Water migration into polymeric insulation of power cables

Anh **HOANG**, Amirhossein **ABBASI**, Erik **ERIKSSON;** NKT HV Cables AB (Sweden), anh.hoang@nkt.com, amirhossein.abbasi@nkt.com, erik.eriksson@nkt.com

Carl-Olof **OLSSON**, Olsson Tech Investigations AB (Sweden), carl-olof.olsson-external@nkt.com

ABSTRACT

This work focuses on analyzing the diffusion of water in the insulation of cables exposed to uniform temperature and temperature gradient by means of finite element simulation. For medium voltage cables without a metallic sheath, simulation results show that the water ingress is primarily controlled by the water permeability of the used polymeric sheath and the operating temperature in the cable conductor. For high voltage cables including a metallic sheath as the radial water barrier, an assumption of a defect occurring on the metallic sheath has been considered. Water migration from outside through the defect into cable insulation is negligible.

KEYWORDS

Power cable, polymeric insulation, water diffusion, water permeability, faulty water barrier.

INTRODUCTION

The presence of water and electric field in polymeric insulation of cable during its operation may trigger water treeing that accelerates the degradation of cable insulation [1]. Thus, water ingress into cable insulation system must be limited to ensure its reliable working in the entire service life of the cable.

For medium voltage applications, cables are typically designed with a wet insulation system, i.e., diffusion of water through the polyethylene sheath embracing the core to the insulation system is permitted. In this case the low operating electrical field in cable insulation allows for the presence of a relatively high water content. The wet design is most relevant from the technical and economical points of view for such comparatively inexpensive products of medium voltage class. For high voltage applications, a metallic sheath (e.g., made of lead) must be included as the radial water barrier protecting the insulation from water ingress and the respective solution is a so-called dry design.

Computer simulation is a powerful tool for analysing the mass transfer processes in general and the diffusion of water into cable insulation in particular. The tool can be effectively applied in developing cost-effective solutions that sufficiently mitigate the risk of cable insulation ageing associated with the presence of water [2]-[3]. In this study, the numerical simulation is employed for analyzing water migration into the cable insulation of the wet design and that of the dry design with a damaged radial water barrier.

MODEL DESCRIPTION

Model equations

The diffusion of water in the cable materials can be described by Fick's law of diffusion. According to Fick's first law, the diffusive flux $\boldsymbol{J}$ is proportional to the gradient of the water concentration c [kg/m^3]:

$$\boldsymbol{J} = -D\nabla c, \tag{1}$$

where D is the diffusion coefficient of water in materials [m^2/s]. Fick's second law expresses the continuity equation:

$$\frac{\partial c}{\partial t} + \nabla \cdot \boldsymbol{J} = 0, \tag{2}$$

that can be rewritten with the consideration of Fick's first law as:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D\nabla c) = 0. \tag{3}$$

For power cables and objects of laminate structure, discontinuity of penetrant concentration at material interfaces has been detected and the ratio of penetrant concentration in two materials is equal to the ratio of their saturation concentration [4]. Thus, the saturation concentration M must be taken into consideration while formulating the diffusion equation. The continuity equation (3) becomes:

$$\frac{\partial c}{\partial t} + \nabla \cdot \left(-DM\nabla\left(\frac{c}{M}\right)\right) = 0. \tag{4}$$

The saturation concentration M [kg/m^3] of water in materials is defined as:

$$M = S \cdot p_{sat.}, \tag{5}$$

where S is the solubility coefficient of water in materials and $p_{sat.}$ is the saturation pressure of water vapor in air. In general, the water solubility coefficient and diffusion coefficient are temperature dependent:

$$S = S_0 exp\left(-\frac{E_S}{RT}\right), \tag{6}$$

$$D = D_0 exp\left(-\frac{E_D}{RT}\right), \tag{7}$$

where S_0 and D_0 are pre-exponent factors, E_S and E_D are activation energies [kJ·mol^{-1}], T is absolute temperature [K], and R is the universal gas constant (R = 8.3145 J·mol^{-1}·K^{-1}). Water permeability (WP) in materials is defined as:

$P = DS$, or

$$P = D_0 S_0 exp\left(-\frac{E_D + E_S}{RT}\right). \tag{8}$$

Relative humidity (RH) [%] of a material is the ratio of the water concentration c to the saturation concentration M of the material:

$$RH = \frac{c}{M}100. \tag{9}$$

Model and its parameters

A numerical model was developed in the finite element simulation tool COMSOL Multiphysics® for studying water migration into the cable insulation of both wet and dry designs, where the latter is featured by a damaged metallic sheath. The wet design cable is illustrated in Fig. 1 and its geometry and material are provided in Table 1.