IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received February 26, 2018, accepted April 1, 2018, date of publication April 6, 2018, date of current version June 5, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2824238

Prospects of Using the Dynamic Thermal Rating System for Reliable Electrical Networks: A Review

JIASHEN TEH[1], (Member, IEEE), CHING-MING LAI[2], (Senior Member, IEEE),
NOR ASIAH MUHAMAD[1], (Member, IEEE), CHIA AI OOI[1], (Member, IEEE),
YU-HUEI CHENG[3], (Senior Member, IEEE),
MUHAMMAD AMMIRRUL ATIQI MOHD ZAINURI[1], (Member, IEEE),
AND MOHAMAD KHAIRI ISHAK[1], (Member, IEEE)
[1]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia
[2]Department of Vehicle Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
[3]Department of Information and Communication Engineering, Chaoyang University of Technology, Taichung 41349, Taiwan

Corresponding authors: Jiashen Teh (jiashenteh@usm.my) and Ching-Ming Lai (pecmlai@gmail.com)

This work was supported in part by the USM Short-Term under Grant 304/PELECT/60313051, in part by the USM Bridging under Grant 304/PELECT/6316117, and in part by the Ministry of Science and Technology (MOST), Taiwan, under Grant MOST 105-2221-E-027-096, Grant MOST 105-2221-E-324-02, Grant MOST 105-2221-E-324-026, and Grant MOST 106-2218-E-027-010.

ABSTRACT Traditional transmission line ratings are limited by a set of fixed conservative weather assumptions that are also known as static thermal rating (STR). Owing to STR, new line corridors are continuously required to address increasing electricity demands while minimizing the curtailment of renewable energy sources (RES). However, the expansion of an electricity network is expansive, long, and limited due to the scarcity in land and space. To overcome this issue, researchers have proposed a dynamic thermal rating (DTR) system that can increase the capacity of existing transmission lines. Research has shown that actual line ratings are higher than STR most of the time. The potential of using the DTR system to increase the reliability of power systems is therefore significant. Almost every country has begun the process of increasing the integration of RES, and consequently, the DTR system has become increasingly important. Exploring and reviewing critical studies on the DTR system are thus beneficial for researchers who are interested in the developments of DTR technology. This review paper begins by comparing the two main DTR system standards. Then, monitoring technologies of the DTR system are reviewed. Notable research on the reliability impacts of the DTR system on electrical networks are surveyed. Interactions with wind power and other smart grid technologies are also examined, and the concept of power system reliability is briefly discussed.

INDEX TERMS Dynamic thermal rating systems, standards, power system, reliability, wind power, weather.

I. INTRODUCTION

The ever-increasing level of greenhouse gas emissions is a current worldwide issue [1]–[7]. Consequently, many countries committed themselves to the United Nations Framework Convention on Climate Change (NFCCC) in 1992 to reduce the amount of greenhouse gases. This international treaty, which is now known as the Kyoto Protocol, was extended in 1997 and represents a hallmark of international collaboration because it is supported by nearly every country. An important means to achieve the aims of the Kyoto Protocol is to gradually eliminate the use of fossil fuel and adopt renewable energy sources (RES) instead. In this regard, the European Commission is striving to fulfil at least 20% of its total energy needs with renewables by 2020, and these figures have been revised to 27% by 2030. A large portion of renewables is expected to be contributed by wind energy. Although the new revolutionary energy policy is commendable, most existing power networks need to be strengthened and expanded before they can accommodate RES. In addition to this obstacle in RES integration, the longer commissioning time of electrical networks than that of RES-based power plants is another issue to be considered. As a result, the capacity of most RES-based generators, such as wind farms, has to be curtailed. From the perspective of wind farm owners, this problem can be overcome with new wind turbine technologies [8]–[11], including the addition of a control system that regulates reactive power and voltage dips, which are important to power system operation and the amount of wind power that can be integrated. Nonetheless, the effectiveness of this solution is limited by the insufficient capacity of electrical networks.

The strong consensus to reduce our reliance on conventional fossil fuel generators is also due to the higher cost of operating fossil fuel generators than wind turbines. To achieve high integration of wind energy, which has been identified as a major driver for grid development in Europe, the European transmission network has devised a decade-long development plan to enhance electrical networks. To date, this pan-European project has saved approximately 30–100 TWh of energy spillage stemming from renewable sources, reducing it to less than 1% of the total energy supply [12]. The promising result of this European project reiterates the indirect influence of grid development on the worldwide effort to reduce greenhouse gas emissions.

However, high population density growth, intensive usage of lands for various developments and increased rejection rate of new electrical line projects indicate that only little space is available for the construction of new transmission and distribution corridors. The relatively new movement of ''smart grid'' offers the possibility of using new technologies to alleviate this issue. The objective of all these technologies, regardless of the choice, is to always relieve network congestion so that RES-based generators can participate in the existing power generation portfolio. One of these promising technologies is the dynamic thermal rating (DTR) system that can increase the capacity of existing transmission lines. Its total installation cost, including both hardware and software, is only a fraction of the total cost of most traditional methods [13]. Moreover, its short implementation time enables rapid connection of wind farms so that they remain idle only for a short period [14]. The DTR system can potentially avoid or postpone the construction of new lines.

The term ''rating'' in the DTR system refers to the maximum allowable conductor current that raises the line temperature without infringing ground clearance and causing the loss of conductor tensile strength due to annealing. Traditionally, electrical lines were given fixed and low rating values known as the static thermal rating (STR). The implementation of STR underestimates the full potential of line capacity because it is calculated based on highly conservative weather assumptions, such as low wind speed (0.6 m/s), full solar radiation (1,000 w/m^2) and high ambient temperature (40°C) [15]. However, actual weather conditions fluctuate continuously and are usually highly favourable, thereby allowing conductors to experience more cooling than what is expected. Thus, actual line ratings are usually much higher than STR, and current transmission line ratings can be increased significantly. Considering temporal atmospheric conditions, line ratings vary dynamically throughout the day, hence the term DTR system [16]. Owing to the advancement of sensors, communication systems and the Internet of Things in the last two decades, the DTR system can now determine line thermal ratings in real time or at specific time intervals [17].

Line rating is considerably affected by the wind cooling effect [18]. Several early studies have shown that the DTR system can increase the line capacity by 10%–30%, with 50% being possible in windy areas [19]–[22]. In conditions of high wind speed and high incident wind angle (close to 90°) with the line, the line rating increases and vice versa [23]–[26], indicating a strong correlation between wind power and line rating [27]. Thus, wind farm integration projects often benefit from the utilisation of the DTR system [28], [29]. Line rating is also determined based on the hottest section of the line, which is known as the critical span and is normally located in shielded areas exposed to minimal wind [30], [31]. Therefore, placing DTR sensors on critical spans is sufficient for the accurate estimation of the line rating [32]–[34]. This condition can ensure maximum line usage and keep the conductor temperature within its design limit. The installation of sensors on all line spans, although ideal for avoiding the need to estimate the line rating, is unnecessary and impossible due to the excessive costs to be incurred. On the basis of the mechanism in which the line rating is defined, line sag and temperature are the two aspects that reflect the line conditions. Hence, DTR sensors are typically designed for the direct measurement of conductor sag or temperature or other parameters that can be utilised to determine both. Many common DTR sensors work by monitoring the weather, line tension, sag and conductor temperature [35], [36].

The discussion above indicates that the capacity of existing transmission networks can be enhanced with the DTR system for integrating wind energy. The DTR system is also advantageous because the expansion of a transmission network can be delayed or avoided completely. This feature is particularly important in cases where land and space restrictions or regulatory requirements inhibit network expansion. This situation and the fact that nearly every country has embarked on a mission to increase the integration of RES make the role of the DTR system more important than ever and justify its increasing popularity. The sensory technology of the DTR system has recently received a massive upgrade, and its cost has been reduced due to the large-scale and efficient manufacturing process. Thus, exploring and reviewing critical studies on the DTR system are beneficial for researchers who are interested in the developments of DTR technology. The novelty of this review is ascribed to the following: (1) reviews and comparisons of the two main international standards of the DTR system; (2) reviews of all major DTR system monitoring technologies; and (3) reviews of notable case studies and research publications that elucidate the impacts of the DTR system on the reliability of power networks.

II. DTR SYSTEM

The real-time rating values of components are generally applicable to power lines, cables and power transformers. However, this work focused on the application of the DTR system to overhead lines (OHL) because these lines provide the most significant form of DTR application. Three standards can be used to calculate OHL capacity in real time. These three standards are provided by the International Council on Large Electric Systems (CIGRE) [37],

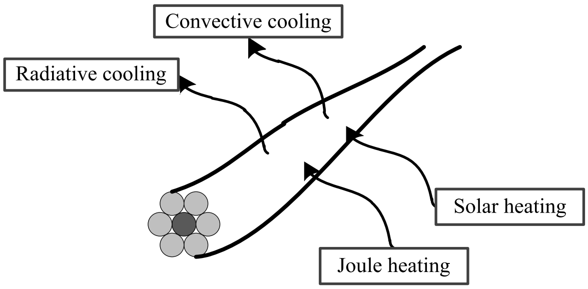


FIGURE 1. **Heat balance diagram of a conductor.**

International Electrochemical Commission (IEC) [38] and Institute of Electrical and Electronics Engineers (IEEE) [16]. Considering that USA utilises the IEEE standard 738 for determining line ratings [39] and that the CIGRE standard is widely adopted elsewhere [14], [15], only IEEE and CIGRE standards were reviewed in this work.

In both standards, OHL ratings are determined according to the first law of thermodynamics (Fig. 1) as follows:

$$Q_j + Q_s = Q_c + Q_r \tag{1}$$

where Q_j is conductor joule heating due to current flow, Q_s is solar radiation heating, Q_c is convective cooling due to wind blow and Q_r is radiative cooling.

