversion & Storage

Department of Electrical Sustainable Energy

Faculty of Electrical Engineering, Mathematics and Computer Science

Delft University of Technology

Abstract

The electricity demand is increasing with the development of industry. Nowadays, sustainable resources used for electricity generation are playing a more and more important role in the power system due to serious energy problems. Higher capability of power transmission and distribution thus becomes significantly necessary to keep the stability and reliability of the whole system. Instead of investing in new infrastructure, this thesis concentrates on existing HVAC power cables using XLPE insulation, trying to find out a way to improve their capability of power transmission without reducing their expected lifetime.

For the purpose of utilization improvement, two models based on a realistic 132kV-XLPE power cable are developed first and then analyzed for AC, DC and combined voltages. Inspirations for creating voltage waveforms at an increased level, and thus improved capability of transmission are obtained from different field distributions in AC and DC voltage situations. The process of space charge development and the formation of the corresponding charge induced field is used in this work.

Secondly, two kinds of hybrid voltage waveforms are created: trapezoidal and ones in shapes of sinusoidal and DC waves. Those types of waveforms are able to force the maximum electric field stress in XLPE to move within a small range, resulting in a higher utilization compared to the AC nominal voltage application. The optimal voltage waveform for the 132kV HVAC power cable is determined based on the highest rms value of voltage.

Thirdly, for the suggested voltage waveform, sensitivities are evaluated for changing load levels, XLPE conductivity and the thermal conductivity of soil which depends on weather conditions. It turns out that the load level has highest sensitivity, followed by XLPE conductivity. Once the ampacity of the power cable is determined, the soil property needs little consideration. These important factors must be taken into account when designing the combined voltage waveform.

Finally, cable terminations are modeled to check the feasibility to cope with the new waveform. The main conclusion is that: it is possible to apply the optimal waveform to existing high-voltage cables using SCT field grading technique in their terminals, while those terminations with stress cones may be endangered if higher voltages than the designed value are applied.

Keywords: cable insulation, space charges, electric field distribution, capacity improvement.

Acknowledgement

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Special thanks to my boyfriend S.Z, who entered, colored and will be a part of my life; to all friends I met in TU Delft as well, for bringing unforgettable and precious memories to me.

This work is dedicated to my mother JL.Wang and my father WS.Li. You are the reason I am here to write.

Contents

List of acronyms

XLPE	Cross-linked polyethylene
FEM	Finite element method
HVAC	High voltage alternating current
HVDC	High voltage direct current
SCT	Stress cone tube

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Introduction

1.1. background

Electric power cables are produced to transmit and distribute electric power in grids. It can be traced back to 19^{th} century [1] when the first power cable is created and laid underground for power transmission. Nowadays, large amount of AC power cables are operating underground and the soil layer works as a protection screen to make the cables less sensitive to bad weather and environmental conditions. High-voltage and medium-voltage power cables have an important role in power systems, especially for transmission and distribution of electricity in the densely populated regions. They are preferred for ensuring safety of life and secure operation in intense settlement areas.

With more and more growth of energy demand and the rapid development of the industry, the implementation scale of the renewable energy resources is increasing [2]. A large number of electric vehicles and heat pumps will be introduced to the power system in the future. It is anticipated that with these additions of load, future distribution grids will face a steep increase in power demand, forcing the utility operators to enhance the power delivering capacity of the grid infrastructure. There are two solutions in general: one is to design and construct new transmission lines and power cables; the other is better utilizations of existing distribution and transmission systems. Compared to the option to replace cables with new design and materials or add more in parallel, trying to improve the utilization of existing cables is obviously much more economical for the infrastructures investment and the huge cost savings of electricity delivery.

Due to the simplicity of control method, the vast majority proportion of high-voltage cables are operating at AC with different types of insulation material in the current power system. The oil-impregnated paper, XLPE and EPR are all in use, offering excellent insulation properties. DC cables are used in special applications, such as long- distance HV submarine cables. It is envisioned that in the future, medium voltage DC grid will emerge and more DC high voltage cable lines will be embedded into the existing grid. An increased share of DC will gradually happen in the AC power system due to advantages that DC offers, such as higher power transmission capacity with the same conductor cross section. Before large implantation of DC grid into the existing power grid, it is always of interest to better utilize the existing AC cable system in order to achieve higher power transmission capacity.

For high-voltage and medium-voltage AC power cables, the improved utilization can be realized by different means such as flexible power flow control or utilization of a voltage waveform that enables high power transfer through the existing cable system. Some effort has been made to use DC for its higher rms value than AC with the same magnitude of voltage. However, as proved in [3], applying DC directly on an existing AC cable will compromise the reliability of the cable system since field distributions in cable joint and termination cannot be properly graded, thus endanger the power cable.

In [3], differences between these two types of cables have been given in many aspects. In addition to the configuration and insulation materials, the most essential difference is that they have different electric field distribution through the insulation layer under operation. For AC cables, the maximum field strength is at the surface of the conductor next to the insulation. While if exposed to DC and under load condition, stress inversion happens the field strength is high near to the outer sheath that is in contrast with AC voltage. The stress inversion is caused by the formation of space charges during DC voltage and they stay in the dielectric for a long time. Space charges can alter electric field distribution in the cable insulation and hence reduce the lifetime of the cable [4], which is a drawback of DC power cables.

However, inspired by these two kinds of inverse filed distributions in AC and DC power cables, there should be a hybrid voltage waveform which create a relative flat field distribution inside the cable. In such a case, an increased voltage amplitude can be applied as the stress on the dielectric is less than the maximum value of AC. The transmission capacity can be improved through the new type of waveform at higher voltage level.

Until this time, people did not pay much attention to combined voltage waveforms other than AC and DC Because it was not possible to create such waveform easily. Nowadays with the rapidly increased capabilities of power electronic converters and the drop of prices, such idea is possible. In this study, a new voltage waveform is suggested so that power transfer capacity of the existing high-voltage AC cable can be increased without endangering its reliability and lifetime.

1.2. objectives

There are three main objectives in this project. Firstly, building a proper model with realistic parameters which is able to show the electrical field distribution under AC and DC voltage in the software COSMOL Multiphysics. Simulation results of electric field distribution at AC and DC waveforms are compared. Then, based on the inspiration obtained from those two types of voltages, an optimal voltage waveform that provides a higher delivery capacity of electric power is given. Finally, realistic models of the cable termination, as one of the most important cable accessories are created in order to make sure the feasibility of the new suggested voltage waveform to the whole cable system. After applying adjustments of the shape of waveforms (if necessary), it can be regarded as the evidence that realizing improved utilization of existing cables is possible.

1.3. contribution

Taking realistic design parameters, both of the underground cylinder section and termination with field grading of a 132kV XLPE AC cable are studied. Models are created and simulated using finite element method (FEM) software COMSOL, considering both electric and heat transfer problems. The electric field distribution which limits the capability of power transmission of existing AC cables is analyzed.

In this thesis, an effort is made to obtain a field distribution in XLPE that is as flat as possible. Starting from trapezoidal voltage waveform, an increased voltage level is tried. Information collected from simulation results of trapezoidal voltage waveforms are investigated to deduce an optimal waveform that includes both AC and DC shapes aiming at improving the efficiency of the usage of insulation.

Terminations as one of the most vulnerable parts of cable are carefully studied before applying optimal voltage waveforms. Especially the tangential field component on the interface of different materials must be kept reasonable. After applying adjustments of the shape of waveforms have (if necessary), it can be regarded as the convincing evident that realizing improved capacity of transmitting power of existing cables is possible.

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2

Simulations of Models of Existing High-voltage Cable

Knowing what kind of physics should be included in the model is one of the most important things before building it. From [1], It is already stated that the electric field at 50Hz AC voltage is capacitively distributed which is dependent on ε, the permittivity of the material; while at DC voltage, the field is determined by the specific electric conductivity σ . The electrostatic physics can be used to deal with the capacitive field. As for the resistive field, the electric conductivity is necessary to be taken into account, so that electric current physics should be used. Here, surface charges and space charges play an important role, resulting in a time-dependent field distribution.

Apart from the electric issue, the heat problem does exist in no matter AC or DC power cables. The heat will be generated in the core when the load current flow through the conductor due to the resistive and dielectric losses, causing the heat transfer to the insulation and soil. Thus, the temperature of conductor, insulation and the soil near to the cable will increase governed by the heat equation. There will be a temperature gradient in operating power cables in steady state, meaning that also the heat transfer physics has to be carefully considered when building a power cable model.

2.1. 50Hz AC Cable Model and Simulation

2.1.1. AC Power Cable Model

In most cases, a cable can be simulated using 2D dimension. For a XLPE single core cable, a simplified 2D model, using the cross-section to be a representative is built in COMSOL software. Since it is found that the value of ε has almost no change with the temperature, only the electrostatic physics is used to solve the electrical problem.

The cross-section as a representation is shown in Figure1. It is assumed that there is no variation along the length of the cable

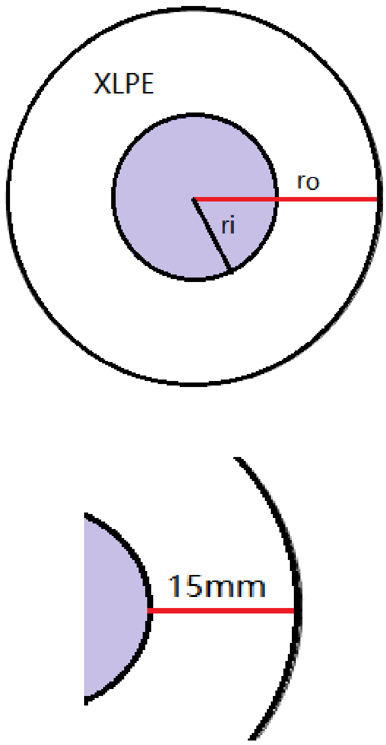


Figure2.1. Simple schematic representation of a 132kV XLPE AC cable

In this realistic 132kV high-voltage AC power cable produced by Nexans company, the inner radius (r_i) of the copper conductor being 11.6 mm, the outer radius (r_o) being 26.6 mm, providing a XLPE insulation thickness of 15 mm. The conductor is set to have electrical potential while the sheath of insulation is connected to ground whose potential is zero. One cutline from the conductor to the sheath is needed to demonstrate the full electric filed distribution of the power cable because of its rotational-symmetric cylinder shape. Attention will be paid to the field strength along the red line in Figure2.1.

The actual amplitude of voltage for a single phase should be:

$$\mathrm{U} = 132 * \frac{\sqrt{2}}{\sqrt{3}} = 107.8\ \mathrm{kV} \tag{2.1}$$

Table2.1. AC power cable data

Definition	Value	
	conductor	XLPE
Radius (mm)	11.6	26.6
Relative permittivity	1	2.3
Voltage amplitude (kV)	107.8	

Based on Maxwell equations of electrostatic fields

$$\vec{E} = -\nabla V \tag{2.2}$$

$$\nabla \cdot (\varepsilon_0\, \varepsilon_r \vec{E}) = \rho \tag{2.3}$$

where ε_0 is the vacuum permittivity, ε_r is the relative permittivity of the insulation and ρ is the space charge density.

With the boundary condition shown in (2.4), meaning that the normal component of electric displacement vector equals zero at the cable sheath and the voltage is applied to the inner conductor.

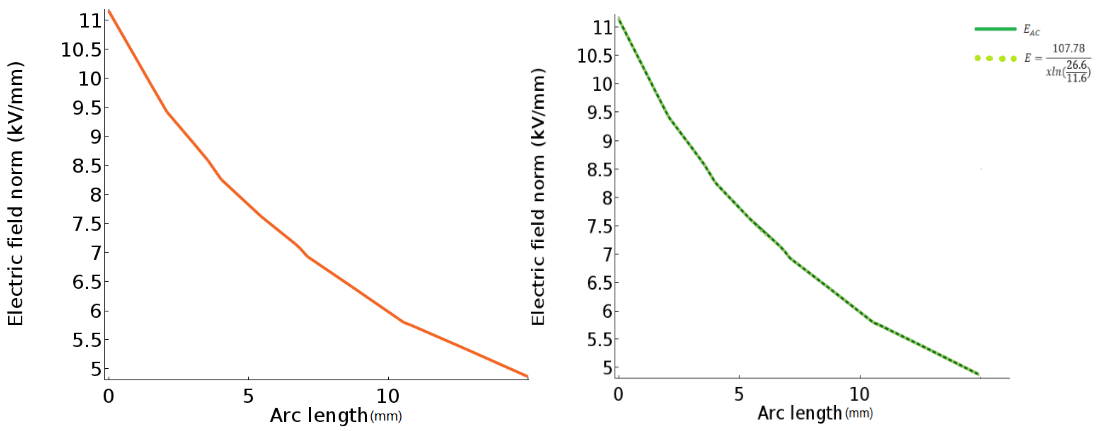
$$\mathrm{V} = 0, \mathrm{V} = V_0 \tag{2.4}$$

The mathematic function along the cutline can be deduced and given in many literatures such as [1].

$$E = \frac{U}{r ln(\frac{r_o}{r_i})} \tag{2.5}$$

2.1.2. Nominal AC Voltage Simulation

Applying 107.8kV as the amplitude of the 50Hz sinusoidal voltage waveform to the conductor and ground the cable at outer sheath, the electric field distribution is shown in Figure2.2a. To verify the model, the curve satisfies the function given in the equation (2.5) is plotted in Figure2.2b together with the simulation result. It is clear that two cures coincide with each other and the maximum field strength 11.2kV/mm appears near to the conductor. This is taken as the upper limit to avoid endangering of XLPE and ensure the expected life time of the cable.



a. b.

Figure2.2. a) field along XLPE arc b) *E* function in cable insulation with *E* in AC model.

Table2.2. Field distribution in AC cable model

	Location (mm)	Value (kV/mm)
E_{max}	11.6	11.2
E_{min}	26.6	4.82

2.2. DC Model and Simulation

2.2.1. Modelling of DC power Cable

When DC voltage is applied, the electric field is resistively distributed which is mainly determined by conductivity. Different from the AC situation, the Electric Current Physics has to be used. And since the conductivity is highly dependent on the temperature, the Heat Transfer model in COMSOL must be introduced in DC applications.

A heat flux exists in the insulation layer because of the heat generation of the cable conductor. Since XLPE has very small amount of dielectric loss, it is ignored in this study. In the heat conduction equation, a source term that depends on the conductivity and the electric field is included. Therefore, the temperature influences the electric field distribution through the conductivity, while in return, the electric field influences the thermal gradient through resistive heating [2].

