IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 14 December 2023, accepted 5 January 2024, date of publication 11 January 2024, date of current version 22 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3352595

TOPICAL REVIEW

Optimizing Grid With Dynamic Line Rating of Conductors: A Comprehensive Review

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This work was supported by Universiti Putra Malaysia and the Advanced Lightning, Power and Energy Research Centre (ALPER) through Inisiatif Putra Berkumpulan under Grant GP-IPB/2022/9717002.

ABSTRACT As the world is pledged towards net zero carbon by 2050, the need for clean and efficient energy transitions is more critical than ever. Optimizing the power grid transfer capacity is crucial for maintaining grid stability and reliability. Ageing infrastructure, population growth, and revolutionary technological developments increase the demand for grid modernization and resilience investments. Climate change and natural disasters highlight the need for adaptive load-shedding schemes. The two possible ways to optimize the grid are an ampacity increase or a voltage increase. While increasing voltage provides the most significant rise in rating, it comes with high investment costs. Out of all the options available, dynamic line rating (DLR) is the most efficient and cost-effective solution. This paper provides a comprehensive review of the optimization of the grid transfer capacity using DLR. The review critically examines different line rating methods, the DLR system, factors that need to be considered before DLR implementation, and its advantages and disadvantages. Also, the review presents the real-world applications and case studies, standards and regulations involved, and current approaches and challenges for implementing DLR in Malaysia. Additionally, we highlight the most commonly used standards to calculate the conductor's ampacity for the steady-state and dynamic state. Moreover, this review work presents how DLR can advance the grid's flexibility, considering its significance for cleaner energy production in the future, challenges related to wind energy power generation, and their mitigations. This work provides a shortcut path for researchers and utilities to understand DLR and as a reference for future research to advance clean energy in response to changing energy needs and climate conditions.

INDEX TERMS Dynamic line rating, grid optimization, grid flexibility, ampacity, clean energy.

NOMENCLATURE

I_T	Global solar radiation
I_{dc}	DC current
K_{angle}	Wind direction factor
N_{Re}	Dimensionless Reynolds number
Nu_β	Nusselt number
Nu_δ	Nusselt number
P_J	Joule heat gain
P_{J_F}	Joule heat gain for ferrous conductor
P_{J_NF}	Joule heat gain for non-ferrous conductor
P_M	Magnetic heating
P_c	Convective cooling
P_{cf}	Forced convective cooling
P_{cn}	Natural convective cooling
P_i	Corona heating
P_r	Radiative cooling
P_s	Solar heat gain
P_w	Evaporative cooling
Q_{se}	Total solar and sky radiated heat intensity corrected for elevation
R_{dc}	DC resistance of conductor

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmed F. Zobaa.

T_a	Ambient air temperature
T_{av}	Average temperature of aluminium strand layer
T_s	Conductor surface temperature
k_f	Thermal conductivity of air at temperature T_{film}
k_j	Factor
q_C	Convection heat loss per rate unit length
q_{c1}	Convection heat loss per rate unit length
q_{c2}	Convection heat loss per rate unit length
q_{cn}	Convection heat loss per rate unit length
q_j	Joule heating
q_r	Radiated heat loss rate per unit length
q_s	Heat gain from sun
α_s	Solar absorptivity of conductor surface
ε_s	Solar emissivity of surface
λ_f	Thermal conductivity of the air
σ_B	Stefan-Boltzmann constant
I	Conductor current
A'	Projected area of conductor
D	Outer diameter of conductor
Do	Outside diameter of conductor
$R(T_{avg})$	AC resistance of conductor at temperature, T_{avg}
α	Solar absorptivity
αc	Linear temperature coefficient of resistance
ε	Emissivity
θ	Effective angle of incidence of the sun's rays
ρf	Density of air

