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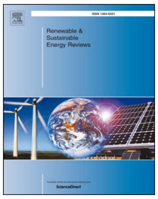

Dynamic thermal rating of transmission lines: A review

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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 re-dispatching 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

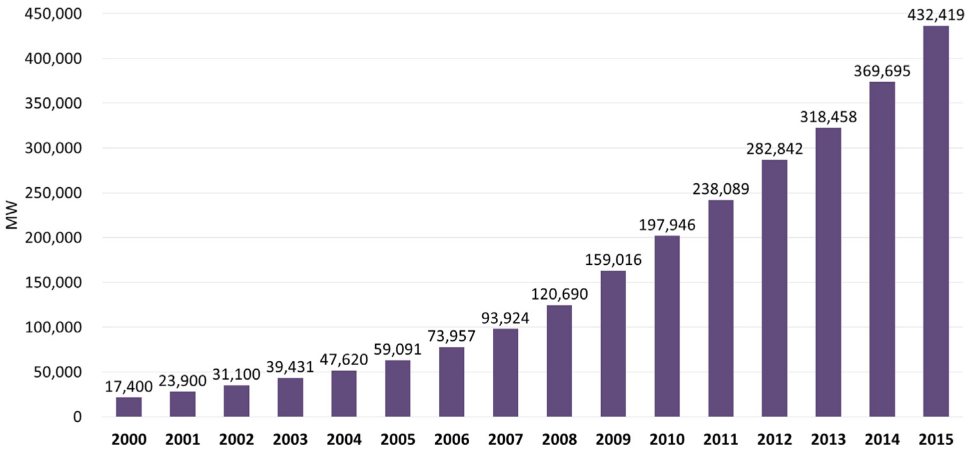

Fig. 1. Global cumulative installed wind capacity 2000 – 2015, Source: GWEC.

transmission lines can be a restriction for development of future wind projects. Integration of large number of renewable energy resources often drives new transmission construction or DTLR deployment. However, it should be noted that transmission system expansion is a time-demanding and costly process. On the other hand, DTLR can be implemented as an economic alternative approach to decelerate the need for building new transmission lines by capturing the real capacity of an existing transmission system. A DTLR system facilitates more wind energy integration since more wind power can be transferred during windy periods as additional line cooling is provided [48]. The proximity of a DTLR system to wind power facilities is critical for realizing the potential of the DTLR system to facilitate full delivery of available wind generation and avoid energy curtailments. New York Power Authority (NYPA) [62] has investigated the correlation between the potential power output of wind farm and the cooling of overhead line conductors. Results illustrate a positive correlation between line rating and generated wind power. NYPA also believes that implementing dynamic ratings on relevant transmission lines can help to mitigate wind farm curtailment [62]. In a similar study, Oncor electric delivery company observed that a potential increase in wind generation is achieved when lines' dynamic capacities increase and therefore a reduction in greenhouse gas emissions is expected through implementation of DTLR systems [11]. The impact of implementing a DTLR system in a wind integrated power system on its reliability is investigated in [28]. Results demonstrate that implementing a DTLR system increases network reliability and allows for higher wind energy penetration. The application of various DTLR systems for improved wind integration is reviewed in [63].

2.3. Economic benefits

Potential economic benefits of DTLR implementation can be assessed from the viewpoints of different market participants, including operators of the energy market, power utilities, and electricity consumers [11]. DTLR implementation incurs a higher cost than implementing a static rating, however, previous literature has demonstrated that higher reliability could be obtained as the result of DTLR integration [15]. To calculate the final cost from a utility perspective, we need to take into account the benefits achieved from DTLR implementation such as deferred transmission line construction and additional transmission capacity over static ratings, which could lead to significant savings. Hence, to make a fair comparison between SLR and DTLR, a complete analysis of the cost and benefits needs to be conducted.

The economic value of the increased capacity released by the DTLR system is evaluated by a number of papers [12–15,18,64–67]. These papers quantify the savings associated with deferring the building of new transmission lines and the total costs to implement an effective DTLR system. Economic evaluation of a DTLR system used in an interconnected electricity generation and transmission system is studied in [14]. In another study [2], an economic cost optimization of a generation and transmission system implementing dynamic line rating is assessed. The integration of DTLR in power system economic dispatch and optimal power flow problems are also evaluated. Results demonstrate the economic benefit of operating a power system by utilizing a DTLR system. The integration of a DTLR system in the security constrained unit commitment problem is evaluated in [16]. It is demonstrated that the integration of DTLR improves the overall system security and economic performance. Study [17] aims at integrating the DTLR system in AC-optimal power flow analyses. It is concluded that DTLR decreases the operation cost in terms of load shedding amount and duration. The impact on reliability of integrating a DTLR system is investigated in [15] using a proposed Markov model. The main conclusion of this stream of literature is that DTLR systems can increase network reliability and reduce the load interruption cost.

The economic impact of flexible rating mechanisms provided by DTLR implementation on energy cost from the electricity market consumers' perspective has also been investigated [12,18,19]. These studies suggest that economic benefits from DTLR implementation could be achieved through relieving congestion on a transmission line connecting two areas with different electricity prices. By relieving the constraints on transmission lines, DTLR enables transmitting renewable energy at lower marginal cost, and therefore reduces the electricity prices in competitive electricity markets [11].

3. DTLR technologies

DTLR technologies include three primary components: DTLR devices which monitor varying operating conditions; communication devices that receive and transmit measured field data; and software that interprets the data and quantifies the line's thermal capacity. For the purpose of DTLR deployment, DTLR devices may be selected considering cost and ease of installation and maintenance, accuracy and operating limitations, durability, reliability, and performance. When deploying DTLR, a comprehensive analysis of site specific considerations needs to be conducted [68]. A comprehensive technical review of alternative technologies for transmission line monitoring is presented in [11]. A review of different real-time monitoring technologies along with their benefits and technical limitations is also introduced in [63]. DTLR technologies considering changing weather conditions are presented in [69].

As stated in the introduction, DTLR systems are classified as indirect and direct methods. Indirect methods measure weather-related data [70–72], while direct methods measure either conductor sag [73], conductor ground clearance [10,74–76], line tension [77–79], or conductor temperature [80–82].