The differences between the two standards in describing all of the elements in (1) are given in Table 1. The definitions of all the additional variables are provided in Appendix. Notably, the IEEE standard 738 provides a highly detailed modelling of line rating calculations on the basis of weather conditions. In the IEEE standard, the final line rating is determined by consolidating all heating and cooling elements as follows:

$$I_{ac} = \sqrt{\frac{Q_c + Q_r - Q_s}{R(T_c)}} \tag{2}$$

In the CIGRE standard, depending on whether the conductor is homogeneous or of the ACSR type, line ratings are determined according to (3) and (4), respectively.

$$I_{dc} = \sqrt{\frac{Q_c + Q_r - Q_s}{K_j R_{dc}\left[1 + \alpha_k \left(T_{av} - 20\right)\right]}} \tag{3}$$

$$I_{dc} = \sqrt{\frac{Q_c + Q_r - Q_s}{R_{dc}\left[1 + \alpha_k \left(T_{av} - 20\right)\right]}} \tag{4}$$

A. IEEE AND CIGRE STANDARDS

IEEE and CIGRE standards consider joule heating for homogenous conductors. The CIGRE standard also considers the ACSR conductor, whereas the IEEE standard does not (Table 1). In the CIGRE standard, conductor skin effects are adjusted for ferrous conductors, and this normally leads to a reduction in the overall line rating by about 0%–3% depending on the number of wire layers [40].

Heating from solar radiation is affected by the position of the sun. The three major components that define the position of the sun are solar declination (height of the sun depending on the day of the year), hour angle (position of the sun depending on the time of the day) and line latitude. In the original version of the IEEE standard 738 created before 2007 [41], solar heating is determined according to fixed tabular values. By contrast, the CIGRE standard offers a highly flexible solar heating calculation because it uses formulas. However, in the revised version of the IEEE standard 738 [16], the tabular values are replaced with formulas as well, and this update makes the solar heating calculations offered by the IEEE standard as competitive as those of the CIGRE standard. The IEEE standard considers direct solar radiation only. Two types of atmospheric conditions are also considered, and they are grouped into either industrial or clear atmospheres. In addition to direct solar radiation, the CIGRE standard also considers reflected and defused radiations but without the distinction for atmospheric conditions. A unique feature of the CIGRE standard is that it considers different types of ground surfaces when calculating the reflected radiation. Both standards agree that solar intensity should be increased as the altitude above sea level increases. With all factors considered, the solar heating provided by the CIGRE standard is generally 10%–15% higher than that provided by the IEEE standard 738 [40].

For convective cooling, IEEE and CIGRE standards have distinct formulas for natural (due to wind blowing) and forced (no wind condition) convections. The calculation for radiative cooling is simple, with only one formula utilised in both standards. With regard to calculation, no significant differences can be observed in the cooling elements of the two standards [40]. Table 1 presents the details of these formulas.

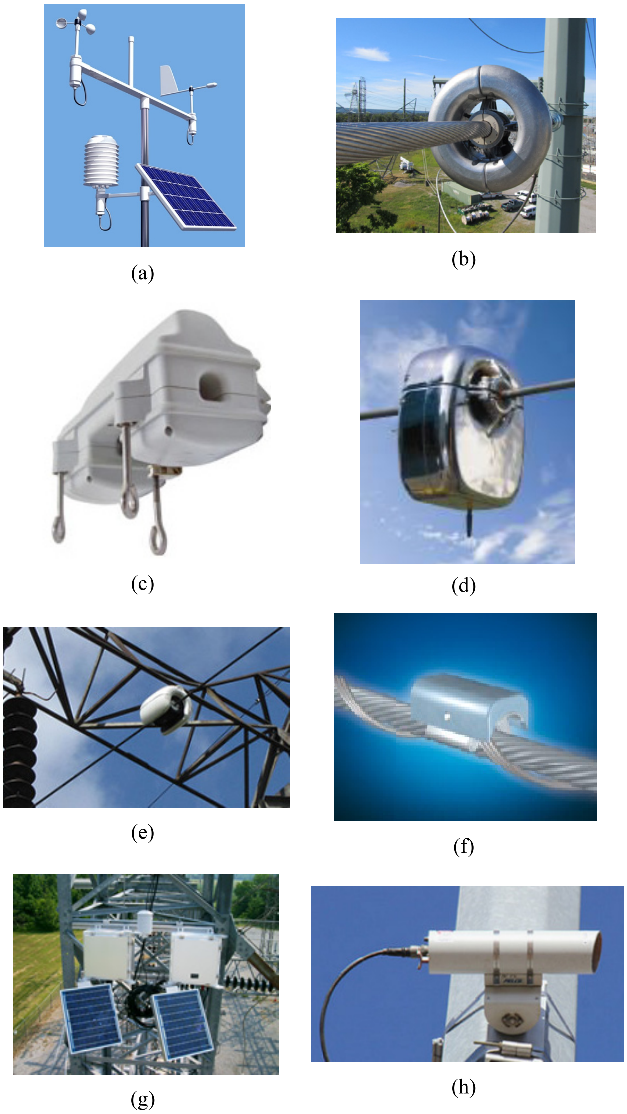
B. DTR SYSTEM MONITORING DEVICES

The DTR system is implemented with a direct or indirect measurement system. A direct measurement system measures weather conditions or conductor temperatures, which are inputs required by IEEE or CIRGE standards. Therefore, it is the simplest system to use. If a direct measurement system is implemented on a continuous basis, real-time line ratings can be obtained and updated periodically, typically for 5 min to an hour [42], [43]. The collected weather data are useful for forecasting future weather conditions and line ratings [44], [45]. Many studies have reported the successful usage of weather data for improving line ratings in various countries, such as the USA [19], [21], [43], [46], Korea [47], Spain [48], Italy [49], Germany [50], [51], Austria [52] and the UK [53]–[56]. Fig. 2a shows an example of a weather monitoring station.

Moreover, conductor temperature can be measured, and the most common commercial sensor for this task is the power donut (Fig. 2b) [57]. Apart from temperature, conductor sag and tension can also be measured by the power donut on the basis of conductor inclination. The device is self-powered by feeding off the electromagnetic field emitted by the energized conductor. It can be easily installed by clamping onto the line,

TABLE 1. Comparison of the equations between IEEE and CIGRE standards.

Elements	IEEE standard 738	CIGRE
Joule heating (Q_j)	$I_{ac}^2R(T_c)$ where $R(T_c) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right](T_c - T_{low}) + R(T_{low})$	Homogeneous conductor: $K_jI_{ac}^2R_{dc}[1 + \alpha_k(T_{av} - 20)]$ where $I_{ac} = \frac{I_{dc}}{\sqrt{1.0123 + 2.319 \times 10^{-5}I_{dc}}}$ ACSR conductor: $I_{dc}^2R_{dc}[1 + \alpha_k(T_{av} - 20)]$ where $I_{ac} = \frac{I_{dc}}{\sqrt{1.0045 + 0.09 \times 10^{-6}I_{dc}}}$
Solar heating (Q_s)	$\alpha Q_{se}\sin(\theta)A'$ where $Q_{se} = K_{solar}q_s$, such that: $q_s = A + BH_c + CH_c^2 + DH_c^3 + EH_c^4 + FH_c^5 + GH_c^6$ $H_c = arcsin[\cos(Lat)\cos(\delta)\cos(\omega) + \sin(Lat)\sin(\delta)]$ $\delta = 23.4583\sin\left[\frac{284 + N}{365}360\right]$ $\theta = arcos[cos(H_c)cos(Z_c - Z_l)]$, such that: $Z_c = C + \arctan(\chi)$ $\chi = \frac{\sin(\omega)}{\sin(Lat)\cos(\omega) - \cos(Lat)\tan(\delta)}$	αSD
Convective cooling (Q_c)	If no wind $Q_{cn} = 0.0205\rho_f^{0.5}D^{0.75}(T_c - T_a)^{1.25}$ else, maximum (Q_{c1}, Q_{c2}) where $Q_{c1} = \left[1.01 + 0.0372\left(\frac{D\rho_fV_w}{\mu_f}\right)^{0.52}\right]k_fK_{angle}(T_c - T_a)$ $Q_{c2} = \left[0.0119\left(\frac{D\rho_fV_w}{\mu_f}\right)^{0.6}k_fK_{angle}(T_c - T_a)\right]$ such that, $K_{angle} = 1.194 - \cos(\phi) + 0.194\cos(2\phi) + 0.368\sin(2\phi)$ or $K_{angle} = 1.194 - \sin(\beta) - 0.194\cos(2\beta) + 0.368\sin(2\beta)$	$\pi k_f(T_c - T_a)Nu$ If wind speed $> 0.5\ m/s$ $Nu_\delta = B_1Re^n[A_1 + B_2(\sin\delta)^{m_1}]$, such that $A_1 = 0.42, B_2 = 0.68\ and\ m_1 = 1.08\ for\ 0^\circ < \delta < 24^\circ$ $A_1 = 0.42, B_2 = 0.58\ and\ m_1 = 0.90\ for\ 24^\circ < \delta < 90^\circ$ else if no wind speed $Nu_0 = A_2(Gr \cdot Pr)^{m_2}$ Else if wind speed $< 0.5\ m/s$ Maximum $(Nu_\delta, Nu_0, 0.55B_1Re^n)$
Radiative cooling (Q_r)	$Q_r = 0.0178D\varepsilon\left[\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right]$	$\pi D\varepsilon\sigma_B[(T_c + 273)^4 - (T_a + 273)^4]$



(a) (b) (c) (d) (e) (f) (g) (h)

FIGURE 2. **Various dynamic thermal rating (DTR) sensors. (a) Weather monitoring station; (b) power donut; (c) FMC-T6; (d) temperature monitoring system; (e) overhead transmission line monitoring device (OTLM); (f) Ritherm; (g) CAT-1; and (h) sagometer.**

and its applications have been tested and reported [58]–[60]. Other similar devices are FMC-T6 (Fig. 2c) [61], temperature monitoring system (Fig. 2d) [62], overhead transmission line monitoring device (OTLM) (Fig. 2e) [63] and easy monitoring overhead (EMO) transmission line sensors [64]. Sensors based on revolutionary techniques, such as the surface acoustic wave-based Ritherm sensor (Fig. 2f) [65], time-domain reflectometry-based fiberoptic distributed temperature sensor [66] and radio frequency cavity resonance-based sensors [67] from Isfahan University of Technology and the University of Manitoba, have also been utilised to measure conductor temperature.

