DYNAMIC LINE RATING OPERATIONAL PLANNING: ISSUES AND CHALLENGES

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ABSTRACT

Network operational planning aims to provide smart and cost effective solutions to postpone conventional transmission and sub-transmission expansion. One emerging measure of improving the efficiency of power lines utilization is Dynamic Line Rating (DLR). DLR has to deal with different uncertainties ranging from production and consumption to meteorological variabilities. This paper presents the application of DLR from operational planning viewpoints and reviews relevant works. It also addresses DLR protection and challenges that the power system has to cope with.

INTRODUCTION

Progressive developments in the smart power grid technology have opened up the possibility to have increased secure transfer capacity for transmission and distribution networks without building new lines [1]. One approach towards this is dynamic line rating (DLR), which determines the actual current-carrying capacity based on continuous measurements rather than conservative assumptions on weather conditions. There are two approaches to determine DLR: indirect and direct. Indirect DLR estimation is a prediction-based method using data from local weather stations or generating the data by using numerical weather modeling. Direct methods on the other hand are based on monitoring line characteristic such as conductor temperature, line sag, the tension through the line and clearance to the ground [2].

One uncertainty for applying DLR to the system is the uncertain behavior of weather conditions and current flows. During recent years several mathematical methods have been proposed to predict the thermal rating of the conductor and to keep the maximum allowable current below safety limits [3]. Another uncertainty is the integration of renewable energy resources (RES) to the grid, specifically wind power plants that have been addressed in some research works [4-6]. The objective of these publications is the estimation of the amount of wind power generation in the presence of DLR and investigating possible ways to apply DLR to the control and management systems. In addition to the aforementioned uncertainties, various sorts of errors and/or failures may take place, such that line capacity will not be estimated correctly.

The purpose of this paper is to illustrate different applications of DLR for operational planning along transmission and sub-transmission (regional) networks [7-8]. Besides, a study of DLR protection has been conducted to get an overview regarding the risk of unfavorable interruptions.

OPERATIONAL PLANNING OF DLR

The increasing demand for electricity, the need for restructuring the generation to renewables, and obtaining an uninterrupted power system make the electric power industry working on possible smart solutions to increase the capacity of the existing lines. DLR technology is a short-term solution that helps to improve power system operational planning by providing a higher current capacity along transmission lines and reducing operational costs in the case of thermal limitations.

Line Rating and Conductor's Temperature

The term DLR was first introduced in the early 1980's for estimating the real time rating of overhead aluminium conductor steel-reinforced (ACSR) conductors. The initial aim was maximizing the load and evaluating the thermal rating for different environmental conditions [9]. IEEE standards discuss both dynamic and static models for calculating heat transfer and heat balance of the overhead conductor temperature [10]. The steady-state relation between heat gain and loss,

$$q_c + q_r = q_S + q_J, \qquad (1)$$

In which q_c, q_r, q_s and q_J are convection heat loss, radiation heat loss, solar heat gain and joule heating respectively.

For any variations in parameters as ambient temperature, T_a, wind speed, V_w, wind direction, φ, and conductor temperature, T_c, equation (1) turns into,

$$q_c(T_a, T_c, V_w, \varphi) + q_r(T_a, T_c) + \\ + m \cdot C_p \frac{dT_C}{dt} = q_S + R(T_c) \cdot I^2, \qquad (2)$$

Where $m \cdot C_p$ refers to conductor mass per unit length times the specific heat of the conductor, $R(T_c)$ is the AC resistance of the conductor at temperature T_c, and I is the conductor current and $\frac{dT_C}{dt}$ the conductor temperature derivative with respect to time.

In order to have an accurate thermal estimation, it is important to seek for independent variables for modeling the weather. However there are some variables, such as ambient and conductor temperatures as well as wind speed and direction, that reoccurs as independently modelled in the literature studied in this paper. In equation (2) some variables and parameters needed for full accuracy are omitted for simplicity.

Time-scale classification of DLR

From decision making perspective, here in this study, we categorize DLR studies into two main time horizons. Long-term studies that refers to (investment) planning and design issues on the one side; and short-term planning, such as weekly, daily, hourly and real-time operation concerning modeling of environmental data uncertainties [11] on the other side.

Long-term planning

The main objective of the long-term planning is the extension and/or expansion of the current transmission networks. The classical approach is to define some (bad, but yet probable case as the) worst case weather conditions, static line rating (SLR), for which planning is done. Since the on-average weather changes for different seasons, seasonal rating was introduced to increase the capacity of the line compared to the worst case scenario. Expected load growth and structural grid changes such as the integration of RES motivates a more efficient and flexible usage of the line capacities. Therefore, DLR as a part of the smart grid technology enables the utilities to postpone expansion through revealing the hidden current capacity.

