Impact of time dependent DC conductivity on electric field distribution in polymeric HVDC interface configurations

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ABSTRACT

The worldwide increasing amount of HVDC systems demands the implementation of cable systems. Especially, extruded HVDC cable systems and their prefabricated accessories are essential for a reliable energy transmission for the next decades. Those insulation systems require a deep understanding of the material behaviour and their interactions to system boundary conditions as temperature and electrical field strength. Especially, due to DC specific effects, detailed investigations in terms of electrical conductivity and space charge behaviour are important.

Within this paper, a novel method for evaluating polymeric insulation interface configurations is described, considering the DC conductivity long term behaviour. A general overview and evaluation of the long-term apparent DC conductivity is given, and an analytical mathematical description is presented. The impact of the individual material characteristics on the interface electric field distribution of a cable – joint configuration is investigated using a numerical field simulation. On the base of the obtained results, a generic relationship between interface electric field distribution and material specific long-term behaviour of DC conductivity is concluded.

KEYWORDS

HVDC, Cable, XLPE, Silicone Rubber, EPDM, DC Conductivity, Modelling

INTRODUCTION

In the recent decade, a rapid integration of polymeric HVDC cable systems has taken place. With the commissioning of the Nemo-Link interconnector in 2019, the first U_0 = 400 kV cable system with cross-linked polyethylene insulation (XLPE) is set into operation [1]. The demand of a dynamic transmission system requires the development of higher system voltage levels. The integration of polymeric HVDC cable systems of a nominal voltage level of U_0 = 525 kV is ongoing within the German corridor projects [2]. Conducted qualification tests on polymeric HVDC cable systems with U_0 > 525 kV are further published [3, 4]. These technical milestones demonstrate the importance of extruded HVDC cable system. However, the integration of extruded HVDC cable systems requires a fundamental understanding of the physical effects of the insulation materials and the related interfaces.

According to Maxwell's equations, the electric field distribution in HVDC insulation systems is controlled by the conductivity *σ*, as shown in equation (1):

$$J = E \cdot \sigma \qquad (1)$$

where *E* is the electric field strength and *J* is the current density. Investigations into the DC conductivity of HVDC insulation materials have been discussed in detail in numerous studies, e.g. [5, 6]. It is often described that the apparent DC conductivity depends on intrinsic and extrinsic influencing factors. Under consideration of the sensitive characteristics of the apparent DC conductivity, the electric field distribution in a DC insulation system shows a temperature dynamic behaviour [7]. The complexity of the DC field distribution become even higher when considering an interface insulation system for cable accessories. Here, different materials (e.g. XLPE, silicone rubber, EPDM) with individual and specific apparent DC conductivity characteristics interact within the configuration. Studies investigating this interface field distribution between cables and cable accessories are presented among others in [8].

Most investigations of the electric field distribution in HVDC cable systems are based on empirical apparent DC conductivity models (see equation (2)). These models describe time constant apparent DC conductivity characteristics with $\sigma_a \neq \mathrm{f}(t)$. However, numerous studies on polymeric insulation materials indicating that the apparent DC conductivity tends to a long-term behaviour with $\sigma_a = \mathrm{f}(t)$ [e.g. 5, 6].

Within the following paper, a novel method for investigating the electric field distribution in HVDC interface configurations is presented. Beside the discussion of the understanding of the apparent DC conductivity, results on long-term apparent DC conductivity measurements are presented. Considering the long-term conductivity behaviour, numerical field simulation studies are conducted to assess the impact of the time dependence of the apparent DC conductivity on the interface electric field distribution.

APPARENT DC CONDUCTIVITY OF POLYMERIC INSULATION MATERIALS

The measurement and evaluation of the apparent DC conductivity is part of extensive research works and published in numerous studies, e.g. [5, 6]. In general, it is often described, that polymeric insulation materials tends so a significant dependency on temperature and electric field [7]. It is further reported that the apparent DC conductivity is defined by material specific intrinsic (e.g. polymer structure, additives, by-products) and extrinsic parameters (e.g. production and process parameters, diffusion behaviour, material interactions, temperature, electric field) [5, 9, 10]. These influencing factors shows clear the significant challenges in the experimental investigation of the apparent DC conductivity of polymeric insulation materials and their application in HVDC insulation system.

The comprehensive description of the apparent DC conductivity *σ* of a solid insulation material is often expressed by an empirical approach in the form of an Arrhenius equation as given in equation (2) [5, 7].