Steady State and Transient Electric Fields until Thermal Limits in a HVDC Multilayer Cable

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ABSTRACT

Joints are critical yet one of the most vulnerable components in a HVDC cable system. In this paper, a multilayer XLPE-Rubber cable is simulated until thermal limits as a preliminary analysis to a cable joint. The results are further validated in an FEM based simulation software, with complete dynamics of transient electric field and temperature distribution. The theoretical results are validated by experimentally measuring leakage currents for multilayer cables at different fields and temperatures. The results are believed to be useful for cable joint manufacturers and utilities.

KEYWORDS

Multilayer cable, cable joints, DC breakdown, load cycle, thermal runaway, XLPE, rubber

INTRODUCTION

Cable Joints are one of the most critical yet vulnerable components in a HVDC cable system. Owing to multifarious factors such as, dissimilar permittivity and conductivity of layers, space charge accumulation at multiple interfaces etc. joints have much higher probability of failure than that of cable insulation [1].

Electrothermal analysis of cable joints had always been a complex problem, not just due to the intricacies of the geometries involved, but also due to the complexities in the processes such as non-linear field and temperature dependent conduction, dissimilar material properties, load dynamics etc. While the literature already exists for electric field and temperature of multilayer cables (and cable joints) [2-7], they are often limited to operating voltages. There is a lacuna regarding the same for breakdown voltages.

The authors had attempted to address the issue in their prior work on multilayer sheet samples [8]. In this paper, the authors have performed a preliminary analysis on the complete dynamics of electric field and temperature distribution of an XLPE-Rubber multilayer cable until thermal limits.

GOVERNING EQUATIONS

A 220 kV, 1000A DC XLPE cable is considered, over which, a rubber layer of same thickness is added, hoping to emulate the phenomena in cable joints, albeit preliminarily, as shown in Fig. 1. The dimensions of the multilayer cable are provided in Table 1.

For the complete electrothermal analysis of the multilayer cable, two approaches were shown in this paper.

- **Steady State Approach**, where current continuity equation is solved analytically and heat continuity equation using FDM, along with appropriate boundary conditions, for steady state conditions.

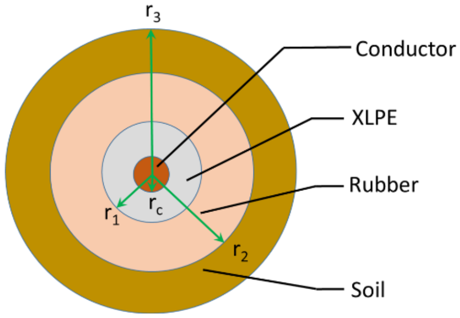

Fig. 1: 2D view of multilayer mable

Table 1: Dimensions of multilayer cable

S. No.	Layer	Thickness
1.	Conductor	40 mm (diameter)
2.	XLPE	25 mm
3.	Rubber	25 mm
4.	Soil	3 m

- **Transient Approach**, where both current continuity and heat continuity equations were solved numerically through FEM software, along with appropriate boundary conditions, for transient conditions (load cycle).

Both the approaches validate each other in addition to the experimental validation via leakage current experiments. In both the approaches, the following field-temperature dependent dc conductivity (σ) model [9] is used.

$$\sigma = A\, e^{a|\boldsymbol{E}| - \frac{b}{T}} \tag{1}$$

The experimentally determined conductivity coefficients for XLPE and Rubber were taken from the authors' prior works [10, 11] and are shown in Table 2 for convenience.

Table 2: Conductivity Coeffieicents of XLPE and Rubber [10, 11]

S. No.	Material	A $(\Omega - \mathrm{m})^{-1}$	a $(V/m)^{-1}$	b (K)
1.	XLPE	2.1279 x 10^{-11}	4.7336 x 10^{-8}	3685.12
2.	Rubber	4.5681 x 10^{-9}	2.4094 x 10^{-8}	4743.85

Steady State Approach

The current continuity equation in cylindrical geometry under steady state reduces to the steady state leakage current (per unit length) (I) which is given by

$$I = \sigma(r)\boldsymbol{E}(r)\,(2\pi r) \tag{2}$$

It is to be noted that for voltages below breakdown, the