3.1. Indirect methods

In indirect methods of DTLR estimation, weather data at specific locations along a transmission line are analyzed to calculate its current-carrying capacity. To calculate the steady-state current-carrying capacity of the transmission line conductor under given weather conditions, the heat balance equation in IEEE thermal model is used [8]:

$$q_c(T_c,\, T_a,\, V_m,\, \varphi) + q_r(T_c,\, T_a) = q_s + I^2.\, R(T_c) \tag{1}$$

where q_c and q_r are the heat removed by convection and radiation to surrounding air, respectively, while q_s and $I^2R(T_c)$ are the heat gained from solar radiation and the heat generated by the current flowing through the conductor, respectively. I is the line loading and $R(T_c)$ is the conductor resistance at temperature T_c (the conductor core temperature). Details on the calculation of each term can be found in [8]. By rearranging (1), the maximum allowable steady-state current-carrying capacity of the conductor can be determined as follows:

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \tag{2}$$

As wind speed and direction vary along a transmission line, conductor temperature may change from one span to another. Thus, allowable line thermal capacity could vary from span to span. The line capacity is estimated at each span. Line rating is then determined by the minimum capacity over all line spans. Thus, the maximum current-carrying capacity of the entire transmission line is calculated as:

$$I(t) = \min_i I_i(t) \tag{3}$$

where $I(t)$ is the line current-carrying capacity at time t, and $I_i(t)$ is the ampacity estimated at a line span i at time t.

For lightly loaded lines, convective cooling of wind is the dominant factor to determine the line ampacity [83]. For heavily loaded lines, the impact of ambient temperature and solar radiation is less significant and Joule heating from the line current is the principal contributor to

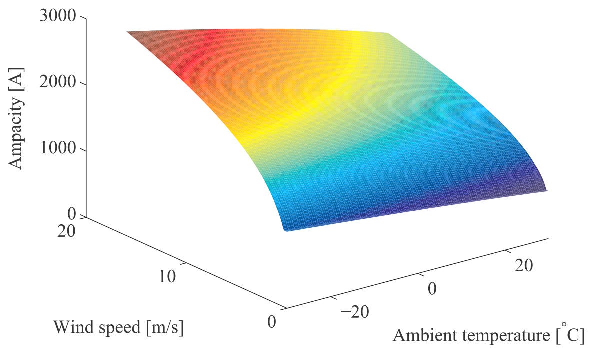

Fig. 2. Expected value of ampacity as a function of ambient temperature and wind speed, assuming wind direction is constant at an angle 45° to the conductor.

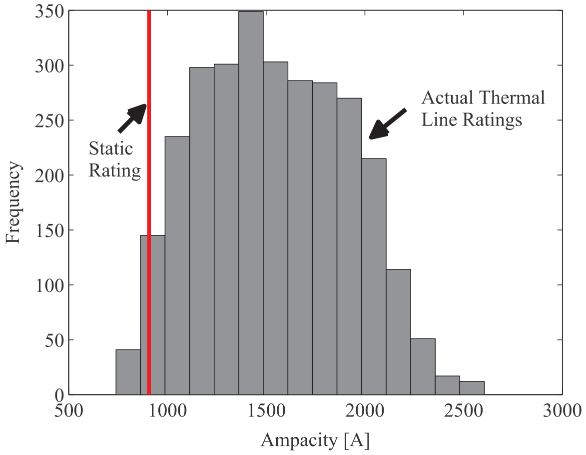

Fig. 4. SLR vs. DTLR.

conductor temperature [83]. At elevated conductor temperatures, the temperature and line ampacity are not very sensitive to solar radiation [83]. At low wind speeds, the heat loss due to radiation can be as much as 40% of the convective cooling term, but the radiative cooling becomes less significant at higher wind speeds [83].

To illustrate the impact of environmental conditions on ampacity estimated by (2), consider Figs. 2 and 3. These figures plot the variation of ampacity for an example 240 kV line. Expected value of ampacity as a function of ambient temperature and wind speed is presented in Fig. 2, where the angle of incidence of wind on the line is held constant at 45° while ambient temperature and wind speed change. Fig. 3 displays line ampacity as a function of wind speed and wind direction when a constant value of 5 °C is considered for ambient temperature while wind speed and wind direction change. As illustrated in Figs. 2 and 3 wind speed has a significant impact on ampacity. Wind direction has more considerable impact on the line rating at higher wind speeds, while its impact is less significant at lower wind speeds. Fig. 4 compares the SLR with the DTLR. Results indicate that by incorporating actual weather data, DTLR, compared to SLR, allows for more current to be transmitted through the power lines for most of the time.

The temperature of an overhead power conductor varies over time with the line current and weather conditions. In steady-state conditions, line rating is calculated in a short time period during which the current and weather parameters are considered to be constant for the entire interval [8]. In steady-state conditions, (1) is used with the assumption that parameters remain constant at the interval being considered. However, in reality, operating and environmental conditions are continuously varying, while rating calculations are only carried out at discrete intervals. In this case, a non-steady-state heat balance Eq. (4) may be used. In (4) the heat capacity of the conductor must be incorporated to avoid large temperature variations [6]. The non-steady-state heat balance equation is defined as follows:

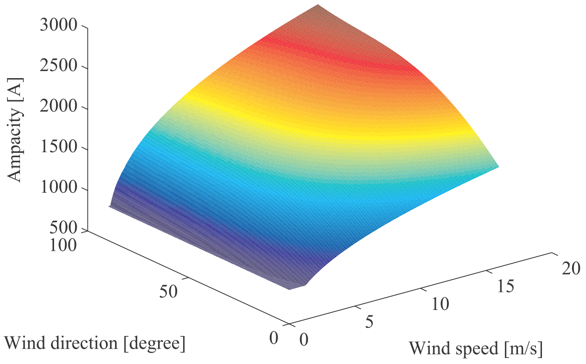

Fig. 3. Expected value of ampacity as a function of wind speed and wind direction, assuming constant ambient temperature of 5 °C.

$$q_c + q_r + m.\, C_p.\, \frac{dT_c}{dt} = q_s + I^2.\, R(T_c) \tag{4}$$

where $m.\ C_p$ is the total heat capacity of the conductor.

