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Dynamic thermal rating of transmission lines: A review

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ABSTRACT

Electrical load growth and the addition of renewable energy generation occur at a rate that can outpace transmission development. As a consequence, transmission lines may become constrained. To accommodate load growth or distributed generation connections, one option is to operate existing transmission facilities up to their actual physical capacity rather than a conservative estimate of line capacity. Dynamic thermal rating of transmission lines provides actual current-carrying capacity of overhead lines based on real-time operating conditions. Dynamic Thermal Line Rating (DTLR) approaches vary significantly from one study to another in implementation, objectives and outcomes. Existing literature has presented several methodologies for DTLR adoption. This paper provides a comprehensive study of the literature on DTLR. It presents a survey and evaluation of various DTLR technologies, DTLR equipment, challenges with DTLR deployment, real world applications, and future approaches to DTLR implementation. The presented work is organized to allow a reader to understand and compare various DTLR approaches.

1. Introduction

The power transfer capacity of a transmission line is primarily constrained by three factors: stability, voltage, and thermal limits. Voltage and stability limits are reliability requirements. Thermal limits, however, are defined by not only reliability concerns, but, more importantly, safety concerns. They express the maximum operating temperature at which a line can be operated without violating safety and reliability requirements. The primary concerns in limiting transmission line thermal capacity are to maintain line clearance and to avoid conductor annealing [1]. Thus, line thermal rating should be determined from the worst case between the maximum permissible temperature and the maximum allowable sag.

Typically, the ampacity of long lines is set by the stability or voltage limits; the ampacity of short lines is determined by thermal limits. When thermal limits are applied, transmission line rating methods are classified into two categories: Static Line Rating (SLR) and Dynamic Thermal Line Rating (DTLR) [2]. Traditionally, transmission lines have been operated based on SLR, which provides the maximum allowable current-carrying capacity based on reasonable assumptions on environmental conditions [3]. Static ratings can be altered daily, hourly, or more frequently based on ambient air temperature. In the last case, they are referred to as ambient-adjusted ratings [4]. DTLR implies that the capacity of transmission lines is dynamically varying according to environmental conditions. Key operating conditions that can be measured to determine real-time line capacity are: (1) weather conditions, such as ambient temperature, wind speed, wind direction, solar radiation, and rainfall; (2) the line characteristics, such as line loading, ground clearance, conductor sag, tension, and conductor temperature. DTLR determination approaches are classified into two groups: direct and indirect methods.

In indirect methods, line rating is estimated from weather data that is measured or forecast along the transmission line. This approach is also called weather-dependent line rating [2]. Measured or forecast meteorological data are considered as the main inputs to weather-based line rating systems; some studies focus on expressing the capacity of a transmission line based on the real-time environmental factors [5]. To implement DTLR, weather sensors can be placed along a transmission line to gather weather data. Alternatively, meteorological variables for dynamic determination of ampacity can also be obtained from Numerical Weather Prediction (NWP) models [6]. The basic principle of weather-based line rating calculations is the evaluation of the conductor heat balance equation. IEC [7], IEEE [8] and CIGRE [9] offer standard methods for the calculation of transmission line ampacity. Indirect methods of calculating DTLR are discussed in detail in Section 3.1.

Direct methods of dynamic line rating are based on direct measurement of power line characteristics such as conductor temperature,

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line tension, ground clearance, and conductor sag. A number of methodologies to estimate the dynamic thermal rating of overhead transmission lines are described in [10] which also outlines key features of each line rating system. Direct methods are discussed in detail in Section 3.2.

Numerous operational and financial benefits from DTLR adoption are demonstrated by electric utilities worldwide [2,11–19]. DTLR enables additional transmission capacity over static rating. DTLR depends on wind cooling and, therefore more cooling is provided to the transmission line when the wind blows. Also, with a higher level of wind speed, the power generation of wind farms increases. A number of studies [20–23] have investigated the correlation between the potential power output of wind farm and the cooling of overhead line conductors. Results confirm a positive correlation between wind generation and line rating. Therefore wind farm curtailment could be mitigated by implementing dynamic ratings on relevant transmission lines. Another valuable aspect of dynamic rating is the ability to handle emergency situations where higher current is allowed for a short time period, taking advantage of the thermal inertia of the conductors [6]. DTLR technology provides additional flexibility to the system, allowing the electric grid to meet both base and peak loading by facilitating access to increased transmission line capacity.