I. INTRODUCTION

The electrical power grids are essential infrastructure for modern power systems, enabling the delivery of electricity from one location to another, thus allowing modern society to function [1]. Power utilities are growing concerned about enhancing the transmission lines' capacity without resorting to new constructions or structural alterations. The ageing transmission line infrastructure significantly influences this concern. Many transmission lines operate beyond their intended lifespan, escalating the risk of power outages due to equipment failure [2]. These ageing lines may not be sufficient to support the demands of revolutionary technological advancements and a growing population [3], [4], [5], [6]. While the integration of renewable energy (RE) sources, energy storage systems (ESS), and electrification of transportation presents opportunities for power system resilience, it also brings challenges, such as intermittent technologies and extreme weather conditions [7], [8], [9], [10]. Integrating these technologies with a growing population further strains the capacity of ageing transmission lines [11]. Environmental factors, including climate change and natural disasters, underscore optimizing grid transfer capacity. The existing grid was not designed to withstand these factors, and they can impact the carrying capacity of overhead lines (OHL) [12], [13]. For instance, higher temperatures during heat waves reduce the current-carrying capacity, resulting in lower thermal ratings and increased thermal expansion [14], [15]. Unpredictable weather phenomena such as flooding, droughts, strong winds, and extreme heat cause significant damage to the power system infrastructure and disrupt power system resilience [16], [17], [18].

Therefore, implementing adaptive load-shedding schemes in the grid [19] and grid optimization is crucial for decarbonization and reducing greenhouse gas (GHG) emissions [20]. Decarbonization involves avoiding developing new transmission lines and reducing the use of non-renewable resources [21], [22], [23]. This approach helps to conserve forests for the right of way (ROW) and reduces the consumption of metals in grid construction [24] and fossil fuel usage in the energy sector. It can decrease GHG emissions and solve the volatility of fossil fuel prices, hence benefitting clean electricity scenarios [25]. Two possible methods to optimize the grid are by increasing ampacity or voltage. Increasing voltage offers the most significant increase in rating, as it reduces the current load value, thereby increasing the margin of ampacity limits. However, this approach comes with high investment costs, requiring changes in power grid components to accommodate higher voltage levels and to reduce the corona effects. Also, this approach is employed when the rating increase justifies the significant investment expenses, as seen in countries like the United States (US) and Germany [24], [26]. The alternative option is to increase ampacity, which can be achieved through various approaches described in Table 1.

Amidst this challenge, DLR is one of the appropriate options. DLR is a system that involves monitoring and modifying the rating of the OHL based on real-time weather conditions and other factors [44], [45], [46], [47]. Previous researchers and utilities have conducted several reviews of DLR, but many have neglected important information, failing to thoroughly address how DLR can optimize the grid and advance grid flexibility. Previous reviews have provided brief information on DLR technologies [8], [37] or focused solely on specific aspects, such as DLR forecasting techniques [48] or the application of DLR in wind power integration [49] or DLR approach with additional flexibility options [50].

This work aims to comprehensively review DLR technology, which can enhance grid capacity and provide cleaner energy. It provides valuable insights and understanding for researchers and engineers in this field, with the ultimate aim of offering a critical analysis of existing literature and identifying areas for future research to advance clean energy in response to changing energy needs and climate conditions. The paper is structured into several sections, each with a specific focus. The second section provides an overview of OHL that explains the factors affecting line ratings and their methodologies. In the third section, different line rating methods are discussed. In the fourth section, the overview

TABLE 1. Summary of methods used to increase ampacity for grid optimization.

Method	Description
Conductor section	A bigger cross-section area decreases the conductor's resistivity, which reduces the heat dissipated due to the Joule effect [27], [29]-[32].
Conductor re-tensioning	Increases the conductor's height or reduces its length in critical spans by cutting out small lengths of wire [27], [30]–[33].
Negative sag devices	A Sagging Line Mitigator (SLiM) device is used to shorten the span length when the line current exceeds a specific level [27], [33].
Height of the line	Increasing tower height, line tension, or insulator string changes increases the OHL rating [24], [32], [34].
Replacement with HTLS conductors	High-temperature Low Sag (HTLS) conductors carry higher currents than regular conductors without compromising tensile strength and reduce sagging at higher temperatures [24], [26], [27], [35]–[43].

of DLR system is presented. It includes the advantages and disadvantages of DLR considerations, real case studies, and relevant standards and policies to demonstrate the application of DLR. In the fifth section, the implementation process of DLR is explained. Section six describes how DLR can improve grid flexibility and resilience, along with other flexibility options. Section seven is the conclusion.