3.1.1. Weather data

Weather conditions along a transmission line can either be collected using sensors mounted on transmission towers or generated using numerical weather models. Line capacity changes depending on the weather data variations. The effect of time resolution of meteorological inputs on dynamic thermal rating calculations is investigated by the authors of [6], including recommendations for selecting update intervals for DTLR calculations.

Weather station sensors generally measure ambient temperature, wind speed, wind direction, solar radiation, and rain rate. The line conductor temperature at the point of measurement can be estimated if the line current and weather data are monitored in real-time. Weather measurement devices make it possible to determine the line rating with no dependence on the actual line loading. They also have low installation cost as they do not require line outage to install, and do not need to be mounted on the actual conductor. Weather sensors measure meteorological variables at the point where the sensor is located and therefore multiple sensors might be required to estimate the actual conductor temperature along the line.

ThermalRate™ systems and weather station sensors are two types of weather measurement devices used in DTLR applications. The ThermalRate™ method is based on conductor replicas that determine the line current-carrying capacity by evaluating the impact of weather condition changes on the conductor heat transfer. It is indicated in [84] that ThermalRate™ device is more accurate and reliable than weather stations at low wind speeds, when the accuracy of rating estimation is most important. Typical weather station sensors include a thermometer, pyranometer, rain gauge, and anemometer. Anemometers may be standard propeller-type or cup-type anemometers, or more sophisticated ultrasonic units. Cup-type anemometers can have measurement errors at wind velocities below 1 m/s [85] and can be calibration and maintenance intensive. This limitation of cup-type anemometers was alleviated by the development of ultrasonic anemometers [86]. Compared to cup-type anemometers, ultrasonic models are quite expensive, but are more accurate at low wind speeds, and are able to simultaneously measure wind speed and direction [86].

An alternative to sensor based systems is to use the Numerical Weather Predication (NWP) data. NWP models predict the local environmental conditions at the location of the transmission line using mathematical models of the atmosphere. These mathematical models can also be used to generate short-term weather prediction or long-term climate forecasts. Weather forecasts with short time-horizons are widely used in the literature to estimate the DTLR of transmission lines [2,38,53,87–100].

3.1.2. DTLR prediction

Due to the need to plan electricity generation and transmission operations in advance, availability of overhead line capacity is often desired several hours in advance. Rating forecasts help utilities to make informed decisions in advance of real-time operation and avoid contingencies by planning dispatch accordingly. DTLR forecasts, although they require accurate predictions of line rating up to a day ahead, allow for substantial market benefits due to a more optimal generation dispatch solution [2]. A weather forecast model is required to predict line capacity several hours in advance. Weather modeling by Fourier analysis of weather data for forecasting transmission line ampacity is presented in [2]. Time series data can also be used to develop stochastic and deterministic models of weather data. Weather pattern recognition and neural network models are also developed to predict weather data for line ampacity forecast applications. An overview of the research on DTLR forecasting is presented in [87].

DTLR estimation requires reliable forecast models in the presence of data uncertainties. Accuracy of line rating forecast is especially more important for clearance limited lines where public safety needs to be met and less critical for lines limited by thermal aging. Therefore, a description of uncertainty needs to be accounted for in ampacity estimations. Line ratings can then be chosen based on the network operator's risk avoidance policy. To address the weather data uncertainties, two areas of work are found in literature. In the first group of papers, referred to as probabilistic DTLR [38,53,92–97], ampacity is estimated using probabilistic approach considering uncertainty. In the second category of papers, which are known as fuzzy based DTLR [2,98,99], a fuzzy method is adopted to effectively model weather data uncertainties used for DTLR estimation. A fuzzy approach is adopted in [98] to model the uncertainty of line rating estimation. In [99], fuzzy reasoning is used to optimally control thermal overloading of transmission lines. A fuzzy rule-based DTLR system is proposed in [2].

One of the greatest potential gains from the use of DTLR is transient emergency rating. Evaluation of the short-term overload capacity of an overhead power line is therefore another area of ongoing DTLR research. A few papers [88–91] have predicted the DTLR of a power line in the form of a series of short-term overload currents associated with a series of short-term time durations. In these studies, statistical methods are adopted to predict the short-term overload capacity of an overhead power line for a specific line segment and the results are compared to the IEEE standard 738 model [8]. The approach helps the power system operator to apply effective load management strategies, particularly during emergency conditions. In [88], the short-term overload capacity of an overhead power line is evaluated under different weather conditions using a Multilayer Perceptron (MLP) based parameter estimation scheme. The MLP parameter estimator is trained continuously using an online adaptive learning algorithm. This approach requires only ambient and conductor temperatures and line loading as inputs. Then, the DTLR of a power line is demonstrated in an I-T thermal limit curve using a series of short-term overload currents associated with a series of short-term time durations. In [89–91], an adaptive nonlinear system identification methodology is proposed to adaptively identify the nonlinear thermal dynamics of a line conductor subject to various weather conditions, and to predict the conductor temperature based on different conductor overloads. This approach requires only ambient and conductor temperatures and line loading as inputs.

3.1.3. Weather-based DTLR software

DTLR software provides real-time information on the conductor temperature and transmission line ampacity by analyzing weather data gathered by sensors mounted on transmission line towers or numerical weather models. The most common weather monitoring systems for ampacity rating are EPRI's DYNAMP [101] and ElectroTech USA's LINEAMPS [2,102]. DYNAMP uses the IEEE thermal model to calculate the line rating in real-time. DYNAMP is also capable of estimating the rating for underground cables and power transformers. LINEAMPS is a weather-based DTLR system that uses historical weather patterns to rate the ampacity and forecast its future values. It predicts transmission line capacities in advance by taking into account weather forecast data and the weather models based on historical data [2]. EPRI's Dynamic Thermal Circuit Rating (DTCR) software calculates real-time capacity based on actual load and real-time or historical weather conditions [103,104]. DTCR can also be used for rating power transformers and underground cables. It is mentioned that by using DTCR software, dynamic rating for power transformers and end-of-line equipment can be calculated based on real-time ambient temperature. [105] presents the results of DTLR field tests when implementing a DYNAMP line rating module with the DTCR software.