In an indirect measurement system, parameters that reflect the conductor temperature, such as line tension and sag, are measured and used to estimate the line ratings. The tension monitoring system is one of the most common indirect measurement methods. This system operates by mounting a load cell in series with the insulator strings. Line tension is a good indicator to be measured because it has a direct relationship with line sag, which is further affected by conductor temperature due to current flow. Hence, determining the line tension indirectly indicates the line rating as well [34]. A popular commercial tension monitoring system currently available on the market is the CAT-1 system (Fig. 2g) [33], [68], [69]. A similar tension monitoring system has also been developed by the University of Basque Country [70]. Calculating the line rating based on line tension has also received considerable research interest [71]–[75] and has been applied in various countries, such as the USA [76], New Zealand [77], Netherlands [72], Brazil [60], Australia [78], China [79] and Spain [79].

An alternative to tension measurement is to monitor line sag by using a sagometer (Fig. 2h) [80]. The advantage of determining line sag is that it can be used directly as a reference to avoid ground clearance infringement imposed by most of the regulators. The line sag method is accepted worldwide, especially in the USA [81], [82] and Belgium [83]–[86]. Apart from a sagometer, the electromagnetic field-based sensors developed by Promethean Devices [87] can also be used. This type of sensor measures the three-phase AC magnetic fields radiated from the line conductor, which are then used to determine line sag and temperature [88].

III. RELIABILITY EFFECTS OF THE DTR SYSTEM ON POWER NETWORKS

Studies on the reliability effects of the DTR system on power networks are reviewed in this section. The basic principles of power system reliability assessment are explained. Several popular methods in power system reliability analysis are also briefly reviewed. Then, current research developments in the academe and industry are reviewed and explained in detail.

A. BASIC PRINCIPLES OF POWER SYSTEM RELIABILITY ASSESSMENTS

Evaluation of the reliability of a power system involves determining the system's capacity to generate and transport sufficient power and thereby satisfy the power demand [89], [90]. The two main approaches for this task are analytical and Monte Carlo simulation (MCS) methods [91], [92]. The analytical method depends on mathematical models, calculations and the concept of probabilities and frequencies for the evaluation of power system reliability [93]. By contrast, MCS simulates random behaviours of power systems, and each simulation is considered an experiment in which the reliability of the power systems is assessed. Then, average reliability indices are obtained through reiterated experiments and aggregation of the reliability indices in each experiment. Despite these analytical methods, the advancement of computers has allowed the wide application of MCS, which has been subsequently proven and accepted to be a robust technique [94]–[97], consequently leading to an

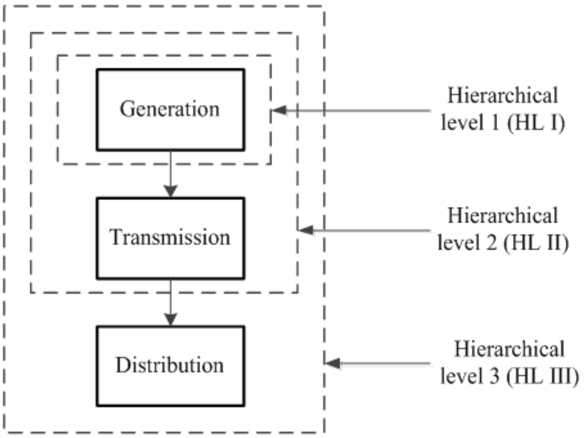


FIGURE 3. Three hierarchical levels of the power system

accurate evaluation of reliability indices because MCS can simulate actual power system operations [98]–[100].

The major obstacle in executing MCS is the expensive computational requirements due to the large size of power systems [101]. Even the most advanced computer setups cannot simulate every possible scenario of power systems within a reasonable timeframe. Consequently, the power system analysis, as shown in Fig. 3, is divided into three subsystems or hierarchical levels (HLs) [102]. The first level (HL I) is only concerned with the capability of the generation system to produce adequate amount of power. At this stage, the transmission and distribution networks are considered fully reliable. The second level (HL II) extends HL I by considering the reliability of the transmission networks. In many cases, HL II is also known as the composite power system analysis. In HL II, the capacity of the transmission network is finite, and the optimal power flow, either AC or DC, is executed to determine power flows. The electricity transportation capability of the system is then analysed. In the third and final level (HL III), the distribution network, along with all the previous levels, is considered. Regardless of which HL is performed, the ultimate goal of all the HLs is to assess the capability of the power systems to satisfy customer load demands [89]. Power system reliability analysis should not be confused with security analysis, as the latter is the capability of the power systems to regain a state of equilibrium after being subjected to physical disturbances [103], [104].

Performing the reliability evaluation of the power systems requires various methods, the categorisation of which is shown in Fig. 4. The figure shows that the power system reliability assessment is performed using either the deterministic or probabilistic technique [89]. Furthermore, both of the previously mentioned analytical method and MCS are classified under the probabilistic technique. Only the probabilistic technique is further discussed in this study because it has been widely agreed to be more useful than the deterministic technique [105]–[108].

The analytical method is composed of the enumeration, population-based and approximation methods. The enumeration model is normally combined with the power system load model to form a risk model and it can be performed in two approaches. The first approach is the loss-of-load-expectation method, which determines the probability of power system loads that exceed the generation capacity. The second approach is the frequency-and-duration method [109], [110], which covers probability, as well as the rate and duration at which the power system components are in the outage mode. The population-based method employs evolutionary programming, such as the genetic algorithm, particle swarm optimisation and intelligent state space pruning to optimise and facilitate the calculation of reliability indices [111], [112]. The advantage of the evolutionary algorithm is that it can discover all or majority of the power system states to approximate a good calculation of the reliability indices [113]. Notable studies that have demonstrated this advantage can be found in [114]–[121]. Finally, the approximate method offers a new approach by using the continuous probability distribution function to approximate the reliability indices [122]. Notwithstanding the benefits of the analytical method, its main limitation is the escalation of the modelling complexity as the number of power system components increases.

The MCS imitates the actual random behaviour of power systems, during which the system component failures are simulated through the use of random variables and suitable probability distributions. The main objective of MCS is to simulate the behaviour of power systems multiple times until the average reliability indices are obtained. The MCS can also simulate large and complicated power systems, rendering the analytical method ineffective. The analytical method requires a large number of contingency enumerations before obtaining a reduced representative model. The MCS avoids this problem by sampling directly the characteristics of the system states. The MCS is conducted either in sequential or non-sequential mode depending on the approach the system states are sampled [94], [123]–[126]. Given the chronological requirements in sequential MCS, it normally requires longer simulation time than the non-sequential MCS. Pseudo- [127], [128] and quasi-sequential [129], [130] MCS do not belong to either groups. Generally, all MCS are performed at a fixed number of iterations or until the convergence criteria are achieved [89], [131].

B. CURRENT RESEARCH DEVELOPMENT

This section reviews notable research works that focus on the reliability effect of the DTR system towards the electrical network.

1) RELIABILITY MODELLING OF DTR SYSTEMS

A model for evaluating the reliability of the DTR system was proposed in [132]. Despite its publication in 2013, it is one of the earliest studies that has directly investigated the reliability issue of the DTR system. In this study, a Markov model for the reliability analysis of transmission lines equipped with the DTR system was proposed. The model was also extended to

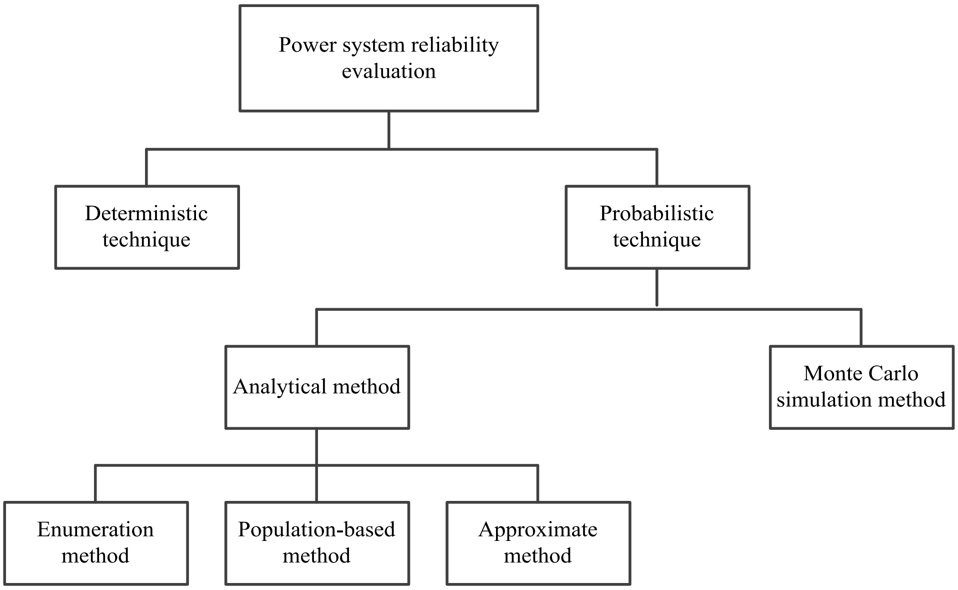


FIGURE 4. Power system reliability evaluation methods

include fuzzy line rating calculation in the composite power system reliability assessment. To achieve this, an interactive resolution technique for solving the fuzzy optimisation problems was developed. This proposal was suggested by the same author to be included into the existing IEEE Standard 738 to capture the uncertainty factors of line rating values [133]. In the study, the author explained that the sampling of the weather data is limited due to the selective placements of the DTR sensors on critical spans. Moreover, hidden calibration issues might exist in the DTR sensors, which may contaminate weather data with errors and uncertainties. An alternative solution to the fuzzy method is the identification of critical spans in a line for the optimum placements of sensors [32]–[34]. This method strategically places the DTR sensors without sacrificing the estimation accuracy of line ratings. From the operational viewpoint, the reliability of the DTR system can be improved by using a weather estimation model based on the regression method [134], [135]. Through the regression method, the weather conditions at locations not covered by the DTR system can be estimated using those sampled by the nearby DTR sensors. This strategy has the advantage of guarding against the outage of DTR sensors when weather or line data are not sampled.

