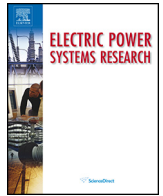




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An approach to dynamic line rating state estimation at thermal steady state using direct and indirect measurements

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ABSTRACT

Dynamic line rating has emerged as a solution for reducing congestion in overhead lines, allowing the optimization of power systems assets. This technique is based on direct and/or indirect monitoring of conductor temperature. Different devices and methods have been developed to sense conductor temperature in critical spans. In this work, an algorithm based on WLS is proposed to estimate temperature in all ruling spans of an overhead line. This algorithm uses indirect measurements – i.e. weather reports and/or downscaling nowcasting models as inputs as well as direct measurements of mechanical tension, sag and/or conductor temperature. The algorithm has been tested using typical atmospheric conditions in Iceland along with an overhead line's real design, showing robustness, efficiency and the ability to minimize error in measurements.

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1. Introduction

Overhead lines (OHLs) are facing new challenges in planning, operation and control. For instance, power system operators seek to push the operational limits [1] while maintaining high reliability levels. Under normal operating conditions the capacity of short and medium OHLs is commonly restricted by the minimum clearance between the conductor and the ground [2], which is defined by the sag of the catenary. To optimize OHLs capacity given this kind of restriction, dynamic line rating (DLR) can be used [3]. With this technique a more realistic ampacity limit can be calculated. DLR sets dynamically ampacity limits using the actual atmospheric conditions, in opposition to the traditional approach (called Static Line Rating (SLR)), where the conductor's capacity is computed taking conservative or worst atmospheric conditions scenarios, that seldom occurs. The dynamic limit is commonly higher than the SLR limit; in Ref. [4] a higher ampacity (compared to the SLR limit) is measured 99% of the time when DLR is used. Consequently, a reduc-

tion in power congestion or bottlenecks and an increment of the margin of maneuver under contingencies is achieved when DLR is implemented. This is particularly beneficial when wind power is connected to the grid [5], because of the relation between wind speed, power generation and conductor ampacity. Indeed, given DLR advantages, applications for control, planning and operation of power systems are available in order to optimize these systems [6]. Examples of such applications are: inclusion of OHL temperature as a constraint to compute optimal power flows [7] or incorporating DLR into the scheduling [8,9]. These applications can be added to the nowadays energy management systems [10].

Direct and indirect methods are used for DLR. Indirect methods are based on computing the conductor's temperature using data from weather stations close to the OHL and/or using atmospheric models coming from the area of influence of the line [11]. In contrast, direct methods take measurements directly from the OHL (frequency of vibration, mechanical tension, sag position, among others [3]) in order to compute either the sag, the mechanical tension or the temperature over the conductor [10]. An additional option to increase reliability is the adoption of hybrid systems (direct and indirect measurements); for instance, in [12] both weather and tension measurements are used to monitor ampacity in OHLs spans. Although a set of DLR technologies is already

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available [13], a methodology to integrate both kinds of measurements to obtain a reliable overview of the entire line capacity is not available.

The conductor's resistance changes as a consequence of variations in temperature, which impacts the power flow [14] and the OHLs protections [15]. To model this, variations in temperature values along OHLs have been included in the line model in Ref. [16] by means of dividing the line into sections, based on gradients of temperature along the entire line. Given the relationship between resistance and temperature, the introduction of PMU measurements to estimate average conductor temperature along OHLs is proposed in Ref. [17]. Here the Weighted Least Square method (WLS) is applied. In a similar way, in [18] the average conductor temperature is computed at steady state and during thermal transients using only PMU, by means of linearizing the state estimation problem. In Ref. [19], an improved model based on PMU is presented. It considers the atmospheric conditions along the line route through π -equivalent circuits connected in series. These series represent sections of the OHL. Temperature is computed in the different sections.

In Ref. [20] the performance of PMU as DLR method is assessed, concluding that even though state estimation techniques are used, the error in the computed temperature is larger than acceptable margins as a result of both atmospheric changes along the line and error in measurements. To improve the conductor temperature estimation when applying PMU, different DLR methods can be used on the same OHL. For instance, in Ref. [21], the thermal resistivity coefficient is optimized through PMU and temperature measurements located in specific points of the line. This optimization is carried out as consequence of computing negative resistances when only PMUs are used. In Ref. [22], PMU and tension monitoring systems are used for DLR. This way, an overview of the line's temperature can be obtained using PMU and critical spans are directly monitored by the mechanical tension system.