Provided that DTLR estimation has adequate accuracy, a number of benefits can be achieved from DTLR adoption. However, to achieve these, accurate measurements and effective estimation tools are essential. On the other hand, there are some risks associated with DTLR. They include thermal aging [1], spatial and temporal variability of ampacity [24], and difficulty to obtain accurate predictions (described in Section 4). A disadvantage of dynamic rating is that it is a varying quantity, and it can be challenging for transmission system operators to deal with. Previous studies on DTLR have indicated various possible opportunities in DTLR implementation. However, its practical limitations have to be addressed. A variety of referenced papers claim that the benefits of DTLR include: improved grid operations and reliability; reduced need for operator intervention; reduced congestion of power lines; accelerated integration of wind generators; reduced carbon footprint; minimized curtailment of distributed generation production; reduced capital costs and investments; and the financial benefits to consumers and market participants. These potential benefits are discussed in details in [11].

In this review paper, Section 2 highlights various DTLR objectives presented in the literature. In Section 3, DTLR monitoring technologies based on different strategies to determine the power line thermal capacity are reviewed. Concerns and issues with implementing DTLR as well as its practical difficulties are discussed in Section 4. DTLR field trial implementation is discussed in Section 5. Future directions of DTLR application are presented in Section 6. Finally, Section 7 outlines the conclusions of this review.

2. DTLR objectives

Increased current-carrying capacity of transmission lines obtained by the application of DTLR technologies can provide multiple benefits to electricity systems. The main areas of applications for DTLR are to mitigate transmission line congestion, facilitate wind energy integration, enable economic benefits, and improve reliability performance of power systems.

2.1. Congestion reduction

DTLR provides a higher current-carrying capacity for transmission lines and thus can mitigate system congestion and reduce generation redispatching in the cases when congestion is caused by the transmission thermal limit. A group of papers have studied DTLR systems with the intention of relieving transmission line congestion and constraints [11,25–27]. In this category of papers, the increased transmission capacity is quantified to improve power system planning and operation. The main objective considered in this group of studies is relieving congestion and transmission constraints. Oncor demonstrated that implementation of a DTLR system can relieve congestion on transmission lines [11]. It is demonstrated that over a two-year period, 180 lines within the Oncor's electric system has experienced congestion at a total cost exceeding 349 million dollars [11]. The results also illustrate that a 5 to 10% increase in line capacity over the static limit can help to mitigate congestion on transmission lines [11]. DTLR implementation can help to reduce congestion costs and therefore load shedding risk [27]. A flexible load shedding scheme based on real-time DTLR is proposed in [27]. In another study [28], it is concluded that the amount of load shedding at high loading levels can be reduced with DTLR implementation. Implementing DTLR is especially important to relieve congestion on the transmission lines that are constrained due to the integration of renewable energy resources and therefore DTLR can help in reducing wind energy curtailment. There is also economic benefit in implementing DTLR system in relieving congestion in a constrained transmission line between the areas with different nodal electricity prices.

2.2. Wind energy integration

A wide number of research studies focus on the impact of dynamic thermal rating on wind energy integration [11,29–54,25,55–61]. The main finding of this literature is that employing DTLR has potential benefits for integration of wind generation and renewable energy to grid. Fig. 1 depicts the global cumulative installed wind capacity between year 2000 to year 2015. World-wide level of commissioned wind generation has observed a 25-fold increase in the last fifteen years. With the increasing penetration of wind power, static thermal limits of

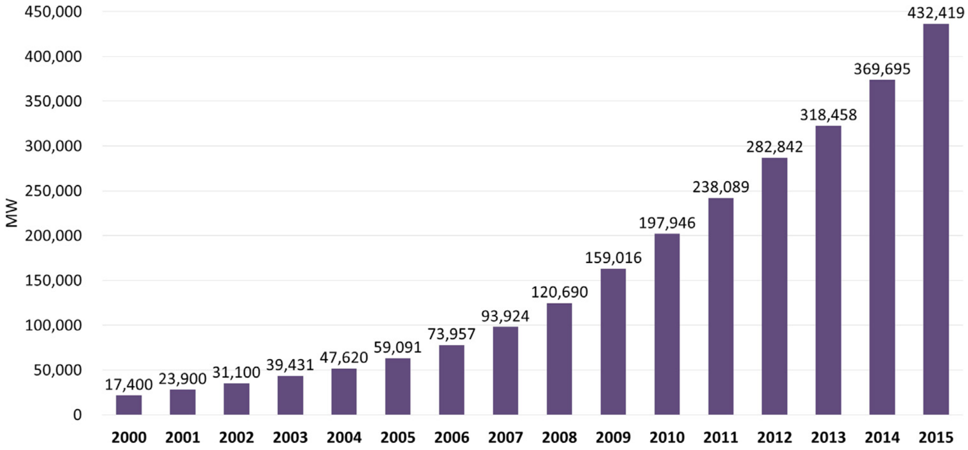

Fig. 1. Global cumulative installed wind capacity 2000 – 2015, Source: GWEC.