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Vulnerability assessment of the power grid against progressing wildfires

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ABSTRACT

Wildfires are common in many forest and grassland ecosystems. Power transmission lines are vulnerable to wildfires in their vicinity, mainly due to increased conductor temperatures as a result of heat released by the fire. This may damage the conductor and lead to violation of safety clearances between conductor and ground. To address the situation, a power system operator may dynamically alter the ratings of the lines in the affected areas to reduce the current flowing through them, thereby assisting with conductor cooling. A unified model is proposed here that allows for dynamically changing the thermal ratings of conductors in the vicinity of a wildfire. The proposed model incorporates the radiative and convective heat released due to a progressing wildfire into the conductor thermal rating calculation in order to derive the updated conductor rating. Case studies are presented to show the effects of a progressing wildfire on a power system. It is shown that dynamically changing the ratings of power lines changes the flow of power through the network, moving the system towards a sub-optimal operating point. Under heavy loading conditions, this may even lead to imbalance between load and generation, therefore forcing involuntary load shedding to avoid system collapse.

1. Introduction

Dispatching the generation units within a power system depends in part on the available capacity of the power transmission lines. While for longer lines, stability and sometimes voltage drop concerns determine the available capacity, for shorter lines thermal rating is often the deciding factor. The latter is determined by the conductor's maximum allowable temperature which in turn limits the conductor's rate of annealing and cumulative loss of tensile strength [1]. To avoid the thermal stress on the conductors and the subsequent damage to them, this temperature must not be exceeded [2]. Initially, thermal rating of power lines was calculated using static methods under the assumption of fixed load and weather conditions [3], often considering worst case scenarios. This was clearly sub-optimal as it often overestimated the stresses to which the line would be exposed. Later, dynamic methods were introduced which allowed for adjusting the thermal rating based on the variations in the operating and environmental conditions of the power grid. As opposed to static thermal rating, dynamic thermal rating (DTR) is able to deal with emergency situations such as unforeseen temperature rise in conductors due to drastic changes in weather conditions or a temporary increase in the loading of the power line. DTR introduces flexibility while ensuring optimal and safe utilization of transmission and distribution capacity.

One of the instances that call for dynamic adjustment of the power line rating is the case of a wildfire approaching the power system. A wildfire can occur in forested or grassland areas due to natural or man-made causes, and its behavior is affected by factors such as topography, weather conditions, and types of fuel, to name a few [4]. Transmission network, in particular, is vulnerable to wildfire threat. It is very common that power transmission lines are built near fire-prone areas. A wildfire can affect a transmission line in different ways. Large fires can damage transmission towers and poles, especially wooden ones, causing the line to completely collapse [5]. In addition, the particles and ions in the smoke and soot from the fire can decrease the electric strength of the insulation strings that insulate the conductors from the tower structure, as well as that of the air which is the insulation medium between the conductors. This, in turn, could potentially lead to insulation breakdown and subsequent flashovers between the conductors or between the conductors and the tower structure. In addition to this, the significant temperature rise in the conductors located in the vicinity of the fire may lead to excessive conductor sag and dangerous decrease in safety clearance of the line, as well as the loss of tensile strength in the conductor which may be irreversible.

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Nomenclature

A	projected area of conductor per unit length [m^2/m]
c_c	specific heat of the conductor [J/K]
D_c	conductor diameter [m]
h_c	convective heat transfer coefficient [W/m^2]
h_M	vertical position of conductor [m]
I	current flow through the conductor [A]
L	flame length [m]
Q_s	solar irradiance heat transfer rate per unit length of conductor [W/m]
Q_{se}	total solar and sky radiated heat flux rate (elevation corrected) [W/m^2]
Q_r	radiative heat loss rate per unit length of conductor [W/m]
Q_c	convective heat loss rate per unit length of conductor [W/m]
$Q_{r,f}$	fire radiative heat transfer rate per unit length of conductor [W/m]
$Q_{c,f}$	fire convective heat transfer rate per unit length of conductor [W/m]
r	distance from the fire front to the object of interest [m]
R	conductor resistance [Ω/m]
t	time [s] or [h], depending on the solution time-frame
T_a	actual air temperature [°C]
T_c	conductor's temperature (usually at the surface) [°C]
$T_{c,max}$	maximum permissible conductor's surface temperature [°C]
T_f	flame zone temperature [°K]
V_f	fire rate of spread [m/s]
V_w	wind speed [m/s]
W	flame width [m]
α	solar absorptivity [dimensionless]
γ	flame tilt angle [degree]
ε_{FZ}	flame zone emissivity [dimensionless]
ε_c	conductor emissivity [dimensionless]
θ_s	effective angle of incidence of the sun's rays [degree]
θ_w	angle of wind direction with respect to conductor axis [degree]
μ_a	dynamic viscosity of air [Pa–s]
ρ_a	density of air [kg/m^3]
ρ_b	fuel bulk density [kg/m^3]
σ	stefan–Boltzman constant [W/m^2K^4]
τ	atmospheric transmissivity [dimensionless]
Φ_c	conductive heat flux [W/m^2]
Φ_r	radiative heat flux [W/m^2]

