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A probabilistic protection against thermal overloads of transmission lines

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ABSTRACT

An innovative overload protection scheme is proposed to enhance the reliability of classical overload relays. The protection logic includes an accurate thermal model of bare overhead conductors, which allows to explicitly estimate the line temperature using the electrical current and weather conditions. In particular, the climatic variables are suitably represented by stochastic models that include the periodic patterns (seasonality) of meteorological phenomena. In this probabilistic context, the decision whether to trip out the transmission circuit is made according to the stochastic distribution of the conductor temperature, which is evaluated in real-time using an optimal discrete filter. Simulation results show the novel overload protection could increase the reliability of classical relays.

1. Introduction

Transmission lines have never been so exploited as in the current organization of the electricity market. Basically, the congestion problems can be overcome by either constructing new lines or raising the capacity of the existing transmission circuits. In the modern market environment, the high costs of building an additional line are usually prohibitive, and so the most attractive solution consists in extending the capacity of existing transmission circuits. Strangely enough, most of the power utilities still use the static deterministic thermal rating to regulate the power flows in transmission lines [1,2]. The static deterministic thermal rating is based on the worst case ambient criterion (e.g., highest ambient temperature and lowest wind speed) and frequently leads to the conservative utilization of power assets. However, the worst case criterion might occasionally cause line sags below the safe clearances and short-circuits to ground in case of adverse weather conditions [2,3].

The real capacity of overhead lines is strongly dependent on the climatic variables, and a dynamic thermal rating can be used to increase the line ampacity [4]. Different monitoring technologies are available [5]: temperature-based, sag/tension-based and weather-based. In the latter case, the line ampacity is dynamically evaluated using real-time climatic measurements from monitoring systems deployed along the transmission circuit. Unfortunately, the costs of the meteorological stations still are a limiting problem, especially for long lines. An alternative solution to the installation of weather monitoring systems relies on probabilistic methodologies [3,6,7], in which specific probability density functions estimated from historical data are used to characterize the stochastic behaviors of climatic conditions. Based on statistical analyses of meteorological time series, the probabilistic methods intend to represent better the weather conditions by moving from the classical ambient criterion used in the static thermal rating to more accurate assumptions about the climatic variables.

Clearly, the overload protections of transmission lines should be tuned according to the real line loadability but, at the present time, the tripping characteristic of relays is determined offline using the worst case ambient criterion. This logic results in limited adaptability to climatic conditions and unreliable protection systems. Hidden failures [8] in protection systems, such as incorrect tuning of relays, commonly trigger multiple or cascading outages that might evolve to power system blackouts.

A solution to the poor adaptability of overload relays to weather conditions has been proposed in [9]. The tripping characteristic of relays (inverse curves) is evaluated online according to the weather conditions obtained from a meteorological station installed in the line. As the main drawback, the approach in [9] requires the deployment of extra weather sensors, thus increasing the total costs.

In this work, we present an innovative overload protection for transmission lines that copes with a variable ampacity obtained from historical weather time series. Moreover, we review the traditional operating principle of overload relays and extend it in order to explicitly compare the conductor temperature instead of the electrical current. The conductor temperature, expressed as a probability density function, is evaluated online using the thermal

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model of conductors, the measured current and stochastic weather models estimated form historical data. Although this work focuses on the transmission systems, the proposed overload protection can be seamlessly extended to the distribution networks. Preliminary results in [10] revealed the proposed protection could improve the performance of classical overload relays.

The paper is organized as follows: the proposed probabilistic protection, as well as the weather modeling techniques, are presented in Section 2. In Section 3, some numerical simulations are reported to compare the performance of the classical relay with the probabilistic overload protection. At last, some concluding remarks and future developments are discussed.

2. The proposed overload protection

The reliability of protection systems [11] consists in two different requirements: dependability, which is the ability to operate correctly when required, and security, which means the ability to refrain from unnecessary tripping. With respect to thermal overload protections, both requirements can be improved if more accurate climatic variables are used instead of the worst case ambient criterion. The classical deterministic weather conditions usually lead to an overestimation of the conductor temperature during the cold seasons with high probability of undesired trips. Conversely, the worst case criterion underestimates sometimes the conductor temperature during the hot seasons, where the risk of failure to operate might become unacceptable.

Another possibility to increase the reliability of overload protections relies on the introduction of the thermal model of bare overhead conductors into the protection logic. As a matter of fact, the classical overload protection refers to a quantity which is not the right variable to be controlled. The true quantity that must be controlled is the line temperature, since damaging effects on the conductors are caused by excessive temperatures rather than overcurrents [10].