Maxwell equations for the insulating material that is weakly conductive such as XLPE, and the heat conduction equation of solid are supposed to be fully coupled and solved in the HVDC model. In this section, an electrical-thermal combined model is given based on theoretical calculations by electrical and thermal properties of that power cable and its surrounding environment.

2.2.1.1. Electric Problem

The accumulation of charges, as an intrinsic property of the DC cables, influences the electric field in the cable insulation to a large extent. Insulating materials allow a weak electrical conduction and this small charge flow is usually not uniform because of a local non-homogeneity of the material. [3]

Unlike the AC situation where the flow of charges inverts its direction too quickly to allow a significant growth of space charge, they develop at the insulation and material interfaces inhomogeneities at DC voltage. This means that the weak charge flow and the resulting field cannot be neglected when building a DC power cable model. Therefore, the Electrostatic Physics which is used in the AC model is not applicable anymore, obviously. The Electric Current Physics that includes the current flow is supposed to be selected when solving electric problems under DC stressing condition.

According to the current density continuity equation (2.3), an inequality occurs when there is difference between charges entering and leaving a region. In that region, charges are accumulated.

$$\nabla \cdot \vec{j} + \frac{\partial \rho}{\partial t} = 0 \tag{2.6}$$

In (2.6), j is the current density and t the time. So that the field is time-dependent.

The charge-induced field E_ρ is associated the charge distribution:

$$\nabla \cdot \left(\varepsilon_0\, \varepsilon_r\, \overrightarrow{E_\rho}\right) = \rho \tag{2.7}$$

Therefore, the electric field within the insulation in the presence of space charge is the sum of Laplacian field and the charge induced field.

$$\vec{E} = \overrightarrow{E_0} + \overrightarrow{E_\rho} \tag{2.8}$$

2.2.1.2. Heat Transfer Problem

The heat problem has to be carefully analyzed in the DC cable model. If the insulation material is heated to above a certain limit, some physical properties will change. Usually the electric breakdown strength decreases with the increasing temperature. When the breakdown strength drops below the applied electric field, the power cable is in danger of failures which is called the thermal breakdown. Actually, there are two heat sources in a power cable: the load current flowing in the core, generating heat through resistive losses, and the dielectric losses that include resistive and polarization losses in XLPE insulation. As $\tan\Delta$ of XLPE is very small, the dielectric losses take a relatively big part due to the quickly and repeatedly change of voltage directions. While at DC voltage, it can be ignored for simplification. In this work, only the principal load heat source is considered.

A lot of research has been done to test the electric conductivity of XLPE for example [4]. It varies with temperature and electric field strength. As the field stress in not so high in this study, the effect of electric field on XLPE conductivity is neglected.

Main source of heat of the power cable is the electrical power loss generated by current flowing through its conductor explained by Joule's Law. And this electric energy is converted into heat energy that spreads through XLPE to the soil, in this case. Differential heat conduction equation (2.9) given in [5] governs in heat transfer problem.

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C}(k\nabla^2 T + h) \qquad (2.9)$$

Where in the following model:

T : temperature (K)

ρ : density of XLPE (kg/m³),

C : thermal capacity of the heat transmission medium (J/kg·K),

k : thermal conductivity of the material surrounding heat source (W/Km),

h : volumetric heat source density (W/m³).

Total amount of electric power P dissipated inside a cube with sides dx, dy, dz is expressed as (2.10)

$$\mathrm{P} = \vec{J} \cdot \vec{E}\, dxdydz \tag{2.10}$$

With

$$\vec{J} = \sigma \vec{E} \tag{2.11}$$

Therefore, the heat source density term h is

$$h = \frac{J^2}{\sigma}\ \mathrm{W}/m^3 \tag{2.12}$$

Here σ is the electric conductivity of copper, as the conductor of the power cable. It is temperature dependent following equation (2.13), see [6]

$$\sigma = \frac{1}{\rho_0 \cdot (1+\alpha(T-T_0))} \tag{2.13}$$

In the above equation ρ_0 is the specific resistivity (Ω·m) at reference temperature and 293.15K is taken in the model; α is the coefficient that describes the variation of resistivity with temperature. For copper, usually α =0.004 is applied

Different materials inside the power cable have different thermal properties and they interact with the outside environment under working conditions. For underground XLPE power cables, part of the generated heat is absorbed by the insulation during transients, while the rest is dissipated to the surrounding soil. The rate of heating inside the power cable must be controlled not to exceed the dissipation rate to the soil surrounded. Otherwise the cable will be threatened by the risk of thermal breakdown attributed to the increased temperature [7]. The ampacity is thus determined at a certain level which is safe from the thermal behavior aspect. 1kA is taken as the fixed nominal current load in the model for simulations in this study.

2.2.2. DC Cable Model

In Figure2.3, an example of the use of electric-thermal model is presented using parameters in Table2.3

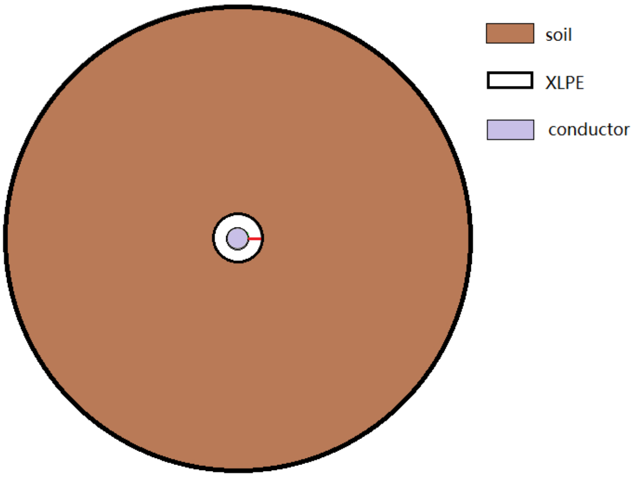


Figure2.3. An underground cable model for DC simulation.

Table2.3 DC Power cable data

Definition	Value		
	conductor	XLPE	soil
Electric conductivity (1/Ω·m)	$\frac{5.96 \times 10^7}{1 + 0.004 \times (T - 293.15)}$	$exp^{-9.1e3/T}$	
Relative permittivity	1	2.3	
Thermal conductivity (W/Km)	400	0.32	1
Density (kg/m³)	8960	924	1300
Heat capacity (J/kg·K)	385	2200	870

Considering the heat transfer between the cable and the surrounding soil, the same simplified configuration as the AC model is encapsulate in a soil cylinder. In theory, the heat generated inside the cable transfers through the soil to very far away. To keep the geometry as simple as possible, a fixed temperature 293.15K at the outer boundary of soil is introduced as an approximation.

In Table2.4, three kinds of soil thickness are simulated to decide the amount of soil that is significantly influenced by the cable. The electric field distribution and temperature gradient are taken into account when the heat transfer arrives at the steady state.

Table2.4. Effect of thickness of soil layer

Soil Radius(mm)	11.6mm		26.6mm		Transient time(s)
	T(K)	E (kV/mm)	T(K)	E (kV/mm)	
200	330.5	3.86	309.4	11.03	42000
260	332.5	3.92	311.4	10.92	50000
320	333.4	3.93	312	10.80	60000

The error between the model and the realistic situation is decreased with the increase of the soil thickness. 260mm is chosen for its acceptable deviations and the moderate transient time duration. The configuration of the whole model is shown in Table2.5.

Table2.5 Configuration of HVDC cable model

	Conductor	XLPE	Soil
Radius(mm)	11.6	26.6	260

Applying DC voltage having the same voltage amplitude as the realistic AC case in 2.1 to this model, the difference between these two kinds of situations can be clearly shown and analyzed.

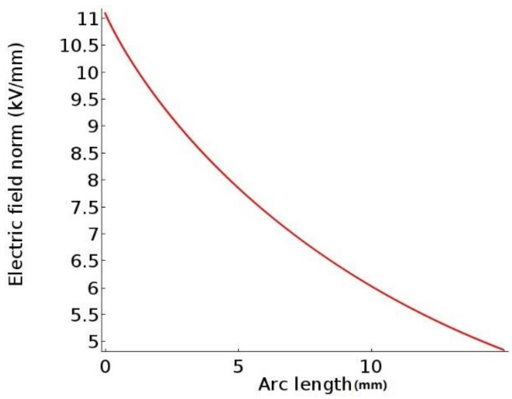
Table2.6 Settings of HVDC cable model

Voltage applied (kV)	107.8
Current rating (kA)	1
Heat source density (W/m³)	$1.05e5(1 + 0.004(T - 293.15))$
Initial & soil boundary temperature (K)	293.15
Loading time (s)	120
Simulation time (s)	50000

2.2.3. Simulation Results of DC Voltage

2.2.3.1 Electric field distribution

The time-dependent field distribution is solved relying on time dependent solver in COMSOL. Four different stages are distinguished to describe the different field distributions that occur under DC voltage. The simulation time is 50000s until the stabilized thermal gradient is formed.



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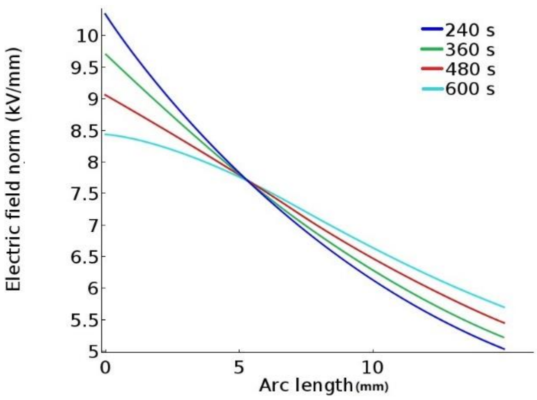

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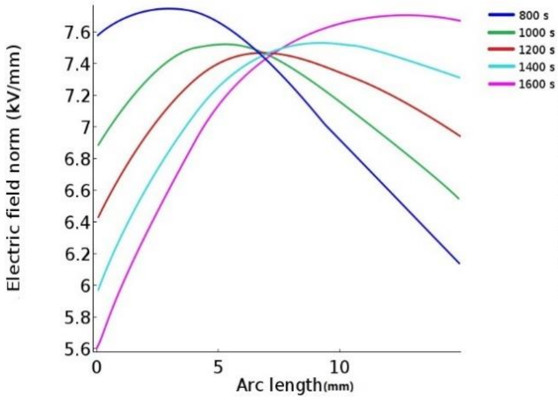

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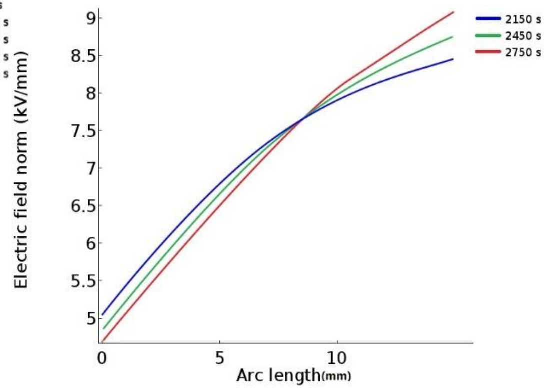


d

Figure2.4. a.) No load situation, cold cable. The field distribution situates along the same curve as is known from the AC cable without the temperature gradient. b.) The cable is loaded. E_{max} decreases with time and stays near to the conductor for a while. The field strength inside the insulation that are away from the conductor are increasing. c.) E_{max} moves along the cutline from inner to outer part. The distribution curves during this period have an overlapping small area, or an intersection point locates around the middle point of XLPE. d.) The field distribution becomes stable as the temperature is stabilized. The so-called stress inversion takes place as it is totally in contrast with the AC voltage situation.

With the same configuration and the voltage level as the 50Hz AC cable model, it is easy to compare and analyze the results of these two different types of applied high voltage.

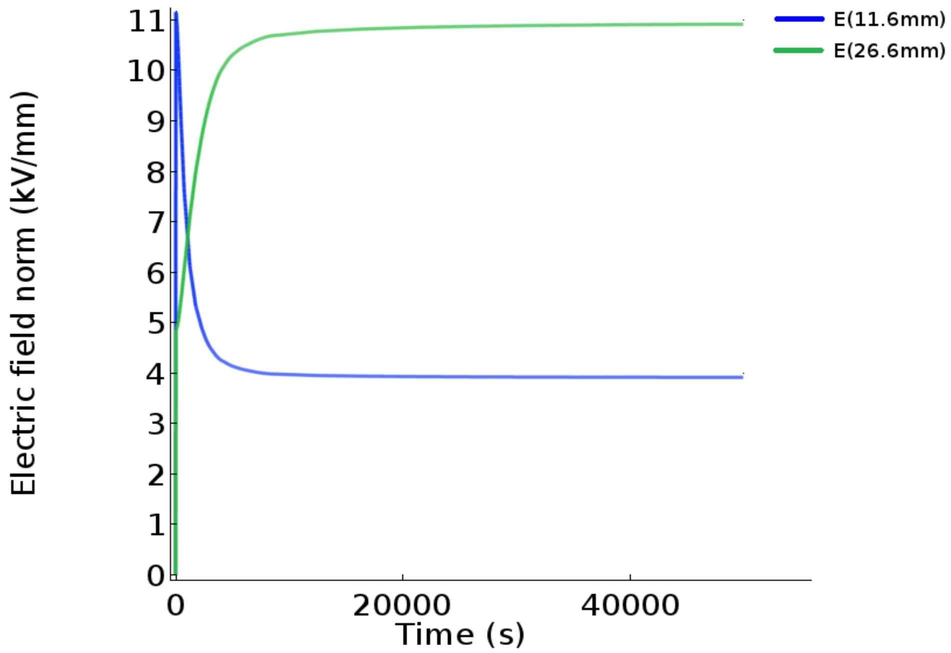


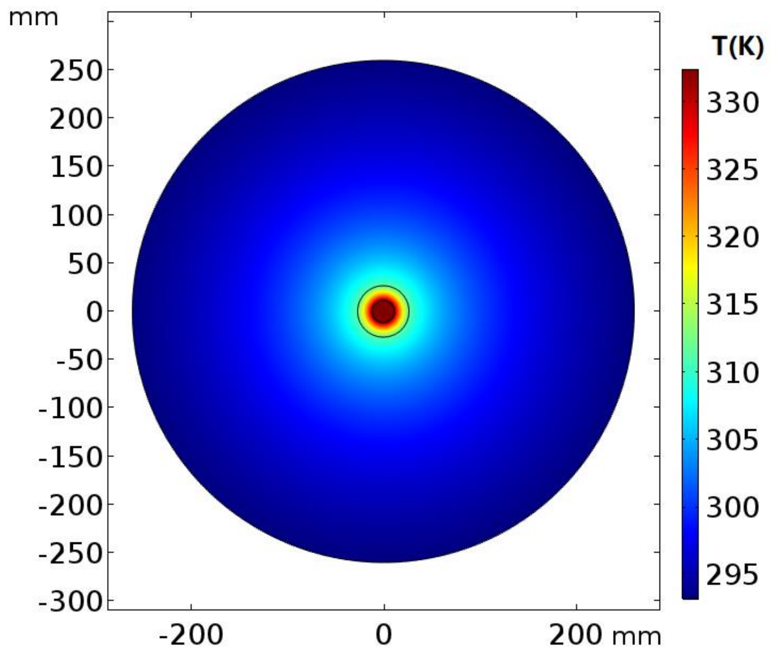
Figure2.5. Field of inner and outer points in XLPE under DC voltage

Table2.7 Electric field stabilized values at DC voltage.

