Cable Capacity Enhancement by Utilizing Trapezoidal Voltage Waveform

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Abstract

To avoid installation of expensive new underground cable connections in locations where peak load exceeds existing cable capacity, it is advantageous to transfer more power through a cable than its nominal power capacity, without endangering its reliability. Dynamic current rating of cables is a typical approach that is used to exceed the nominal cable capacity for a short time period. In this paper a new method for cable capacity enhancement based on dynamic voltage rating is introduced. The method can be applied if multilevel converters are installed at both ends of cable as will become more commonplace in the future when an inverter rich power system is realized. In this study the influence of trapezoidal voltage waveform on the electric field distribution inside cable insulation is investigated. The results shows that by using trapezoidal waveform it is possible to achieve a more homogeneous field distribution inside the cable insulation. This enables better utilization of the insulation system which translates into higher continuous power transfer capacity.

1. Introduction

Energy demand currently supplied by fossil fuels will be gradually replaced by electric energy produced from variable renewable energy recourses like sun and wind. Demand of electric energy due to electric vehicles and, electric heat pumps are examples of change of used energy carrier. Increase of electricity demands will overload the existing transmission and distribution grid specially during peak load (and generation) periods. This requires solutions that are acceptable from both technical and economic considerations. A straight forward solution is to expand and upgrade electric grids by means of new overhead lines or underground cable installation. Installing a new overhead line due to environmental and public concerns as well as technical issues (e.g. offshore windfarm grid) is not well-received in the recent years. Installing new cable connections is costly and is reserved only for situations in which no other solution is available.

To increase power transfer capacity of a given cable, either voltage applied to the cable or the current passing thorough it must be increased. Applying voltage level above the nominal voltage of the cable, reduces the cable insulation lifetime and results in early failure of the cable. Operating the cable at higher current than the nominal current, overheat the cable insulation and causes faster insulation aging, resulting in shorter lifetime and earlier failure of the cable. Therefore, none of the above methods can be applied carelessly. In this regards, dynamic cable current rating has been introduced to better utilize cables and to exceed nominal cable capacity fora short time period without overheating the cable. This is done by utilizing the thermal capacity of cable and soil around the cable. With this approach more current can be passed through a cable connection in case the initial temperature of the cable conductor is less than the permissible value (the permissible value is different for different insulation material. It is typically 90° C for XLPE insulation). The thermal capacity of the conductor and other parts of the cable in combination with thermal resistances of the material forms a time constant. This implies that the, conductor's temperature does not increase above the permissible value instantly. By doing proper calculation it is possible to pass more power through a cable for a short period while avoiding the overheating of the cable by the current.

Recently [1] have suggested to use DC over existing medium voltage AC cable lines by installing Multi-Level Modular Converter (MMC) at both ends of the cable line. The article propose to apply DC voltage level equal to peak value of cable's nominal AC voltage level, to keep the maximum voltage level equal to the nominal value while increasing the RMS value of the voltage. Considering other factors such as reduction of skin/ proximity effect, charging current, cable loss and dielectric loss under DC and on the other hand higher losses of the converters (compared to conventional transformers), the article suggested that a capacity enhancement of at least 50% can be achieved through this approach. The arguments presented in [1] are based on the following assumptions. Firstly by utilizing Voltage-Source Converters (VSC) polarity reversal is avoided. This ensures that despite formation of space charges under DC, charge induced field enhancement due to polarity reversal does not occur. Secondly, partial discharge (PD) rate of occurrence at DC is less frequent than under AC and in general breakdown strength of insulation under DC is higher than AC. Therefore, if the highest electric field is limited to the maximum electric field inside insulation at nominal AC voltage level, then it would be safe to operate the cable under DC.

Even though the aforementioned assumptions are all acceptable, operating an existing AC cable system under DC is not recommended due to existence of cable joints and terminations in the system. In these components, different field grading techniques are used to relief electric stress from the regions with high electric field. The functionality of some of these methods (e.g. non-linear resistivity and high permittivity layers) that are commonly used in medium voltage cables, depends on the frequency of applied voltage. Changing the 50 Hz to DC, disturbs proper functionality of joints and terminations made based on those stress grading methods. It leads to field enhancement on certain area of these components which can quickly lead to failure of joints and terminations. This phenomenon is illustrated in the following Figure 1. Considering large integration of power electronics based components in the future power system [2] the concepts of using an alternative voltage waveform for power transfer is worth investigation. In this paper a new voltage waveform is proposed which can increase cable power transfer capacity while keeping the electric stress in all part of insulation less than the maximum electric stress the cable was designed for. The new voltage waveform has a RMS value higher than the AC peak voltage.

