Electrical Power and Energy Systems 91 (2017) 222–229

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Dynamic thermal rating of power lines – Model and measurements in rainy conditions

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ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form 21 February 2017
Accepted 2 April 2017

Keywords:
Dynamic thermal rating
Transmission lines
Numerical model
Rain
Measurements

ABSTRACT

The transfer capabilities of overhead power lines are often limited by the critical power line temperature that depends on the magnitude of the transferred current and the ambient conditions, i.e. ambient temperature, wind, precipitation, etc. To utilize existing power lines more effectively and more safely concerning the critical power line temperatures and to enforce safety measures during potentially dangerous events, dynamic assessment of the thermal rating is required. In this paper, a Dynamic Thermal Rating model that covers the most important weather phenomena, with special emphasis on rain, is presented. The model considers a dynamic heat generation due to the Joule losses within the conductor and heat exchange with the surrounding in terms of convection, radiation, evaporation, rain impinging and solar heating. The model is validated by comparison of the skin and core temperature of the power line with measurements under realistic environmental conditions.

1. Introduction

The increasing complexity of electrical power systems and increased demands for electrical power constantly pressure the transmission system operators (TSOs) to improve transmission capabilities. The placement of new transmission lines into the system, which is immediate solution to the problem, is unfortunately limited due to the difficulty of acquiring new transmission line corridors, the extensive financial burden and vast societal consensus for the environmental care. As a result, some existing lines are already overloaded causing bottlenecks that may and have already caused blackouts in the past [1]. The TSOs are thus striving to increase transmission capacity of existing overhead lines without compromising system stability.

The transmission capacity, i.e. maximum allowed current, is often limited by the maximum allowed temperature of the conductor. The temperature of the power line must not exceed a certain value, e.g. 80 °C in the Slovenian power system, which determines the maximal permissible sag of the power line. The temperature of the power line also affects the resistance and consequently the power loss [2], while its variation plays an important role in the structural decay of the power line [3]. Traditionally, the current carrying capacity of the line is assessed for unfavourable weather conditions, namely ambient temperature of 35 °C and wind velocity of 0.6 m/s without rain [4]. A more sophisticated approach is to dynamically determine the capacity considering the current weather conditions or the weather forecast, which would result in an increase of the current carrying capacity of the line, since most of the time more favourable conditions are expected. However, in order to implement dynamic determination of maximal allowed current, the temperature of the overhead line at given conditions has to be known.

The most straightforward approach to determine the power line temperature would be direct measurement, e.g., with Overhead Transmission Line Monitoring system (OTLM) devices [5]. Such an approach would, however, require vast number of measuring devices to effectively cover the whole power system. An alternative is a class of emerging indirect estimates that rely on the measurements of line resistance using synchronous voltage and current measurements by phase measurement units (PMUs) [6–9]. This alternative requires installation of several PMUs and adequate state estimation algorithms. Another option, considered in this paper, is to model the heat generation and exchange between the line and the surroundings to compute the line temperature.

With an appropriate physical model, a TSO can use metrological measurements combined with the weather forecast to predict line temperature in all segments of the transmission line and hence identify potential hot spots, i.e. spans with expected critical

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http://dx.doi.org/10.1016/j.ijepes.2017.04.001
0142-0615/

temperature. Such Dynamic Thermal Rating (DTR) systems have been developed for the past 30 years [10]. The CIGRE [11] and IEEE [12] guidelines usually serve as base models for evaluating line temperatures and thermal currents of overhead lines based on ambient conditions. Various discussions on DTR systems and their practical application can be found in [11]. The DTR model parameter uncertainty, as well as the diversity of uncertainty sources, has been taken into consideration in [13]. Recently, a self-validated computing framework for indirect loadability analysis has been proposed in [14].

However, all above mentioned guidelines [11,12] do not account for the effect of rain precipitation, which can have a significant impact on the cooling of the line in rainy conditions. Recently, a DTR model with consideration of precipitation has been introduced in [15]. The presented model significantly improves the agreement between the computed and measured skin temperatures in rainy conditions in comparison with the CIGRE or IEEE std. 738-2012 models. This paper proposes improvements of the model in [15]. Namely, instead of steady-state heat balance, radial and temporal dependant heat transport is considered, evaporation due to drying is introduced in addition to evaporation due to the incoming rain flux, and dependence of the wetted area on the precipitation rate is incorporated to cover broader range of rain rates.

The rest of the paper is structured as follows. First, the mathematical model describing heat generation and heat transport within the overhead line, including heat exchange with the surrounding, is presented. The paper continues with description of an in-house experimental site used to perform reference measurements [16–18]. In the results section, a comparison of the model results with the measurements is presented. It is clearly demonstrated that the model shows good agreement with the measurements.