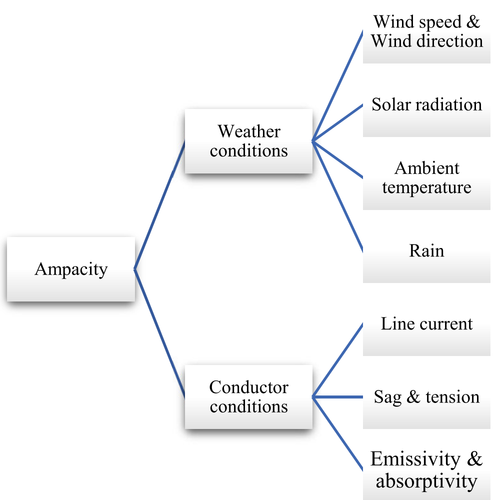

FIGURE 1. Factors influence conductor's line rating.

II. OVERHEAD LINE CONDUCTORS

OHL conductors are vital in transmitting and distributing electrical energy across vast distances. These conductors come in various structures, diameters, and materials, which are crucial factors in calculating the line rating of a transmission line. Depending on its properties and intended application, each type of conductor offers unique advantages and disadvantages. The OHL conductors are divided into two main groups: conventional and modified. Conventional conductors are made of round wire strands of various materials, with a core wire and single or multiple-strand layers according to the conductor size. Modified conductors are upgraded versions of conventional conductors that improve power transmission capacity under specific conditions [51]. The selection of conductor type for a transmission line can significantly impact its line rating [52], [53], [54]. The line rating is crucial for minimizing sagging while preventing damage to the conductor and equipment due to excessive temperature [55]. In practice, transmission lines are assigned a rating based on the most demanding conditions, with a high level of reliability [53]. Nevertheless, if the rating is set too optimistically, it can lead to clearance violations [56], [57], [58], sagging [24], conductor annealing [24], [59], [60], [61], and elevated temperature creep [56], [61]. Figure 1 illustrates that both weather and conductor conditions [62], [63], [64], [65] affect a conductor's line rating.

Weather conditions affect the line temperature and line rating, which can cause line to elongate and sag. The wind is a significant factor in determining line rating by having a powerful cooling impact on the conductors regardless of the ambient temperature [52], [53], [56], [66], [67]. The fluctuation in wind speed along the span's length and the site conditions like trees or building structures pose a challenge in practical applications. Several management strategies have been developed to mitigate the variability of wind data by neglecting wind direction, determining mean wind speed and defining upper and lower boundaries [56]. Solar radiation can be measured if the value is volatile due to varied cloud cover. The absolute varying maximum values can be easily determined by relying on diurnal variation according to location, date and time of day. The solar radiation influence is typically negligible and can significantly raise the conductor temperature at low current values during low wind speed [52].

Ambient temperature significantly impacts the ampacity since it can influence both convective and radiative cooling [52], [53]. Generally, a line can be rated at higher capacity during winter because of its ability to dissipate more heat due to low ambient temperature [56]. Rain is another weather factor that can considerably affect line rating. However, it is often disregarded in line with standards because modelling

FIGURE 2. Range of line rating methodologies [72].

heat loss rate requires multiple more significant parameters. For the DLR systems, the impact of rain must be considered to ensure accurate results [52], [68], [69], [70].

The conductor's condition, such as the line current, sag, tension, and surface properties, affects the line rating. Monitoring the transmission connections provides information on the electric flow along the line, which remains relatively uniform along the entire line length, with slight decreases due to losses in the line resistance that result in conductor heating. Although the line current is variable, efforts are made to determine its limiting value while considering all other relevant factors [53]. In order to determine line rating, the factors of conductor sag and tension play a crucial role. Conductor sag, the vertical distance between any point on a conductor and a straight line between the two attachment points, is determined by the mass per unit length of the conductor, the tension, and the span length. It is possible to determine the conductor tension by measuring the sag, which can then be used to calculate conductor temperature [56]. It should be noted that the tension and sag are both affected by the average temperature along the line, which means that the critical span is not the one with the highest line temperature [53].

The thermal radiation and absorption properties of a conductor's surface, emissivity and absorptivity are additional factors that affect the heat balance equation. Both parameters change over time due to ageing [71], dust and pollutants accumulation, and solar radiation exposure. Since there is considerable uncertainty surrounding the precise measurement of emissivity and absorptivity, manufacturers of conductors typically assign conservative values for DLR. It is worth noting that the changes in emissivity and absorptivity are similar at low temperatures, but at higher temperatures, the effect of absorptivity reduces on the heat balance equation [55].