2.1. Thermal model

The thermal model of bare overhead transmission lines is a first-order nonlinear differential equation that expresses the instantaneous thermal balance between heat gains and losses in the conductor [12]:

$$mc\frac{dT_c}{dt} = q_j(i, T_c) + q_s(S) - q_c(T_c, T_a, \nu, \varphi) - q_r(T_c, T_a) \quad (1)$$

where mc is the total heat capacity of the conductor, T_c is the conductor temperature, q_j and q_s are the Joule and solar heat gains, q_c and q_r are the convective and radiated heat losses, i, T_a, S, ν and φ are the conductor current, ambient temperature, solar radiation, wind speed and wind direction, respectively.

A sensitivity analysis has been performed in order to evaluate the contribution of each exogenous variable of thermal model to the conductor temperature. The sensitivity coefficients are analytically estimated using the partial derivatives of thermal model in (1) with respect to external inputs. By simply varying one input at a time, it is possible to obtain the variation of sensitivity coefficients of the conductor temperature with respect to that particular input, as illustrated in Fig. 1. The conductor used throughout this paper is the ACSR ⌀31.5 mm. Panels (a) and (b) show the sensitivity coefficients of the conductor temperature are approximately linearly dependent on the current and the ambient temperature, respectively. On the other hand, panels (c) and (d) confirm the strong nonlinear dependence of the conductor temperature on the wind speed and direction, respectively. Note also the discontinuity present in panel (c) around $\nu \approx 1.3$ m/s, which results from the change in the constants of the forced convection to correct the convective heat losses at low and high wind speeds. Since the sensitivity coefficient of the conductor temperature to the solar radiation is independent of the magnitude of this particular input, we have omitted its corresponding graphical representation (it is constant).

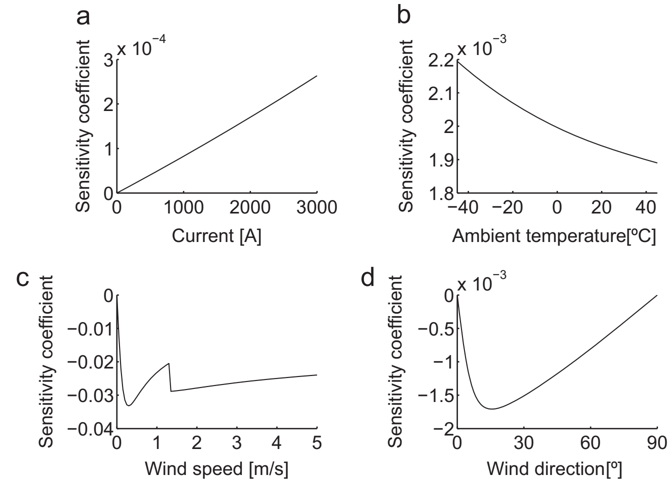

Fig. 1. Variation of sensitivity coefficients of the conductor temperature with respect to the electrical current (a), ambient temperature (b), wind speed (c), and wind direction (d). Parameters: $T_c = 50.5\,^\circ$C, $i = 1500$ A, $S = 500$ W/m^2, $T_a = 0\,^\circ$C, $\nu = 2.5$ m/s, $\varphi = 45^\circ$.

A careful investigation of the sensitivity coefficients reveals that, among the various exogenous variables, the wind velocity plays a crucial role in the thermal balance of overhead conductors, which calls for an accurate model. In fact, the order of magnitude of such a parameter is substantially higher than any other variable. The ambient temperature and the wind direction are important as well, whereas the conductor current becomes a relevant input as its magnitude increases. Last, the solar radiation is undoubtedly the less important quantity in the thermal balance, since the sensitivity coefficient of the conductor temperature to this input is equal to $9.92 \times 10^{-6}\,^\circ\mathrm{C\,m^2/W}$.

2.2. Weather models

As stressed by the sensitivity analysis, the weather variables have a major impact on the performance of overload protections for overhead transmission lines. Traditionally, deterministic approaches have been used to choose the climatic conditions. The idea behind these methods is simple: to identify the most adverse climatic conditions such that the line temperature will be always below its maximum design limit for all credible sets of weather variables. Fortunately, the climatic conditions in a real power system are seldom as severe as the classical ambient criterion. In effect, these reference values have long been recognized to provide an incorrect risk distribution of the line overheating (low in the winter, but high in the summer).

Climatic variables present different seasonal patterns that should be included in the weather models. For example, the ambient temperature is characterized by an annual periodicity that results in the four seasons. Overlapped with the annual pattern, there is an oscillation of temperature with daily frequency. Fig. 2 illustrates different seasonal decompositions of the ambient temperature recorded at each hour in Venice from 1992 to 2006 [13]. Panel (a) reveals that the yearly seasonal index of the ambient temperature varies from $-15\,^\circ$C to $+15\,^\circ$C around the annual mean temperature. Such an oscillation of 30 °C is definitely not negligible and should be considered when modeling this variable. Panel (b) shows that the ambient temperature within 24 h fluctuates between $-2\,^\circ$C and $2\,^\circ$C around the daily mean temperature. Even