2) RELIABILITY EFFECTS OF DTR SYSTEMS IN WIND-INTEGRATED POWER NETWORKS

The capability of the DTR system to improve the reliability of wind-integrated power systems has also been widely investigated. In [136], common wind simulation standards in the industry were adopted to estimate line ratings for network planning and operation. This approach enables the identification of optimum conductor routes for the estimation of additional wind energy that can be accommodated. Reliability frameworks for modelling the wind-integrated power systems were proposed in [27] and [137]. In both frameworks, the network reliability with variable conductor ratings was assessed. The effects of failures and uncertainties in the DTR system were also considered, and the effect of the correlation between conductor ratings due to common weather conditions was built into the model. A framework that employed the weather-based methods to estimate probabilistic line rating forecasts for overhead lines was proposed in one study [138]. The study can be used by system operators within a selected risk policy with respect to the probability of a rating being exceeded.

Aside from academic research, studies on DTR systems have also received widespread attention in several practical wind energy-related applications. For example, the Dungannon–Omagh 110 kV line in Northern Ireland is equipped with DTR systems, which enhances wind integration capacity [54], [85], [139]. Meanwhile, according to the weather and line data from the Dungannon–Omagh and Kells–Coleraine 110 kV lines in Queen's University Belfast, high wind generation certainly corresponds to high line capacities [140]–[142]. The prospect of the DTR systems on the Skegness–Boston 132 kV line in the UK was also studied by Areva T&D, E.ON Central Networks and the Northern Ireland Electricity [53], [143], [144]. The study indicated that the maximum line rating was considerably higher than the STR in most cases and that the efficiency of wind energy integration could be improved by 20%–50% when the cooling effect of wind was considered. A consortium consisting of Alstom Grid, Durham University, Astrium, Parsons Brinckerhoff and Scottish Power Energy Networks implemented the DTR system onto a 132 kV line to facilitate a connection of over 200 MW of wind power [55]. The DTR system in this study incorporated over 90 km of overhead lines and some key learning points from related preceding research;

strategies for the close-loop control of distributed generation schemes and wide area implementations of the DTR system were also presented. Their study shows that the DTR system can provide 67% upgrade in line ampacity at only 62% of the re-tensioning cost [145]. From the Twenties Project, which was funded by the European Union, the DTR system could uprate line ratings by more than 10% throughout the day and possibly more than 100% in windy days [140], [146]–[148]. In Sweden, a study revealed that transmission lines in the country were not maximised for wind power integration, indicating the need for line uprating by the DTR system [149]. In the on-shore wind farms in Spain, a strong correlation between wind speed and line rating was observed, and this correlation was found to have favourable effect on the 66 kV evacuation lines of their wind farms [150].

3) JOINT RELIABILITY EFFECTS OF DTR SYSTEMS WITH OTHER SMART GRID TECHNOLOGIES ON POWER NETWORKS

Various studies have shown that the reliability benefit of the DTR system can be further improved when it is combined with other technologies. A model that uses the probabilistic framework for optimal demand response scheduling, together with the DTR system in the day-ahead planning of transmission networks, has been proposed [151]. The demand response program has also been used before with the DTR system to increase the utilisation of wind generation [152]. The results from these studies show that considerable benefits can be realised by coordinating the demand response program and the DTR system. Moreover, the flexibility of the power system analysis is improved when the DTR system is used. This result is possible because the high line ratings offered by the DTR system relax the constraints of transmission line capacity and load shedding strategy [153]. Furthermore, the effect of the demand response program on various levels of load demand, together with the DTR system, has also been studied [154]. The studies have shown that applying the demand response program on load sectors is more beneficial than on the system load and that the DTR system enhances the reliability effect of the program. Meanwhile, an optimal real-time transmission congestion management algorithm based on real-time thermal loading has been proposed for the competitive electricity market [155].

In [156], energy storage technologies were combined with the DTR system by utilizing the inherent variability in power line ratings due to changing weather conditions. As a result, power system reliability was enhanced, conventional network reinforcement was deferred and the availability of energy storage in commercial service markets was increased. A reliability framework that considers the DTR system, overhead line technologies and their associated ageing risk has also been proposed [157]. In a related study, the effect of the DTR system on the ageing failure probability of transmission line has also been addressed through the use of the Arrhenius model [158].

4) OTHER RELIABILITY STUDIES ON DTR SYSTEMS

A comprehensive assessment of the potential of the DTR system in the Finnish distribution network for the proliferation of electric vehicles (EVs) and distributed generations was performed in [29]. The study confirmed that the application of the DTR system was more suitable for overhead lines than underground cables. It also concluded that the DTR system was most useful when networks were highly loaded by either demand or generation. The modelling approach of the DTR system according to the USA standard has more sophisticated wind model compared with the UK standard, whereas the UK standard has better uncertainty model [39]. Nonetheless, both of these novel strengths have been suggested to be carried forward into future developments of weather-based DTR systems. A case report for the application of the DTR systems on the 138 kV line running from Columbia Power Plant Substation to the Portage Substation was provided in [159]. The report covered conductor temperature measurement systems, real-time interface, monitoring and handling of raw data, rating process, thermal transient conductor response, suppressed rating during the transient period, thermal transient response display and alarm processing. The DTR system has also been investigated together with the system integrity protection scheme, such as the operational tripping scheme (OTS) [160]. The desirable features of the DTR system have been used to enhance the existing OTS, thereby reducing the likelihood of premature generation tripping. Finally, a new probabilistic method for accounting the variable ratings due to the DTR system during network planning was proposed in [161]. The result of the study shows that the proposed method allows additional loads to be connected to the network at a quantified level of risk.

IV. CONCLUSION

DTR systems can increase the line rating safely and securely without sacrificing engineering and social requirements. DTR systems regulate line ratings based on real-time weather conditions and line physical properties; thus, line ratings can be improved without causing annealing or infringing ground clearance. Furthermore, the use of DTR systems avoids/delays the construction of new lines. Accordingly, DTR systems can satisfy the needs of power system operators and country regulators that need to protect the interests of other parties. The literature reviews form the consensus that DTR systems are beneficial for wind power integration due to the positive correlation of wind power generation and line ratings; high wind speed produces further wind power and provides considerable conductor cooling. DTR systems have also been utilised with other smart grid technologies, such as demand-side management (DSM), energy storage and conductor technologies, to improve the power system reliability. In the present review paper, a literature review is performed, focusing on the current standards used by DTR systems, the development of the DTR sensor technology and the effects of DTR systems towards the reliability of the power system.

The review on the current reliability modelling of the DTR system reveals that the IEEE Standard 738 is preferred over the CIGRE Standard. The survey shows that the reliability modelling of DTR systems has been performed using the Markov model, Event tree analysis (ETA) and fuzzy method, and the choice of the method depends only on the modelling requirement because all these methods are equally applicable. For example, if time factor is important and is required, then the Markov model is suitable; otherwise, the ETA is sufficient. Meanwhile, the fuzzy method is deemed the most appropriate if the uncertainty factors of the line ratings and weather data are highly significant to be ignored. This review paper also collected recent experience of DTR system applications by various institutions in the industry and the academia. All the reported experiences agree that DTR systems are beneficial for increasing the ratings of existing lines and that the STR largely underestimates the potential of the actual line capacity. The several promising field pilot studies of DTR systems indicate that a wide usage of DTR systems is possible. Nonetheless, caution should be exercised because DTR systems also interact with other conditions and technologies in actual power system applications. In this aspect, the reviews on the reliability effects of DTR systems in consideration of the DSM, transmission network management and expansion, energy storage, line conductor material technology and ageing process are also presented in this paper. These considerations indicate that the reliability effects of DTR systems are complicated and their prudent usage should be enforced. Despite the aforementioned components in evaluating the reliability of DTR systems, several emerging topics, such as the cyber-physical interaction of the power system, electric vehicles (EVs) and the combination of EVs and RES, are still lacking in the literature. Hence, the authors of this paper recommend that future works on the reliability assessment of DTR systems should focus on these topics while advancing existing research for DTR systems.

APPENDIX

A. DEFINITION OF IEEE STANDARD 738 VARIABLES

I_{ac}	Conductor current.
T_c	Conductor operating temperature.
$R(T_c)$	Conductor AC resistance as a function of T_c.
T_{high}, T_{low}	Defined high and low temperature values of a conductor as stated in the Aluminium Electrical Conductor Handbook.
$R(T_{high})$	Conductor AC resistance at high temperature.
$R(T_{low})$	Conductor AC resistance at low temperature.
$R(T_c)$	Conductor AC resistance as a function of T_c
α	Solar absorptivity.
Q_{se}	Corrected total heat flux rate.
θ	Solar radiation angle between the incident ray and overhead line.
A'	Projected area of the conductor per unit length.
K_{solar}	Solar altitude correction factor.
q_s	Total solar- and sky-radiated heat flux rate.
$A, B, C, D,$ E, F and G	Constant values for clear or industrial atmospheric conditions.
H_c	Altitude of the sun.
Lat	Latitude.
ω	Number of hours from local sun noon times at 15 °C.
δ	Solar declination.
Z_l	Azimuth of the line (constant).
Z_c	Azimuth of the sun.
C	Constant obtained from the solar azimuth table in IEEE Standard 738.
χ	Solar azimuth variable.
D	Conductor diameter.
ρ_f	Air density.
V_w	Wind velocity.
μ_f	Dynamic viscosity of air.
k_f	Thermal conductivity of air at T_{film}.
K_{angle}	Wind direction factor.
T_a	Ambient air temperature.
T_{film}	Average temperature between T_a and T_c.
ϕ	Angle between the wind direction and conductor axis.
β	Angle between the wind direction and perpendicular to the conductor axis.

