International Journal of Heat and Mass Transfer 80 (2015) 660–672

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of rainfall transients on thermal and moisture exposure of underground electric cables

Jeffrey S. Marshall *, Andrew P. Fuhrmann

School of Engineering, The University of Vermont, USA

ARTICLE INFO

Article history:
Received 23 June 2014
Received in revised form 28 August 2014
Accepted 26 September 2014

Keywords:
Underground cables
Cable heat transfer
Moisture transport
Thermal engineering
Power cable insulation
Rainfall

ABSTRACT

Cable ampacity analysis is generally performed assuming constant worst-state environmental conditions, which often correspond to a dry soil condition or to a condition with uniform ambient soil moisture content. The characteristic time scale of thermal variation in the soil is large, on the order of several weeks, and is similar to the time scale between rainfall events in many geographic locations. Intermittent rainfall events introduce significant transient fluctuations that influence the thermal conditions and moisture content around a buried cable both by increasing thermal conductivity of the soil and by increasing the moisture exposure of the cable insulation. This paper reports on a computational study of the effect of rainfall events on the thermal and moisture transients surrounding a buried cable. The computations were performed with a finite-difference method using an overset grid approach, with an inner polar grid surrounding the cable and an outer Cartesian grid. The thermal and moisture transients observed in computations with periodic rainfall events were compared to control computations with a steady uniform rainfall. Under periodic rainfall conditions, the temperature and moisture fields are observed to approach a limit-cycle condition in which the cable surface temperature and moisture content oscillate in time, but with mean values that are significantly different than the steady-state values.

1. Introduction

Determination of the current-carrying capacity (or ampacity) of underground electric cables is one of the key factors limiting operation of electric distribution systems, particularly in residential areas. Cable lifespan depends in a nonlinear manner on several factors, primary among which are insulation temperature, electric stress magnitude, and exposure of insulation to moisture [13]. The effect of temperature on insulation lifespan is often approximated by an exponential (Arrhenius) expression [20,18,19], so that the peak temperature values have a disproportionately large influence on lifespan degradation compared to the average temperature value. In order to reduce peak temperatures, ampacity is usually set for cable systems based on worst-case environmental conditions, usually consisting of dry conditions or conditions with uniform background soil moisture content. Water has a duel role on the cable lifespan. On the one hand, the thermal conductivity of most soils increases by a factor of 3–4 between dry and saturated conditions [12]. As a consequence, the presence of water decreases insulation temperatures, which has a favorable effect on cable lifespan. On the other hand, exposure to water can give rise to formation of water treeing degradation within the cable insulation [13], which over time can lead to deterioration of the insulation material and shortening of the cable lifespan.

The increasing availability of plug-in electric vehicles (PEVs) is expected to substantially increase electric loads in the near future, particularly within residential communities where underground cable systems are commonly used [6,31,5]. Moreover, the electric load associated with PEVs has large stochastic variation, depending on the percentage of a community that has electric vehicles. In order to accommodate residential PEVs while minimizing the cost of upgrading infrastructure, new charge-control schemes have been proposed to better manage electricity availability in distribution systems without exceeding load limits [27].

In the presence of large fluctuations of the electric load, it is important to have a good understanding of other transients imposed on the heat and moisture transfer around the cable, the most important of which originate from intermittent rainfall events. Rainfall is a key factor in determination of cable temperature and water exposure under actual environmental conditions. In many geographic areas around the world, between 25–40 rainy days during a year account for two-thirds of the total annual

* Corresponding author at: School of Engineering, The University of Vermont, Burlington, VT 05405, USA. Tel.: +1 (802) 656 3826.

E-mail address: jmarsha1@uvm.edu (J.S. Marshall).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.09.070
0017-9310/