	Location (mm)	Value (kV/mm)
E_{max}	26.6	10.92
E_{min}	11.6	3.92

2.2.3.2 Heat distribution

The heat caused by ohmic losses spreads to XLPE and the soil around the cable, forming a thermal gradient shown in Figure2.6



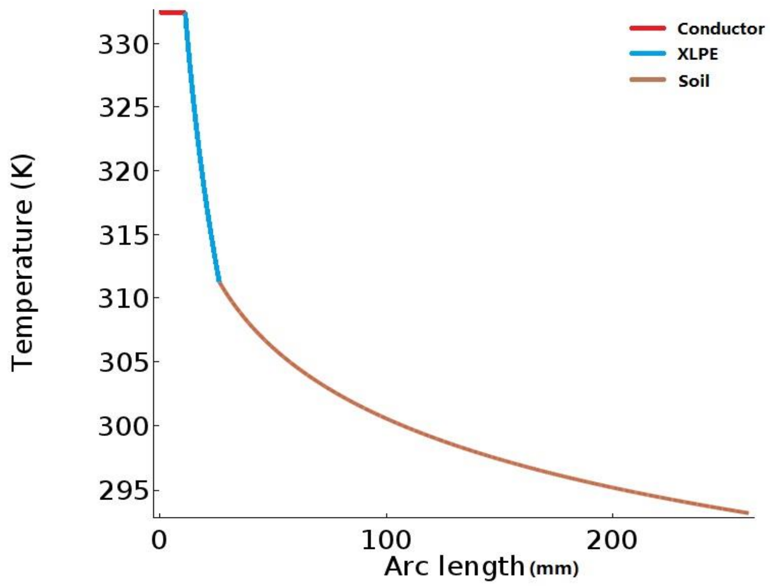


Figure2.6 Temperature distribution at steady state

As mediums that absorb and transmit heat from the cable core, XLPE and the surrounding soil have different thermal properties which lead to different temperature distribution. Attention is given to the thermal gradient of the insulation layer as it must be controlled to avoid endangering the reliability of cable. For the inner conductor, the designed temperature is 90°C while it is usually operated under that value [8]. In this model, the stable running temperature of the cable core is around 60°C ,see Figure2.7, which is safe and in the normal range for the high-voltage cable.

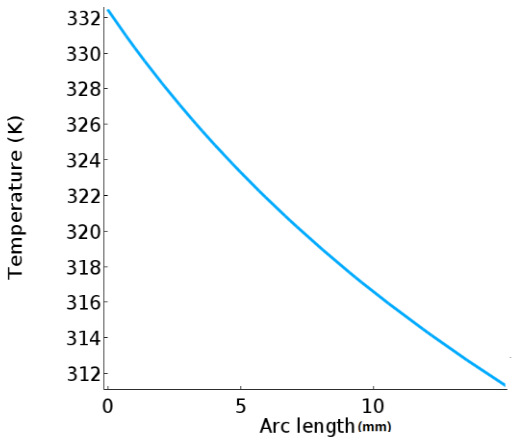


Figure2.7 Thermal gradient of XLPE

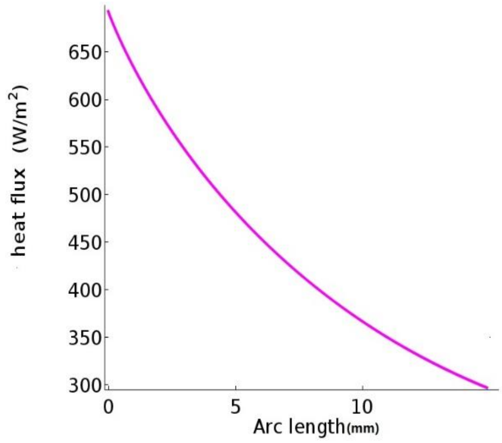


Figure2.8 Heat flux of XLPE

The heat flux generates a flow of energy per unit that spreads outside and it decreases with the distance away from the conductor, as the heat source since some thermal energy has been absorbed by XLPE.

Table2.8 Thermal data at steady state

	Temperature(K)	Heat flux density(W/m^2)
conductor	332.4(60°C)	703
XLPE	311.4(40°C)	306

The model that contains the soil cylinder is used for following research as the heat transfer problem is included. Moreover, it is seen that the field distribution becomes almost stable at around 20000s. Since the heat transfer is not affected by electric problems, the simulation time is set to be 25000s for those different kind of voltage waveforms.

2.2.4. Comparation and Analysis of AC and DC Cable Simulations

The stress-inversion phenomenon at DC voltage is caused by the thermal gradient as the temperature is an important influencing factor of conductivity σ of XLPE. In fact, the difference between AC and DC field distribution is attributed to space charges inside XLPE according to following equations:

$$\rho = A(1 - e^{-\frac{t}{\tau}}) \tag{2.7}$$

$$\tau = \frac{\varepsilon}{\sigma} \tag{2.8}$$

The ratio ε/σ varies with the temperature, thus generating space charges in the dielectric. It explains the reason why there exist a difference between AC and DC field curves. As the result of the development and accumulation of space charges, E_{max} moves from inner to outer position within XLPE. The entire charge-induced field is completely established when the thermal gradient reaches to its steady state. And known from [1], it is equal to the difference between those two curves of AC and DC.

In reality, AC cables have thermal problems as well due to the power dissipation and it is not affected by electrical issues. Taking only ohmic losses into account, the temperature gradient will be the same with DC cable as long as the given current is the same. Nevertheless, it’s reasonable to ignore the temperature effects when studying electrical problems. On the one hand, the permittivity of XLPE is almost constant with the change of temperature. On the other hand, from the space charges aspect, the time interval in one voltage direction is so short at 50 Hz. Those quite little quantity of space charges disappear immediately when the polarity reversal occurs, leaving no influence on electric field distribution.

This can be verified by applying a much lower frequency than 50Hz AC voltage waveform to the model. For example, using 1000s as the period. With the increased length of period, the amount of internal charges is enough to redirect the electric field. Indicated in Figure2.6, the electric field at outer sheath gradually increases and stabilizes at the same value as the DC voltage.

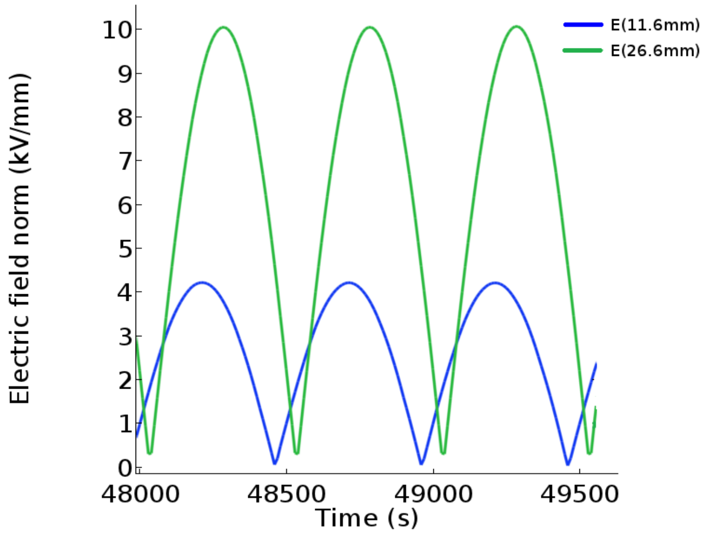


Figure2.9. Field of inner and outer points in XLPE under very low frequency AC voltage

Consequently, the electric field distribution within XLPE under DC voltage keeps the same as AC during no load; when the cable is loaded, the field is determined by electrical conductivity. Space charges play an important role in the resistive field which is time-dependent, resulting in the stress inversion. Therefore, the maximum voltage level of AC cables is limited to the field strength near to the conductor, while DC cables are designed concerning the stress at outer sheath under the operating temperature.

2.3 Insights from AC and DC voltage simulations

The voltage level of the existing power cables is restricted to the maximum field strength in the insulation. Based on the analysis of field distribution within

XLPE under AC and DC voltage, some insights for finding new voltage waveforms that provide increased utilization of power cables with higher voltage grade are obtained.

During the transition process from capacitive to resistive field, E_{max} that is near to the cable core will decrease with the formation of the time-dependent charge-induced field. A higher voltage level than the nominal one probably can be realized and kept for a while if the voltage is increased slowly. Once E_{max} moves away from the conductor and reaches the maximum allowable value, 11.2kV/mm at outer sheath, the polarity reversal must be operated. A new kind of periodic voltage waveform that contains both AC and DC shapes, giving not only the improved voltage level, but also a relatively flat field distribution can be created. Hence, the higher power transmission capability is possibly obtained through the better utilization of XLPE. Two types of combined waveforms are discussed in the next section.

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3

Trapezoidal Voltage Waveform at Nominal Voltage Level

By observing the development of resistive field at DC voltage, the movement of E_{max} in XLPE is enlightening for realizing relatively flat distribution. Voltage waveforms having trapezoidal shapes can be seen as DC voltage with polarity reversals plus transition zones, t_{DC} and t_{rise}, separately. In this chapter, five symmetrical trapezoidal voltage waveforms with different t_{rise} and t_{DC} at the nominal voltage level,107.8kV are applied to the DC cable model. Simulation results are studied for the further research of improved voltage grade.

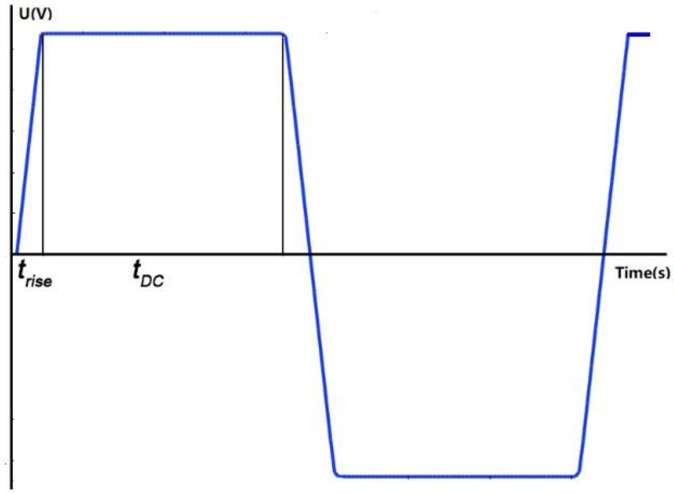
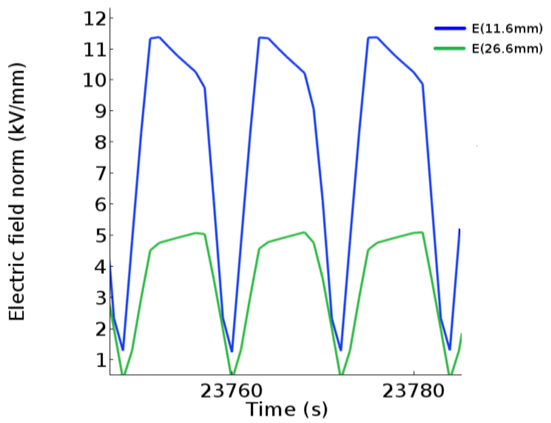


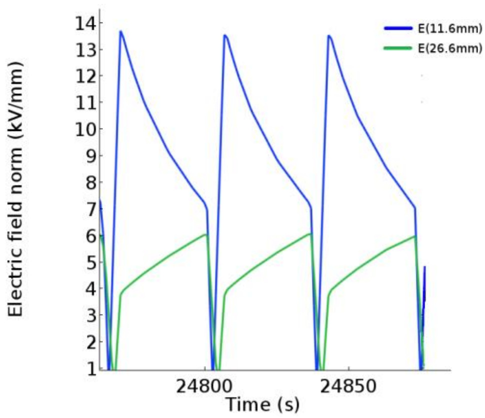
Figure3.1 Periodical trapezoidal voltage waveform

3.1 Three Cases Using the Same t_{rise}

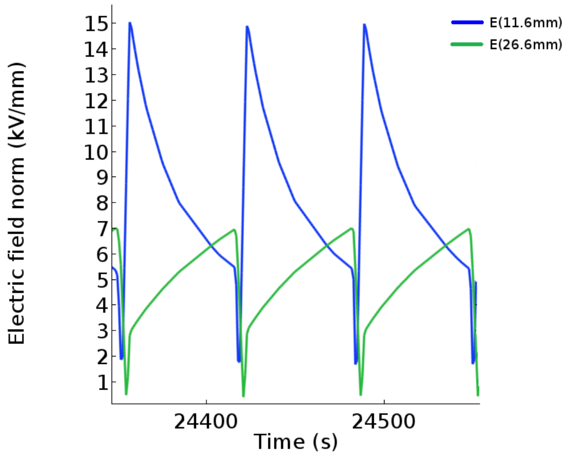
Using 3s as the rise time with different length of DC voltage section, trapezoidal voltage waveforms are simulated. Attention is given to the change of electric field of two points at their steady states: 11.6mm near to the conductor and 26.6mm at the cable sheath.



a.Case1 $t_{DC} = 6s$



b. Case2 $t_{DC} = 30s$



c. Case3 $t_{DC} = 60s$

Figure3.2. Field of inner and outer XLPE under trapezoidal waveform when $t_{rise} = 3s$

