Macroscopic Conductivity Models Fit for HVDC Cable Insulation

Bassel **DIBAN**, Giovanni **MAZZANTI;** University of Bologna, Italy, bassel.diban2@unibo.it, Giovanni.mazzanti@unibo.it
Ludovic **BOYER** SuperGrid Institute, Villeurbanne, France, ludovic.boyer@supergrid-institute.com;
Jerome **CASTELLON**, University of Montpellier, France, jerome.castellon@umontpellier.fr;

☒ **Young Researcher** (Proved full-time engineering and science university researchers and Ph.D.students under 35 YO)

ABSTRACT

Macroscopic conductivity models are the simplest and more common method used for electric field calculation in HVDC cables. Due to the scarcity of parameters of those models in the literature, it becomes necessary to fit the macroscopic models mostly found in the literature to the conductivity measurements of the state-of-the-art HVDC cable insulation. This paper introduces fitting models of the electrical conductivity measurements previously performed on HVDC cable insulation. The models are further modified to best fit the measurements introducing a synergistic relationship between parameters and stresses applied on the cable i.e., electric field and temperature. A comparison among all models found in the literature with their relevant parameters is also carried out.

KEYWORDS

HVDC Cables, Conductivity, Modelling, Fitting, Least Squares Method.

INTRODUCTION

HVDC cable systems are getting more attention in the last decades with an aspiration to reach higher operating voltages (hence higher operating electric fields). The latter implies developing new insulating materials having low values of electrical conductivity to be suitable for DC applications [1]. DC electrical conductivity is considered one of the most critical parameters in determining the validity of a certain insulating material in DC systems. The main reason is the dependency of the electric field distribution on the conductivity in DC cable systems as the poling DC field causes space charge mobility, trapping and/or de-trapping inside the cable insulation, hence changing the capacitive electric field distribution into a more complicated field distribution, dissimilar to the AC system where the electric field is still capacitive due to the absence of such space charge accumulation and mobility [2]. Physical models for describing the space charge behavior inside the insulation have been introduced with the proper fitting parameters to the space charge measurements (e.g., bipolar charge transport equation) [3]. Another simpler method for describing the space charge behavior is to be represented by the electrical conductivity in a phenomenological way, where the electrical conductivity is represented by a closed-form function of the temperature and electric field, then the charge density can be calculated as the charges accumulated at the discontinuities of permittivity and conductivity from Equation (1) [1]. The former methods are called physical (or microscopic) models, while the latter are called phenomenological (or macroscopic) models for DC electrical conductivity.

$$\rho = J.\nabla\left(\frac{\varepsilon}{\sigma}\right) \qquad (1)$$

While physical models are mainly used in numerical calculations in the full cables and accessories (joints and terminations) as a compromise with the difficulty in both finding its fitting parameters and its application, the macroscopic models are mainly directed to the applications where preliminary field calculations are required (e.g., cable design and standardization) due to its simplicity in both finding the fitting parameters and its application. In this paper, the five macroscopic DC conductivity models mostly found in the literature are used to fit the experimental conductivity measurements in [4]. Furthermore, these models are modified in such a way that the experimental data have a better fit to those new models.

THEORETICAL

The fitting method used in this study is the least squares in which coefficients of the best fit are obtained by minimizing the residual (i.e., the difference between the fit and the data), as follows:

$$r_i = y_i - \hat{y}_i \qquad (2)$$

$$\begin{aligned} min\,(S) &= min\left[\sum_{i=1}^{n} {r_i}^2\right] \\ &= min\left[\sum_{i=1}^{n} (y_i - \hat{y}_i)^2\right] \end{aligned} \qquad (3)$$

Where n is the number of data points. S is the sum of squares to be minimized. r_i are the residuals of the i^{th} data point. y_i is the i^{th} data. $\hat{y}_i$ is the i'th fit to data.

The electrical conductivity in DC cables is described by non-linear equations. Therefore, a non-linear least-squares method will be used in this application where the coefficients cannot be estimated using simple matrices. Hence, an iterative method is used as follows:

- Start with an initial estimate of each coefficient considered in the model based on the experience with fitting of similar models found in the literature.
- Produce a fitted surface for the current set of coefficients.
- Adjust the set of coefficients using one of the following algorithms:
  1) Levenberg-Marquardt: it is usually used when coefficients constraints are not provided.
  2) Trust-region: it is more efficient but it requires