3.2. Direct methods

Direct monitoring devices gather data about the line characteristics via one of the following variables: conductor sag, line tension, conductor clearance to ground, or conductor temperature. Direct monitoring systems typically use additional inputs from a weather monitoring system to calculate line ratings.

3.2.1. Conductor temperature sensors

Due to large variations in wind speed and wind direction along a transmission line, conductor temperature can vary along the line from one span to another. Various research has demonstrated that conductor temperature can be measured either at a single point [106] or in a distributed fashion [107–112]. Whilst direct measurement of conductor temperature is obtained, it is the surface temperature, not the average conductor core temperature that actually impacts sag. For this reason, line temperature monitoring devices are more accurate under high current conditions, but less accurate with low electrical load on the line. The monitor's mass and the impact on air flow may also affect the measured temperature and cause a hot spot at the connection point [113]. Additionally, multiple outages may also be required for equipment installation and maintenance.

Power Donut™ sensor and EPRI's conductor temperature sensors are among conductor temperature measurement instruments that monitor the conductor temperature at the point where they are mounted on the line, conductor current, conductor vibration, line inclination, and conductor sag [55]. As indicated in [114], Power Donut™ sensors may be considered to be expensive, and measure surface rather than core temperature. The Power Donut™ is self-powered or powered directly from the measured conductor. Conductor temperature is directly measured at only one location along the transmission line. It can be installed without an outage [106], and is capable of simultaneously monitoring several parameters including current, line inclination, line to ground voltage, and local conductor temperature [106]. The equipment can also be used for line sag and tension monitoring. Different aspects of conductor temperature monitoring systems are compared in [63].

A transmission line temperature monitoring system, called Distributed Temperature Measurements (DTM), is proposed by [109]. It uses optical fibers to measure conductor temperature distribution along the line. The system employs a sonar pulse transmitted through the length of the transmission line and its reflection time corresponds to the conductor temperature [112].

3.2.2. Line tension monitors

Conductor tension can be measured either locally or at a dead end. By knowing the tension, the conductor sag and therefore its core temperature can be determined [115]. The real-time tension is converted to an equivalent wind speed to calculate line ampacity based on the heat balance equation. Line tension monitors are ideal for lines with a high current density of greater than $1\ A.\ mm^{-2}$. They can also give very accurate estimates of sag at high temperatures [105]. Tension monitors are also considered to be more accurate when used for a transmission line that has almost the same tension in its multiple suspension spans. Tension monitoring devices can sometimes give the utility an accurate measure of average line temperature and sag, however, they do not determine the hot spots on the line. Multiple outages may also be required for equipment installation and maintenance.

Nexans' CAT-1 conductor tension monitoring system [78,79,116] includes CAT-1 units and load cells. CAT-1 units include power sources, data loggers, and communication equipment. Load cells are tension monitoring devices mounted on the line conductor. Calculating line rating using the CAT-1 system is more challenging when the line is loaded at less than 20% of its static limit [11]. This system needs to be calibrated in order to determine the relationship between conductor temperature and line tension.

A new monitoring system based on conductor tension measurement is called the Tension and Ampacity Monitoring (TAM) system [77]. The TAM system monitors and estimates the conductor creep and the maximum allowable conductor temperature.

3.2.3. Conductor sag monitors

The main limiting factor in transmission lines design is the conductor clearance at the maximum allowable conductor temperature. Sag can be derived through the measurement of conductor inclination [117–119], vibration frequency [113,120], target monitoring [10], and wave travel time [121]. Similar to tension monitors, sag monitoring devices are ideal for lines with a high current density of greater than $1\ A.\ mm^{-2}$ [122]. A concern is that wind blowing on conductor may affect the measured sag.

Power Donut™ sensor is an inclination measurement device which measures conductor angles and thus its sag. Using this device, line tension and conductor sag are derived based on transmission line angle or inclination [106].

Ampacimon is an overhead line monitoring system that directly determines real-time sag data based on conductor vibrations measurement [113]. The State Change equation [120,123] is used to convert the measured sag to the average conductor temperature. In the case of vibration frequency measurement, sag is measured directly with no need of other parameters or calibration. None of conductor data, topological data, weather data, sagging data, the span length, and the position of the sensor in the span is required to measure conductor sag [113]. However, a minimum level of current is required flowing on the line in order for the equipment to operate [123]. Field tests indicate that the sag measurement accuracy is less than 20 cm [120].

EPRI's Video Sagometer uses target monitoring and image processing to measure conductor sag. This approach can be less accurate at low power levels, however, the advantage is that it does not require line outages during installation [4,62].

Sag stopwatch devices measure the transmission line sag from wave travel time [121]. The authors of [114] developed an approach that measures conductor sag based on the current induced in a resistive wire which can then be used to calculate the average conductor core temperature. A field test was conducted to evaluate the accuracy of the method, indicating that the measured sag was within 0.2% of the actual sag.

Differential Global Positioning System (DGPS) [124] is a recently proposed technology to measure conductor sag. Line sag is calculated based on the conductor to ground clearance measured using altitude data obtained from the Global Positioning System (GPS) device [113].

3.2.4. Conductor clearance monitors

Conductor clearance from the ground can be effectively measured using sonar [74], laser [125], microwave or magnetic field technologies [10]. Promethean Devices' Real-Time Transmission Line Monitoring System (RT-TLMS) [75,76] is conductor clearance measurement device which measures the magnetic field around the conductor associated with the level of current flowing through the conductor. It does not require outage for installation, calibration, or maintenance. Promethean device uses a non-contact and ground based technology to monitor conductor sag. A real world deployment of DTLR system using Promethean device is described in [76] and a summary of its performance is also provided. Clearance to ground can also be measured with the use of sonar [74]. This approach is used by Lindsey's TLM™ conductor monitor that measures actual conductor ground clearance, conductor temperature, line loading, and vibration [126].