III. LINE RATING METHODS

In line with the IEEE 738 standard, grid operators in the US use several line rating methodologies based on different methods involving fixed assumptions or variable inputs [66]. Figure 2 illustrates the range of line rating methodologies from the least dynamic to the most dynamic. Grid operators must choose the appropriate methodology depending on operational and environmental conditions to ensure a reliable and efficient transmission line.

A. STATIC LINE RATING

Traditionally, the power sector calculates static line ratings (SLR) based on worst-case weather conditions [73]. SLR is the most straightforward and least dynamic line rating methodology, which requires determining the worst-case weather conditions over the whole line for an extended period [56], [72], [73], [74], [75], [76], [77], [78]. SLR depends on constant wind speed and ambient temperature assumptions. Ideally, the worst weather scenario for line transmission would be zero wind speed, the highest ambient temperature, and the highest solar radiation. Figuring out the highest ambient temperature and zero wind speed is challenging. Hence, SLR represents a conservative line rating rather than a worst-case scenario [78], [79], [80]. SLR mainly represent the equipment manufacturer's nameplate rating, which usually assumes worst-case conditions and changes when the value of SLR is updated. Consequently, SLR may be consistent over time [66], [72]. This rating simplifies equipment specifications while providing a significant margin of safety.

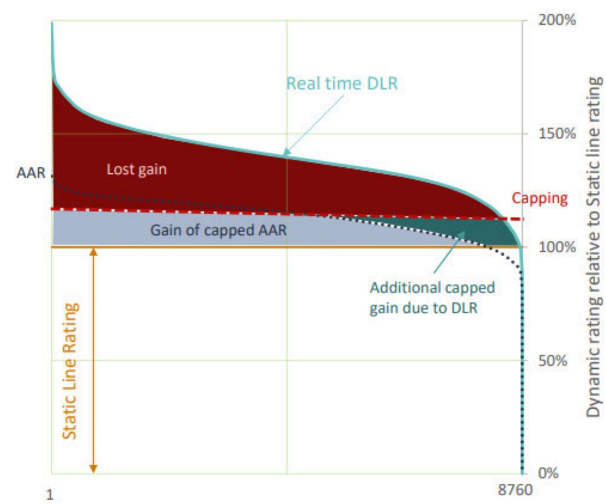

FIGURE 3. Illustration of DLR relative to AAR and SLR [83].

Assume the actual rating is always more prominent than the SLR would be wrong. According to studies by the power industry, many power lines safely operate at 130% of their static-rated capacity for 90% of the year, as shown in Figure 3 [3], [73], [81]. SLR causes transmission lines to underutilize, restrict their full potential and raise their operation costs [56], [74], [77], [82]. While these assumptions are conservative, there are cases wherein the actual ratings based on actual conditions are less than SLR, exposing conductors to the potential for thermal damage or increased sagging [56], [76], [77]. This situation may be catastrophic to the power system, resulting in blackouts owing to over-congestion [77].

B. SEASONAL LINE RATING

Seasonal line ratings are comparable to SLR but differ between assumptions regarding summer and winter ambient conditions [66], [72]. Summer ratings generally apply between May and October, while winter ratings apply from November to April. Seasonal line ratings are widely used because of significant weather pattern differences between seasons in various countries [66], [72]. The weather patterns change significantly between seasons in numerous countries. For instance, according to records from the United Kingdom (UK) Meteorological Office, for more than 100 years, the change in temperature between summer and winter has been around 10°C in normal conditions, resulting in a current difference of approximately 73A for a 400 kV standard OHL thermal rating [78].

C. AMBIENT-ADJUSTED RATING

Ambient Adjusted Ratings (AAR) are more dynamic than the traditional SLR and seasonal line ratings, as they vary more frequently, ranging from daily, hourly, to even every 15 minutes [3], [66], [72]. Precise ambient temperature forecasts are crucial for successfully implementing AAR since they strongly rely on them. Although AAR may suggest higher available capacity during lower temperatures like the winter and overnight hours, they often overestimate this capacity due to fixed wind speed assumptions [66]. Thus, adjusting the wind values in parallel with the temperature is essential to avoid significant risks when implementing AAR [3], [66]. Several transmission owners and AAR vendor utilizes relevant ambient temperature data from online weather monitoring service to calculate updated line ratings based on temperature forecasts. The National Oceanic and Atmospheric Administration (NOAA) ratings have also applied this approach of temperature forecasting to update line ratings [72].

