Diffusion of Water and Ions in High Voltage XLPE Cable Cores Submerged in Salt Water and Impacts on Testing

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ABSTRACT

Testing of high voltage cables according to the recommendations by Cigre TB722 is discussed, based on calculations of water diffusion and measurements of ion migration in an extruded 52 kV XLPE subsea cable. Calculations show that, for this cable design, 1000 h is required to obtain an uniform relative humidity in the insulation after pre-conditioning, and thus even conditions for water tree growth. The measured sodium ion concentration in the insulation screen increased from 2 to 6 ng/mg after two years. This indicates that ions do migrate into the insulation screen but at a very low diffusion rate. Water tree analysis of electrically aged samples show that it is not likely that these ions are causing inception of vented trees from the insulation screen.

KEYWORDS

High voltage cable, wet design; test regime; pre-conditioning; extruded insulation; relative humidity, diffusion of ions; water treeing

INTRODUCTION

The application of extruded lead as a water barrier sheath in future extruded high voltage power cable designs will likely be severely limited, as lead is on REACH's candidate material list for inclusion in Annex XIV. Cables with an alternative water barrier sheath design, or with a wet design have been developed for some years and are available for high voltage cables. In wet design extruded cables, water molecules are allowed to enter the insulation system over time during service. As subsea high voltage cable cores traditionally have been designed for dry service conditions, their performance when subjected to water is less known. The technical brochure Cigre TB 722 [1] recommends a test protocol for qualification of wet dielectrics, which includes wet pre-conditioning and accelerated electrical ageing of high voltage cable cores up to 72.5 kV. The purpose of the pre-conditioning is to ensure that the cable cores are sufficiently and uniformly saturated with water prior to being energized with an electrical field. In [1] the recommended duration for pre-conditioning at 55 °C is minimum 500h or the time required to reach the same saturation level at the conductor screen as a sample with 5.5 mm insulation after 500 h. While a target relative humidity (RH) is not specified in [1], the threshold for initiation of water tree growth in XLPE is about 70% RH [2]. However, the incepton rate and growth of water trees is strongly reduced if the relative humidity is below 100% RH [3]–[5].

The recommendation specifies that the saturating medium should be salt water, typically tap water added 3-6% sodium chloride [1]. However, the diffusion rate for ions in the insulation system and in particular the insulation screen is not known. It is therefore uncertain whether the cable samples will be in equilibrium with respect to ion migration after the pre-conditioning period. This could have an impact on the results after ageing, as ions and defects located at the interfaces between the XLPE insulation and the semi-conductive screens can be initiation sites for vented water trees in the insulation. Vented trees are considered more detrimental to service lifetime than bow-tie trees. It is also not clear if the migration of the sodium chloride ions cause any vented water trees if they reach this interface.

The main purpose of this paper is to discuss the wet pre-conditioning procedure in [1] and the effect of migration of salt water ions on vented water treeing from the insulation screen.

Diffusion in Polymers

Water and other small molecules can migrate into polymers due to the free volume available between polymer chains, and be transported along concentration gradient towards areas of lower concentration. Using measured material properties, the absorption and diffusion of water in cable geometries can be modelled, using the continuity of the partial pressure of water across boundaries to compensate for solubility differences between materials [6]–[8]. The measured water transport coefficients for modern XLPE [9] have been slightly altered compared to commercial XLPE [10] from the 1980s Given the development of electrical insulation, it is likely that production processes, antioxidants and other additives have changed. The water transport properties of other insulation materials are expected to differ more, e.g. through use of fillers or using other insulating polymers. For example an electrically insulating polyether ether ketone has a diffusion coefficient around 200 times lower than XLPE [11], while a thermoplastic polyurethane for cable use have been found to have a solubility coefficient over 200 times higher than XLPE [10].

In case of ion migration into the insulation screen, the extremely low electrical field across the semiconducting screens leads to the dominant driving force being the concentration gradient. Migration is then likely occurring through a diffusion process. Although the sodium and chloride ions in salt water are dissociated from each other, electroneutrality means that they will migrate into a hydrophobic polymer as ion pairs [12]. Thus, detecting one migrated ion of the pair likely also means that the other is present in the same amount. For a semiconducting polymer the presence of polar groups in carbon black will have an effect on the ion transport, likely increasing the sorption of ions [13]. The diffusion of sodium chloride has been found to be many decades lower than water in other polymers [10], [13], [14]. The diffusion rate of sodium chloride in semiconducting polymers is therefore expected to be significantly lower than the diffusion rate for water.