Table3.1. E_{max} of two points in Case 1,2 and 3

	Case 1.	Case 2	Case 3
t_{rise}(s)	3	3	3
t_{DC} (s)	6	30	60
11.6mm (kV/mm)	11.35	13.64	14.92
26.6mm (kV/mm)	5.15	6.23	6.88

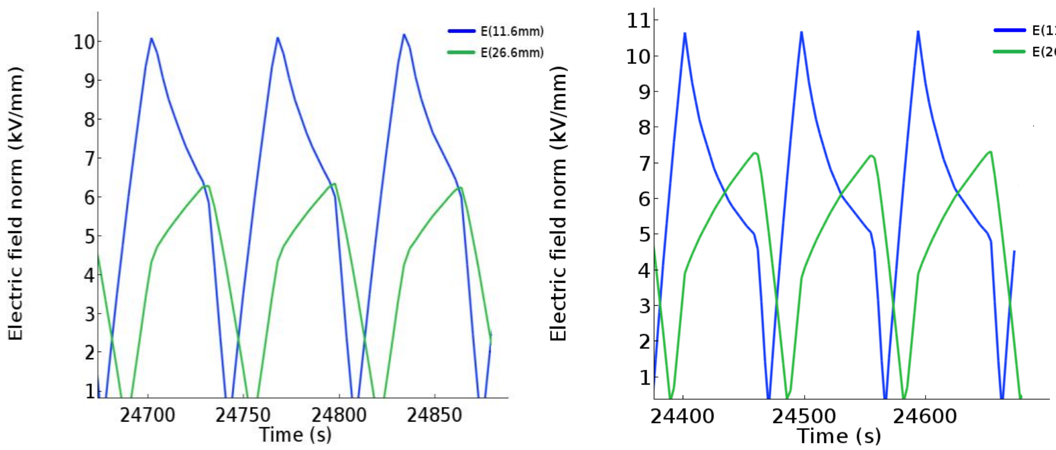
Using 3s to increase the voltage from 0 to 107.8kV. In Case1, these two points keep their maximum values almost the same as AC condition when the voltage stops increasing. The field strength does not exceed the upper limit 11.2kV/mm during the whole process of simulation, meaning the transition rise time for polarity reversal is enough to neutralize the influence that space charges left. The maximum value near to the conductor in Case2 finally stabilizes at 14.10kV/mm, which is definitely not allowed. A phenomenon that is very similar to the second case can be observed in Case3. E_{max} of point 11.6mm gets to

15.42kV/mm that is even higher than 14.10kV/mm in Case2.

Since a longer t_{DC} is used in Case3 than that in Case 2, space charges are accumulated to a larger amount and thus generate a larger induced field. Therefore, the ratio of t_{DC} to t_{rise} is extremely important to keep the cable safe at trapezoidal voltage waveforms. And the total duration in one direction of each cycle, the length of a half period, in other words, determines whether the field strength on the cable sheath increases under the applied voltage waveform.

3.2. Two Cases Using Different Combinations of t_{rise} and t_{DC}

In Case3. The period is long enough to show the effect of space charges. It can be predicted if a longer t_{rise} within a same half period as Case3 is applied, E_{max} near to the cable core will decrease. The t_{DC} becomes to 30s in Case4 when 18s is used as the rise time to keep the period same as Case3. As for Case 5, the same length of DC section in the voltage waveform as Case3, followed by 18s rise time is applied to the model.



a. Case4 $t_{DC} = 30s$ b. Case5 $t_{DC} = 60s$

Figure3.3 Field of inner and outer XLPE under trapezoidal waveform when $t_{rise} = 15s$

Table3.2. E_{max} of two points in Case 4 and 5

	Case 4.	Case 5
t_{rise}(s)	18	18
t_{DC}(s)	30	60
11.6mm (kV/mm)	10.43	10.65
26.6mm (kV/mm)	6.35	7.28

Seen in Figure 3.3 and Table3.2, E_{max} at 11.6mm stabilizes at a lower value than 11.2kV/m in Case 4 and 5 as the expectation made before. It Indicates that increasing the voltage slowly provides the possibility to apply a higher voltage magnitude and realize the higher power transmission capability of cables.

Based on these five cases above, it can be assumed that if t_{rise} is continuously extended from 18s, E_{max} at cable core will stabilize at a lower level, meaning that more space is left to improve the voltage magnitude.

3.3. Discussions about t_{rise} & t_{DC} in Half a Cycle

3.3.1 The Rise Time

Since a longer t_{DC} is used from Case1 to 3, space charges are accumulated to a larger amount and thus generate a larger induced field. In these cases, the insulation experiences the sum of the space charge field and the one induced by the DC voltage having inverted direction. Thus leading to a maximum field near the inner conductor of the cable. These results correspond with [1], illustrating that for HVDC cables, the polarity reversal should always be seriously tested before making it into use. Fast transitions are usually not allowed due to the superposition of field strength. Therefore, the ratio of t_{DC} to t_{rise} is extremely important to keep the cable safe at trapezoidal voltage waveforms.

Observing Table3.1, with different length of period, E_{max} near to the conductor in Case4 and 5 stables at the same value with different DC time durations, unlike situations in the first three cases. It implies the existence of a critical rise time at a certain voltage level. When a t_{rise} which is longer than the critical value used in a trapezoidal waveform, E_{max} at point 11.6mm never exceeds 11.2kV/mm even when a longer t_{DC} is applied.

3.3.2 The DC Section in Trapezoidal Waveform

Besides the different behaviors of field stress of inner XLPE, attention should be paid to things happened at 26.6mm. There is a difference in E_{max} at outer sheath between Case 4 and Case5, caused by different t_{DC}. The Case5 has the larger value that indicates the impact of DC section in the trapezoidal voltage waveform. From Figure3.1, it is noticed that the slope of both field stress trajectories decreases during t_{DC}. And it can be estimated the electric field strength will stabilize at the end values which are equal to those in the DC model if t_{DC} is long enough.

The similar story can be applied to other points at different locations in the XLPE showing that it takes time for the capacitive field to transit to the resistive one. Since the time constant is exponentially inversely proportional to the temperature, points at different distance away from the conductor have different time constants. The lower temperature at the sheath of XLPE results in a larger time constant than that at conductor vicinity.

And the total duration in one direction of each cycle, the length of a half period, in other words, determines whether the field strength on the cable sheath increases under the applied voltage waveform.

3.4. Summary

The induced field as the result of space charges starts to redirect the field distribution once the total amount of space charges reaches to a critical amount. And since the flow of charge maintains the same direction which allows a build-up of charge, the total duration in one direction of each cycle, the length of a half period, in other words, determines whether the field distribution is significantly affected under the applied trapezoidal voltage waveform

In conclusion, for the purpose of applying a higher voltage level to the existing AC power cable through the trapezoidal voltage waveform, the induced field formed by space charges has to leave an impact on the field distribution within the insulation. For t_{rise}, the lower limit requires t_{rise} to be larger than the critical value for the possibility of improving the voltage level. The rising process cannot be too slow in the meanwhile. Except for some loss of flexibility to re-arrange the distribution, a relatively big part of power will be missed. For the length of cycle, it has to exceed a specific value for enough amount of space charges. Otherwise it has little difference with the 50Hz AC case and thus no probability to optimize the field distribution.

Reference

[1] Kreuger, F. H. *Industrial High Voltage*; Delft University Press: Delft, 1995; Vol. [vol. Iii], Industrial High DC Voltage : 1. Fields, 2. Breakdowns 3. Tests

4

Trapezoidal Voltage Waveforms at Increased Level

This study concentrates on finding out the optimal voltage waveform which gives the highest utilization of cable insulation. For this purpose, based on gained insight from simulation results in last chapter, waveforms with increased voltage level are tried in this section.

For the safety of the realistic AC power cable used in this study, 11.2kV/mm is taken as the maximum *E* that is allowed after thermal stabilization. Since this is the maximum stress designed for a specific expected lifetime of that cable. Looking back to the DC voltage situation, E_{max} gradually moves away from the conductor within the XLPE and finally appears at the sheath, the stress inversion happens then. When a waveform with trapezoidal shape is applied to the power cable, this movement of E_{max} repeats periodically. Therefore, making use of the E_{max} movement at a high level and forcing it to shift between different locations within the insulation layer offers probabilities to find the optimal voltage waveform that gives the highest utilization of the cable.

4.1 A Group of Results

After the resistive electric field is completely established under 107.8kV DC voltage, E_{max} is 10.92kV/mm which is lower than 11.2kV/mm. It is not difficult to imagine if a higher DC voltage is applied, the end value at sheath will be larger than 10.92kV/mm. Higher voltage levels are simulated starting from symmetrical trapezoidal shapes of voltage waveform.

As stated before, the effect of induced-field created by space charges has to be used at an increased voltage level, which means the rise time should be larger than the critical value mentioned above. Considering about the DC voltage duration, it is already concluded that it determines what value the electric filed strength the outer sheath can reach. In order to obtain the highest power transmission capability, the ability of every part in insulation layer to withstand the field strength is supposed to be utilized as much as possible. Therefore, the DC voltage in trapezoidal waveforms should stop once the tolerant value is reached at point 26.6mm in the model.

The power gain provided by trapezoidal waveforms (constant load level) has to be compared to the rms value of nominal AC voltage. Since 132kV is the line voltage of power cable, the rms value is

$$\frac{132}{\sqrt{3}} = 76.2\text{kV} \tag{4.1}$$

If the electrical field within XLPE can be kept uniform at 11.2kV/mm, this would give a DC voltage as high as

$$11.2 \times 15 = 168\text{kV} \tag{4.2}$$

Theoretically, a gain of 2.2, as shown in (4.3) can be achieved.

$$\frac{168}{76.2} = 2.2 \tag{4.3}$$

Higher voltage grades are tried as followed with an increasing t_{rise} and its corresponding t_{DC}. The rise time keeps E_{max} under the upper limit while the DC section is decided by controlling *E* at the outer part of XLPE arrives at 11.2kV/mm. Following these requirements, a group of trapezoidal voltage waveforms are found and listed in Table4.1.

Table4.1 Results of trapezoidal voltage waveform at increased voltage level

Cases	Time (s)		Voltage (kV)		Power Gain
	t_{rise}	t_{DC}	U_{max}	U_{rms}	
1	22.5	196	120	112.2	1.47
2	25	160	125	114.6	1.50
3	29.5	136	130.5	116.6	1.53
4	31	120	134.5	118.2	1.55
5	33.5	106	136.0	117.3	1.53
6	37	96	137.5	115.8	1.51
7	40	88	139.0	114.8	1.50

It is more important to focus on the rms value of the waveform than the maximum voltage value because the capability of transmitting is actually determined by the former one. Since the voltage waveforms that are applied have trapezoidal wave shapes, they can be translated to piecewise functions for a clear description of U_{rms}

In a half period,

$$U = \begin{cases} kt & t < t_{rise} \\ U_{max} & t_{rise} \le t \le t_{DC} \\ -k(t - 2t_{rise} - t_{DC}) & t_{rise} + t_{DC} < t < 2t_{rise} + t_{DC} \end{cases} \tag{4.4}$$

So, the rms value can be calculated through equation (4.2)

$$U_{rms} = \sqrt{\frac{\int_0^{t_{rise}} (kt)^2 + \int_{t_{rise}}^{t_{rise}+t_{DC}} U_{max}{}^2 + \int_{t_{rise}+t_{DC}}^{2t_{rise}+t_{DC}} \left(-k(t - 2t_{rise} - t_{DC})\right)^2}{2t_{rise} + t_{DC}}}$$

$$= \sqrt{\frac{2\int_0^{t_{rise}}(kt)^2 + \int_{t_{rise}}^{t_{rise}+t_{DC}} U_{max}{}^2}{2t_{rise}+t_{DC}}}$$

$$= U_{max}\ \sqrt{\frac{2/3t_{rise}+t_{DC}}{2t_{rise}+t_{DC}}} \tag{4.5}$$

Based on data in Table 1, analysis can be made from two aspects. Issues about the 'time' which contains rise time and DC time; and the other aspect relates the 'voltage', both U_{max} and U_{rms} are included.

4.2 Discussion

During the process of simulations to estimate and then determine t_{rise} , t_{DC} and U_{max} values, conclusions deducted in 3.3 are used. At first, when increasing U_{max}, t_{rise} should be also increased at the same time and t_{DC} has to be shortened. Secondly, due to the fact that E_{max} stays on the boundary of core at point 11.6mm for a while and then moves away, there is a possibility that it has already left the conductor during the rise time. It becomes necessary to observe the field distribution in the whole part of XLPE.

4.2.1. Effects of t_{rise}

Based on 8 waveforms found above, fitting curves for t_{rise} and t_{DC} are plotted in graphics shown in Figure4.1 and Figure4.2 separately.

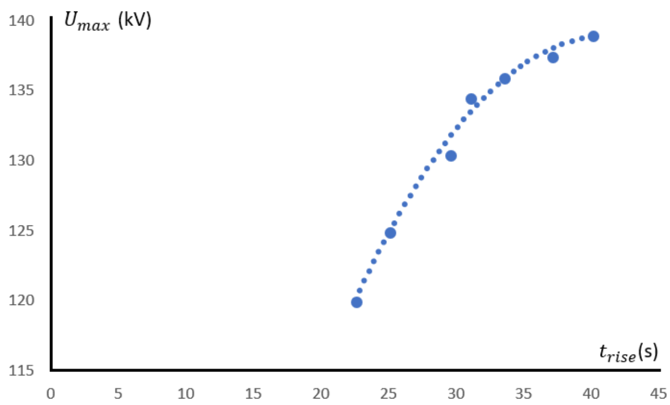


Figure4.1. Fitting curve of t_{rise} and U_{max}

Figure4.1 shows that the rate of change of t_{rise} reduces from Case 1 to 8, meaning that U_{max} becomes less influential to *E* near to the cable core. This can be answered by the movement tendency of the maximum value of *E*. Since during the process of voltage rise, E_{max} starts to move away and not at the conductor boundary anymore, U_{max} therefore has a greater impact on the location where the maximum electric field strength exactly happens.

Known from the DC voltage case that the electric field curve of the point which locates in the middle of XLPE layer, around 7.7mm away from the core is quite flat and hardly changes with time. The closer to the middle area the point locates, the smaller variation range of stress it has and thus slower rate of change. The decreasing growth rate of t_{rise} to U_{max} corresponds to the decreasing rate of change of E_{max} at further distance further away from the conductor

4.2.2. Effects of t_{DC}

Since t_{DC} of all 8 cases are determined by letting the electric field strength of point 26.6mm at outer sheath increase to 11.2kV/mm, different initial *E* from the start of DC voltage in waveforms needs different time to reach that value.

