STEM-EDS of Inception Sites of Vented Trees in a HV XLPE Subsea Cable

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ABSTRACT

High voltage XLPE cable cores have been subjected to wet ageing following the recommendations in CIGRE TB 722. The electrical ageing was performed at 500 Hz and 10 kV/mm. Vented water trees were detected initiating and growing from the semi-conductive screens. The inception sites of the trees were cut by cryo-microtomy and studied using scanning transmission electron microscopy with energy dispersive X-ray spectroscopy (STEM-EDS). Inorganic impurities were detected on both sides of the smooth XLPE-semiconductive screen interface close to the inception site.

KEYWORDS

High voltage XLPE cables, Vented water trees, STEM-EDS, Inception site

INTRODUCTION

The transition from medium voltage (MV) 36 kV inter-array subsea power cables to high voltage (HV) 72.5 kV is crucial to facilitate the increase in production of renewable offshore wind energy. This voltage level is expected to further increase to 145 kV [1]. Future designs of HV subsea cables for inter-arrays also include semi-wet or wet designs where water molecules are allowed to diffuse into the insulation systems.

The primary aging mechanism of wet-design cross-linked polyethylene (XLPE) cables is water treeing. This is a slow process which over the course of several decades can eventually result in service failure [2]. The pre-requisite for water treeing is an alternating electric field and a water electrolyte. Water trees consist of strings of micro-voids filled with water and there are likely paths or channels between the voids which facilitate transport of dissolved ions. The physical and chemical changes in the polymeric material associated with water treeing are permanent, as re-wetting of dried water trees restores their appearance [2, 3]

Significant advancements have been achieved in the cleanliness of cable materials, as well as in the manufacturing and handling processes of subsea cables. In particular, development of compounds resulting in a smooth interface between the insulation and semi-conductive screens has been important to prevent increased electrical field at the XLPE-semiconductive screen interface. This is crucial, as voltage stress enhancements could also promote water treeing [2]. Vented water trees are initiated at the semi-conductive screens and are considered more critical as they do not stop growing during service. Less critical are the bow-tie water trees initiated from small contaminants within the insulation, which stop growing after some time. [5, 6]

Impurities can originate from several sources, such as the carbon black used as a filler material in the semi-conductive screens, residues from the polymerization, antioxidants, and the surrounding environment [6, 7]. It is important to determine which impurities are causing inception of vented water trees, and from this how they can be inhibited. Research performed more than 20 years ago has paid much attention to the composition of foreign particles within the treed regions and on the insulation-screen interface [8]. By internal reflection Fourier transform infrared spectroscopy (FTIR-IRS), the presence of K, Ca, Mg and Si, amongst others, has been detected in the water tree. At the tree initiation sites, Si, O and S have been observed [9]. Other techniques, including micro-particle induced X-ray emission (micro-PIXE) and ionic chromatography, have detected organic and inorganic impurities such as sulphate, oxalate and acetate in resin pellets used for the semi-conductive screens [10].

The semi-conductive screens consist of carbon black particles uniformly dispersed in a polymer matrix, typically composed of ethylene-vinyl acetate (EVA) or ethylene acrylates [11, 12]. The polar nature of the ethylene copolymers gives rise to distinctive interactions with water molecules and ionic impurities present within the matrix. The polar groups in the polymer matrix enables hydrogen bonding with water molecules, thereby facilitating diffusion. Conversely, interaction between the polymer matrix and ionic impurities can impede diffusion, leading to comparatively slower diffusion rates than for water at the same conditions [13].

The main objective of this paper is to investigate the mechanism for vented water tree initiation in high voltage subsea power cables. In particular, vented water trees growing from an apparently smooth and contamination free interface between the insulation and semi-conductive screens normally observed in high voltage cables have been studied. The analysis includes cryo-microtomy of sections close to the XLPE-semiconductive screen interface which are characterized by scanning transmission electron microscopy with energy dispersive X-ray spectroscopy (STEM-EDS).

EXPERIMENTAL

Test object/pre-conditioning/ageing

An extruded 52 kV XLPE high voltage subsea cable with a conductor cross section of 400 mm^2 was aged in the laboratory according to CIGRE TB 722 [14]. The test conditions are shown in Table 1. The cable core was soaked in salt water (3.5 wt. % NaCl) at 55 °C. The wet pre-conditioning time was more than 1000 hours to ensure a water content of at least 95 % RH across the insulation wall prior to electrical ageing [14]. The ageing of the cable