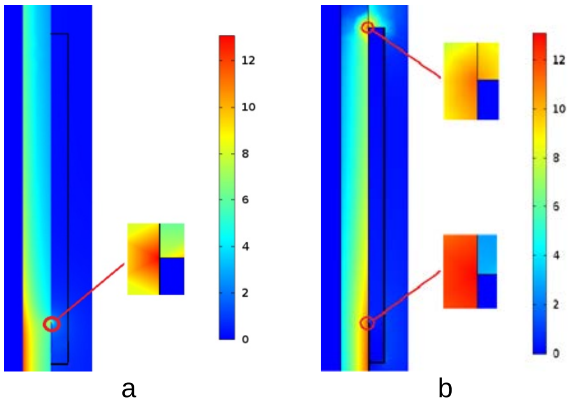

Figure 1. Concentration of electric field on top of the resistive field grading layer when DC is applied to a termination made for AC cable line. Electric field distribution under a) AC and b) DC.

The issues of electric field distribution in joints and terminations and present high cost of converters as well as other more detail concerns such as possible difference in quality of semiconducting layer near on the ground side and near on the conductor side, must be investigated separately and are not treated in this paper.

2. Modelling of electric field variation due to space charge formation

The electric field distribution inside cable insulation disturbs due to formation of space charges under DC applied voltage. COMSOL Multiphysics is used to model this phenomena.

2.1 Electrical equations

The equation that governs electric field distribution is Poisson's equation:

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V) = -\rho \tag{1}$$

$$E = -\nabla V \tag{2}$$

In the above equations, V is voltage, E is electric field, ρ is space charge density, ε_0 and ε_r are permittivity of vacuum and relative permittivity of insulation medium. The solution of Poisson's equation under no space charge, and space symmetry in z and φ directions (coaxial cable) is given in equation 3.

$$E = \frac{V_0}{r \ln\left(\frac{r_o}{r_i}\right)} \tag{3}$$

In equation 3, the conductor is at potential V_0 and the sheath is at ground potential, r is the distance from the center of the conductor, r_i is the radius of conductor and r_o is the inner radius of the sheath. Since relative permittivity is relatively constant with temperature and because space charges does not accumulate under AC, field distribution in AC cables follows equation 3 which means the insulation region close to the conductor experiences the highest electric stress. Under DC, accumulation of space charges inside insulation alters the distribution of electric field in the insulation. Space charges form whenever $\nabla\left(\frac{\varepsilon}{\sigma}\right)$ is non-zero inside an insulation material exposed to an electric field. Under DC due to the unipolar applied field, the magnitude of space charges grows over time until it reaches its final value. The amount of accumulated charge can be enough to disturb the electrostatic field distribution. Under AC 50 Hz, the magnitude of space charges cannot grow due to change of electric field's direction every 10 milliseconds. Charge accumulation on the interface of two dielectric follows equation 4. The time constant can be approximated with equation 5 [3].

$$\rho = A(1 - e^{\frac{-t}{\tau}}) \tag{4}$$

$$\tau \approx \frac{\bar{\varepsilon}}{\bar{\sigma}} \tag{5}$$

In equation 5, $\bar{\varepsilon}$ and $\bar{\sigma}$ are average permittivity and conductivity of the two dielectrics. Since conductivity is strongly temperature dependent (unlike permittivity), even a homogeneous dielectric at a temperature gradient is susceptible to space charges formation, this is because $\nabla\left(\frac{\varepsilon}{\sigma}\right) \neq 0$. Polymeric insulation such as XLPE has crystalline and amorphous regions inside them, which have different conductivities, and hence space charges can form in the amorphous region. Modelling of space charge accumulation in XLPE as consequence of crystalline and amorphous regions requires precise understanding of the morphological structure of the insulation. Effect of XLPE morphology on space charge formation is not treated in this paper. Here, it is assumed that XLPE is a uniform dielectric and only space charge formation due to temperature gradient is analyzed. To study formation of space charges under temperature gradient and its effect on electric field distribution in cable insulation, Poisson's equation (1) must be solved simultaneously together with the following equations [4, 5].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot J = 0 \tag{6}$$