Seen from 5 cases above, the derivative of the electric field strength curve at outer sheath decreases with time until it gets to the stabilization. As shown in Figure4.2, with the increasing value of initial *E*, t_{DC} that is needed for the development of electric field at point 26.6mm has less differences.

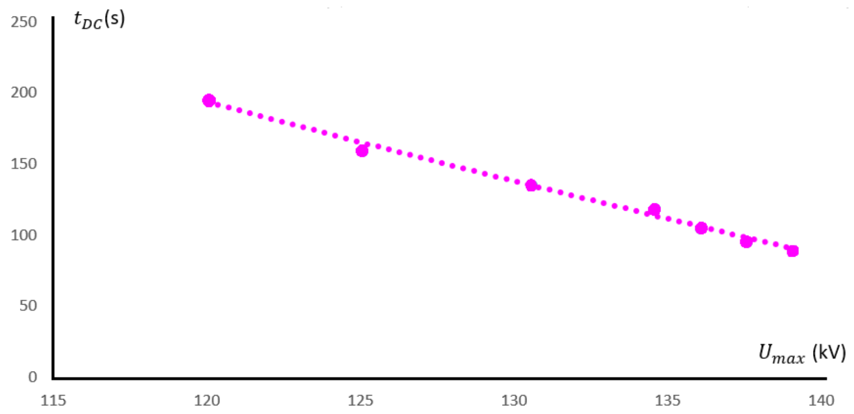


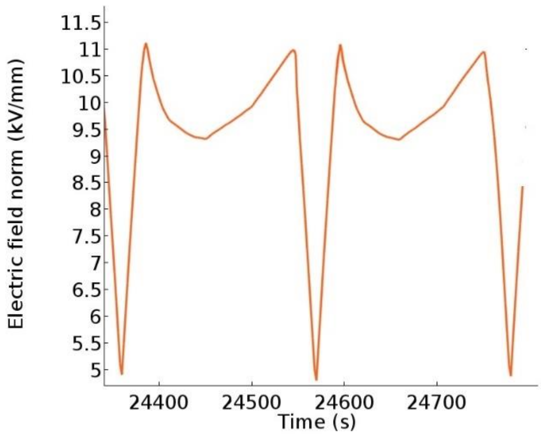
Figure4.2 Fitting curve of t_{DC} and U_{max}

4.2.3. U_{max} and U_{rms}

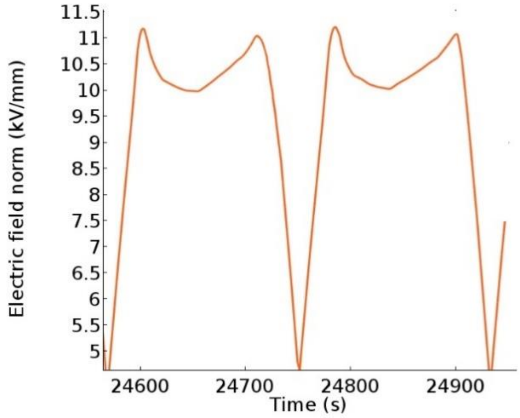
Unlike U_{max} that is continuously increased from Case 1 to 8, U_{rms} stops increasing and begins to decrease when the rise time is around 31s. This can be explained by observing equation (4.2) that both t_{rise} and t_{DC} are influencing factors of U_{rms}. It is impossible to keep U_{rms} continually increasing with U_{max} as t_{DC} becomes more sensitive to the increased voltage grade than the rise time. The results show that Case4 provides the highest value of U_{rms} when the voltage is increased to 134.5kV. In that case, E_{max} has left the cable core and moves to around 4mm away from the conductor at the end of voltage rising process.

4.2.4. E_{max} inside XLPE

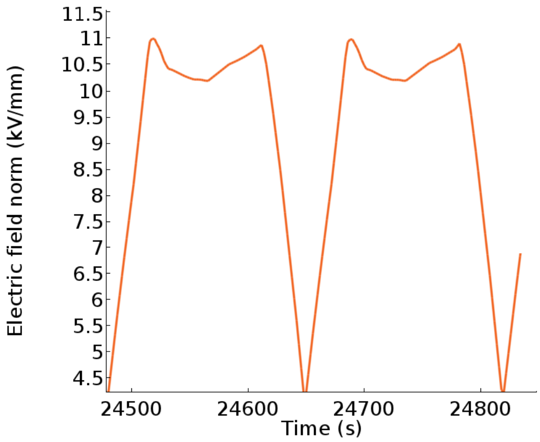
Due to that the maximum value of electric field is the most important factor which must be concerned not to endanger XLPE insulation, the exact value of E_{max} as well as its location deserve attentions. E_{max} in Case2,4 and 7 are studied and the compared.



Case2



Case4



Case7

Figure4.3 E_{max} in Case2,4 and 7

Indicated in Figure4.3, the locus of E_{max} that moves within a small range represents the utilization of insulation is quite good. Controlled under the same upper limit 11.2kV/mm, the range of E_{max} in Case4 is smaller than that in Case2, confirming the higher utilization and thus higher capacity of power transmission. The lower limit is determined by the applied voltage level U_{max}.

Case7 has the smallest range of E_{max} movement among these three cases while its U_{rms} is not the largest one. It illustrates that power losses during t_{rise} are great.

4.3 Conclusions about trapezoidal voltage waveform

Observing the data in Table4.1, U_{rms} values of Case4 and 5 are quite close to each other, making the optimal combination of t_{rise} and t_{DC} stays within a particular range.

The utilization of XLPE insulation is optimized through an electric field distribution that is much flatter than that in nominal 50Hz AC case. Keeping the field stress at higher level through a trapezoidal voltage waveform, this method is verified being useful to improve the power transmission capability of HVAC power cable.

In conclusion, trapezoidal shape of voltage waveforms that are carefully designed probably offer a kind of so-called optimal waveform. When keeping the current constant, the maximum power capability can be 1.55 times larger than that under nominal 132kV AC voltage. Nevertheless, another shape of waveform must be investigated based on the knowledge of trapezoidal ones to reduce the power lost during the transition zones, and thus further improved the utilization of high-voltage power cables.

5

Optimal Voltage Waveform

5.1 Sinusoidal in combination with DC voltage waveforms

At an increased voltage level, DC section is supposed to be included in the voltage waveform in order to make use of the stress inversion inside the cable insulation. And in AC power systems, sinusoidal shapes of waveforms are widely used and they are not difficult to produce.

Inspired by these facts, a new kind of voltage waveform is created and illustrated in Figure5.1. A half period of the voltage is formed by inserting DC voltage into two quarter cycles.

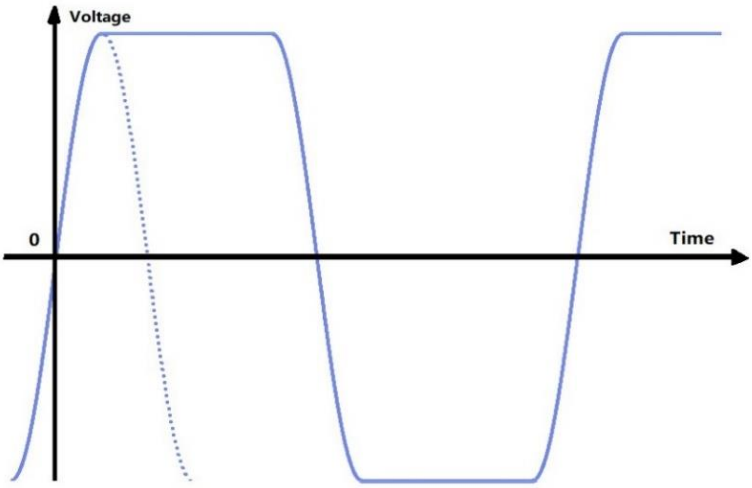


Figure5.1 Sinusoidal in combination with DC voltage waveforms

This type of waveforms can be represented by piecewise functions in (4.3), and the equation to compute U_{rms} is shown in (4.4).

$$U =$$

$$\begin{array}{ll} U_{max} \times \sin(\frac{\pi t}{2t_{rise}}) & t < t_{rise} \\ U_{max} & t_{rise} \leq \ t \leq t_{DC} \\ U_{max} \times \cos(\frac{\pi}{2t_{rise}} \times (t - t_{rise} - t_{DC})\ ) & t_{rise} + t_{DC} << 2t_{rise} + t_{DC} \end{array}$$

(5.1)

$$U_{rms}$$

$$= \sqrt{\frac{\int_0^{t_{rise}} {U_{max}}^2 sin^2 \frac{\pi t}{2t_{rise}} + \int_{t_{rise}}^{t_{rise}+t_{DC}} {U_{max}}^2 + \int_{t_{rise}+t_{DC}}^{2t_{rise}+t_{DC}} {U_{max}}^2 cos^2 \left(\frac{\pi(t - t_{rise} - t_{DC})}{2t_{rise}}\right)}{2t_{rise} + t_{DC}}}$$

$$= \sqrt{\frac{{U_{max}}^2 (t_{rise} + t_{DC})}{2t_{rise} + t_{DC}}}$$

$$= U_{max} \ \sqrt{\frac{t_{rise}+t_{DC}}{2t_{rise}+t_{DC}}} \quad (5.2)$$

5.1.1 A group of results

Using rules to find the pairs of t_{rise} and t_{DC} that are similar to trapezoidal ones, a group of sinusoidal in combination with DC voltage waveforms are applied to the power cable model and recorded in Table5.1. U_{max} of every case is controlled to be the same as the corresponding one that applies trapezoidal shapes. All three other parameters t_{rise}, t_{DC} and U_{rms} are endured meanings of references and comparisons. Still the power gain is calculated on the basis of the rms value 76.2kV of 132kV AC power cables.

Table5.1 Results of Sin&DC voltage waveform at increased voltage level

Case	Time (s)		Voltage (kV)		Power Gain
	t_{rise}	t_{DC}	U_{max}	U_{rms}	
1	26	192	120	113.4	1.48
2	28.5	160	125	116.5	1.52
3	31.5	132	130.5	119.3	1.56
4	34	120	134.5	121.7	1.59
5	37.5	106	136	121.0	1.58
6	40.5	98	137.5	120.9	1.58
7	43	88	139.0	120.6	1.58

5.2 Comparisons of trapezoidal and sin&DC voltage waveforms

From Table5.1, t_{rise} values are a bit larger than those of trapezoidal cases. It is attributed to the fact that the voltage is a bit higher at every moment during the rising process if the same t_{rise} is used. It is an overall effect that leads to a relative larger t_{rise} when the combined sinusoidal and DC voltage waveform is applied due to that a higher voltage grade requires a longer rise time.

The difference between t_{rise} of these two kinds of waveforms at the same level decreases with the increase of U_{max}. This can be explained by the increase of rise time. Since E_{max} begins to move towards the outer sheath of power cable, impacts of the higher U_{max} is partially released due to the less sensitivity of points which locates further from the conductor.

The DC time interval has almost no difference in every couple of cases because of the same upper limit of electric field strength at the cable sheath. In each couple of case, the time constant of point 26.6mm remains constant under the same temperature gradient, which answers their very similar t_{DC} with understandable deviations.

5.3 Discussion

Clearly expressed in Table4.1 and Table5.1, U_{rms} and the power gain in cases having sinusoidal rise time are larger compared to the trapezoidal ones under the same voltage level. It can be answered by equation (4.2) and (4.4).

Since two cases with the same U_{max} have little difference between values of t_{DC}, U_{rms} of them are compared in (5.3)

$$U_{max}\sqrt{\frac{t_{rise}+t_{DC}}{2t_{rise}+t_{DC}}} > U_{max}\sqrt{\frac{2/3t_{rise}+t_{DC}}{2t_{rise}+t_{DC}}} \tag{5.3}$$

Equation(5.3) shows that t_{rise} is the effective parameter which determines the relation between these two polynomials. The sinusoidal &DC case has a larger U_{rms} than the trapezoidal due to t_{rise} is a bit longer in the former case.

The maximum voltage level that gives the maximum U_{rms} is 134.5kV in both two groups of simulations, meaning that the influence on power cables by these two types of voltage waveforms are quite similar.

5.4 Conclusion

To sum the above study up, the optimal voltage waveform which supplies the highest power transmission capacity is considered to be found. For the shape of waveform, two quarters of a sinusoidal wave are used for transition of bi-directional DC voltage.

Case 4, 5, and 6 in Table5.1 deduced close U_{rms} results. Considering the approximation made in the computation of U_{rms} and power gain values, a range between 34 and 40s can be chosen for t_{rise}, while t_{DC} is between 98 - 120s. The highest efficiency of XLPE utilization is achieved through limiting the electric field distribution by the combination of sinusoidal and DC voltage waveforms

There are two main reasons to take this option. The case whose U_{rms} value is the largest one should be applied to meet the requirement of finding out an optimal voltage waveform that gives the highest capability of power transmission for existing XLPE AC power cables. Instead of ideal simulation situations in the software, errors and signal problems brought by the real waveforms have to be considered from the reality point of view. It is better to apply a smooth voltage waveform to the power cable for less partial discharges that damage the insulation. The combined sinusoidal and DC waveshapes have continuous derivatives during polarity reversals. And it could be an advantage that derivatives of these two kinds of waves are equal to zero at connect points.

6

Sensitivity Analysis

6.1 Sensitivity to the load

6.1.1. Effects of the thermal gradient

The so-called optimal voltage waveform in the last chapter is obtained on condition that 1kA is the fixed nominal current rating. In practice, the demand of power fluctuates all the time so that the load must be controlled to keep the reliability of the power system. If the nominal current is applied during the peak time in a day, a reduced load is needed at night due to less electricity consumption. Since the current flowing through the conductor is the heat source of the power cable, different load level will form different temperature gradient. The heat transfer issue is coupled with electric problems in the model and they jointly decide the field distribution, for this reason, the sensitivity of voltage waveform to the fluctuated load is supposed to be studied.

Due to that the heat transfer is not affected by electric problems, using 107.8kV as the amplitude, DC voltage at nominal level with decreased currents are applied to the cable model.