B. DEFINITION OF CIGRE STANDARD VARIABLES

K_j	Resistance correction factor due to skin effects.
α_k	Temperature coefficient of resistance per degree Kelvin.
T_{av}	Mean temperature.
R_{dc}	DC resistance at 20 °C.
S	Global solar radiation measured by the global solar radiation meter.
$(Gr \cdot Pr)$	Rayleigh number.
σ_B	Stefan–Boltzmann constant.

REFERENCES

[1] Z. Wang, F. Yin, Y. Zhang, and X. Zhang, "An empirical research on the influencing factors of regional CO_2 emissions: Evidence from Beijing city, China," *Appl. Energy*, vol. 100, pp. 277–284, Dec. 2012.

[2] M. Blesl, A. Das, U. Fahl, and U. Remme, "Role of energy efficiency standards in reducing CO_2 emissions in Germany: An assessment with TIMES," *Energy Policy*, vol. 35, no. 2, pp. 772–785, 2007.

[3] J. Bentzen, "Estimating the rebound effect in US manufacturing energy consumption," *Energy Econ.*, vol. 26, no. 1, pp. 123–134, 2004.

[4] S.-H. Jin, "The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential electricity use in South Korea," *Energy Policy*, vol. 35, no. 11, pp. 5622–5629, 2007.

[5] J. Liu, Z. Cheng, and H. Zhang, "Does industrial agglomeration promote the increase of energy efficiency in China?" *J. Cleaner Prod.*, vol. 164, pp. 30–37, Oct. 2017.

[6] Y. Fernando and W. L. Hor, "Impacts of energy management practices on energy efficiency and carbon emissions reduction: A survey of Malaysian manufacturing firms," *Resour., Conservation Recycling*, vol. 126, pp. 62–73, Nov. 2017.

[7] P. W. Griffin, G. P. Hammond, and J. B. Norman, "Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective," *Appl. Energy*, to be published.

[8] P. del Río, A. C. Silvosa, and G. I. Gómez, "Policies and design elements for the repowering of wind farms: A qualitative analysis of different options," *Energy Policy*, vol. 39, no. 4, pp. 1897–1908, 2011.

[9] P. Breeze, "Wind farms, electrical optimization, and repowering," in *Wind Power Generation*. New York, NY, USA: Academic, 2016, ch. 7, pp. 59–65.

[10] P. Hou, P. Enevoldsen, W. Hu, C. Chen, and Z. Chen, "Offshore wind farm repowering optimization," *Appl. Energy*, vol. 208, pp. 834–844, Dec. 2017.

[11] L. Serri, E. Lembo, D. Airoldi, C. Gelli, and M. Beccarello, "Wind energy plants repowering potential in Italy: Technical-economic assessment," *Renew. Energy*, vol. 115, pp. 382–390, Jan. 2018.

[12] "Ten-Year Network Development Plan 2014," in *Proc. Eur. Netw. Transmiss. Syst. Operators Electricity (ENTSOE)*, 2014.

[13] T. O. Seppa, "Increasing transmission capacity by real time monitoring," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, Jan. 2002, pp. 1208–1211.

[14] "Guidlines for increased utilization of existing overhead transmission line," in *Proc. CIGRE Brochure*, 2008.

[15] "Guide for the selection of weather parameters for bare overhead conductor ratings," in *Proc. CIGRE Brochure*, 2006.

[16] *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*, IEEE Standard 738-2012 (Revision of IEEE Standard 738-1993), 2007, pp. 1–72.

[17] K. Morozovska and P. Hilber, "Study of the monitoring systems for dynamic line rating," *Energy Proc.*, vol. 105, pp. 2557–2562, May 2017.

[18] A. k. Deb, *Powerline Ampacity System: Theory, Modeling and Applications*. Boca Raton, FL, USA: CRC Press, 2000.

[19] D. A. Douglass and A. Edris, "Real-time monitoring and dynamic thermal rating of power transmission circuits," *IEEE Trans. Power Del.*, vol. 11, no. 3, pp. 1407–1418, Jul. 1996.

[20] D. A. Douglass and A.-A. Edris, "Field studies of dynamic thermal rating methods for overhead lines," in *Proc. IEEE Transmiss. Distribution Conf.*, Apr. 1999, pp. 842–851.

[21] D. A. Douglass, A. Edris, and G. A. Pritchard, "Field application of a dynamic thermal circuit rating method," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 823–831, Apr. 1997.

[22] T. O. Seppa, M. Clements, R. Payne, S. Damsgaard-Mikkelsen, and N. Coad, "Application of real time thermal ratings for optimizing transmission line investment and operating decisions," in *Proc. CIGRE*, 2000, paper 22-301.

[23] M. W. Davis, "A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines—Part I: General description and justification of the real time thermal rating system," *IEEE Trans. Power App. Syst.*, vol. PAS-96, no. 3, pp. 803–809, May 1977.

[24] M. W. Davis, "A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines part III: Steady state thermal rating program continued-solar radiation considerations," *IEEE Trans. Power App. Syst.*, vol. PAS-97, no. 2, pp. 444–455, Mar. 1978.

[25] M. W. Davis, "A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines—Part II: Steady state thermal rating program," *IEEE Trans. Power App. Syst.*, vol. PAS-96, no. 3, pp. 810–825, May 1977.

[26] M. W. Davis, "A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines part IV: Daily comparisons of real-time and conventional thermal rating and establishment of typical annual weather models," *IEEE Trans. Power App. Syst.*, vol. PAS-99, no. 6, pp. 2184–2192, Nov. 1980.

[27] J. Teh and I. Cotton, "Reliability impact of dynamic thermal rating system in wind power integrated network," *IEEE Trans. Rel.*, vol. 65, no. 2, pp. 1081–1089, Jun. 2016.

[28] J. Heckenbergerova and J. Hosek, "Dynamic thermal rating of power transmission lines related to wind energy integration," in *Proc. 11th Int. Conf. Environ. Electr. Eng. (EEEIC)*, May 2012, pp. 798–801.

[29] A. Safdarian, M. Z. Degefa, M. Fotuhi-Firuzabad, and M. Lehtonen, "Benefits of real-time monitoring to distribution systems: Dynamic thermal rating," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 2023–2031, Jul. 2015.

[30] P. M. Callahan and D. A. Douglass, "An experimental evaluation of a thermal line uprating by conductor temperature and weather monitoring," *IEEE Trans. Power Del.*, vol. PWRD-3, no. 4, pp. 1960–1967, Oct. 1988.

[31] P. Musilek, J. Heckenbergerova, and M. M. I. Bhuiyan, "Spatial analysis of thermal aging of overhead transmission conductors," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1196–1204, Jul. 2012.

[32] J. W. Jerrell, W. Z. Black, and T. J. Parker, "Critical span analysis of overhead conductors," *IEEE Trans. Power Del.*, vol. PWRD-3, no. 4, pp. 1942–1950, Oct. 1988.

[33] M. Matus *et al.*, "Identification of critical spans for monitoring systems in dynamic thermal rating," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 1002–1009, Apr. 2012.

[34] J. Teh and I. Cotton, "Critical span identification model for dynamic thermal rating system placement," *IET Generat., Transmiss. Distrib.*, vol. 9, no. 16, pp. 2644–2652, 2015.

[35] I. Albizu, E. Fernández, A. J. Mazón, and J. Bengoechea, "Influence of the conductor temperature error on the overhead line ampacity monitoring systems," *IET Generat., Transmiss. Distrib.*, vol. 5, no. 4, pp. 440–447, 2011.

[36] B. S. Howington and G. J. Ramon, "Dynamic thermal line rating summary and status of the state-of-the-art technology," *IEEE Trans. Power Del.*, vol. PWRD-2, no. 3, pp. 851–858, Jul. 1987.

[37] "The thermal behaviour of overhead line conductors," *Electra*, vol. 114, pp. 107–125, 1992.

[38] *Overhead Electrical Conductors—Calculation Methods for Stranded Bare Conductors*, document IEC TR 61597:1995, 1985.

[39] D. M. Greenwood *et al.*, "A comparison of real-time thermal rating systems in the U.S. and the U.K," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1849–1858, Aug. 2014.

[40] N. P. Schmidt, "Comparison between IEEE and CIGRE ampacity standards," *IEEE Trans. Power Del.*, vol. 14, no. 4, pp. 1555–1559, Oct. 1999.

[41] *IEEE Standard for Calculation of Bare Overhead Conductor Temperature and Ampacity Under Steady-State Conditions*, ANSI/IEEE Standard 738-1986, 1985, pp. 1–19.

[42] J. F. Hall and A. K. Deb, "Prediction of overhead transmission line ampacity by stochastic and deterministic models," *IEEE Trans. Power Del.*, vol. PWRD-3, no. 2, pp. 789–800, Apr. 1988.

[43] W. J. Steeley, B. L. Norris, and A. K. Deb, "Ambient temperature corrected dynamic transmission line ratings at two PG&E locations," *IEEE Trans. Power Del.*, vol. 6, no. 3, pp. 1234–1242, Jul. 1991.

[44] R. Billinton, H. Chen, and R. Ghajar, "Time-series models for reliability evaluation of power systems including wind energy," *Microelectron. Rel.*, vol. 36, no. 9, pp. 1253–1261, 1996.

[45] S. D. Foss and R. A. Maraio, "Dynamic line rating in the operating environment," *IEEE Trans. Power Del.*, vol. 5, no. 2, pp. 1095–1105, Apr. 1990.

[46] O. A. Ciniglio and A. K. Deb, "Optimizing transmission path utilization in idaho power," *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 830–834, Apr. 2004.

[47] M. B. Wook, M. Choi, and A. K. Deb, "Line-rating system boosts economical energy transfer," *IEEE Comput. Appl. Power*, vol. 10, no. 4, pp. 36–39, Oct. 1997.