To avoid thermal stress and violation of safety clearance, the first mitigation action is to adjust (i.e. reduce) the flow of power through the affected lines in order to maintain the conductor's temperature within the permissible range. This can be achieved by dynamically modifying the thermal ratings of the lines based on the fire behavior, its distance to the line, and weather parameters. These modified line ratings should then be incorporated into the operation of the power grid.

Usually, optimal power flow (OPF) program is used by utilities to determine the optimal dispatch of the generating units. Here, the objective is to find the most economical operating point subject to various operational constraints. One of the constraints which controls the flow of power through the network is the available capacity of the transmission lines, which is determined by their ratings. As such, changing the ratings of one or more lines (for example due to a wildfire approaching them) would change the operating point of the system which could lead to increased costs. In extreme cases, lack of local generation in conjunction with reduction in line capacity may force utilities into shedding loads, which is highly undesirable and has large financial implications.

The main purpose of this paper is to provide a framework for assessing the impact of a progressing wildfire on the power system and assist grid operators in making updates to the line ratings (to be used in OPF and generation dispatch). An algorithm is proposed that incorporates the heat produced by the wildfire into the thermal rating calculation of the power lines in order to find the modified thermal rating in the presence of a wildfire. The proposed methodology applies equally well to both power transmission networks and power distribution networks with overhead conductors. Although, it should be noted that the threats posed by wildfires to the distribution systems are mostly in rural or less densely populated areas. This is because in urban areas, which are typically more densely populated, many overhead conductors are usually replaced with underground cables. In addition, less availability of fuel in these areas can help hinder the rate of spread of the fire.

It should be emphasized that the reduction in insulation breakdown due to wildfire smoke and soot could potentially pose a major threat to the transmission network. However, under this condition, the system operator faces limited options. As opposed to the reduced available capacity of a conductor due to temperature rise that can be temporarily balanced with reducing the current through the line, the electric stress on the conductors is a function of the voltage between them, which does not change by reducing the current through the line. Therefore, if severe smoke approaches one or more lines, it is the decision of the system operator whether to continue operating the lines as before or to shut them down completely. In other words, this is a binary (all or none) decision. This decision can be made heuristically by the system operator based on the information received from the field/fire crew, e.g. the intensity of the fire, the type of fuel, the distance to the conductor, the wind speed, etc. Currently, to the best of our knowledge, an explicit mathematical relationship that relates the amount of smoke to the operability of the line does not exist in the literature, and as such, we have not included this aspect in the paper.

The rest of this paper is organized as follows: Sections 2 and 3 review the state-of-the-art in DTR and wildfire behavior models, respectively. Based on the models proposed in the literature, a comprehensive model is then developed in Section 4 for calculating DTR of transmission lines in the presence of wildfires. Section 5 presents a case study of a test power system and shows how a wildfire can impact its operation. Finally, Section 6 summarizes the concluding remarks.

2. Calculating the dynamic line rating

Several studies have addressed the problem of calculating DTR in power networks. Electric Power Research Institute (EPRI) proposed a simple algorithm to adjust the nameplate rating of a power line solely based on variations in the ambient temperature [3]. In a more detailed approach, IEEE Standard 738-1993 [6] proposed a thermal balance model for DTR of bare-conductor overhead transmission lines. The model is a first order differential