3.2.5. DTLR software based on direct methods

Nexans' IntelliCAT™ software calculates dynamic ratings based on conductor tension measurements. Nexans has developed a capacity forecast engine which predicts line ampacity for the day-ahead electricity market and updates ampacity predictions at 15-min time intervals during day of operation [4]. Oncor used IntelliCAT™ software to calculate real-time ratings for its DTLR project. SMARTLINE™ DTLR system is a line rating software that uses reliability-based rating and forecasting techniques to calculate actual capacity limits and reliable capacity forecasts. The SMARTLINE™ system rating is based on directly monitored clearances by the Lindsey's TLM™ conductor monitor. Ampacimon device has a built-in software that develops a predictive model for short-term ampacity prediction.

3.3. Comparison between direct and indirect methods

Weather monitoring devices are considered to be the simplest method to implement as there is no need to install instruments on the line itself. It is indicated that weather monitors are ideal for relatively lightly loaded lines with a current density of less than $0.5\ A.\ mm^{-2}$ [68]. Field tests indicate that weather data measurement devices are also the least expensive and highly reliable, and they do not require any special calibrations [68]. However, these devices may not accurately represent the worst conditions along a line. In weather-based line rating models, compared to the direct methods, more uncertainty is involved in ampacity estimation as the line temperature and ampacity are determined indirectly by theoretical models and calculations. Direct conductor temperature equipment are point sensors. In contrast, conductor tension and sag monitoring systems correspond to the weather conditions along the entire transmission line. In [55] detailed explanation on different DTLR measurement sensors including price, application, installation, and pros and cons is provided. Accuracy of different DTLR monitoring devices and their measuring capability is presented in [113].

Sag or tension monitoring systems require field data analysis, calibration, to determine the average conductor temperature along entire line sections. Large errors in rating are likely to result from lightly loaded lines when the line rating is calculated by tension and sag monitor systems. Further, direct monitoring devices lack accuracy when the conductor temperature rise over ambient is small [127]. Indirect measurement systems are inherently less accurate than the direct measurement of sag or tension since an assumed relationship between conductor temperature and measured data from indirect methods is required. A comparison of different DTLR methods is presented in Table 1. This comparison is based on a feasibility study into the use of dynamic rating technology in New Zealand [68], and expanded based on the papers cited in this section.

4. Challenges and considerations for DTLR implementation

This section describes concerns and issues associated with the deployment of DTLR technology. Possible solutions to overcome practical

Table 1
A comparison of different dynamic line rating methods [68].

Monitor	Cost				Accuracy				
	Purchase cost	Install Cost	Maintain Cost	Line Outage	Measurement Reach	Normal Wind High Load	Normal Wind Low Load	Low Wind High Load	High Wind High Load
Weather	low	low	low	no	variable	good	good	low	good
Temperature	high	medium	high	no	variable	good	low	good	good
Tension	high	high	high	yes	multi-span	good	low	high	good
Sag	high	medium	high	no	variable	good	low	high	good
Clearance	high	medium	high	no	variable	good	low	high	good

difficulties in DTLR implementation are also suggested.

4.1. Transmission line selection for DTLR implementation

One concern in implementing DTLR is the identification of suitable transmission lines. The proximity of wind generation is an important factor in the potential of the DTLR system to integrate more wind generation to the grid. A number of papers have studied the impact of DTLR implementation on the integration of new wind farms. These papers investigate the correlation between wind generation and line rating.

Lines can also be selected for DTLR employment based on their typical load levels, as many direct DTLR devices are not able to accurately measure data when transmission lines are lightly loaded. Therefore, dynamic rating does not seem to be useful for lightly loaded transmission lines, except during contingencies [62]. Another option is to select transmission lines with high historical constraint problems [11]. In particular, lines can be selected among frequently congested lines as congestion constraints can necessitate increased capacity. An example of transmission line selection criteria for potential DTLR deployment is introduced by NYPA in their DTLR project [62].

It should be noted that transmission transfer capability is affected by three operating constraints: stability, voltage limits, and thermal limits [129]. For longer transmission lines, the thermal limit is likely to be a critical factor, as voltage or stability limits restrict the capacity of the transmission line. Thus, a shorter transmission line may be selected for the deployment of DTLR system to utilize the full thermal capacity of line conductor. For shorter power lines the current-carrying capacity of line is usually set by a thermal limit, while for longer lines capability in transmitting power is affected by voltage limits [128]. Stability limits usually determine the capability of very long lines [128]. Fig. 5 shows the power transfer limits as a function of line length.

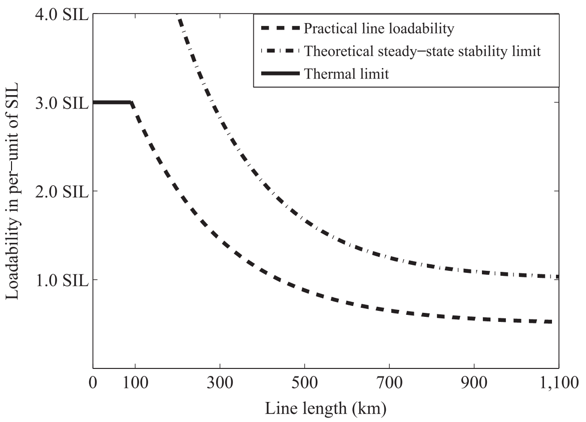

Fig. 5. Transmission line loadability curve for 60-Hz overhead lines [128] (SIL stands for Surge Impedance Load).

4.2. Identifying critical spans

Conductor temperature varies along the length of the line mainly due to spatial variations of the wind. The transmission line ampacity is determined by the line segment that receives the least cooling. This line span is referred to as a critical span. Several critical spans might exist on a transmission line [130]. Hence, determining where and how many devices are required to monitor all crucial line spans is a challenge for DTLR system implementation. The effective wind speed at each line span is the primary consideration for installing monitoring devices on the transmission line. In order to locate sensors on line, line length, transmission line orientation, distance between line sections, and sheltering have to be considered. The experience with sag monitor devices [113] shows that a device every 3 km is generally a good value that has to be adapted depending on terrain condition. Oncor realized that, due to the volatility of wind along the line, the locations of the critical spans are not static [11]. Hence, it might be necessary to monitor the entire power line.