D. DYNAMIC LINE RATING

DLR is the most advanced and complex method of transmission line rating [82]. It considers ambient factors such as weather conditions, solar radiation, line tension, and photo-spatial sensors. This method enables the DLR to use real-time measurements to determine the thermal rating of the line, which varies dynamically with each new measurement [27], [66], [75], [78], [83], [84], [85]. DLR evaluates the worst-case weather conditions for the next 5 to 15 minutes [3], [56], [72]. The detailed overview of the DLR system will be discussed in the following section.

IV. OVERVIEW OF DYNAMIC LINE RATING SYSTEM

DLR systems are installed at different spans along the line, especially for long lines, to collect and analyze data on conductor and weather conditions [27], [53]. This system optimizes grid capacity when wind speeds are high during cooler weather and night while maintaining an appropriate risk level [66]. Studies indicate that wind speed significantly impacts DLR, with higher wind speeds resulting in a considerable increase in DLR [66], [78], [86], [87]. DLR can be divided into two types, which are Ambient-Adjusted (DLR-AA) and Real Time Monitoring (DLR-RTM). DLR-AA only considers real-time variations in ambient temperature, while DLR-RTM considers real-time ambient temperature and effective perpendicular wind speed in the transmission line [48], [88]. Despite the volatility and unpredictability [89], DLR provides an advanced, accurate, and reliable method for rating transmission lines [56].

Noteworthy, before implementing DLR, several factors must be considered. Firstly, the transmission line should be inspected to determine its current state before applying any feasible strategies. It is necessary to evaluate electric and magnetic fields, as they can affect conductor sag and line ampacity [90]. The conductors must always maintain an appropriate distance from buildings, objects, and people or vehicles passing beneath and near the line. Installing tension monitors requires proper coordination and scheduling as it requires a line outage. Implementation, maintenance, and calibration costs are intensive [56]. Cybersecurity is a growing concern, as DLR technologies rely on wireless communications, which makes them exposed to denial-of-service attacks [76], [91], [92], [93], [94]. Transmission line selection for DLR implementation is crucial, as lines can be selected based on their average load levels or past constraint issues [95], [96], [97].

A. ADVANTAGES AND DISADVANTAGES

DLR technology provides several technical, economical and environmental advantages to the power system. Regarding technical advantages, it can improve reliability by establishing thermal limits for transmission lines dynamically, especially during summer and informing relay settings, increase efficiency of the generation resources [56]. Also, DLR technology may boost transmission system situational awareness by providing real-time information about the current-carrying capabilities of the conductor and detecting risks like transmission icing and conductor galloping, enhance power security concerning failures of transmission or generation components [52] as more electric-delivery alternatives must be aided during a disruption to mitigate load interruptions and facilitate recovery and restoration after an event [73], [76].

Economically, DLR provides numerous advantages, including reducing production and congestion costs [52], [56], [98], deferring capital costs [56], [99] and optimize asset utilization by providing access to the market for wind generators, reducing wind power curtailment [52], [73], [75], allowing a fast introduction of RE plants [24], [73], [100]. This technology can significantly benefit transmission owners incorporating wind generation as DLR can increase the rating of transmission lines as wind speed increases, reducing the need for costly interconnection facilities. Also, DLR can reduce the volatility of electricity prices, couple electricity markets [101], enhance the mean connection capacity between various locations of the power system, increase the percentage of low-carbon, and low-marginal-cost electricity consumed [52].

In terms of environmental advantages, DLR technology can reduce the resource usage and energy footprints associated with these processes [24] by minimizing the need for a large number of metals in constructing and replacing conductors as the weight of an ordinary OHL conductor alone reaching 817 kg/km and increasing for wider sections. In addition, DLR helps to prevent the destruction of forests that would otherwise be necessary to accommodate new power lines in the environment, which can act as a carbon sink. These advantages are summarized in Figure 4.