[48] F. Soto, D. Alvira, L. Martin, J. Latorre, J. Lumbreras, and M. Wagensberg, "Increasing the capacity of overhead lines in the 400 kV Spanish transmission network: Real time thermal ratings," in *Proc. Sesja CIGRE*, 1998, pp. 22–211

[49] E. Bartolomeo, G. Bruno, S. Tricoli, G. Pirovano, S. Chiarello, and D. Mezzani, "Increasing capacity of two Italian lines by the adoption of devices for monitoring environmental conditions and conductors temperature or by using high-temperature conductors," in *Proc. CIGRE Session*, 2008.

[50] H. Dräger, D. Hussels, and R. Puffer, "Development and implementation of a monitoring-system to increase the capacity of overhead lines," in *Proc. CIGRE Session*, 2008, pp. B2–101.

[51] R. Puffer, M. Schmale, B. Rusek, C. Neumann, and M. Scheufen, "Area-wide dynamic line ratings based on weather measurements," in *Proc. CIGRE*, 2012, pp. 1–10.

[52] M. Muhr, S. Pack, S. Jaufer, W. Haimbl, and A. Messner, "Experiences with the weather parameter method for the use in overhead line monitoring systems," *E&I Elektrotechnik Informationstechnik*, vol. 125, no. 12, pp. 444–447, 2008.

[53] T. Yip, C. An, G. Lloyd, M. Aten, and B. Ferri, "Dynamic line rating protection for wind farm connections," in *Proc. CIGRE/IEEE PES Joint Symp. Integr. Wide-Scale Renew. Resour. Power Del. Syst.*, Jul. 2009, pp. 1–5.

[54] J. Black, S. Connor, and J. Colandairaj, "Planning network reinforcements with Dynamic Line Ratings for overhead transmission lines," in *Proc. 45th Int. Univ. Power Eng. Conf. (UPEC)*, Aug./Sep. 2010, pp. 1–6.

[55] S. C. E. Jupe, D. Kadar, G. Murphy, M. G. Bartlett, and K. T. Jackson, "Application of a dynamic thermal rating system to a 132kV distribution network," in *Proc. 2nd IEEE PES Int. Conf. Exhibit. Innovative Smart Grid Technol.*, Dec. 2011, pp. 1–8.

[56] *Implementation of Real-Time Thermal Ratings*, SP Energy Netw., 2013.

[57] *USi: Real-Time Answers/Integrated Solutions*. [Online]. Available: http://www.usi-power.com/

[58] S. D. Foss, S. H. Lin, H. R. Stillwell, and R. A. Fernandes, "Dynamic thermal line ratings, part II—Conductor temperature sensor and laboratory field test evaluation," *IEEE Power Eng. Rev.*, vol. PER-3, no. 7, pp. 18–19, Jul. 1983.

[59] J. S. Engelhardt and S. P. Basu, "Design, installation, and field experience with an overhead transmission dynamic line rating system," in *Proc. Transmiss. Distrib. Conf. Exposit.*, Sep. 1996, pp. 366–370.

[60] C. A. M. Nascimento *et al.*, "The state of the art for increased overhead line ampacity utilizing new technologies and statistical criteria," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo., Latin Amer.*, Nov. 2004, pp. 464–469.

[61] *Multilin Intelligent Line Monitoring System*. [Online]. Available: http://www.gegridsolutions.com/multilin/catalog/fmc.htm

[62] Arteche. [Online]. Available: https://www.arteche.com/en/central-documentation?search_api_views_fulltext=smART&field_idioma=All

[63] OTLM. [Online]. Available: http://www.otlm.eu/

[64] Easy monitoring overhead (EMO) transmission Available:. [Online]. Available: http://www.ohtlgrid.com/en/ueberemo/ueberemo.html

[65] *Ritherm*. [Online]. Available: http://www.ribe.de/en/elektroarmaturen/produktspektrum

[66] A. Hartog, "Distributed fibre-optic temperature sensors: Technology and applications in the power industry," *Power Eng. J.*, vol. 9, no. 3, pp. 114–120, Jun. 1995.

[67] M. Ghafourian, G. E. Bridges, A. Z. Nezhad, and D. J. Thomson, "Wireless overhead line temperature sensor based on RF cavity resonance," *Smart Mater. Struct.*, vol. 22, no. 7, p. 075010, 2013.

[68] T. O. Seppa, H. W. Adams, and D. A. Douglass, "Use of on-line tension monitoring for real-time thermal ratings, ice loads and other environmental effects," *Proc. CIGRE Session*, 1998, pp. 22–102.

[69] *CAT-1 Monitoring System*. [Online]. Available: http://www.nexans.co.uk/eservice/UK-en_GB/navigate_191695/CAT_1_Transmission_Line_Monitoring_System.html

[70] I. Albizu, E. Fernandez, P. Eguia, E. Torres, and A. J. Mazon, "Tension and ampacity monitoring system for overhead lines," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 3–10, Jan.2013.

[71] J. K. Raniga and R. K. Rayudu, "Dynamic rating of transmission lines-a New Zealand experience," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, Jan. 2000, pp. 2403–2409.

[72] M. Boot, F. Wild, H. Van der Wey, and G. Biedenbach, "Overhead line local and distributed conductor temperature measurement techniques, models and experience at TZH," in *Proc. Sesja CIGRE*, 2002, paper 22-205.

[73] T. O. Seppa, E. Cromer, and W. F. Whitlatch, Jr., "Summer thermal capabilities of transmission lines in Northern California based on a comprehensive study of wind conditions," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 1551–1561, Jul. 1993.

[74] T. O. Seppa, "A practical approach for increasing the thermal capabilities of transmission lines," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 1536–1550, Jul. 1993.

[75] T. O. Seppa, "Accurate ampacity determination: Temperature-sag model for operational real time ratings," *IEEE Trans. Power Del.*, vol. 10, no. 3, pp. 1460–1470, Jul. 1995.

[76] *Research & Development: The Science of Innovation*. [Online]. Available: http://www.energy.ca.gov/research/index.html

[77] D. A. Douglass, Y. Motlis, and T. O. Seppa, "IEEE'S approach for increasing transmission line ratings in North America," in *Proc. CIGRE Biennial Session*, 2000.

[78] D. J. Spoor and J. P. Roberts, "Development and experimental validation of a weather-based dynamic line rating system," in *Proc. IEEE PES Innovative Smart Grid Technol.*, Nov. 2011, pp. 1–7.

[79] Z. He and Y. Liu, "The field application analysis of dynamic line rating system based on tension monitoring," in *Proc. IEEE Power Eng. Autom. Conf.*, Sep. 2011, pp. 284–288.

[80] *Span Sentry: Dynamic Line Rating System*. [Online]. Available: https://www.edmlink.com/products-edm/item/span-sentry-5

[81] C. Mensah-Bonsu, U. F. Krekeler, G. T. Heydt, Y. Hoverson, J. Schilleci, and B. L. Agrawal, "Application of the global positioning system to the measurement of overhead power transmission conductor sag," *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 273–278, Jan. 2002.

[82] K. E. Holbert and G. T. Heydt, "Prospects for dynamic transmission circuit ratings," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, May 2001, pp. 205–208.

[83] J. Lilien, S. Guerard, S. Godard, J. Destiné, and E. Cloet, "Microsystem array for live high voltage lines monitoring," in *Proc. CIGRE Session*, 2006, p. 8.

[84] P. Schell, B. Godard, V. D. Wilde, and O. Durieux, "Large penetration of distributed productions: dynamic line rating and flexible generation, a must regarding investment strategy and network reliability," in *Proc. Integr. Renew. Distrib. Grid Workshop (CIRED)*, Lisbon, Portugal, 2012, p. 280.

[85] H.-M. Nguyen, J.-L. Lilien, and P. Schell, "Dynamic line rating and ampacity forecasting as the keys to optimise power line assets with the integration of res. the European project twenties demonstration inside central western Europe," in *Proc. 22nd Int. Conf. Exhib. Electr. Distrib. (CIRED)*, Stockholm, Sweden, Jun. 2013, pp. 1–4.

[86] H. M. Nguyen, J. J. Lambin, F. Vassort, and J. L. Lilien, "Operational experience with dynamic line rating forecast-based solutions to increase usable network transfer capacity," in *Proc. 45th Session Council Large Electr. Syst. (CIGRE)*, 2014, pp. 1–11.

[87] *Dynamic Line Rating Systems for Transmission Lines*, U.S. Dept. Energy, Washington, DC, USA, 2014.

[88] S. Syracuse, P. Halverson, C. Barlow, and A. Hernandez, "Non-contact, real-time sensor system for accurate, secure, wireless monitoring of critical HV transmission line operating parameters," in *Proc. IEEE PES joint Tech. Committee Meeting, TP&C Subcommittee*, Atlanta, Georgia, 2009.

[89] R. N. Allan and R. Billinton, *Reliability Evaluation of Power Systems*. New York, NY, USA: Plenum, 1984.

[90] R. Billinton and R. N. Allan, *Reliability Evaluation of Engineering Systems: Concepts and Techniques*. Harlow, U.K.: Longman Scientific & Technical, 1987.

[91] R. Billinton *et al.*, "A reliability test system for educational purposes-basic data," *IEEE Trans. Power Syst.*, vol. 4, no. 3, pp. 1238–1244, Aug. 1989.

[92] R. Ghajar and R. Billinton, "A Monte Carlo simulation model for the adequacy evaluation of generating systems," *Rel. Eng. Syst. Safety*, vol. 20, no. 3, pp. 173–186, 1988.

[93] R. Billinton and W. Li, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*. London, U.K.: Plenum, 1994.

[94] A. C. G. Melo, M. V. F. Pereira, and A. M. Leite da Silva, "A conditional probability approach to the calculation of frequency and duration indices in composite reliability evaluation," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 1118–1125, Aug. 1993.

[95] G. J. Anders, *Probability Concepts in Electric Power Systems*. 2017.

[96] P. Renuga, N. Ramaraj, and A. Primrose, "Frequency and duration method for reliability evaluation of large scale power generation system by fast Fourier transform technique," *J. Energy Environ.*, vol. 5, pp. 94–100, May 2006.

