Numerical analysis of space charge behavior considering ionic charges of cross-linking byproducts

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ABSTRACT

The most major problem and interesting issue of HVDC cables is the accumulation of space charges. In this study, we used finite element simulation to investigate the space charge behavior of low-density polyethylene (LDPE) and cross-linked polyethylene (XLPE) specimen structures, taking into account the dissociation of XLPE by-products and the behavior of ionic charges. Our simulation results revealed that the ionization of cross-linking by-products led to a hetero-charge distribution in the dielectric material, and that the initial impurity concentration had a noticeable effect on the accumulation of charges and the rate of electric field distortion.

KEYWORDS

Numerical Analysis; Space Charge; Dielectrics; HVDC Cable

INTRODUCTION

The growing demand for Renewable Energy Sources (RES) and interconnected power grids has led to an increase in the importance of High Voltage Direct Current (HVDC) cables in the global power industry. HVDC cable systems can enhance the overall power grid by promoting availability, flexibility, and sustainability through the integration of RES [1-2]. Consequently, there has been a significant rise in the use of HVDC cable systems worldwide over the past two decades. Commercial HVDC projects have primarily employed mass impregnated (MI) cables and extruded cross-linked polyethylene (XLPE) cables [3-4]. While HVDC MI cables have been the preferred insulation for HVDC applications, particularly for submarine projects, since 1950, the use of extruded cables has increased considerably in recent decades. Today, the installation length of extruded cables is comparable to, or even surpasses, that of MI cables, indicating a vast potential for extruded cables in future HVDC applications. Although XLPE has been used as an insulation material for High Voltage Alternating Current (HVAC) cables for a long time due to its improved thermodynamic performance, there are still challenges to overcome to achieve high voltage and power in DC [2,5]. Specifically, the crosslinking process with Dicumyl peroxide (DCP) at high pressure and temperature generates by-products that can locally increase the electric field in a DC environment by accumulating space charges [6-7]. Therefore, low DCP content and sufficient degassing time are essential for using XLPE in a DC environment.

Previous studies have analyzed the space charge behavior of polymer insulating materials using the pulsed electro-acoustic (PEA) method, a space charge measurement technique [8-9]. The research results showed that while Low-Density Polyethylene (LDPE) exhibits a homo-charge aspect, where charges of the same polarity injected from the electrode are distributed, XLPE promotes the storage of space charge due to by-products of DCP decomposition. As a result, not only the carriers injected from the electrode by the high field, but also the behavior of charges generated by ionization of by-products contribute to the accumulation of space charge in XLPE, resulting in the formation of hetero-charges. Since ionization can occur under low electric fields, both injection and ionization mechanisms are expected to occur when a DC electric field higher than the charge injection threshold of 10 [kV/mm] is applied to the dielectric. The space charge distribution will be determined by competition between the two charge generation mechanisms.

Numerical simulations of space charge behavior help understand physical phenomena by modelling charge generation, transportation, and extinction processes. While there have been many simulation studies on LDPE, studies on XLPE are rather limited, including the behavior of ionic charges by cross-linking by-products. Therefore, this paper analyzes the space charge behavior of LDPE and XLPE flat samples using the bipolar charge transport (BCT) theory that simulates the space charge behavior of polymer materials [10]. The results show that both homo-charges and hetero-charges were observed according to the presence or absence of the ionization process of cross-linking by-products. Furthermore, the location of maximum electric field and its intensity were compared. Additionally, by assuming that degassed XLPE with reduced the initial concentration of by-products, the space charge accumulation profiles and electric field distortion rate were compared.

SIMULATION METHOD OF SPACE CHARGE BEHAVIOR

To simulate the accumulation of space charge in the dielectric, we utilized the BCT model and constructed the simulation model using COMSOL Multiphysics, a finite element analysis software. The “Transport of Diluted Species” and “Electrostatics” modules within the software were employed and configured depending on the type of charges considered in LDPE and XLPE.

Bipolar Charge Transport Model

The BCT model is designed to explain how electrons and holes transport and accumulate in polymeric insulation materials. The model uses five different processes to describe the behavior of charge: injection, hopping, trapping, de-trapping, and recombination. When the electric field at the interface between the electrode and the dielectric exceeds a threshold field (10kV/mm), a large amount of charge is injected, and mobile charges are created within the insulation [11-12]. These charges move towards the opposite electrode in the direction of the