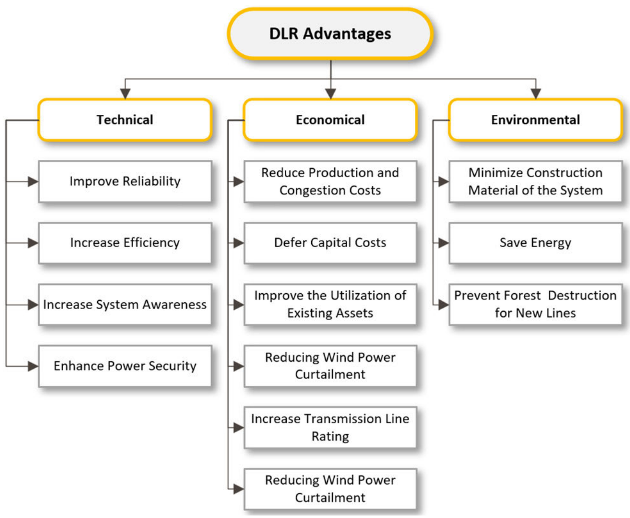

FIGURE 4. Advantages of DLR.

Aside advantages, DLR technologies have some limitations related to reliability, accuracy, and price among vendors. Due to slow regulatory approval processes, regulatory environments may not stimulate transmission-owning companies to invest in DLR implementation [73]. Also, the accuracy and reliability issues of the technology can arise from measurement and modelling flaws, malfunctioning devices, unreliable mathematical models, and weather forecasting errors [76], [102], [103]. DLR implementation requires operational knowledge and experience [52], [76], [104], [105], significant implementing cost, reducing the thermal headroom [76], sensor placement, forecasting challenges, limiting elements, and automation and data coordination [72]. Nonetheless, DLRs remain an attractive option for reducing transmission congestion and optimizing the use of transmission capacity.

B. CASE STUDIES

DLR technology has been available for an extended period, but widespread implementation has been limited. Several prominent small-scale studies of DLR have been conducted, and commercial devices that measure the effects of line rating have been evaluated. These general case studies are included in Table 2 along with a summary of the experience and country or state that used that method. Table 2 indicates that many countries are interested in implementing DLR systems for enhancing thermal capacity and reducing congestion, commonly using temperature sensors and monitoring systems. Different countries prioritize different applications of DLR, such as the US focusing on reducing congestion and enhancing transmission capacity, while the UK and Spain emphasize RE transition. These case studies are a helpful reference for other countries planning to implement DLR systems, including Malaysia, which is currently exploring DLR. As Malaysia's DLR system deployment status is still in the preliminary phases, further research is necessary before fully integrating the system into the country's power grid. In 2014, an Adaptive Load Shedding Scheme (ALSS) was implemented to assess and maintain safe load levels on power transmission lines. The scheme is a sophisticated framework that relies on the Real-Time Analysis and Prediction (RTAP) application within the Tenaga Nasional Berhad (TNB) Wide Area Intelligent System Framework [106]. Two Lindsey sensors are installed on the 275 kV Pantai Remis-Ayer Tawar lines. The sensors are installed in each line to measure the ground clearance, and the data is sent to the SMARTLINE cloud server through satellite communication [86], [107].

It is important to note that there may be unique challenges and considerations for implementing DLR in Malaysia, such as climate and geography. The country experiences hot and humid weather throughout the year since it is located in the tropical region, with variations in ambient temperature and rainfall [108], [109]. Malaysia faces increasing energy demand driven by population growth, digitalization, electromobility, and sector coupling [110]. Hence, the Generation Development Plan for Malaysia states the need for new thermal and RE plants to meet the growing demand. The influx of RE sources poses stability concerns that can be addressed by integrating a battery energy storage system (BESS). Malaysia's commitment to reducing carbon emissions and transitioning to a green economy adds to the significance of DLR implementation. The government aims to achieve a 31% RE capacity mix by 2025 and become a carbon-neutral nation by 2050. The current SLR system in Malaysia's grid causes operational constraints, leading to the underutilization of available capacity [111], [112], [113]. Studies have shown that integrating DLR with line

TABLE 2. Case studies summary of DLR implementation worldwide.