$$J = \sigma E + \frac{\partial D}{\partial t} \tag{7}$$

$$\frac{\partial T}{\partial t} = \frac{1}{DC}(k\nabla^2 T + h) \tag{8}$$

Equation 6 is the continuity equation in which J is the total current density and ρ is space charge density. Equation 7 is total current density inside the dielectric which is written as sum of conduction current (Ohm's law) and displacement current. Heat transfer in solids is governed by equation 8, in which T is the temperature (K), D is the density (kg/m^3), C is the thermal heat capacity (J/kgK), k is the thermal conductivity (W/Km) and h is the volumetric heat source density (W/m^3). Heat sources inside a cable are the Ohmic loss in the conductor, sheath and armor and dielectric loss inside the insulation. For simplicity it is assumed that the cable does not have an armor and the cable is perfectly cross bounded or single point bounded and hence there is no circulating current. Eddy and proximity current loss in the sheath and dielectric loss in XLPE are both small and are ignored here, hence only conductor loss is considered in this study which is the consequence of a fixed current load of 1 kA . Permittivity of the material is assumed to be constant with temperature and only the conductivity of copper and XLPE are considered to be temperature dependent. In this study it is assumed that the conductivity of XLPE is not field dependent because the maximum electric field in this case study is such that the field dependency of conductivity is negligible. Table 1 shows the parameter used in the model. Notice that Poisson's equation and continuity equation are solved only for the cable so permittivity of soil is not needed in this model. It is a common trick to consider permittivity of metal a very large value in electrostatic simulation to force the material act similar to a metal (zero internal electric field). In this model the conductor is modelled with its conductivity and the relative permittivity of conductor is assigned as 1. In any case the permittivity of the inner conductor does not influence the electric field distribution in the insulation since the outer part of the inner conductor is connected to a fixed voltage.

2.2 Model implementation and results

The cable is for 132 kV AC and hence the maximum nominal stress in the cable insulation occurs at peak voltage which is equal to 107.8 kV. To shorten simulation time [6], the soil layer is considered as a circle around the cable with a fixed temperature of 293.15 °K at the outer boundary. The error created by this approximation on the temperature gradient inside XLPE is small and hence was accepted. Figure 2 shows the geometry used to model the coupled thermal-electrical phenomena.

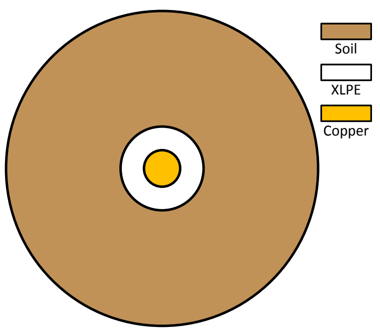

Figure 2. Geometry used to model electric field in cable impacted by space charge formation (soil thickness is not proportional)

Table 1. Parameters used in the simulation

	Conductor	XLPE	soil
Relative permittivity	1	2.3	-
Thermal conductivity (W/Km)	400	0.32	1
Density (kg/m^3)	8960	924	1300
Heat Capacity (J/kg·K)	385	2200	870
Outer radius (mm)	11.6	26.6	2600
$\sigma_{cu} = \frac{5.96 \times 10^7}{1 + 0.004 \times (T - 293.15)}$	$\sigma_{XLPE} \sim exp^{-9100/T}$		

COMSOL Multiphysics is used to solve the differential equations involved in this study. Despite the model was performed as 2D, but due to assumption of cylindrical soil layer the model reduces to a very simple 1D model. This however is enough to show the concept aimed at this paper. A step DC voltage is applied to the cable at t=0 s. Load of 1 kA is added to the cable at t=50 s. Figure 3 shows electric field distribution inside the cable 50 s after it is powered and after 50000 s when the cable reaches to the relatively stable thermal equilibrium. This is the so called field inversion in DC cables. Figure 4 shows the transient change of the electric field inside the insulation over time after loading of the cable. Figure 5 shows the time needed for field inversion, $5\tau \sim 11000\ s$. As can be seen from Figure 5, initially the electric field near the sheath jumps to around 5 kV/mm instantly after applying the step voltage. This is because field distribution is governed by equation 3 and because there is no space charge in the insulation yet. When the cable is heating up, the conductivity of insulation gets different values across the insulation thickness (due to different temperature) and hence space charges form, which alters the initial field distribution. Figure 6 shows the evolution of temperature on the surface of conductor and sheath of the cable. As can be seen the difference between conductor and sheath temperature (which is an important parameter in this study) reaches a relatively constant value after 11000 second while the absolute value of temperature changes even after 50000 seconds. More detail on the effect of temperature gradient on space charge accumulation in HVDC cables can be found in [3, 7].