[97] D. Elmakias, *New Computational Methods in Power System Reliability*. Springer, 2008.

[98] R. Billinton and T. K. P. Medicherla, "Overall approach to the reliability evaluation of composite generation and transmission systems," *IEE Proc. C, Generat., Transmiss. Distrib.*, vol. 127, no. 2, pp. 72–81, 1980.

[99] R. Billinton and J. Tatla, "Composite generation and transmission system adequacy evaluation including protection system failure modes," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no. 6, pp. 1823–1830, Jun. 1983.

[100] S. H. F. Cunha, M. V. F. Pereira, L. M. V. G. Pinto, and G. C. Oliveira, "Composite generation and transmission reliability evaluation in large hydroelectric systems," *IEEE Trans. Power App. Syst*, vol. PAS-104, no. 10, pp. 2657–2663, Oct. 1985.

[101] M. Čepin, *Assessment of Power System Reliability*. London, U.K.: Springer-Verlag, 2011.

[102] R. Billinton and R. N. Allan, "Power-system reliability in perspective," *Electron. Power*, vol. 30, no. 3, pp. 231–236, Mar. 1984.

[103] P. Kundur, *Power System Stability and Control*. New York, NY, USA, 1993.

[104] P. Kundur, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387–1401, May 2004.

[105] R. Billinton, M. Fotuhi-Firuzabad, and L. Bertling, "Bibliography on the application of probability methods in power system reliability evaluation 1996-1999," *IEEE Trans. Power Syst.*, vol. 16, no. 4, pp. 595–602, Nov. 2001.

[106] Power System Engineering Committee, "Bibliography on the application of probability methods in power system reliability evaluation 1971–1977," *IEEE Trans. Power App. Syst.*, vol. PAS-97, no. 6, pp. 2235–2242, Nov. 1978.

[107] R. Billinton and K. Chu, "Early evolution of LOLP: Evaluating generating capacity requirements [history]," *IEEE Power Energy Mag.*, vol. 13, no. 4, pp. 88–98, Jul./Aug. 2015.

[108] M. T. Schilling, R. Billington, A. M. L. da Silva, and M. A. El-Kady, "Bibliography on composite system reliability," *IEEE Trans. Power Syst.*, vol. 4, no. 3, pp. 1122–1132, Aug. 1989.

[109] W. Wood, M. P. Bhavaraju, S. J. Solowski, and D. C. Widman, "A probabilistic approach to off-peak electric energy evaluation," *IEEE Trans. Power App. Syst.*, vol. 95, no. 4, pp. 1501–1506, Jul. 1976.

[110] A. C. G. Melo, M. V. F. Pereira, and A. M. L. da Silva, "Frequency and duration calculations in composite generation and transmission reliability evaluation," *IEEE Trans. Power Syst.*, vol. 7, no. 2, pp. 469–476, May 1992.

[111] L. Wang and C. Singh, "Population-based intelligent search in reliability evaluation of generation systems with wind power penetration," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1336–1345, Aug. 2008.

[112] C. Singh and L. Wang, "Role of artificial intelligence in the reliability evaluation of electric power systems," *Turkish J. Elect. Eng.*, vol. 16, no. 3, pp. 189–200, 2008.

[113] V. Miranda, L. de Magalhaes Carvalho, M. A. da Rosa, A. M. L. da Silva, and C. Singh, "Improving power system reliability calculation efficiency with EPSO variants," *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1772–1779, Nov. 2009.

[114] A. M. L. da Silva, L. C. de Resende, L. A. da Fonseca Manso, and V. Miranda, "Artificial neural networks applied to reliability and well-being assessment of composite power systems," in *Proc. 10th Int. Conf. Probablistic Methods Appl. Power Syst.*, May 2008, pp. 1–6.

[115] R. C. Green, Z. Wang, L. Wang, M. Alam, and C. Singhy, "Evaluation of loss of load probability for power systems using intelligent search based state space pruning," in *Proc. IEEE 11th Int. Conf. Probabilistic Methods Appl. Power Syst.*, Jun. 2010, pp. 319–324.

[116] R. C. Green, L. Wang, and C. Singh, "State space pruning for power system reliability evaluation using genetic algorithms," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2010, pp. 1–6.

[117] N. A. A. Samaan, "Reliability Assessment of Electric Power Systems Using Genetic Algorithms," Ph.D. dissertation, Dept. Elect. Eng., College Station, TX, USA, Texas A&M Univ., 2004.

[118] R. C. Green, L. Wang, M. Alam, C. Singh, and D. S. S. S. R. Depuru, "An examination of artificial immune system optimization in intelligent state space pruning for LOLP estimation," in *Proc. North Amer. Power Symp.*, Aug. 2011, pp. 1–7.

[119] S. B. Patra, J. Mitra, and R. Earla, "A new intelligent search method for composite system reliability analysis," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Exhib.*, May 2006, pp. 803–807.

[120] R. C. Green, L. Wang, Z. Wang, M. Alam, and C. Singh, "Power system reliability assessment using intelligent state space pruning techniques: A comparative study," in *Proc. Int. Conf. Power Syst. Technol.*, Oct. 2010, pp. 1–8.

[121] M. Benidris and J. Mitra, "Composite power system reliability assessment using maximum capacity flow and directed Binary Particle Swarm Optimization," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2013, pp. 1–6.

[122] M. M. Alavi-Sereshki and C. Singh, "A generalized continuous distribution approach for generating capacity reliability evaluation and its applications," *IEEE Trans. Power Syst.*, vol. 6, no. 1, pp. 16–22, Feb. 1991.

[123] M. R. Bhuiyan and R. N. Allan, "Modelling multistate problems in sequential simulation of power system reliability studies," *IEE Proc. C, Generat., Transmiss. Distrib.*, vol. 142, no. 4, pp. 343–349, 1995.

[124] J. Lin, L. Cheng, Y. Chang, K. Zhang, B. Shu, and G. Liu, "Reliability based power systems planning and operation with wind power integration: A review to models, algorithms and applications," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 921–934, Mar. 2014.

[125] A. Sankarakrishnan and A. Billinton, "Effective techniques for reliability worth assessment in composite power system networks using Monte Carlo simulation," *IEEE Trans. Power Syst.*, vol. 11, no. 3, pp. 1255–1261, Aug. 1996.

[126] M. Benidris, S. Elsaiah, and J. Mitra, "Power system reliability evaluation using a state space classification technique and particle swarm optimisation search method," *IET Generat., Transmiss. Distrib.*, vol. 9, no. 14, pp. 1865–1873, 2015.

[127] J. C. O. Mello, M. V. F. Pereira, and A. M. L. da Silva, "Evaluation of reliability worth in composite systems based on pseudo-sequential Monte Carlo simulation," *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp. 1318–1326, Aug. 1994.

[128] A. M. L. D. Silva, L. A. D. F. Manso, J. C. D. O. Mello, and R. Billinton, "Pseudo-chronological simulation for composite reliability analysis with time varying loads," *IEEE Trans. Power Syst.*, vol. 15, no. 1, pp. 73–80, Feb. 2000.

[129] A. S. N. Huda and R. Živanović, "Distribution system reliability assessment using sequential multilevel Monte Carlo method," in *Proc. IEEE Innovative Smart Grid Technol.—Asia (ISGT-Asia)*, Nov./Dec. 2016, pp. 867–872.

[130] H. Niederreiter, "Quasi-Monte Carlo methods and pseudo-random numbers," *Bull. Amer. Math. Soc.*, vol. 84, no. 6, pp. 957–1041, 1978.

[131] J. Teh, "Analysis of dynamic thermal rating system of transmission lines," Ph.D. dissertation, School Elect. Electron. Eng., Univ. Manchester, Manchester, U.K., 2016.

[132] H. Shaker, H. Zareipour, and M. Fotuhi-Firuzabad, "Reliability modeling of dynamic thermal rating," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1600–1609, Jul. 2013.

[133] H. Shaker, M. Fotuhi-Firuzabad, and F. Aminifar, "Fuzzy dynamic thermal rating of transmission lines," *IEEE Trans. Power Del.*, vol. 27, no. 4, pp. 1885–1892, Oct. 2012.

[134] J. Teh and I. Cotton, "Risk informed design modification of dynamic thermal rating system," *IET Generat., Transmiss. Distrib.*, vol. 9, no. 16, pp. 2697–2704, 2015.

[135] J. Teh and I. Cotton, "Risk assessment of dynamic thermal rating system," in *Proc. IET Int. Conf. Resilience Transmiss. Distrib. Netw.*, 2015, p. 6.

[136] D. M. Greenwood, G. L. Ingram, and P. C. Taylor, "Applying wind simulations for planning and operation of real-time thermal ratings," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 537–547, Mar. 2017.

[137] D. M. Greenwood and P. C. Taylor, "Investigating the impact of real-time thermal ratings on power network reliability," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2460–2468, Sep. 2014.

[138] F. Fan, K. Bell, and D. Infield, "Probabilistic real-time thermal rating forecasting for overhead lines by conditionally heteroscedastic auto-regressive models," *IEEE Trans. Power Del.*, vol. 32, no. 4, pp. 1881–1890, Aug. 2017.

[139] J. Cunningham and J. Colandairaj, "Methodology for applying real-time ratings to wood pole supported overhead lines," in *Proc. 44th Int. Univ. Power Eng. Conf. (UPEC)*, Sep. 2009, pp. 1–5.

[140] J. Fu, D. J. Morrow, and S. Abdelkader, "Integration of wind power into existing transmission network by dynamic overhead line rating," in *Proc. 11th Int. Workshop Large-Scale Integr. Wind Power Power Syst. Well Transmiss. Netw. Offshore Wind Power Plants*, 2012.

[141] J. Fu, S. Abbott, B. Fox, D. J. Morrow, and S. Abdelkader, "Wind cooling effect on dynamic overhead line ratings," in *Proc. 45th Int. Univ. Power Eng. Conf. (UPEC)*, Aug./Sep. 2010, pp. 1–6.