4.3. Reliability of DTLR system

DTLR systems may not have the resolution and accuracy to always represent the actual line rating. Validation and verification of rating technology is essential in ensuring the quality and reliability of DTLR systems deployed for practical use. DTLR uncertainties can be derived from various sources such as measurement inaccuracies and model inaccuracies. Measurement inaccuracies include varying weather data along the line, and DTLR device inaccuracy. The detection of bad data is important for accurate DTLR estimation. However, this problem has not yet been adequately addressed, and future work is still required in this area. Model inaccuracy includes inaccuracy of mathematical rating models, conductor data inaccuracy, errors in topological data, and nonlinear behavior of the conductor. Different error sources, mitigation techniques, and various errors in rating calculations are explained in detail in [113].

A concern with DTLR systems with local measurements is the lack of sufficient number of measurements along long transmission lines to acquire accurate estimation of the varying operating conditions. This leads to inherent inaccuracies in data measurements. Missed data due to DTLR instrument malfunction, failure of the equipment, or communications issues are also considered as issues with the deployment of DTLR systems. Communicating measured data to utility control centers is considered a challenge in DTLR implementation. Inaccuracy of data measurements can be related to sampling interval of weather data as long intervals cause significant DTLR calculation errors. DTLR device performance under specific operating conditions can be considered as another source of data inaccuracy [6]. For instance, lightly utilized lines cannot be accurately monitored using conductor temperature, sag, or tension monitoring devices [105,122]. A possible solution would be using a technology that can calculate ratings under light loads, such as weather sensors. However, uncertain weather variables are another concern that makes the real-time rating even more challenging. For instance, wind data is the most influential weather factor on line thermal capacity, but it is more difficult to accurately model the wind, especially at lower wind speeds. Calculation speed is also an important factor for real-time application of DTLR systems, and it depends on the method and computing platform used.

In direct methods of DTLR implementation, the accuracy of the thermal rating depends on how precisely the relationship between the measured temperature and conductor sag can be established. Conductor temperature and sag are stochastically related not deterministically as assumed in SLR technology. To improve accuracy of mathematical rating models developed for design purposes, a calibration process has to be performed.

Line ratings need to be continuously available. Thus, different rating methodologies, such as static rating, ambient-adjusted, or dynamic rating, can be selected depending on data availability and line loading conditions. Installing a combined monitoring system also ensures that ratings are constantly available. For instance, devices to measure conductor sag and clearance can be used for validation and verification purposes of weather-based line rating. NYPA realized that it is often required to use weather stations to measure wind when its EPRI sensors and Video sagometers were not able to estimate effective wind speed [62]. A proposed approach for DTLR is to estimate a weighted average value based on the various direct and indirect rating methods and their respective rating uncertainties, especially in the case of uncertainty and limitation in DTLR calculations [127]. Also, forecast weather data can serve as a backup to real-time measurements. To effectively model the measurement uncertainties, methodologies such as fuzzy logic, neural networks, and mathematical modeling can be applied for DTLR estimation. To account for volatility of wind data, parameter identification algorithms can be used to continually update uncertain parameters. Fuzzy theory is adopted in [98] to model the uncertainties of DTLR calculation. Another concern with DTLR adoption is the ampacity persistence [11]. A long-lasting lower DTLR value is more valuable than a higher DTLR value with short duration.

4.4. Integration into system operation

DTLR has not yet gained wide acceptance by utilities, mainly because system operators need to be confident in the DTLR system to provide accurate ratings with high availability and reliability [11]. In this regard, accuracy of the calculated rating, reliability of the DTLR system in terms of confidence in the estimated ratings, and continuous availability of line rating are significant for real-time integration of DTLR into system operations [62]. Although system operators may benefit from line ratings in relieving power flow constraints, the volatility and varying nature of the ratings and the difficulty to predict ratings in advance can be a challenge for them. Power system operators generally adopt fixed line capacity limits to plan dispatch. Many system operators may not accept the challenges of DTLR technologies as they are more concerned about system safety and reliability, not about the economy of system dispatch achieved by reducing system congestion. In the case of transmission congestion, higher-cost generation is dispatched to meet the load demand. Consequently, energy customers may experience an increase in electricity prices in the form of congestion charges. Therefore, the owner of the constrained transmission line is not directly affected by such circumstances and thus is not willing to remove the constraint. Furthermore, for transmission lines that are only lightly loaded, system operators may not consider dynamic ratings useful. Another concern is how DTLR technologies can be best integrated into system planning, engineering, and operations. It is an issue whether control of the DTLR system should be performed by engineers at the transmission facilities, or directly by system operators [4]. This is another concern to be considered in real-time applications of DTLR systems.

One of the main challenges for system operators when implementing DTLR system is the rating variability. To minimize the rating variability, the average value of ratings over a time horizon can be considered. Moreover, limiting the range of rating values can be considered as another solution to smooth the high variability of line ampacity values. The other suggestion would be to cluster dynamic rating values in finite states. DTLR implementation is further limited by the lack of effective load reduction methods to handle occasional unfavorable ratings. Dispatching the line based on highly variable real-time ratings is not practical due to generation dispatch and load response limitations. If the weather conditions (and thus DTLR) change suddenly, the generation or load would have to respond quickly to avoid exceeding conductor temperature limits.

4.5. Financial impacts of DTLR

The financial benefits of DTLR systems are evaluated in a number of papers [2,11–19]. The financial impact of DTLR technologies on the electricity consumers, generation companies, and transmission facility owners is investigated. However, due to the difficulties in predicting grid capabilities and congestion [4,11], it is difficult to forecast economic outcomes of DTLR systems. Since grid congestion is very volatile, predicting the grid behavior is considered to be difficult for real-time assessment of DTLR benefits. Reliability benefits of DTLR deployment are considered to be significant. However, quantifying the value of reliability improvements is a key challenge. In order to evaluate the economic benefits of utilizing DTLR, various measurable quantities need to be defined [55].