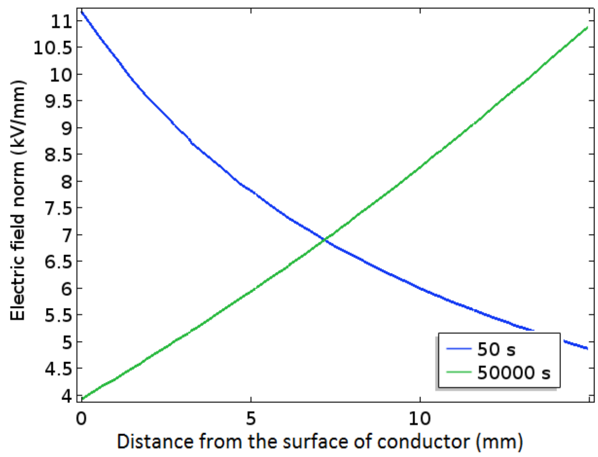

Figure 3. Field inversion in loaded DC cables

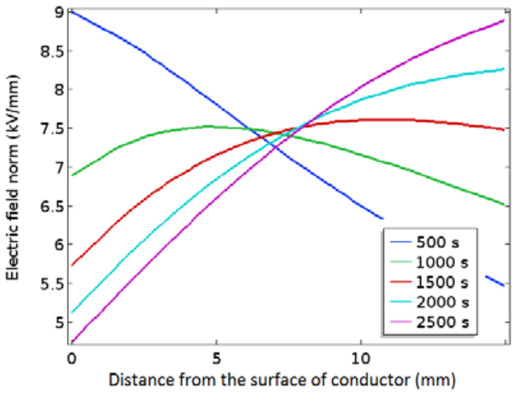

Figure 4. Change of electric field inside cable insulation over time due to formation of space charges because of temperature gradient

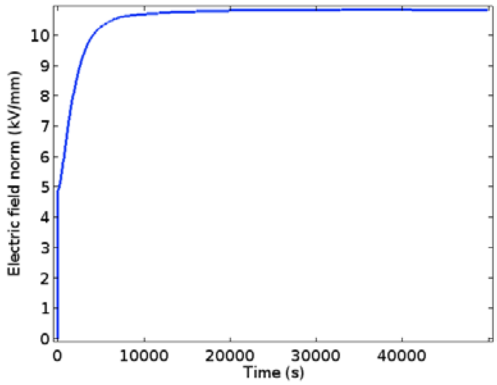

Figure 5. Electric field evolution at insulation part next to the sheath, $5\tau \sim 2200\ s$.

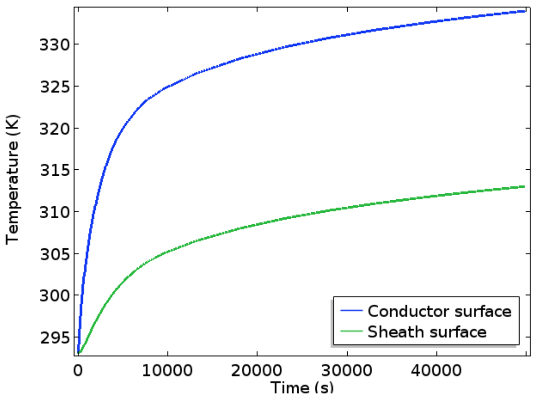

Figure 6. Temperature evolution on the surface of conductor and sheath

3. Effect of voltage waveform on electric field distribution

As can be seen from Figure 4, the electric field inside the cable becomes relatively flat between 1000-1500 s after applying unipolar stress to the cable. If the voltage waveform is controlled properly, it is possible to keep the electric field distribution relatively flat across the insulation. In such case it is possible to (theoretically) apply a higher voltage on cable insulation without exceeding the maximum allowed electric field on any part of insulation. To do so a trapezoidal voltage as shown in Figure 7 is applied to the cable. In this case it is assumed that the cable has already reached a thermal equilibrium. This means the cable is operated under AC first until thermal equilibrium is achieved thereafter the new waveform is applied. Transient consideration for changing the waveform from AC 50 Hz to trapezoidal waveform is not discussed here. The RMS value of this waveform is $1.32 \times V_{rms\_50Hz}$. Figure 8 shows the electric field on the surface of conductor and sheath. Figure 9 shows the maximum electric field inside insulation. As it is clear from Figure 8 and 9 the maximum electric field swings from the conductor to the sheath and the maximum does not always occur at the inner conductor or the sheath.