[142] S. Abdelkader, D. J. Morrow, J. Fu, and S. Abbot, "Field measurement based PLS model for dynamic rating of overhead lines in wind intensive areas," in *Proc. Int. Conf. Renew. Energies Power Quality*, 2013, pp. 1–6.

[143] H. T. Yip, C. An, G. J. Lloyd, M. Aten, R. Ferris, and G. Hagan, "Field experiences with dynamic line rating protection," in *Proc. 10th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, 2010, p. 34.

[144] M. Aten and R. Ferris, "Dynamic line rating protection of wind farms. overview of project," in *Proc. IET Conf. Substation Technol., Analysing Strategic Pract. Issues Modern Substation*, 2009, p. 10.

[145] D. Roberts, P. Taylor, and A. Michiorri, "Dynamic thermal rating for increasing network capacity and delaying network reinforcements," in *Proc. CIRED Seminar, SmartGrids Distrib.*, 2008, p. 61.

[146] *TWENTIES Project*. [Online]. Available: https://windeurope.org/about-wind/reports/twenties-project/

[147] A. McLaughlin, M. Alshamali, J. Colandairaj, and S. Connor, "Application of dynamic line rating to defer transmission network reinforcement due to wind generation," in *Proc. 46th Int. Univ. Power Eng. Conf. (UPEC)*, Sep. 2011, pp. 1–6.

[148] J. Fu, D. J. Morrow, S. Abdelkader, and B. Fox, "Impact of dynamic line rating on power systems," in *Proc. 46th Int. Univ. Power Eng. Conf. (UPEC)*, Sep. 2011, pp. 1–5.

[149] A. Bergstrom, U. Axelsson, and V. Neimane, "Dynamic capacity rating for wind cooled overhead lines," in *Proc. 22nd Int. Conf. Exhibit. Electr. Distrib. (CIRED)*, 2013, p. 0631.

[150] E. Fernandez, I. Albizu, M. T. Bedialauneta, A. J. Mazon, and P. T. Leite, "Review of dynamic line rating systems for wind power integration," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 80–92, Jan. 2016.

[151] K. Kopsidas, A. Kapetanaki, and V. Levi, "Optimal demand response scheduling with real-time thermal ratings of overhead lines for improved network reliability," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2813–2825, Nov. 2017.

[152] M. Ali, M. Z. Degefa, M. Humayun, A. Safdarian, and M. Lehtonen, "Increased utilization of wind generation by coordinating the demand response and real-time thermal rating," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3737–3746, Sep. 2016.

[153] W.-Q. Sun, Y. Zhang, C.-M. Wang, and P. Song, "Flexible load shedding strategy considering real-time dynamic thermal line rating," *IET Generat., Transmiss. Distrib.*, vol. , no. 2, pp. 130–137, 2013.

[154] M. M. Esfahani and G. R. Yousefi, "Real time congestion management in power systems considering quasi-dynamic thermal rating and congestion clearing time," *IEEE Trans Ind. Informat.*, vol. 12, no. 2, pp. 745–754, Apr. 2016.

[155] F. Qiu and J. Wang, "Distributionally robust congestion management with dynamic line ratings," *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 2198–2199, Jul. 2015.

[156] D. M. Greenwood, N. S. Wade, P. C. Taylor, P. Papadopoulos, and N. Heyward, "A probabilistic method combining electrical energy storage and real-time thermal ratings to defer network reinforcement," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 374–384, Jan. 2017.

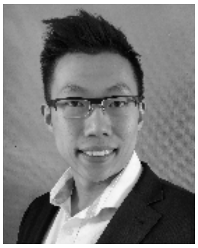
[157] K. Kopsidas, C. Tumelo-Chakonta, and C. Cruzat, "Power network reliability evaluation framework considering OHL electro-thermal design," *IEEE Trans Power Syst.*, vol. 31, no. 3, pp. 2463–2471, May 2016.

[158] J. Teh, C.-M. Lai, and Y.-H. Cheng, "Impact of the real-time thermal loading on the bulk electric system reliability," *IEEE Trans. Rel.*, vol. 66, no. 4, pp. 1110–1119, Dec. 2017.

[159] R. K. Henke and S. C. Sciacca, "Dynamic thermal rating of critical lines-a study of real-time interface requirements," *IEEE Comput. Appl. Power*, vol. 2, no. 3, pp. 46–51, Jul. 1989.

[160] Y. Cong, P. Regulski, P. Wall, M. Osborne, and V. Terzija, "On the use of dynamic thermal-line ratings for improving operational tripping schemes," *IEEE Trans. Power Del.*, vol. 31, no. 4, pp. 1891–1900, Aug. 2016.

[161] D. M. Greenwood and P. C. Taylor, "Unlocking the benefits of real-time thermal ratings through probabilistic power network planning," *IET Generat., Transmiss. Distrib.*, vol. 8, no. 12, pp. 2055–2064, 2014.



JIASHEN TEH (M'17) received the B.Eng. degree (Hons.) in electrical and electronic engineering from Universiti Tenaga Nasional, Kajang, Malaysia, in 2010, and the Ph.D. degree in electrical and electronic engineering from the University of Manchester, Manchester, U.K., in 2016. He is currently a Senior Lecturer with the Universiti Sains Malaysia (USM), Penang, Malaysia, an Adjunct Professor with the Green Energy and Electronic Center, National Taipei University of Technology, Taipei, Taiwan, and an Advisor of the IET-USM on Campus society. His research interests include power system reliability analysis, renewable energy sources, and smart grid applications. He is also currently working toward his professional engineering registration with the BEM and IET. He is a member of the IET and a registered Graduate Engineer with the Board of Engineers Malaysia (BEM).

CHING-MING LAI (M'16–SM'17) received the B.S. degree (Hons.) in aeronautical engineering from the National Huwei University of Science and Technology, Yunlin, Taiwan, in 2004, the M.S. degree in electrical engineering from National Central University, Chungli, Taiwan, in 2006, and the Ph.D. degree in electrical engineering from National Tsing Hua University, Hsinchu, Taiwan, in 2010. In 2012, he established UPE-Power Technology Co., Ltd., Taichung, Taiwan, the company is developing switching power supplies, and power converters for renewable energy resources. Since 2016, he has been with the Graduate Institute of Mechanical and Electrical Engineering, Taipei Tech. He is currently an Associate Professor with the Department of Vehicle Engineering, National Taipei University of Technology, Taiwan. His research interests include electric vehicles, power electronics, and high-efficiency energy power conditioning systems. He is a Life Member of the Taiwan Power Electronics Association and the Society of Automotive Engineers, Taipei, a member of the IEEE Power Electronics, the IEEE Industry Applications, and the IEEE Industrial Electronics Societies. She received the honor of the top-rated prize from the National Huwei University of Science and Technology. She was a recipient of the 2008 Young Author's Award for Practical Application from the Society of Instrument and Control Engineers, Japan, and the Best Paper Award at the 2013 IEEE International Conference on Power Electronics and Drive Systems.

NOR ASIAH MUHAMAD (M'13) received the bachelor's degree in electrical and electronic engineering from the Universiti Teknologi Petronas, Malaysia, in 2002, the master's degree in electrical power engineering from The University of South Australia in 2006, and the Ph.D. degree from the University of New South Wales, Sydney NSW, Australia, in 2009. She was a Researcher and a Senior Lecturer with the Institute of High Voltage and High Current, the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, for 13 years. She is currently a Senior Lecturer with the School of Electrical and Electronic, Universiti Sains Malaysia. Her research interests include power system equipment monitoring started in 2005, and the main topics related to this interest are insulation diagnosis and new systems for condition monitoring.

CHIA AI OOI received the Ph.D. degree in electrical and electronic engineering from the University of Cardiff, U.K. She was one of the researchers on Energy Storage for Low Carbon Grids Project funded by EPSRC. This research project includes the participation of eleven universities in the U.K. and 27 industry partners in Europe. She is currently a Senior Lecturer with Universiti Sains Malaysia. Her research interests include energy storage, power electronics, renewable energy, energy management, and power system.

YU-HUEI CHENG (M'12–SM'17) received the M.S. and Ph.D. degrees from the Department of Electronic Engineering, National Kaohsiung University of Applied Sciences, Taiwan, in 2006 and 2010, respectively. He is currently an Associate Professor with the Department of Information and Communication Engineering, Chaoyang University of Technology, Taichung, Taiwan. His research interests include algorithms, big data, bioinformatics, biomedical engineering, cloud computing, computational biology, computational intelligence, database, data mining, electronic circuit, embedded systems, evolutionary computation, fuzzy systems, information retrieval, Internet of Things, machine learning, multimedia engineering, mobile medical, power electronics, and renewable energy. He is a member of the International Association of Engineers and a Senior Member of the Universal Association of Computer and Electronics Engineers.

MUHAMMAD AMMIRRUL ATIQI MOHD ZAINURI was born in Kuala Lumpur, Malaysia, in 1988. He received the B.Eng., M.Sc., and Ph.D. degrees from Universiti Putra Malaysia (UPM), Selangor, Malaysia, in 2011, 2013, and 2017, respectively. His research interests include power electronics, power quality, renewable energy, and artificial intelligent. He is currently a Senior Lecturer with the School of Electrical and Electronics Engineering, Universiti Sains Malaysia, Gelugor, Malaysia. He is a Research Member of the Centre of Advanced Power and Energy Research and the University of Malaya Power Energy Dedicated Advanced Centre.

MOHAMAD KHAIRI ISHAK was born in Kedah, Malaysia. He received the B.Eng. degree in electrical and electronics engineering from the International Islamic University Malaysia, Malaysia, the M.Sc. degree in embedded system from the University of Essex, Colchester, U.K., and the Ph.D. degree from the University of Bristol, Bristol, U.K. He is currently a Senior Lecturer of mechatronics engineering with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia. He is also a registered Graduate Engineer with the Board of Engineers Malaysia. His research interests include embedded system, real-time control communications, and robotics. His emphasis is given toward the development of theoretical and practical methods which can be practically validated. Recently, his significant research effort has been directed toward important industrial issues of embedded networked control systems.

• • •