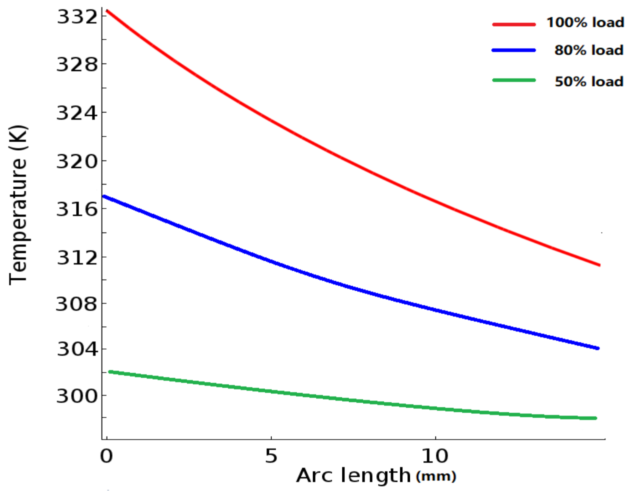


Figure6.1 Temperature gradient at different current ratings

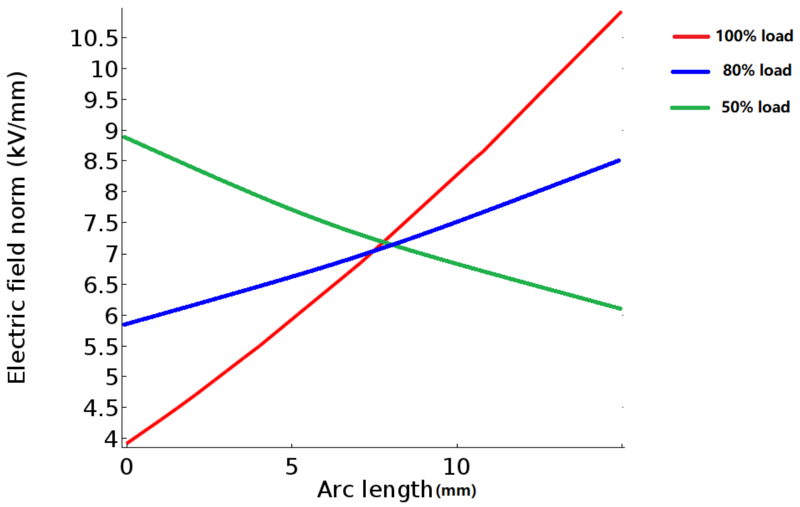


Figure6.2 Field distribution at different current ratings

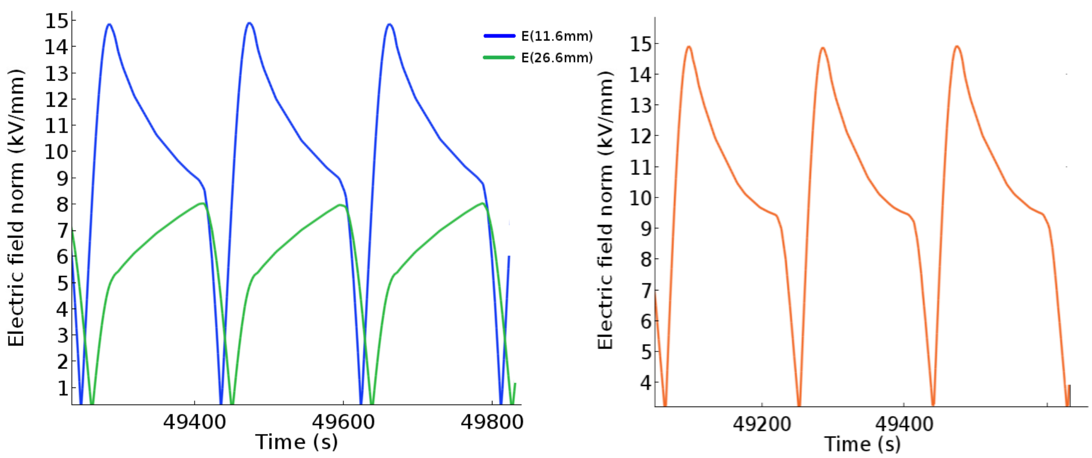
The current that flows through the conductor of power cables is the heat source that generate heat and finally leads to a thermal gradient within XLPE. This gradient results in the change of conductivity at different locations, therefore affects the resistive field to a large extent. In addition to the absolute temperature values, the temperature drop ΔT between inner and outer insulation also decreases with the reduce of current ratings.

Clearly shown in Figure6.1 and 6.2 that with a smaller ΔT when 80% of nominal load is given, *E* near to the conductor is not that much lower compared to that in the 1kA case. So that the electric field distribution is flatter due to smaller differences of XLPE conductivity. As for the 50% nominal load case, the stress inversion does not happen because of the small ΔT formed by the current.

In fact, the electric field distribution does not depend on the absolute temperature but the temperature drop ΔT only. The larger ΔT is, the greater effects of space charges. [1]

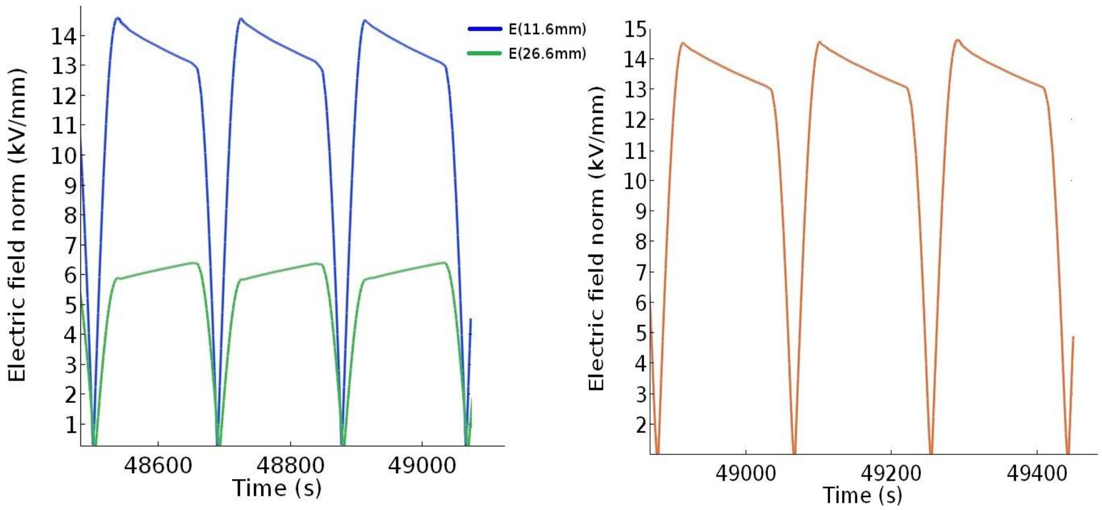
6.1.2 Sensitivity of the optimal voltage waveform to the load

To test the sensitivity of the optimal waveform given in Chapter 5 to the load-changed situations, the current rating is adjusted to 80% and 50% after stabilization of the electric field at rated current. Applying the waveform in Case4 of sin & DC simulations, electric stress of inner and outer XLPE distributions, and also the locus of E_{max} are shown below.



a.Inner and outer XLPE　　　　b. E_{max}

Figure6.3 *E* inside XLPE at 80% load current under optimal voltage waveform



a.Inner and outer XLPE b.E_{max}

Figure6.4 *E* inside XLPE at 80% load current under optimal voltage waveform

The sinusoidal & DC voltage waveform found before takes advantage of the charge-induced field. Seen from Figure6.3, E_{max} near to the conductor in both current ratings goes beyond the limit value, 11.2kV/mm. This is caused by smaller $\Delta\mathrm{T}$ of XLPE and higher end values of field strength at the cable core. For this reason, the optimal voltage waveform for the rated current load is not allowed to be applied anymore when the load decrease happens. Furthermore, it is observed that when current is reduced, E_{max} inside XLPE stays at the conductor and does not move forward during the DC section of the voltage. The reduced load level leads to a lower temperature at the conductor, compared to nominal situation, so that its time constant becomes longer.

In case of the 80% load situation, the shape of new voltage waveform can still be used for realization of increased voltage grade and capacity of power transmission. But it is impossible to increase U_{max} to the value as much high as the nominal load case.

However, it is another story when 50% load is simulated. There is no stress inversion so that E_{max} stays at the location near to the conductor which limits the voltage level. Instead of making it bounce within a specific range in insulation, the way of improving the cable utilization is to increase U_{max} to an acceptable value which keeps the electric field at point inner XLPE under 11.2kV/mm.

In general, the sensitivity of the optimal voltage waveform is increased with the difference between the rated and the reduced load levels. The sinusoidal in combination with DC voltage waveshape is possible to be used with adjusted t_{rise} and t_{DC} if $\Delta\mathrm{T}$ is large enough, or the new kind of voltage is not allowed to be applied.

6.2 XLPE conductivity

The conductivity of XLPE is strongly dependent on temperature and also influenced by the field strength. In the model used in this study, the strength effect is ignored. The accurate mathematical formulas have not been given, only general deduction based on experiments. Different conductivity expressions are taken for HVDC cable research such as [2,3,4]. In this work, 3.3e-14 S/m at 20°C is used. This value should be analyzed since it is an effective parameter that determines the field distribution, especially under a waveform that contains DC sections.

Based on the DC voltage simulation using 1e-15S/m at 20°C, which is lower than 3.3e-14 as the conductivity, two main differences are found when different σ values are applied.

Table6.1 Different XLPE conductivity situations

σ (S/m)	Stationary time (s)	E_{min} (kV/mm)	E_{max} (kV/mm)
3.3e-14	50000	4.8	10.9
1e-15	60000	3.5	11.6

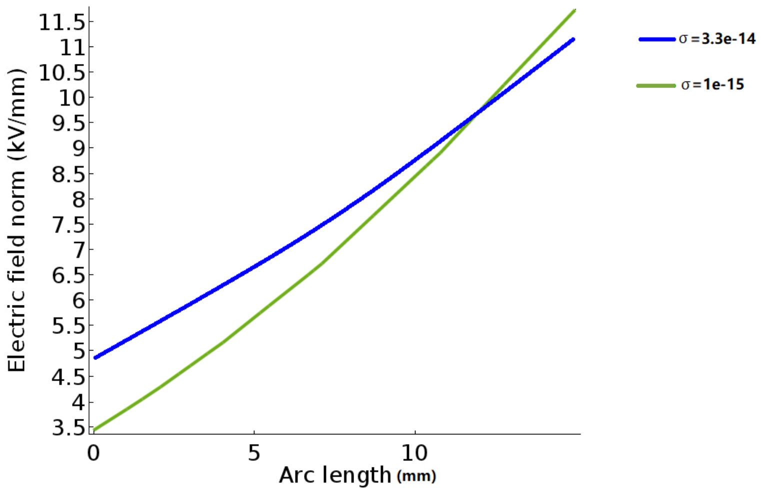


Figure6.5 Field distributions with different XLPE conductivity

Firstly, it takes longer time for the model that has the lower σ to reach the steady state. It is explained by equation (2.8) that the time constant τ is inversely proportional to σ, meaning the field induced by space charges in the insulation with lower conductivity need more time to form.

Secondly, the stress difference between inner and outer XLPE is enlarged when a lower σ is used in the model. The conductivity related with temperature used in this work is expressed in (6.1)

$$\sigma = e^{\frac{\alpha * 10^3}{T}}, (\alpha < 0) \tag{6.1}$$

Where α is a specific coefficient and T is the temperature (K).

At steady state, the difference in σ values between inner and outer XLPE can be evaluated by (6.2)

$$\frac{\sigma_i}{\sigma_o} = e^{\alpha * 10^3 * (\frac{1}{T_i} - \frac{1}{T_o})} \tag{6.2}$$

Based on the same thermal gradient in both cases,

$$\frac{1}{T_i} - \frac{1}{T_o} < 0 \tag{6.3}$$

Therefore, $\frac{\sigma_i}{\sigma_o}$ increases with the decrease of specific coefficient α, which means a lower conductivity at a fixed temperature creates a more obvious stress inversion phenomenon.

These results indicate that the XLPE conductivity is quite a sensitive factor to the field distribution if the new kind of voltage waveform is applied. In reality, accurate tests must be taken before designing the waveform and applying it to existing power cables.

6.3 Thermal conductivity of soil

The thermal conductivity of the soil influences the heat transfer and thus thermal conditions when power cables are operating underground. As it is a climate-changing parameter, effects of various types of soil and corresponding thermal conductivity values have to be studied for the reliability of the cable system.

In Table6.2 [5], the variation of the soil thermal conductivity depending weather conditions is given.

Table6.2 Variation of the soil thermal conductivity with soil conditions

Soil condition	Thermal conductivity (W/K·m)
Very moist	1.4
moist	1
Dry	0.5
Very dry	0.3

It is easier to disperse the heat generated by the cable in the soil with more moisture than normal, and hence results in less heat amount kept by XLPE insulation [6]. Whereas in dry areas, the heat increases remarkably with decreasing thermal conductivity of the soil, limiting the current carrying capacity in case of thermal breakdown.

When the nominal voltage 107.8kV and rated current 1kA in this study is applied with different soil thermal conductivities, the field distributions at steady state under DC voltage have almost no difference due to the same temperature drop ΔT, see Figure6.6.

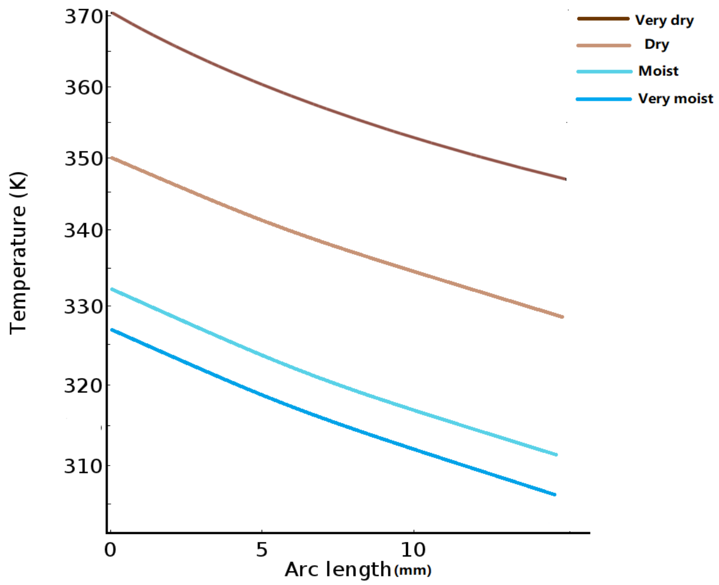


Figure6.6 Temperature distribution of XLPE surrounded by different soil conditions

A dangerous situation is noticed when the soil is very dry since the conductor temperature has exceeded the limit value 90°C, which makes it necessary to decrease the load level.