Country	Method Used	Improvement
Australia	It used TRCalc software and enhanced CIGRE methods for 5-minute dispatch on 132 kV and 330 kV.	Increased the grid's transfer capacity [50], [56], [73].
Belgium	It used Ampacimon sensor and its energy management system (EMS) software on several OHL.	Increased capacity up to 30% and wind cooling can raise thermal ratings by over 200% of seasonal [73], [75], [115]–[117].
Bulgaria	It used a line monitoring sensor on 110 kV power line in the Balkans.	Increased 26.6% average ampacity gain with SLR exceeding DLR only 4% of the time [118].
Canada	It used on DC bi-poles to analyze wind plant installation.	Increased capacity up to 22% over SLR 76% of the time and saved over $10 million [73], [75], [76], [119]–[122].
China	It used Monte-Carlo simulation method in double-circuit 110 kV lines connected with 120 MW wind power system in Hebei.	Provided the probability of temperature violation [123].
France	It used sag sensors on several 400 kV lines to improve the integration of wind farms and help operators detect issues like icing.	Increased the capacity of power lines by up to 200% and line current by up to 30% [73], [75], [76].
German	It used DLR to study the benefits for short-term and long-term.	Saved cost for over 403 million Euros in the short-term and 908 million annually in capital and operating system costs [124].
Ireland	It used DLR with other smart grid solutions on the Dungamon-Omagh 110 kV line to improves wind integration capacity.	Increased line ratings up to 26%, handle up to 75% of wind energy on their system, and reduced congestion caused by wind farm expansions [73], [76], [125].
Italy	DLR used on some critical transmission lines for optimal future power and as a temporary supply power solution.	Increased line capacity and wind energy generation [75], [76], [126]–[129].
Korea	It examined DLR as solution to improve the outage rates on some transmission lines.	Increased the maximum loading limits by 35% while maintaining safety [76].
Russia	It used DLR for several years, and its deployment is still ongoing.	Improved economic efficiency by up to 8% resulted in economic benefits in the joint operation of the system [73], [130], [131].
Spain	It used DLR to 400 kV transmission lines around Madrid.	Increased line capacities and proved strong correlation between wind speed and line rating, which positively impacted the 66 kV lines [13], [14], [128], [135].
Sweden	It implemented DLR in a 130 kV sub-transmission network with 60 MW wind power integration, and a pilot installation of 145 kV power line.	Presented weather-dependent spare capacity between SLR and DLR [125], [133]–[135].
UK	It used DLR at all major circuits in England and Wales to connect wind generation to the grid.	Increased the capacity of power lines by up to 30% and improved efficiency of wind integration by 20% - 50% [73], [125].
Uruguay	It used DLR and hourly forecasts at the sub-hour level.	Increased its wind power generation [75].
US	It monitored and integrated the DLR system into control systems.	Increased wind generation 30% - 44%, line capacity increased between 30%-70% compared to SLR, and potentially saving $4 million [74], [76], [76], [119] , [129].

TABLE 3. Available standards and policies for DLR.

Standard/Policy	Description
CIGRE-TB 601	Discusses the thermal rating method for overhead transmission lines, considering both steady-state and short-circuit transient conditions [136].
CIGRE-TB 324	Discusses calculations concerning the acceptable installation of sag cable during the building of OHL and present data on conductor creep tests [137].
CIGRE-TB 638	Discusses the factors that impact the electrical characteristics of power lines, including the design of the conductors and towers [137].
CIGRE-TB 299	Discusses the safe thermal rating for OHL based on weather parameters [138].
CIGRE-TB 353	Discusses developing safe thermal rating estimates for OHL considering the usual clearance buffers and safety margins [139].
CIGRE-TB 498	Discusses methods for measuring the temperature of conductors and determining how temperature, sag, and tension are affected by weather conditions [140].
CIGRE-TB 207	Discusses the design and installation of overhead lines concerning environmental conditions, such as wind, ice, and snow [141].
CIGRE-TB 345	Discusses the dynamic rating of overhead transmission lines, which involves real-time weather conditions and conductor temperature monitoring [142].
IEEE 738	Discusses calculation concerning the temperature and ampacity of bare overhead conductors for both steady-state and transient conditions [143], [144].
IEEE 1283	Discusses the effects of high-temperature operation on electrical conductors, connectors, and accessories [145].
IEC 60826	Discusses the design of overhead power lines to withstand severe weather conditions and extreme synoptic winds [146].
IEC 61597	Discusses the method to calculate stranded bare conductors [147].
Energy Independence and Security Act of 2007	Encourages utilities to modernize the transmission system and develop "smart grid" technology [114].
FERC Order 2000	Requires transmission-owning utilities to transfer control to regional transmission organizations (RTO), giving them operational authority over the transmission facilities including security aspects [114].

temperature sensors and weather monitoring can optimize the grid up to 30% spare capacity [107].