Short-term operational planning

DLR is well suited for the short-term operational planning such as scheduled maintenance of overhead lines from a week ahead or up-rating the loaded lines if weather conditions allow. Updating the thermal rating of the critical lines based on the changes of the weather conditions is the main emphasis of the short-term studies. It is especially valuable in an emergency situation when higher capacity is needed. In order to keep track of changes in the meteorological data, weather forecast models are introduced for making informed decisions prior to the operation. This is especially important when it comes to managing the short-term overload capacity of transmission lines. Generally, ampacity estimation can be predicted in different time periods based on the importance of the line and the limitation of clearance to the ground for each line.

There are different techniques to handle uncertainties in the DLR calculation, of which probabilistic, hybrid possibilistic–probabilistic (fuzzy-based) and interval-based techniques are three common ones [11]. While each technique describes different method to achieve an accurate model, all of them work to show the effect of input parameters on the output of the model. In a brief, for the probabilistic technique, model input parameters are treated as random variables with a known probability density function (PDF). Combination of both random and probabilistic parameters forming the second technique as fuzzy-based DLR based on fuzzy set theory. And finally, an interval-based technique is to some extent similar to a probabilistic modeling with a uniform PDF, assuming that a specific variable obtains its value from a known interval [11].

The application of probabilistic DLR estimation is widespread through different research works. Modeling the climate changes through a Markov Chain Monte Carlo algorithm is carried out in [6, 12-13] not only to predict the conductor temperature each hour but also to increase the reliability of the DLR implementation. Modelling weather variables as multivariate correlated Gaussian random variables are used in [14] to characterize the weather data uncertainties each hour. The simulation is carried out by a Monte Carlo technique, then based on the minimum ampacity obtained at different spans, they estimate the maximum current capacity of the entire transmission line.

A probabilistic forecast method to model and predict the ampacity of overhead lines up to 27 hours ahead is introduced in [15] based on combining numerical weather prediction and a machine learning algorithm to calculate the ampacity of two lines located in Northern Ireland. The benefits of this method is in a daily operation to overcome some thermal constraints while providing safe and reliable operating conditions.

Comparing probabilistic to fuzzy (hybrid possibilistic–probabilistic) techniques indicates that fuzzy DLR has a better performance in terms of measuring inaccuracies. Besides, they are less computationally burdensome estimating the line thermal rating [16]. Despite advantages of hybrid possibilistic–probabilistic solutions, there are still very few papers working in this area [13, 16- 17]. In [13] the authors suggest an hourly prediction method by extending their Markov model to a fuzzy-based reliability model. They use an interactive method resolution (IMR) technique to solve the optimization problem for the load curtailment model. A fuzzy-based solution to calculate the DLR is introduced in [17]. The method presented is capable of calculating the DLR by predicting some specific weather variables an hour ahead. Ambient temperature, solar hour angle, as well as the wind speed and direction are the input variables that were characterized as fuzzy numbers. It was [17] concluded that if there is a good weather forecast, fuzzy evaluation can effectively model the measurement inaccuracies and condition changes.

During operation
System operation includes all the activities for predicting and estimating the thermal rating from several minutes prior to the real-time operation to on-line monitoring and measurement during operation [18]. Weather monitoring system is done through two common ways based of the network topology. One way is by using weather stations to measure data in a specific point of the line and the other is by getting access to on-line data sources from satellites. In addition to weather monitoring system, direct monitoring of the line's characteristic can offer more accurate estimation for the line's ampacity associated with the weather measuring system [4, 19-20]. In this regard [21] suggests a probabilistic state estimation method to predict and estimate the conductor's average temperature. This method uses an Extended Kalman Filter algorithm based on a dynamic heat transfer. Weather conditions, current intensity, conductor parameters and direct measurements of the line's characteristic are considered as input parameters. The reason behind direct measurements is to increase the accuracy of the DLR calculation in critical spans.

Curtailment in Combination with DLR
Installing additional generation units such as wind power plants will bring extra capacity to the system. At the same time, however, it will increase the risk of lines' thermal overloading. One practical way to relieve a critically overloaded line is the curtailment of consumption or production to ensure the availability of overhead transmission lines [22-23].
Since, there is a positive correlation between wind farms' outputs, wind speed and cooling of the conductor it is important to find a way to increase the capacity while keeping the system under the safety margins. Combining curtailment and DLR provides this opportunity to maintain both criteria at the same time. Such scheme allows larger amount of production to be connected to the grid with deduction in economic risks compared to using only the curtailment method. Moreover, it can relieve the possible congestion brought by RES integration. An approach presented in [24] is a flexible load shedding model to compromise between benefits of obtaining an allowed higher, more flexible current rating of the line, and the increased risks for system instability caused by weather data uncertainty. In fact, this combination will help to minimize the rate of produced energy curtailment per year and to increase the flexibility of the overall system.

DLR AND PROTECTION OPERATION

Increasing the demand for more electricity and migrating the electricity generation from fossil fuels to RES are some uncertainties that have been added to the electrical power networks. One way to mitigate the amount of curtailed energy in case of a risky situation is improving the protection system along the overhead lines. It also incorporates in reducing possible economical risks brought by unnecessary curtailment. In this regard, overload and overcurrent are two classical protection systems that prevent the conductor exceeds its thermal limits. One approach to improve the typical system is combining the DLR technology with the protection operation. Table 1 indicates different states for the DLR using terminology from protection operation.