In general, the weather condition that determines the soil thermal conductivity influences absolute temperatures of the cable conductor and insulation. In most cases, it is possible for the optimal voltage waveform to be applied under various soil condition to power cables due to the same ΔT and thus the same stress distribution. However, the voltage waveform must be re-designed which has been discussed in 6.1 when the load is changed for the safety of cable from the thermal problem aspect.

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7

Optimum Waveforms Applied to Cable terminations

A high-voltage power cable consists of not only the cylinder volume, but also accessories such as joints and terminations. Special attention in design perspective and materials is necessary to be paid on cable accessories since they are the most vulnerable parts of the cable network from electrical and thermal aspects, see for instance [1]. When a cable end is terminated, field concentrations occur at the end of cable screen which is stripped off. For that reason, a tangential component is introduced and results in a non-radial field distribution in that region. Such a tangential field component may cause partial and surface discharges, leading to premature failures way before the expected cable life time, consequently [2]. In order to improve the field distribution at the end region where the ground shield is stripped off, the insulation is usually enclosed in a stress control tube(SCT) or a stress relief cone [3].

In this work, these two types of stress control techniques that are often used are investigated, especially the tangential field component E_t along the interface between XLPE and the field grading material for the possibility of applying the optimal voltage waveform that obtained before.

7.1 SCT field grading

In order to minimize and avoid field enhancement, SCT with field grading abilities is involved in some HVAC cable terminations as shown in Figure7.1.

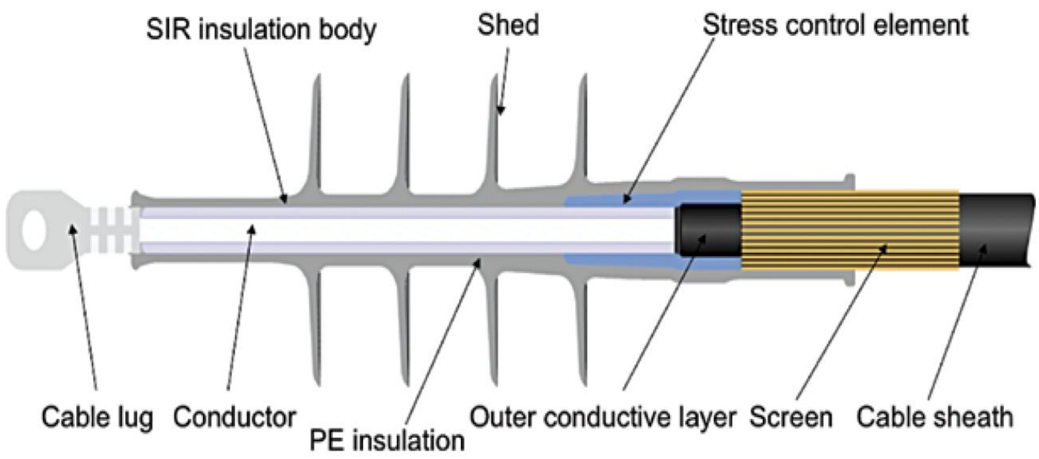


Figure7.1 A typical design of HVAC outdoor cable termination [4]

The main function of such stress control tube is to provide a more uniform field distribution along the cable length by making use of the rule that the field strength in high-ε material is lower than that in an adjacent region with low-ε value. With the help of stress relief of special materials with high permittivity value, the field distribution around the cable termination can be modified.

7.1.1 SCT termination model

Using 2D axis-symmetric model in COMSOL, a simple realistic termination of a 132kV AC power cable is built to investigate stress distribution problems as shown in Figure7.2. In this model, the termination material has ε_r=30 and σ=5e-11S/m. The outer porcelain sheds is ignored for simplicity of the model configuration, and the air around the outdoor HVAC cable termination is regarded as boundary condition of electric problems.

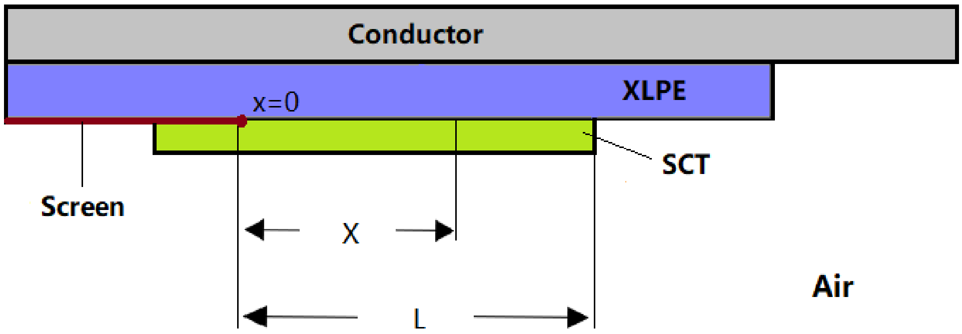


Figure7.2 XLPE cable termination with SCT field grading model

Heat transfer issues have to be considered for its influence on field distribution when the voltage contains DC sections. Different from the underground coaxial cylinder part of cable which is governed only by conduction, both convection and conduction exist when outdoor terminations are under operation due to the fluid external environment. In the thermal steady state, a certain amount of heat called convective heat flux is emitted from the terminal to air expressed in (7.1) [5]

$$\mathrm{q} = \mathrm{h} * (T_{ext} - T) \tag{7.1}$$

Where,

q: heat flux density(W/m^2)

h: heat transfer coefficient (W/$m^2 \cdot k$)

T_{ext}: external temperature

T: solid temperature

In this work, the thermal distribution within the termination is studied. The complexity of heat transfer problems in the model is reduced remarkably by defining specific coefficient *h* as the thermal boundary conditions. In this case, heat convection in the air does not have to be solved anymore.

Based on the location of heat source and the termination configuration, different *h* should be applied to different solid boundaries which are exposed to the air. Using their heat flux densities and temperatures at stationary state data in Table2.5, calculations can be made for *h* values of the conductor and XLPE at the rated load level, see (7.2) and (7.3)

When the external temperature T_{ext} is set to be 20°C

For the conductor surface,

$$h_c = \frac{703}{(332.4-293.15)} = 17.9 \tag{7.2}$$

and for XLPE,

$$h_{XLPE} = \frac{306}{(311.4-293.15)} = 16.7 \tag{7.3}$$

Since three h values are supposed to satisfy (7.4),

$$h_{SCT} < h_{XLPE} < h_c \tag{7.4}$$

a rough estimation is applied for the value of h_c. With the symmetry settings on two ends of the termination model, thermal boundary conditions using heat transfer coefficients are completed and shown in Table7.1

Table7.1 Heat transfer coefficients in the SCT termination model

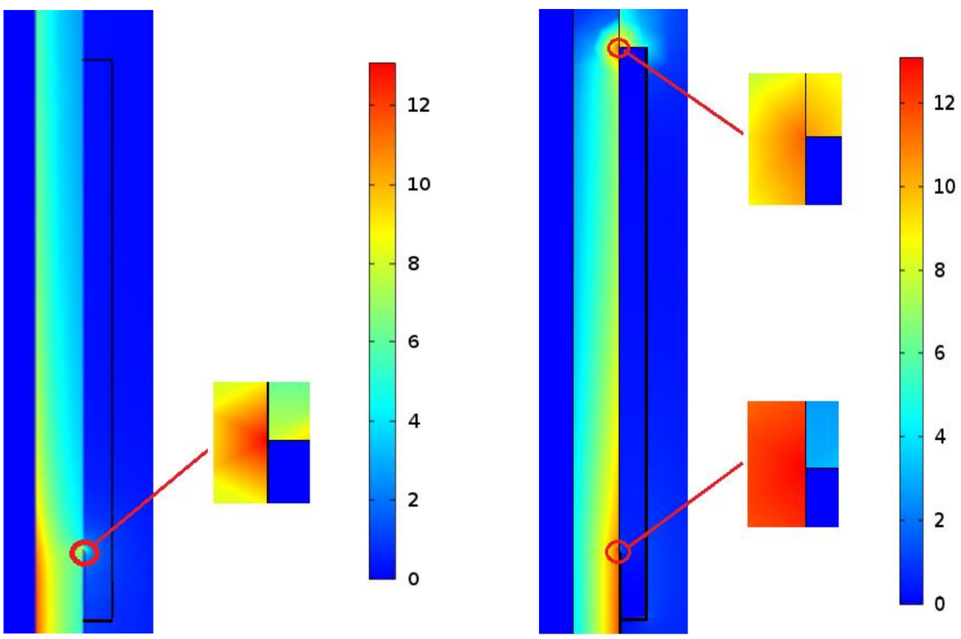
	conductor	XLPE	SCT
h(W/$m^2 \cdot k$)	17.9	16.7	15.5

The thermal distribution is kept the same with the underground cylinder part of HVAC cable. However, it is clear that temperature should be lower at the cable terminal due to its easier heat dissipation. Simulation results will nevertheless be studied to give basic rules.

7.1.2 AC and DC simulations at nominal voltage level.

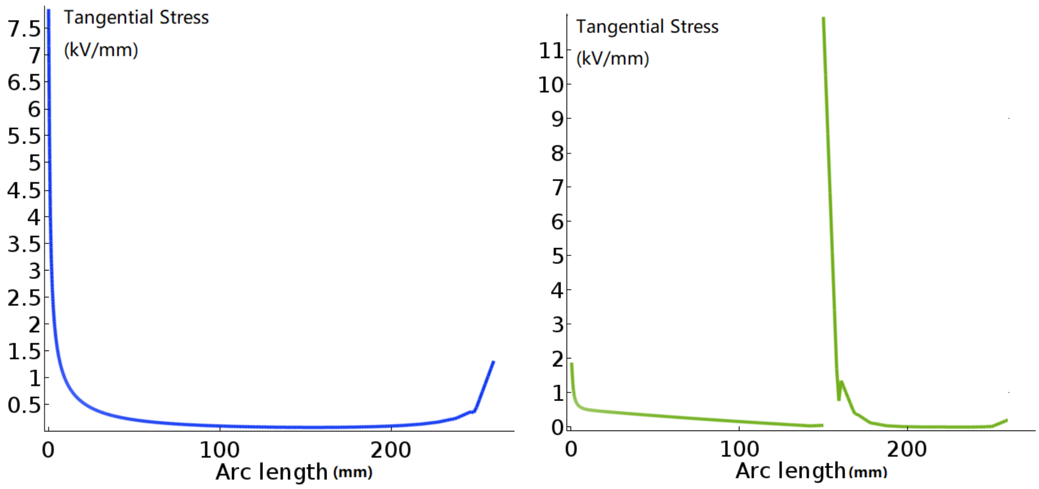
The simulation is performed at 50Hz AC voltage with the amplitude 107.8kV together with rated load 1kA at first. Then DC voltage at the same level is simulated for the purpose of application of the new voltage waveform.

Clearly indicated in Figure5.3, the field concentration appears only at x=0 at AC voltage, while it happens at both two ends of terminating material when DC voltage is applied. The stress inversion makes the stress at screen conjunction high. And shown in Figure 5.4b, it is not quite serious from tangential component point of view. On the top of SCT, as explained in [6] that the material used for stress control in AC cable is more conductive than XLPE, so that equipotential lines are pushed to concentrate in the stress control medium. Without any protection at the end of SCT, the termination with epsilon field grading designed for AC cables cannot be directly used for DC cables.



a b

Figure7.3 a) Electric field under AC voltage b) Electric field under DC voltage



a b

Figure7.4 a) E_{tmax} along x at AC voltage b) E_t along x at DC voltage

The maximum tangential electric field at the interface at 107.8kV nominal 50Hz AC voltage is 7.8kV/mm, which is regarded as the upper limit. In order to ensure the cable terminal is out of danger for the reliability when optimal waveforms applied, E_t at x=0 should be kept lower than 7.8kV/mm and there is no serious concentration at x=L.

7.1.3. Effects of terminal material properties on field grading

Since many types of material are used to modify the field distribution at cable termination, effects of different ε_r and σ values within wide ranges are supposed to be understood. Moreover, the influence of frequency of voltage have to be considered due to the sinusoidal parts of the new optimal waveform has a much lower frequency range than 50Hz. An analytical method to calculate the field distribution in cable terminations using linear SCT technique has been developed in [7]. And it also reveals effects on E_t of those three influential factors mentioned above.

It can be concluded that the major E_t concentration gradually moves from the shield conjunction to the material end with its increasing conductivity and the decrease of voltage frequency. If the medium is much more conductive compared to XLPE, field concentrations will happen at the medium top at low frequencies. Based on this fact, an upper limit of SCT conductivity is formed to avoid failures when using hybrid voltage waveform containing DC sections. Besides, σ value of the medium cannot be too small since it has little effect for the field improvement during t_{DC} of voltage waveforms.

As for ε_r of the SCT material, it becomes less sensitive with the decrease of voltage frequency. For application of the selected optimal waveform at higher voltage levels, a range of the relative permittivity of SCT can be probably defined.

7.1.4. SCT cable termination at optimal voltage waveform

The availability of new voltage waveform is checked by applying the voltage waveform in Case4 of Table5.1 to the termination model with SCT field grading,

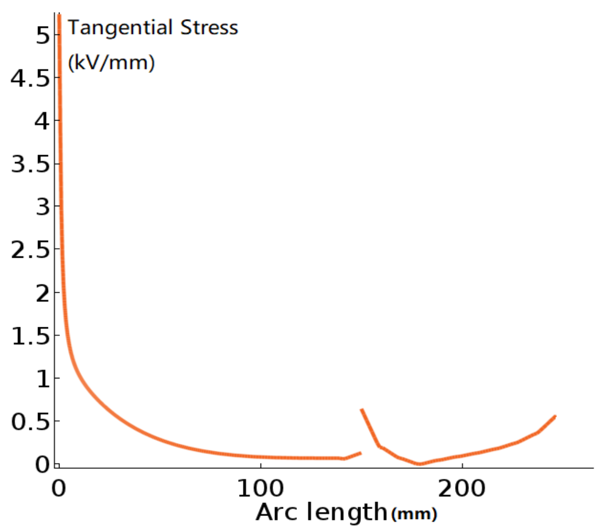


Figure7.5 Variation of E_{tmax} with x at optimal voltage

Seen from Figure7.5, the maximum tangential stress at the screen conjunction is 5.2kV/mm which is lower than 7.4kV/mm satisfies the requirement of the stress control. The field concentration on the SCT top during t_{DC} under the hybrid waveform is released compared to DC voltage and there is no field concentration happens there. So that this kind of termination can be used to the entire 132kV HVAC power cable for the utilization improvement.