5. DTLR case studies

In this section, several projects demonstrating dynamic thermal rating technology applications are summarized. These practical projects pave the way for future DTLR deployment. Further DTLR applications are discussed in [113]. Table 2 highlights different DTLR devices that

Table 2
DTLR devices used in applications.

DTLR system	DTLR device	References
Direct weather measurement system	Weather sensors	[36,37,62,64,68,70,80,101,132,140,141]
	ThermalRate™	[62,142–144]
Conductor temperature monitoring system	Power Donut™	[34,36,50,59,80,85,113,137,141,145]
	Surface Acoustic Wave (SAW) sensor (Ritherm)	[82,140,146–149]
	Overhead Transmission Line Monitoring (OTLM)	[149,150,151]
	Temperature Monitoring System (SMT)	[41,142,152–154]
Line tension measurement system	CAT − 1	[11,55,67,68,78,106,108,113,135,138,155-159]
Conductor sag monitoring system	Ampacimon	[47,54,25,120,139,160–162]
	GPS	[124,163–165]
	Phasor Measurement Units (PMU)	[166–172]
	Video Sagometer	[4,62,73,173]
Conductor clearance monitoring system	Sonar technology	[74,113]
	RT-TLMS	[11,76]

have been used in various DTLR application projects. Some of the DTLR case studies discussed in this section are implemented on real world power systems [11,36,47,55,53,62,64,101,113,120,131,133–141] while other cases are simulated [37,70,132].

5.1. Indirect methods of weather measurement systems

Different case studies are developed to estimate line ampacity from meteorological variables [36,37,53,70,131–133]. Two real-time thermal rating projects, one in the United States of America and one in the United Kingdom, are compared in [134]. In the UK methodology [53], a probability distribution for each weather variable is assumed in order to model weather data uncertainties using Monte Carlo simulation techniques. Here, the main concern is whether various assumptions, such as independence of weather variables and distribution fitting procedures, are accurately modeled. This study does not identify a critical span. A more sophisticated wind estimation model could be developed to improve the line rating estimation.

An Idaho DTLR application project [131], examines the wind cooling effects on several power lines. A wind modeling tool, WindSim, is employed to estimate and simulate wind conditions along a transmission line using information from nearby weather stations. The method provides a good wind estimation model. However, further improvement can be potentially obtained to validate the model and improve its accuracy. Additional software programs take the estimated wind speed of WindSim model and the load on the line, and determine the cooling effect to adjust the rating of the line.

The US proposed methodology incorporates advanced CFD wind simulation to model the wind patterns. It uses historical data to quantify the error to improve wind forecasts. However, further improvement in wind prediction can be considered. Overall, the US system has a more sophisticated wind model (higher resolution wind data) while the uncertainty model in the UK DTLR system is more advanced. Contrary to US, the UK model does not seek to locate the limiting line span, but instead an acceptable level of risk is assumed.

Red Eléctrica de España (REE) Spain [70] and KEPCO, South Korea [132] adopted a weather based dynamic line rating system dependent on actual weather conditions. In [64], a DTLR system is implemented on an overhead power line located in a 130 kV regional transmission network. Technical and economic aspects of DTLR are evaluated in this study. The results indicate that DTLR can potentially improve line capacity and facilitate the increased penetration of wind power. TransGrid, electric power transmission in Australia, implemented a weather based DTLR system on several 330 kV and 500 kV transmission lines [133].

A physical CIGRE model and statistical PLS model have been implemented in the Northern Ireland Electricity (NIE) transmission network to predict the conductor temperature from available weather data [37]. Results show that dynamic PLS model captures the variation in the conductor temperature more accurately than the steady-state CIGRE model. Since Fall 2008, Eon Central Networks UK has used automatic DTLR calculation based on CIGRE 207 [101] utilizing local weather measurements. Another US project [36], has employed DTLR weather data monitoring system on the Skegness-Boston line. Results of this study indicate that DTLR enables $20-50\%$ more wind generation to be integrated into the electric grid.

5.2. Direct DTLR rating methods

Real world case studies that adopt DTLR based on direct methods use either the conductor temperature, tension, sag or clearance measurements. In the next sections we discuss each category in more details.

5.2.1. DTLR case studies that utilize direct conductor temperature monitoring systems

Transpower, New Zealand system operator, explored the application of various DTLR technologies to increase the current-carrying capacity of its major power lines [135,136]. Transpower investigated the application of a conductor temperature monitoring system to implement DTLR on its transmission lines. It concluded that DTLR can help with the efficient control of transmission line capacity [135]. The experience of Nuon Energy, a Dutch utility company, on transmission line and power transformer temperature monitoring is demonstrated in [137] where a dynamic rating system is implemented on a 150 kV line.

5.2.2. DTLR demonstration using line tension measurement systems

Transpower New Zealand has also investigated the use of direct tension monitoring systems in DTLR applications [135,136]. DTLR is implemented to remove existing restrictions on the development of hydro generation. Feasibility and reliability of using real-time line ratings were tested in California in the late 1990's [138]. A CAT-1 unit was installed on a 230 kV transmission line. The test project indicated that the monitored line could have $40-80\%$ more power transfer when using real-time line ratings instead of static ratings [138]. Fingrid, a transmission system operator in Finland, has installed a CAT-1 measurement unit [55] to evaluate DTLR application in Finalnd related to wind energy integration into power system. An American Electric Power (AEP) project on wind farm integration in west Texas is another DTLR real world application based on tension monitoring [113]. The amount of wind power that can be delivered to load centers is constrained by the static limit of the nearby transmission lines. Results show that a minimum of $10-15\%$ increase in the delivery of wind power is enabled through real-time ratings. Kansas City Power and Light (KCPL) company has installed tension measurement system to relief congestion on its 345 kV transmission line [113].

5.2.3. DTLR demonstration using conductor sag or clearance measurement systems

Belgian Elia and French RTE have experimented with the Ampacimon sag measurement system on 380 kV and 220 kV overhead lines of their grid [120,139]. The monitoring devices based on vibration monitoring convert conductor motion to sag. Measurements show a margin of error of around $20\ cm$. DTLR systems implemented on an Elia 400 kV line and RTE 225 kV line show that the actual ampacity is much higher than the static rating, most of the times by at least 25% [120]. The Belgian Elia has also implemented DTLR on its 70 kV network to allow more distributed generation to be integrated into the power grid, and minimize the curtailment of the distributed generation production [47].