Table1: Different states for DLR

States	Action is Needed	Action is Taken	Protection Operation
RMS<AA<EA	No	No	Correct Action
AA<RMS<EA	Yes	No	Failure to Operate
EA<AA<RMS	Yes	Yes	Correct Disconnection
RMS<EA<AA	No	No	Correct Action
EA<RMS<AA	No	Yes	Maloperation
AA<EA<RMS	Yes	Yes	Correct Disconnection

In Table 1 the term AA stands for the Actual Ampacity, EA for Estimated Ampacity and RMS for the RMS current that momentary flows through the line.
Clearly, failing to operate is one of the critical conditions that indicates that the DLR has been over-estimated. It can be defined as a situation in which the line is overloaded, but this overloading cannot be detected by the protection system. Under-estimation of the DLR is the other condition that cause wrong operation of protective devices. This can emanate from measurement errors or failure of communication sensors and can lead to unnecessary disconnections of production or loads, and/or costly usage of fast ramping production units, to change the power flows in the grid.

Thermal Overload protection

In order to prevent overheating of conductors in case of any faults or heavy loads, overload protection is installed in the power lines [25]. The principle of this protection relies on the quantity of the current compared with the predefined, offline, threshold. But as the conductor temperature is dependent on the current, line characteristics, and ambient variables, it would be more efficient to make the threshold variable and online. Thus, the model would be able to estimate the temperature of the conductor in a specific time interval and compare it with the maximally tolerable conductor temperature rather than comparing current intensity with the worst case current. Fig. 1. illustrates an overall scheme of the overload protection combined with DLR, at which CB refers to the circuit breaker.

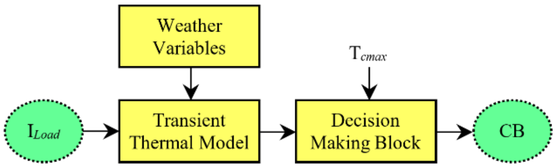

Fig. 1. A general protection scheme combined with DLR

The benefit of such modification is the better utilization of the power system considering the realistic weather condition and at the same time protecting the network in case of true risky weather conditions. In [26] research has been done modeling the weather as stochastic variables with Monte Carlo integration and linear filtering to estimate the distribution of the conductor temperature. Results indicate that the used method provides a fast approximation of conductor temperature which is necessary for a reliable operating decision.

UNCERTAINTY AND RELIABILITY

One of the DLR challenges is assessing the accuracy and validity of the models for calculating the line's rating. In order to reduce feasible risks brought by DLR, one can apply different DLR methods under similar conditions, e.g. in a same line, to find the most reliable method for each case depending on its application [27].

Bad data, difficulty in modeling weather variables and device inaccuracies are some other uncertainties from the measurement viewpoint that degrades the estimation accuracy. Besides, any modelling flaws, as well as deviations in geographical and conductor's parameters data may lead to inaccurate DLR estimations. Therefore, it is of great importance to analyze the risk of each DLR implementation to see how reliable it would be. Increasing the DLR reliability by optimizing the system operation is discussed in [28]. Authors in [29] estimate the reliability of DLR in heavily loaded networks to reduce the loss of load expectation considerably.

When weather variables change suddenly, operators need to have a fast reliable response to keep the system in a safe mode. One way of hedging for sudden weather changes is considering the average value of rating over a time horizon [30]. Calculating rating of components far from their observation point and using pre-defined critical spans are some other great uncertainties that should be investigated considering the reliability of DLR.

DISCUSSION

Dynamic thermal line rating associated with the protection system can increase the productivity of the line and the system, provided that accurate and reliable meteorological input models are applied. There are several challenges for the utilization of the DLR in power grids. Adjusting the rating of other electrical components such as transformers and protective relays with DLR technology is one of these issues [31]. Location-dependency of weather parameters is one other problem because the weather can vary through different spans or even through specified distances within each span. Thus, there is a need to identify critical spans and spots for monitoring and measurement [32]. Forecasting the weather data in a shorter time prior to the real-time operation and increasing the accuracy of the spatial resolution needed for the DLR forecasting are some issues good to consider in the future studies. Another subject in this regard is the emergence of technological advances that makes the system smarter and complicated. One of the features of a smart grid is usage of smart sensors and measurement systems like PMUs in the system [33]. As a result it is important to take the reliability of these systems into account while working on the DLR estimation.

CONCLUSION

This paper studies the application of DLR with focus on the operational planning viewpoint and stochastic aspects. Besides providing a thorough literature study, the paper discusses protection operation and schematic improvements.

In the end, increased renewable energy and load growth might lead to investments in new lines being necessary. Methods like DLR can help to release the SLR thermal constraints and increase the capacity of lines without large-scale investments, or at least postponing them.

Among different methods introduced for DLR operation, a generalized protection, combined with curtailment can have a significant effect on the short-term operational planning and help improving the reliability for network operators.

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