Furthermore, considering many types of materials are used in SCT of existing cable terminations and taking 7.4kV/mm as the maximum tangential stress at the XLPE surface, a range of conductivity and relative permittivity is given through a series of simulations. Obviously, the electric conductivity of SCT is the dominant property determines the field distribution.

Table7.2 Parameter range of SCT material

parameters	ε_r	σ(S/m)
range	$\varepsilon_r > 15$	$2.5\mathrm{e}-11 < \sigma < 1\mathrm{e}-10$

7.2 Stress cone field grading

The stress cone is a significantly important component of high voltage cable terminals for field grading. A well-designed stress cone that is carefully shaped can gradually reduce and make the electric field linearly distributed in cable terminals. Nowadays, prefabricated rubber stress cones are widely used in high voltage AC cable terminations with the curved earthed electrode. Previous research mainly focused on two aspects, one is to improve the geometry of rubber stress cone face curve. As proposed in [8], for example, the optimized design of curvature is able to uniformly disperse the equipotential lines and keep the tangential filed component E_t constant at a reasonable value. The other is to use better materials such as high-ε_r or nonlinear insulation materials [9].

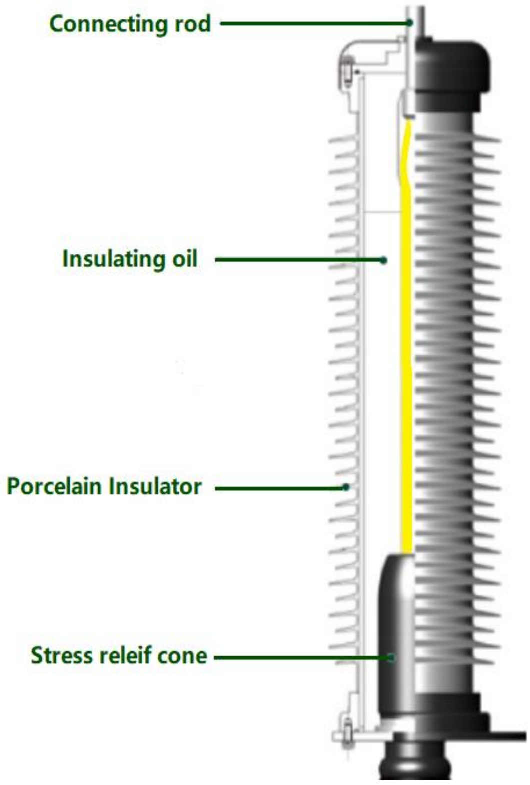


Figure7.6 Typical HVAC outdoor termination with a stress cone [10]

7.2.1 Stress cone termination model

Using realistic standard of Nexans company of the stress cone design, a model is built and solved in COMSOL with Electric Current and Heat Transfer physics. Since the oil is not included in thermal problems of this model, convective heat flux as boundary conditions are set to be very similar to the SCT model in 7.1.1. The field distribution along the interface of XLPE and cone is studied.

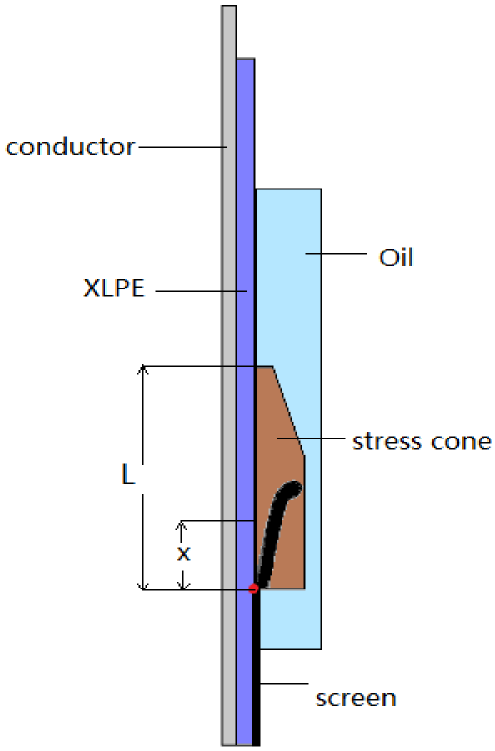


Figure7.7 132kV cable termination with stress cone model

7.2.2. AC and DC simulations at nominal voltage level.

Like simulations did in 7.1.2, the nominal 50Hz AC voltage waveform is applied to investigate the electrical field distribution on the interface, and then for DC voltage at the same level of 107.8kV.

As illustrated in Figure7.7a, the field strength at the interface gradually decreases from the screen conjunction and E_t is kept quite low and almost uniform. It is attributed to the specially designed curvature AC high voltage cable which provides remarkable modification for the field distribution. In the DC case, similar to the situation in the SCT field grading model, the field concentration happens at the top of stress cone caused by its much larger conductivity compared to XLPE. These results are in accordance with the fact in [7] that both a longer deflector and a cone must be chosen to prevent field concentrations.

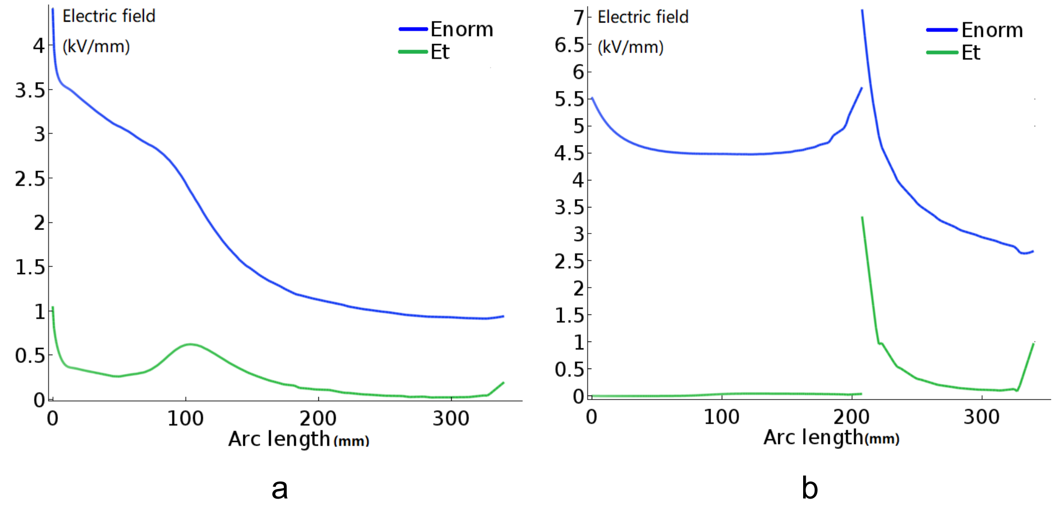


Figure 7.8 a) Field distribution at AC b) Field distribution at DC

7.2.3. Application of the new voltage waveform

Simulation results of electric field that varies with *x* at optimal sin&DC voltage waveform with amplitude 134.5kV are shown below.

Seen in Figure7.8 and 7.9, the local field strength is high at the cone top and there is no concentration at the screen conjunction during the whole period. It can be conducted that the conductivity has dominant effects on the field distribution due to the long length of the period. A more intensive tangential stress than that in the nominal DC voltage case can be observed by the higher voltage level.

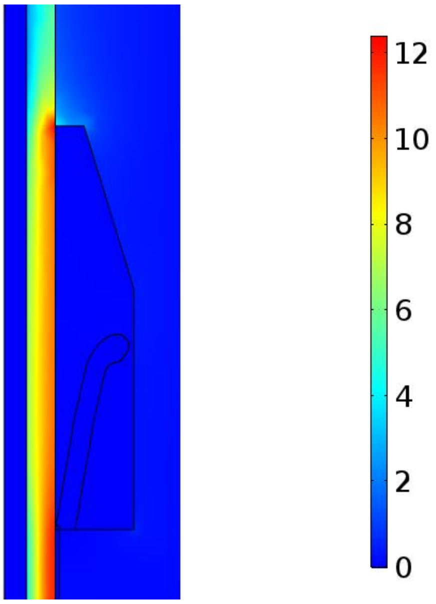


Figure7.9 Electric field at the stress cone under the optimal voltage waveform.

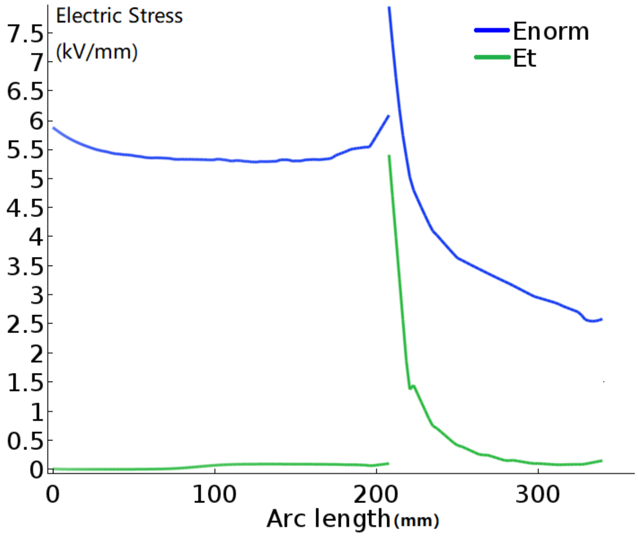


Figure7.10 Variation of E_{max} with x at optimal voltage

Unlike those high-voltage cable terminations with SCT field grading techniques, materials used in stress cones do not have wide ranges of permittivity and especially, conductivity values. In general, terminations with stress cones designed for 50Hz AC voltage may have local strength which is too high and endanger the operating performances.

7.3 Summary

Electric filed distributions of terminations of power cables have to be seriously controlled when applying new kind of voltage waveforms. It is possible to apply the optimum voltage waveform obtained in Chapter5 which gives the largest power gain of the power transmission capability for the 132kV AC cable termination with SCT field grading techniques under certain circumstances. The range of relative permittivity and conductivity values are listed in Table7.2. However, a higher voltage which exceeds 107.8kV is not allowed to be applied to terminations using well-designed stress relief cones. The Interface of XLPE and the stress cone will be endangered by the tangential component of electric field. Moreover, the junction at the end of the stress cone will be exposed to high risks of breaking down.

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8

Conclusion

8.1 conclusions

This thesis focuses on finding a new kind of voltage waveform that provides improvement of transmission capability of existing HVAC power cables. In general, the suggested voltage waveform can be used for better utilization of HVAC power cables by improving the transmission capabilities. To obtain the highest efficiency without endangering the cable system, the waveform should be carefully designed for not only the main body which is underground, but also cable accessories.

Taking a realistic 132kV XLPE cable as an example, investigations are made for pursing a higher utilization of the insulation. Models for AC and DC voltage applications are built, simulation results for electric field distribution within XLPE insulation under trapezoidal and sin&DC voltage waveform at nominal and higher levels are collected. In this work, the sensitivity analysis of influencing factors and feasibility of the suggested voltage waveform applied to typical cable terminations are included as well. These thesis objectives are met.

In the AC and DC models established in COMSOL software relying on FEM to solve problems, the electric current and heat transfer physics governed by specific equations are coupled to determine the electric field distribution. The upper limit of electric field stress, which appears near to the cable core is confirmed by the amplitude of nominal AC voltage. This value is used in the following research since it is one of the most important issues to secure the expected lifetime of cables is confirmed in this part. At DC voltage, the so-called stress inversion happens due to the temperature gradient, and thus the electrical conductivity gradient along XLPE.

Hybrid waveforms are investigated starting from the nominal voltage level with periodic and symmetrical trapezoidal shape. By collecting data from various combined waveforms, rules are established for creating trapezoidal waves at higher voltage levels without sacrificing the long-term reliability of power cables.

In Chapter 4 and 5, a group of voltage waveforms that satisfy the requirements of electric field strength limit for the trapezoidal shape are found. There are tradeoffs between the rise time and the DC section and the one that provides the highest transmission capability is found based on simulation results. To further increase the utilization by decreasing the power losses during the transition zones, the voltage waveform is modified to a combination of sinusoidal & DC shape. A series of waveforms having that kind of shape are determined under the same upper limit of field strength value that has been used for the trapezoidal cases. After comparing these two types of periodic and hybrid waveforms, the so-called optimal voltage waveform is finally established.

It has been found in earlier research that some factors, which might not be constant in reality may affect field distributions within the insulation. Therefore, impacts of these influencing factors on the field distribution, and thus their sensitivities to the optimal voltage waveform have to be evaluated. The load level, the electric conductivity of XLPE and soil conditions are namely studied in Chapter 6. It is found that the voltage waveform has to be adjusted with the change of load level or the actual electrical conductivity of XLPE, while the hybrid voltage waveform needs little modification if the soil property is the only variable of operating conditions of power cables.

Due to special and complicated configurations, terminations are much more vulnerable than the main body of cable from both electrical and thermal point of view. It is demonstrated that SCT cable terminals can be operated under the optimal voltage waveform if the stress control medium has reasonable electrical conductivity and permittivity, while this is not possible for terminations with stress cones.

8.2 Future work

Since the field distribution within XLPE under the optimum waveform is different with the one created by 50Hz AC voltage (even though the maximum field is controlled to be less than the permissible value), it is necessary to know whether the lifetime of power cables will be influenced by the hybrid new waveform. This has to be evaluated by lifetime experiments.

Based on this thesis, there remains some future work to do. Firstly, a more accurate and complicated cable model is supposed to be built for the further research of this project. This thesis uses simplified models to illustrate that it is possible to improve the utilization of existing power cables. In practice, different materials within the cable inevitably result in some problems. The semiconducting layer, for example, may distort the field distribution at DC voltage by influencing the space charge formation. Secondly, a more realistic and accurate XLPE conductivity which can be obtained in the lab should be used due to its high sensitivity to the voltage waveform. In addition, the decaying behavior has to be considered in order to keep the long-term appropriate application of the new waveform designed for a specific HVAC power cable. Finally, another kind of cable accessory, cable joints deserve even more attention than cable terminations. Since the thermal problem is usually more serious due to its underground installation, a proper model for a typical cable joint should definitely be analyzed.