5.3. Combined measurement systems

An application of real-time rating for integrating wind farms in the UK is demonstrated in [36], where dynamic line rating is applied to a 132 kV line to enable more wind generation to be connected to the grid. The rating of the line is calculated dynamically from local weather measurements to coordinate allowed generation automatically. In this project, the algorithms have been validated using Power Donut™ conductor temperature monitoring sensors. Amprion GmbH, a German transmission system operator, carried out a pilot study on DTLR by two separate DTLR determination methods [140]. The first system measures conductor temperature using SAW sensors. In the second system, weather station sensors are placed on the line towers to measure meteorological variables. The results show that the accuracy of indirect monitoring systems is comparable to direct monitoring systems considering adequate safety margins [140].

In a Brazilian case study, a 238 kV transmission line was selected for DTLR research. The line monitoring system was comprised of 6 Power Donut™ sensors and a weather station with sensors for wind speed and direction, ambient temperature, solar radiation and a rainfall gauge [141]. CEMIG, a Brazilian power company, compared the CAT-1 tension monitor with Power Donut™, and Sonar technologies [113]. Results of this study indicate that both tension and Power Donut™ systems have a strong correlation when applied to the same span. Sonar system has also a good correlation with that of tension and conductor temperature monitoring systems [113].

NYPA and Oncor also demonstrated DTLR technologies for transmission lines. NYPA worked with EPRI using their technologies and approaches [62], while Oncor deployed Nexans' CAT-1 conductor tension monitoring system [11]. In NYPA's project, DTLR was implemented on three 230 kV transmission lines using four different technologies to analyze the correlation between increased transmission capacity and increased wind power generation:

- EPRI Sensors for conductor temperature and current measurement
- ThermalRate™ systems
- Video Sagometers
- Weather stations to monitor relevant weather variables

In Oncor's project CAT-1 conductor tension monitoring system was installed to provide dynamic rating on eight transmission lines in central Texas where there are constraints on power transmission [11]. Validation and accuracy assessment of the DTLR technology was part of the project. To validate the performance of its tension monitors, secondary monitors using two technologies were adopted to monitor conductor position in specific spans. The first technology for the validation purpose is video Sagometer to monitor line sag, and the second one is the RT-TLMS by Promethean.

DTLR monitoring has also been implemented in other case studies as described in detail in [55,63].

6. Future of DTLR applications

DTLR systems can form the basis for an improved approach to setting reliable and safe static ratings for transmission lines and adjusting the static ratings to meet load growth. Transmission owners implementing DTLR systems must also be mindful of the next limiting element of electricity grid. Future developments of DTLR technologies may involve calculating dynamic ratings for terminal equipment in substations on real-time basis. The protection settings also need to be updated on a real-time basis for DTLR systems to be effectively employed. Unlike overhead lines, terminal equipment are impacted primarily by ambient temperature. Ambient-adjusted ratings based on real-time ambient temperature data can be used to rate end-of-line equipment. As an alternative, transmission lines' real-time capacities can be limited to specific percentage of the static ratings.

Oncor and NYPA offer guidance on several aspects of DTLR demonstration that address issues with deploying DTLR technologies. They also identify several key opportunities for DTLR technologies expediting future implementation of the technology [11,62]. Challenges of DTLR implementation, such as ensuring reliability and validity of DTLR system, integrating dynamic rating into system operations, and verifying financial benefits of DTLR technology, have to be considered for future DTLR deployment. As discussed in Section 2, a great majority of research studies focus on DTLR application in integrating wind power resources. However, improving dispatch of solar power can also be considered as another possible application for future DTLR implementation. The impact of DTLR implementation on photovoltaic power integration can be considered as an interesting area warranting future investigations.

Forecasting dynamic ratings of transmission lines for additional grid flexibility and contingency management is another area for DTLR applications. In particular, work can be done to improve the quality of DTLR forecasts. Also, the combination of real-time rating systems with reliable line rating forecast models can advance further development of DTLR systems and their future deployment. As the greatest gains to DTLR can come from the transient emergency ratings, evaluating short-term overload capacity of overhead power lines provides another opportunity for DTLR applications. When integrated into system operation, a DTLR system can provide the operator with real-time thermal capacity of the line, line load, time to reach the thermal limit of the line, remaining time to clearance violation, and comparison to allowable sag limit; the DTLR system could function as an alarm system that tracks both the dynamic rating and load. With this approach, a system operator may re-dispatch the system or take an action for the occurring contingency when the line loading and dynamic rating converge. DTLR system could also operate in the background, providing information to the operators only on as needed basis or in emergency situations.

7. Conclusions

This paper provides a comprehensive review of dynamic thermal rating of transmission lines. A review of various DTLR objectives is presented based on the need to increase transmission line rating. Previous studies used DTLR to integrate wind generation into the power grid, reduce congestion, and evaluate potential financial benefits that can be realized using DTLR. Various DTLR devices that are used for monitoring overhead line thermal rating have been reviewed. Operating conditions that can be measured to determine line rating include weather data, conductor sag or ground clearance, tension, and conductor temperature. Potential challenges for DTLR deployment are also discussed. This paper also presents different DTLR case studies, categorized based on the different technologies they adopt for implementation.

Dynamic ratings may provide more additional capacity of transmission lines than the rest of the transmission system can safely accommodate. Therefore, thermal rating for terminal equipment such as power transformers, circuit breakers and protection relays should be considered for future developments in DTLR technologies. Future research into dynamic line rating can be directed towards developing a more practical model for industry. Development of a more accurate DTLR forecasting engine, capable of predicting line thermal capacity in advance of real-time operations, can be considered as another possible research area. Although previous work has demonstrated many advantages of DTLR over static thermal rating, reliable calculation models capable of predicting the thermal behavior in the presence of data uncertainties represent an essential requirement for real-time DTLR deployment.

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