Modeling of the Thermoelectric Performance of a ±320 kV HVDC Underground Cable System

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ABSTRACT

The thermoelectric performance of a ±320 kV HVDC underground cable system is examined by means of analytical and FEM modeling. Both cable and joint geometry are investigated under steady-state and transient conditions, analyzing the different phases of a PQ test. Results facilitate the theoretical assessment of the cable system actual performance prior to the real PQ test.

KEYWORDS

Electric field, field inversion, HVDC cable system, PQ test.

INTRODUCTION

HVDC solutions gain increasingly more ground in solidly insulated transmission lines because of their higher cost-effectiveness than the respective HVAC ones, particularly for long distances. Thanks to Voltage Source Converter (VSC) technology, XLPE insulated cable systems have already been installed and are currently in operation.

In the present study, focus is made on the theoretical evaluation of the combined thermoelectric performance of a ±320 kV underground cable system. First, the electric field distribution is considered in the cable, under a given temperature drop across the XLPE insulation layer. Due to its resistive nature, HVDC field is substantially different than that of a HVAC cable [1]. Results derived from analytical models existing in literature are presented, covering both steady-state and transient conditions. An improved numerical algorithm is proposed [2], [3], making the analytical models used more robust and stable under different operating conditions. They are also compared against Finite Element Method (FEM) [4], showing a good agreement.

Since analytical methods are mostly limited to simple cylindrical geometries, FEM is subsequently employed to simulate the electric field distribution in more complex geometries such as a cable joint. Results in critical regions of the joint are shown, which are of importance before actual testing. The effect of inputs, such as the electrical conductivity of insulation, is also investigated [5].

FEM, including both electrical and thermal analyses, is then used in order to simulate the full heat cycles specified by IEC 62895 [6] and Cigré TB 496 [7] for a prequalification (PQ) test. Emphasis is given on the importance of the ambient conditions which have to be considered in order to control the temperature difference over the cable insulation. Time-dependent thermal and electrical profiles are presented. These provide in advance the designer with a full theoretical assessment of the actual performance of the whole cable system which is going to be later PQ tested. Finally, the electrical behavior under impulse voltage is modeled and investigated.

THEORETICAL BACKGROUND

In this section, the theoretical background for the calculation of the electric field distribution is presented under both transient and steady-state conditions. The generic formulation can be applied to any arbitrary geometry, while it is significantly simplified in cases of axisymmetric geometry.

Transient electric field distribution

Contrary to HVAC cables, the electric field under DC stress is temperature and time dependent. This is attributed to the resistivity of the dielectric medium which depends on temperature and electric field [1]. The transient electric field distribution can be described by the following equations:

$$\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \tag{1}$$

$$\vec{J} = \sigma \vec{E} \tag{2}$$

$$\vec{E} = -\nabla V \tag{3}$$

$$\nabla \cdot \left(\varepsilon \vec{E} \right) = \rho \tag{4}$$

where $\vec{J}$ the current density, $\vec{E}$ the electric field, ρ the space charge density, V the voltage potential, σ the dielectric conductivity, and ε the dielectric permittivity.

Due to the absence of any comprehensive theoretical model for the conduction in polymeric materials, the dielectric conductivity is usually described by the following empirical expression [1]:

$$\sigma = \sigma_0 e^{\alpha (T - T_{ref})} e^{\beta (E - E_{ref})} \tag{5}$$

where σ_0 the dielectric conductivity at reference temperature T_{ref} and electric field E_{ref}, and α, β the temperature and field coefficient of dielectric conductivity, respectively.

In order to calculate temperature T in (5), the heat transfer problem must be solved, which for transient conditions in solid medium is given by:

$$dC_P \frac{\partial T}{\partial t} + k \nabla^2 T = Q \tag{6}$$

where d, C_P and k the material density, heat capacity at constant pressure and thermal conductivity, respectively, while Q the external heat source including also the resistive heating by leakage current on dielectric medium.

Steady-state electric field distribution

The steady-state electric field distribution can be calculated by simplifying (1) and (6) to: