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Numerical simulation of coupled heat, liquid water and water vapor in soils for heat dissipation of underground electrical power cables

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HIGHLIGHTS

- Wind farms and heat dissipation in underground power cables.
- Cable lifetime, cable temperature and properties of surrounding soil.
- Coupled model for heat dissipation, liquid water and vapor transport in soils.
- Numerical simulation under real weather conditions.
- Cable temperature depending on construction of transmission line system.

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ABSTRACT

The trend towards renewable energy comes along with a more and more decentralized production of electric energy. As a consequence many countries will have to build hundreds or even thousands of miles of underground transmission lines during the next years. The lifetime of a transmission line system strongly depends on its temperature. Therefore an accurate calculation of the cable temperature is essential for estimating and optimizing the system's lifetime.

The International Electrotechnical Commission and the Institute of Electronics and Electrical Engineers are still employing classic approaches, dating back from the 1950s, that are missing fundamental phenomena involved in heat transport in soils. In recent years several authors [4,37] pointed out that for a proper computation of heat transport in soils, physical processes describing heat, liquid water and vapor transport must be coupled and the respective environmental weather conditions need to be considered.

In this study we present a numerical model of coupled liquid water, vapor and heat flow, to describe heat dissipation from underground cables. At first the model is tested and validated on a downscaled experiment [32], secondly the model is applied on a simplified system to demonstrate the strong relation of the cable temperature on soil water content and finally the model is applied using real weather conditions to demonstrate that small changes in the design of underground transmission line systems can lead to considerable improvements in both average as well as peak-to-peak temperatures.

1. Introduction

In the past the high prices and operational limitations of laying power cables subterraneously was one of the major reasons for using overhead lines. In the last years the need to connect an increasing number of new wind farms, is forcing many countries to face the prospect of installing hundreds of miles of new cables and hundreds more pylons across the countryside. Therefore the use of underground power cables has become now the only valuable alternative.

Increasing their lifetime is one option of reducing the high costs of underground transmission line systems. Ageing of underground power cables [21] can be accelerated by thermal (expansion/contraction, melting/flow of insulation, chemical reaction), electrical (electrical/water treeing, intrinsic breakdown), mechanical (yielding, cracking, rupture) and environmental factors (corrosion). These ageing mechanisms depend strongly on temperature: in the 80–110 °C range the degradation rate doubles with an increase of

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8–10 °C [15]. An experimental study [14] demonstrated that the mechanism of electrical treeing is very sensitive to temperature: the average growth rate can be more than 100 times faster at 70 °C than at 10 °C.

Hence a correct design of a buried underground power cable is based on its thermal analysis, needed to determine the ampacity of the cable, i.e., its current capacity. The detailed calculations employed to design an underground cable system have been developed many years ago: The International Electro-technical Commission (IEC) and the Institute of Electronics and Electrical Engineers (IEEE) employ the classic approach of Neher and McGrath [33]. This approach is based on the assumption that the soil is homogeneous and the thermal conductivity is constant. Clearly, these assumptions are not realistic, and although the soil used to fill the trench may have homogeneous properties, the soil surrounding the backfill has different properties. Because of the limitations of the classic approach, several analytical [13,18,34] and numerical [12,16,17,29] studies have been proposed.

However, these studies are still missing some fundamental physical aspects of heat dissipation in natural soils. Since early works in the 1950's and 1960's [20,38], it was found that the movement of soil heat, water vapor, and liquid water in soils are coupled. A very important process that determines the coupling between water and heat, is the transport of latent heat by vapor flux within the soil. Latent heat transport is not only related to changes in humidity but in non-isothermal processes it is also driven by temperature gradients. Soil temperature may be significantly underestimated when the energy transfer associated with vapor is not considered [37].

On the other hand, infiltration fronts after heavy rainfall events cause strong convective transfer of thermal energy away from the cable and can lead to sudden cooling of the cable. Sudden changes of temperature lead to shrinking and following expansion of the cable. These mechanical stresses within the system can favor electric treeing and shorten the system's life-time.