As a consequence of the fact that critical span changes in time and space (which limits the OHL capacity), the number and location of spans to monitor have to be defined. In Ref. [23] a heuristic methodology to identify critical spans based on computing conductor temperature in each span is proposed. In that study the span temperature is estimated using data from historical weather reports and climate models. In Ref. [24] a similar methodology is developed considering the clearances to ground, instead of the conductor temperature. Although methodologies to identify critical spans tend to use optimization algorithms, a risk level is assumed in the spans that are not being monitored. In consequence, it is desirable to know or at least to estimate the state of all spans in an economical and reliable way. An option to estimate weather conditions along the line is to interpolate atmospheric parameters in space (nowcasting) using meteorological models and/or a set of atmospheric measurements [25] taken close to the influence area of the OHL. Thus, with a set of monitoring stations covering critical spans and nowcasting along the OHL, a reliable overview of the entire conductor temperature can be achieved. However, even assuming that a complete conductor capacity monitoring system is available in each span, errors in the computing of conductor temperature as a result of uncertainties in both measurements and conductor parameters are presented [26]. Moreover, error is higher for low currents [27]. This is common in OHLs that operate at low capacities in order to guarantee the reliability criteria $N - 1$. Consequently, various efforts have been carried out in order to quantify the impact of different kinds of errors over temperature estimation. In Ref. [27] a methodology to analyze the influence of conductor temperature measurement errors over the computed ampacity is presented. In Ref. [28] an estimation algorithm based on the Monte Carlo method is developed. It considers uncertainty in the heat transfer model and in atmospheric measurements. A

similar analysis is presented in [29], by applying affine arithmetic in order to identify critical spans and to find out the corresponding temperature.

The previous state estimation algorithms only apply to direct [17,18] or indirect measurements [28,29], but not to hybrid systems. Therefore, to minimize errors in temperature estimation of all spans of an OHL, this work proposes a state estimation (SE) algorithm based on WLS. In this algorithm the elements of the Jacobian matrix, the elements of the measurement weight matrix and the measurement functions are presented in a novel way. It uses the available direct and indirect measurements and adds the advantage of including redundant measurements as numerical weather prediction (NWP) and downscaling atmospheric nowcasting models, thus increasing reliability. This is important, since reliability is affected when DLR devices are included in the system [30]. In Fig. 1 the SE problem is shown. It is expected that the measurements (z) and the OHL parameters contain errors (e). The SE issue is stated with the objective of obtaining the best estimated both of the electrical RLC parameters and of the temperature (T_S) in each ruling span of the OHL. This paper is organized as follows: the different methods to compute the average conductor temperature are discussed in Section 2. In Section 3, the proposed methodology is presented and the algorithm to minimize errors in temperature estimation along the entire OHL is developed. Finally, simulation results obtained from testing this algorithm under typical atmospheric conditions are presented in Section 4. The simulations are based on real OHL data.

2. Review of dynamic line rating methods

In this section, mathematical models and approximations employed to calculate the temperature of OHL conductors using direct and indirect measurements are presented. These expressions are used as measurement functions in the formulation of the proposed SE algorithm. This algorithm estimates the conductor temperature in steady state, which occurs during normal operating conditions. In steady state, it is assumed that the current intensity and environmental conditions are constant during a certain period of time, typically 1 h [10]. Thus, the thermal transient term can be neglected. To use steady state analysis, temperature is estimated at the moment that the conductor reaches the thermal equilibrium, which is a conservative assumption. With this temperature value, the maximum conductor ampacity can be calculated. However, if a short-term overload occurs, the state estimation is affected, being necessary to do a continued estimation. The possibility of including thermal transients in a dynamic state estimation problem will be object of future research.

2.1. Indirect measurements – heat transfer equilibrium

Indirect method refers to the use of atmospheric conditions to compute the conductor temperature. This method is based on the heat transfer between the conductor and the environment as a consequence of heat losses and heat gains. Any change in the thermal conditions produces a thermal transient until the conductor reaches the thermal equilibrium. This equilibrium can be described by the heat balance

$$Q_J + Q_S = Q_C + Q_R \quad (1)$$

where Q_J and Q_S are the heat gains by Joule effect and solar radiation, and Q_C and Q_R are the heat losses by cooling and radiation. The inputs of (1) are the wind speed and direction, the solar radiation, the ambient temperature and the current intensity. As a consequence of wind variations in time and space, it is recommended to use average values [31] as input for the heat balance equation. These

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