2. The DTR physical model

The numerical model for dynamic thermal rating presented in this paper is based on the CIGRE equilibrium model [11]; however, extended with additional terms describing the rain precipitation [15] and the radial diffusion of heat through the power line [19]. The problem is schematically presented in Fig. 1. A heat transfer within an aluminium conductor is solved as

$$\lambda_{Al}\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}T_{Al}+q_i(T_{Al})=\rho_{Al}c_{pAl}\frac{\partial T_{Al}}{\partial t}, \tag{1}$$

and within a steel core as

$$\lambda_{St}\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}T_{St}=\rho_{St}c_{pSt}\frac{\partial T_{St}}{\partial t}. \tag{2}$$

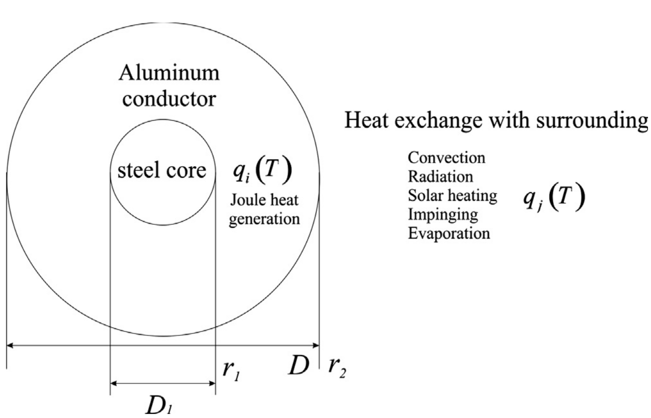

Fig. 1. Scheme of the DTR core problem.

The problem is closed with the following boundary conditions

$$\left.\frac{\partial T_{St}}{\partial r}\right|_{r=0}=0, \tag{3}$$

$$\left.\frac{\partial T_{St}}{\partial r}\right|_{r=r_1}=\left.\frac{\partial T_{Al}}{\partial r}\right|_{r=r_1}, \tag{4}$$

$$T_{St}(r_1)=T_{Al}(r_1), \tag{5}$$

$$-\lambda_{Al}\left.\frac{\partial T}{\partial r}\right|_{r=r_2}=\sum_j q_j, \tag{6}$$

and the initial state

$$T(r,t=0)=T_a, \tag{7}$$

where $\lambda_{\{Al,St\}}, r, T, q_i, \rho$ and c_p stand for effective thermal conductivity [19], radii, temperature, heat source term, density and specific heat capacity, respectively, q_j describe different heat terms due to the weather conditions and T_a stands for ambient temperature. The index *st* stands for steel and *al* form aluminium. The radius $r_1=D_1/2$ stands for interface between the steel core and the aluminium conductor and $r_2=D_2/2$ for the skin of the power line. In Eq. (2), we assume that only small portion, i.e. below 1%, of electric current flows through the steel core [19].

The Joule heating is described as

$$q_j=\frac{4}{\pi D^2}I^2R(T)\left[\frac{\mathrm{W}}{\mathrm{m}^3}\right] \tag{8}$$

with temperature dependant conductivity $R(T)$ defined as [11]

$$R(T)=R_{20}(1+\alpha_{20}(T-20\,^\circ\mathrm{C})), \tag{9}$$

where R_{20} stands for resistivity at 20 °C, $\alpha_{20}=4.5e-3\,^\circ\mathrm{C}^{-1}$ for the thermal resistance coefficient, and D stands for the line diameter.

The convection is incorporated as

$$q_c=-h(T_s-T_a)\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right], \tag{10}$$

with h standing for the convection coefficient [11] that relates to the Nusselt number as $Nu=hD/\lambda_a$ and λ_a is the air thermal conductivity defined as

$$\lambda_a=2.368\cdot10^{-2}+7.23\cdot10^{-5}T_f-2.763\cdot10^{-8}T_f^2\left[\frac{\mathrm{W}}{\mathrm{mK}}\right], \tag{11}$$

with the film temperature $T_f=(T_a+T_s)/2$, where T_s is the surface temperature of the conductor. The Nusselt number is determined empirically with $Nu=BRe^n$ [20,21], where B and n stand for empirical parameters that characterize the power line properties – wind angle and natural convection, and Re stands for the Reynolds number $Re=uD/v_f$, with u standing for effective wind velocity, i.e. normal component of the wind regarding the power line, and v_f is the kinematic viscosity computed as:

$$v_f=\frac{1}{\rho_a}(17.239+4.635\cdot10^{-2}T_f-2.03\cdot10^{-5}T_f^2)\cdot10^{-6}\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right], \tag{12}$$

$$\rho_a=\frac{1.293-1.525\cdot10^{-4}H+6.379\cdot10^{-9}H^2}{1+0.00367T_f}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right], \tag{13}$$

where H stands for altitude of the power line.

The above model is only one among several empirical relations defining the heat transfer due to convection, e.g. the Churchill–Bernstein relation [22], the McAdams relation [23], the Zhukavskas relation [24], etc.