Nomenclature

Roman letters

A_g	area of outer grid cell [m^2]
b	cable submergence depth [m]
c_S	specific heat of soil [J/kg · K]
c_w	specific heat of liquid water [J/kg · K]
C	effective soil heat capacity [J/m^3 · K]
C_w	heat capacity of water [J/m^3 · K]
d	cable diameter [m]
D	rainfall duration parameter (=τ_R/τ_L) [dimensionless]
D_{TL}	liquid thermal migration coefficient [m^2/s · K]
D_{TV}	vapor thermal migration coefficient [m^2/s · K]
D_T	total thermal migration coefficient[m^2/s · K]
$D_{\theta L}$	liquid isothermal diffusivity [m^2/s]
$D_{\theta V}$	vapor isothermal diffusivity [m^2/s]
D_θ	total isothermal diffusivity [m^2/s]
F	dimensionless rainfall period (=τ_P/τ_L) [dimensionless]
f_{out}	heat supply rate to each outer grid cell [W/m^3]
h	convective heat transfer coefficient [W/m^2 K]
h_{lv}	specific enthalpy of vaporization [J/kg]
H_x, H_y	grid size in x and y-directions [m]
I	rainfall intensity parameter $(=\overline{Q}_{rain}/K_{\theta 0})$ [dimensionless]
K_e	Kersten number [dimensionless]
K_θ	hydraulic conductivity [m/s]
L	latent heat of vaporization [J/m^3]
N_c	number of outer grid cells which receive a heat supply [dimensionless]
q_{surf}	cable heat flux per unit depth [W/m^2]
$\bar{q}$	average cable surface heat flux [W/m^2]
$\mathbf{Q}$	net water flux [m/s]
Q_{rains}	liquid flux due to rainfall, per unit depth [m/s]
r	radial coordinate [m]
R	cable radius (=d/2) [m]
R_I	radius of inner grid [m]
S	effective saturation (=θ/θ_{sat}) [dimensionless]
t	time [s]
T	absolute temperature [K]
T_f	temperature value at fringe point [K]
T_0	ambient temperature [K]
T_{surf}	average temperature around cable surface [K]
x	horizontal coordinate [m]
y	vertical coordinate [m]
v_{max}	maximum liquid velocity magnitude [m/s]
$\mathbf{v}$	liquid velocity [m/s]

Greek letters

ϕ	azimuthal coordinate [dimensionless]
η	soil porosity [dimensionless]
λ	effective thermal conductivity of soil [W/m · K]
λ_{dry}	thermal conductivity of dry soil [W/m · K]
λ_{sat}	thermal conductivity of saturated soil [W/m · K]
θ	moisture content [dimensionless]
θ_f	value of moisture content at fringe point [dimensionless]
θ_{sat}	moisture content of saturated soil (=η) [dimensionless]
θ_{surf}	average moisture content around cable surface [dimensionless]
ρ_s	effective density of soil [kg/m^3]
ρ_w	density of liquid water [kg/m^3]
τ	time scale [s]
τ_C	convective time scale (=$b/K_{\theta 0}$) [s]
τ_D	diffusive time scale $(= C_0 b^2/\lambda_0)$ [s]
τ_L	time scale of daily load variation [s]
τ_R	rain duration time scale [s]
τ_P	time scale between rain events [s]
ξ	dimensionless depth (=$-y/b$) [dimensionless]

precipitation [28]. This range corresponds to a typical average interval of 9–14 days between significant rainfall events. The range of time intervals associated with rainfall events is therefore similar to the time scale associated with heat transfer in the soil surrounding an underground cable [1], with the consequence that the temperature field around underground cables in regions with frequent rainfall may be nearly always in a transient state, influenced on a short time scale by the daily load variation and on a longer time scale by soil moisture variation associated with rainfall.

There is a substantial literature on prediction of cable ampacity based on thermal analysis within cables and the soil surrounding the cables. A survey of steady-state analytical methods is given by Neher and McGrath [23], which has also been extended to transient problems [24,2,16,4]. These analytical models are subject to a number of simplifications, including the assumptions that the ground surface is an isotherm and, for transient calculations, that the heat source changes as a series of discrete step functions. Numerical solutions for cable thermal fields have been reported using the finite-element method [7,14,22], the finite-volume method [8], and a boundary-element method [10]. Application of overset grid methods to cable thermal analysis were reported by Garrido et al. [9], Vollaro et al. [30], and Marshall et al. [17]. Overset grid methods are well suited for cable heat transfer problems since the characteristic length scale for heat transfer varies over a large range, from the cable diameter to the submergence depth of the cable. Problems with soil heterogeneity on cable heat transfer were examined by Tarasiewicz et al. [29] and Hanna et al. [11], and nonlinear effects due to temperature-dependent insulation electrical resistance was examined by Kovač et al. [15].

The effect of moisture variation on underground cable thermal fields was first examined computationally by Anders and Radhakrishna [3] using a finite element method, and later by Freitas et al. [8] using a finite volume method. Both of these studies neglect thermal convection caused by fluid velocity associated with moisture gradients, and they assume that the ambient moisture level is uniform. Specifically, the studies assume that no additional moisture is added to the system at the soil–air interface (i.e., no rainfall). A primary observation of these studies is the formation of a local dry region surrounding an underground cable, within which the temperature gradient associated with the cable thermal field causes moisture to migrate away from the cable. The presence of this dry region decreases the soil thermal diffusivity in the region surrounding the cable, which in turn increases the cable surface temperature. Moya et al. [21] report an experimental study of heat and moisture transport around a heated cylinder in unsaturated soil. The experimental results are found to compare well with numerical computations using a finite-volume method. The paper concluded that the primary influence of moisture on the cable surface temperature is through the influence of moisture on the soil thermal conductivity. This observation might seem to justify the common approach of simply prescribing a conservative thermal conductivity value for the soil and determining ampacity using only solution of the thermal equation. However, one problem with that approach is that cable insulation degradation is sensitive not only to thermal conditions, but also to water exposure.