Another important issue for a correct computation is the estimation of soil thermal conductivity. The seminal study of de Vries [20] demonstrated that soil thermal conductivity is dependent on the soil textural composition. Moreover Campbell et al. [9], showed that soil thermal conductivity increased dramatically with temperature in moist soils. These results are a clear indication that thermal conductivity cannot be assumed to be a constant parameter and that knowledge of soil water content is necessary for a correct estimation of thermal conductivity.

Overall, to correctly describe heat dissipation of buried underground cables it is necessary to simulate coupled heat, liquid water and vapor fluxes for non-homogeneous materials and to include in the computation the dependence of thermal conductivity on soil properties and water content.

In this paper, we present a two-dimensional numerical model for computation of coupled heat, liquid water and vapor fluxes of an underground power transmission system. The numerical model will be applied:

1. to a downscaled experiment to validate the model,
2. to a system with realistic dimensions, but simplified geometry in order to highlight the importance of considering water flow when discussing heat dissipation from an underground cable,
3. to a system with realistic dimensions and geometry under consideration of real weather conditions during a 300 day-period.

Aim of this study is to demonstrate the key role of water flow – in particular of weather and soil conditions – in the overall energy budget and to present and validate a numerical model for heat dissipation from an electrical power cable under consideration of hydraulic dynamics. In this way we present an approach that opens new possibilities to optimize the design of underground transmission line systems under the constraints of the region's weather and soil conditions.

2. Theory

2.1. Description of coupled model

The following description follows mainly Bittelli et al. [4] where a one dimensional model of coupled heat, water and vapor flow has been introduced and validated with an evaporation experiment from bare soil under real weather conditions. Here we will provide a short description of the equations employed. More detailed informations about the parametrizations of soil hydraulic properties and interactions between soil and atmosphere can also be found in Ref. [7].

2.1.1. Transport equations

Liquid water flow is described by Richards' equation, where water flow q_w is driven by a gradient in water potential (sum of matric potential ψ and gravitational potential gz) and is proportional to the hydraulic conductivity K:

$$q_\mathrm{w} = -K\nabla(\psi + gz) \tag{1}$$

K depends in a highly non-linear way on the matric potential ψ.

According to Fick's law water vapor flow is driven by a gradient in water vapor concentration. Vapor concentration depends on both humidity h and temperature T. Therefore the total water vapor flow q_v can be formulated as sum of an isothermal flux component $q_{\mathrm{v,i}}$ and a temperature driven flux component $q_{\mathrm{v,T}}$:

$$q_\mathrm{v} = q_{\mathrm{v,i}} + q_{\mathrm{v,T}} = -D_\mathrm{v}c'_\mathrm{v}\nabla h - D_\mathrm{v}hs\nabla T \tag{2}$$

where D_v is vapor diffusivity, c'_v saturated vapor concentration, s the slope of saturation vapor concentration function and humidity $h = c_\mathrm{v}/c'_\mathrm{v}$ is the fraction between vapor concentration c_v and saturated vapor concentration c'_v.

Thermal energy flow in soils can be divided into sensible, latent heat and the convective part carried by flowing liquid water. Sensible heat flow is driven by a gradient in temperature T and is proportional to the thermal conductivity λ. Latent heat flow is the thermal energy carried by water vapor. It is proportional to the sum of latent heat of vaporization L and thermal energy of liquid water $\mathrm{TC_w}$. Thermal energy carried by liquid water is proportional to water flow q_w and thermal energy of water $\mathrm{TC_w}$. Therefore the total heat flow q_h is:

$$q_\mathrm{h} = -\lambda\nabla T + (L + \mathrm{TC_w})q_\mathrm{v} + \mathrm{TC_w}q_\mathrm{w} \tag{3}$$

Conservation of mass provides the relation between flow of water, both in liquid as well as vapor form, and change of water content $\rho_\mathrm{w}\theta$, where ρ_w is the density of water and θ the volumetric water content:

$$\rho_\mathrm{w}\frac{\partial\theta}{\partial t} = -\nabla\cdot(q_\mathrm{w} + q_\mathrm{v}) \tag{4}$$

Under low water potentials, the hydraulic conductivity of liquid water becomes very small and therefore the contribution of vapor flow can then be in the same range as liquid water flow or even bigger making vapor flow a key element of water transport. The contribution of water vapor to the local water content, however, can be neglected.