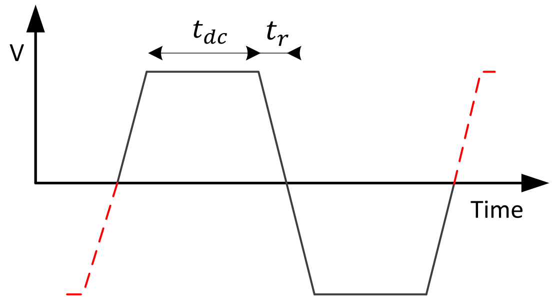

Figure 7. Trapezoidal waveform used in this simulation. $t_{dc} = 150$ s and $t_r = 17.5$ s

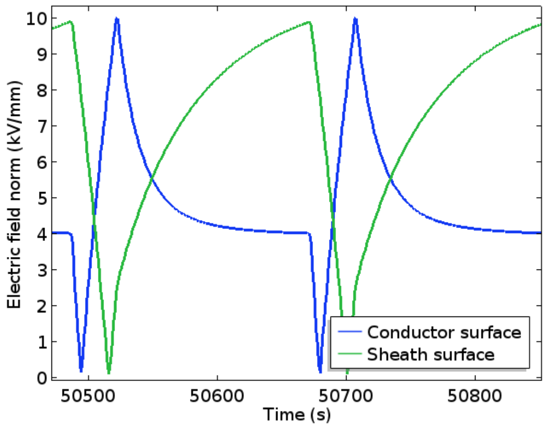

Figure 8. Maximum electric field on the surface of conductor and sheath under steady state

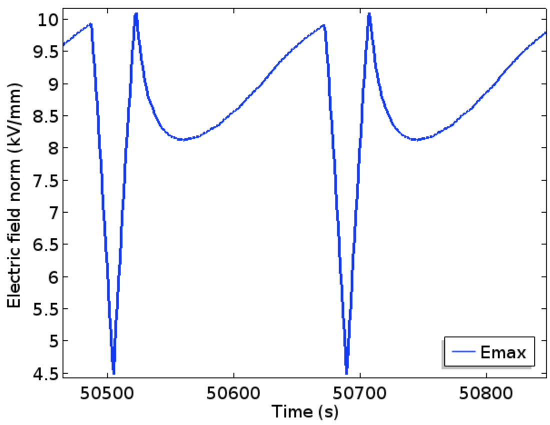

Figure 9. Maximum electric field throughout cable insulation

The maximum electric field shown in Figure 9 is 10.1 kV/mm, while the maximum field in the AC case is 11.2 kV/mm as shown in Figure 3. This means a voltage increase by a factor 1.1 still keeps maximum field below 11.2 kV/mm when this particular trapezoidal shape is used. The rms equivalent of this waveform is $1.45 \times \mathrm{V}_{\mathrm{rms\_50Hz}}$. This is more than DC voltage equal to the peak of AC voltage. The RMS value can be increased further if better trapezoidal waveform or other voltage waveform is used as the excitation generated by the inverters of a future inverter rich power system.

4. Conclusions

By coupling Poisson's equation, continuity equation and heat transfer in solids equation, formation of space charges due to temperature gradient was investigated. It is shown that impact of space charges on field distribution can be exploited to better utilize cable insulation. Under AC 50 Hz maximum electric field occurs close to the conductor while at DC voltage under load maximum electric field occurs close to the cable sheath. This results in inefficient usage of cable insulation system for both AC and DC cables. To create a more uniform field distribution inside cable insulation, a trapezoidal voltage waveform was introduced. It was shown than with a trapezoidal voltage waveform with $t_{dc} = 150\ s$ and $t_r = 17.5\ s$ it is possible to achieve a RMS value of 1.45 times than of V_{rms_50Hz} without exceeding electric field at any point of the dielectric above the maximum allowable AC electric field strength. As such, theoretically it is possible to achieve a continuous 45% capacity enhancement by using the proposed voltage waveform compared to AC case. By tuning parameters of trapezoidal waveforms or by using other waveforms even higher RMS voltage values are achievable.

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