Chemical ageing of subsea mass impregnated insulation cable paper

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ABSTRACT

This paper describes an accelerated ageing experiment of mass impregnated oil/paper insulation. The ageing was performed at four temperatures (70, 90, 110 and 130 °C) for two types of papers (Papers A and B) and at two humidity levels (0.1 and 1 wt %). The results show the influence of the initial moisture content of the paper on the ageing criterion. The humidity content of the cellulose paper has a decisive role in the degradation rate of the paper, as higher initial humidity greatly accelerates degradation.

KEYWORDS

Mass impregnated cables, cellulose, ageing

INTRODUCTION

Transition from fossil energy sources to renewables depend on reliable and efficient transmission of electrical power over long distances. For long-distance subsea transmission of large amounts of electric energy, high voltage direct current (HVDC) mass impregnated (MI) cable is the preferred solution [1]. The electrical insulation of such cables consists of lapped Kraft paper impregnated with a high-viscosity compound (the "mass"). They are also referred to as mass-impregnated non-draining (MIND) cables. The insulation is enclosed by a lead sheath for protection against moisture intrusion. External layers of polyethylene, steel tapes, steel wire armor, polypropylene yarn, and an asphaltic compound provide mechanical strength and protection against corrosion [2].

Although conventional HVDC MIND cables apply a well proven design, the physical phenomena and mechanisms limiting their power rating and operational life are not understood in detail. Improved knowledge on these limiting factors may facilitate improved MIND cable designs (e.g. increased power rating without increasing dimensions), and more flexible operation of existing MIND cables, without compromising the excellent reliability record of this technology. An increase in power rating by increasing the current rating of the cable will increase the temperature in the insulation. It is vital to know how this will affect both the short and long-term properties of the cable by understanding the dominant ageing mechanisms of the insulation system at increasing temperatures. Moreover, very little has been written on the specific ageing of mass impregnated insulation systems. The main reason is that the operating temperature of mass-impregnated HVDC cables is very low. Nevertheless, the temperature at which a cable operates will affect the rate of degradation. The rate of most chemical reaction rates doubles every 2-25 °C, depending on the activation energy.

Over time, the mechanical strength of the paper will decay. Even though, it is commonly acknowledged that the ageing is governed by temperature, a lot of research shows that water and oxygen influence the ageing of solid and liquid insulation significantly, in addition to this other contaminants (such as low molecular acids) produced during the ageing process also accelerates the ageing [3].

The causes for ageing of paper can be:

- Pyrolysis where heat can cause the breaking of the β-glucosidic bonds and the opening of the rings. This process results in the formation of free glucose molecules but also water, carbon monoxide and various acids.
- Oxidation where the presence of oxygen will cause the formation of water after reaction with the hydroxyl groups (OH)
- Hydrolysis where water will cause the breaking of cellulose molecules.

As ageing proceeds the molecular weight and degree of polymerization (DP) of the cellulose is reduced due to molecular cellulose chains being cut. The relation between the chain scissions (η) and measured DP is:

$$\eta = DP_0/DP_t - 1$$

DP_0 is the initial degree of polymerisation and DP_t is value after an ageing period t.

Most analyses of paper degradation have been based on the work of Kuhn and co-workers in 1930 [4], which was extended by Ekenstam in 1936 to relate rates of degradation to DP [5]. Ekenstam considered random, first order chain scission and showed a direct relationship of reciprocal DP with time. He further showed that this relation, combined with the Arrhenius equation, can be mathematically expressed as:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = A \cdot e^{\frac{-E}{RT}} \cdot t$$

Here, R is molar gas constant (8,314 (J/mole*K)), T the absolute temperature in Kelvin and E is the activation energy in kilojoule per mole. A is a constant depending on the chemical environment (such as water and oxygen content).

The aim of the work presented herein is to perform ageing experiments on MIND cable insulation: mixtures of cellulose and mineral oil. The most widely used parameter to assess the ageing status of the cellulose insulation of electrical equipment is the measure of the degree of polymerization (DP): the average number of glucose units of the cellulose molecules which is related to the mechanical strength of the paper (tensile strength). When the DP becomes very low, the mechanical properties of the paper insulation change, possibly influencing the oil and heat transport. Degraded paper could also be critical if the cable is subjected to external forces such as anchors or