C. STANDARD AND POLICIES

During the design process, policies and standards provide a framework that ensures compliance with specific criteria, regulations, and safety requirements. These standards and policies establish guidelines and best practices that must be adhered to in the design and implementation of a system, thereby ensuring that the final product meets the necessary quality standards. They aim to increase the transmission system's reliability and efficiency while ensuring the energy sector's security and independence [114]. Although there are existing policies and standards for DLR, the guidelines may need to be more comprehensive to assist utilities and researchers in a more precise direction for the safe and effective implementation of this technology. It is essential to acknowledge that improvements can be made as technology progresses and further research is conducted. As such, a list of available policies and standards for DLR of conductors is presented in Table 3.

V. DYNAMIC LINE RATING PROCESS

The process of DLR implementation involves line identification, sensing and monitoring, communication, computing and forecasting and data validation, as shown in Figure 5.

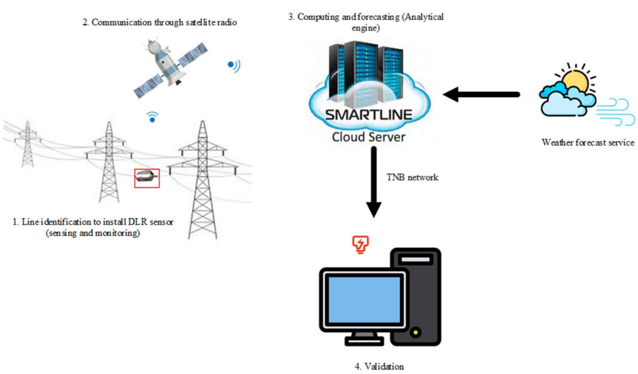

FIGURE 5. DLR system overview.

A. LINE IDENTIFICATION

In the DLR process, the first step is identifying the transmission lines that will be monitored and controlled. This step is critical in determining the efficiency of the DLR system. The selected line should be the most critical location along the transmission line where the load is high [148] and weather conditions are challenging [149], [150]. The single line along the transmission line may vary in terrain, geographical location, and weather conditions [53], [151]. Thus, it is crucial to choose the right critical line [152]. Choosing an uncongested line can have consequences that affect the market activity and reduce cost-effectiveness. The DLR system is also not beneficial if the lines are limited by voltage, stability, or substation [72]. Once the critical spans have been identified, monitoring and sensing equipment can be installed in these locations [153].

B. SENSING AND MONITORING

DLR's monitoring and sensing component involves using sensors to measure the line rating parameters of the transmission line. The sensors collect the data and transmit them to the control system, which is used to calculate the real-time conductor's ampacity or temperature [154], [155], [156]. The sensors allow continuous monitoring of the transmission line, which can provide early warning of potential issues that could impact line performance. Direct and indirect are the two main types of monitoring techniques used in DLR [27], [157], [158]. The distinction between these two techniques varies depending on the source. Several consider sag monitoring a direct method, but most consider any method that monitors transmission line characteristics as a direct method [53].

The direct monitoring technique is based on observing the limiting element of the line, such as conductor sag, line tension, conductor clearance to ground, or conductor temperature [37], [53], [76]. These systems usually depend on a different monitoring system to calculate line ratings [37]. Direct monitoring technique offers excellent accuracy and precision [159], but the installation is complex, and high maintenance costs are associated with adequately covering all spans or segments of a line. The industry monitors line sag, line tension, and conductor temperature for DLR measurement [160].

The indirect methods rely on monitoring ambient weather conditions and using monitoring theoretical models to calculate the sag [37], [53]. Installing weather stations at one or multiple points along the line is necessary for indirect methods, and typically, weather sensors are mounted directly on the line's pylons. A mathematical model determines the conductor's temperature and predicts the overload capacity for specific periods [161], [162]. Implementing the indirect method is simple [163] because the instruments are not directly installed on the transmission line. According to field tests, weather data measurement devices are cost-effective and reliable, and special calibrations are unnecessary [37], [56]. The biggest limitation of indirect methods is the uncertainty due to the varying nature of weather quantities [37], [53].

Utilities need to decide the location of the sensors on whether to use ground-based or line-based. Each approach has its pros and cons. Line-based conductors offer more precise and accurate information on line conditions compared to ambient weather condition measurements. However, line-based sensors have restrictions in their ability to extrapolate data for unmonitored line spans. Line-based sensor installation and maintenance involve transmission line outages. Ground-based sensors are easier to install and maintain but have increased susceptibility to physical manipulation [72].

TABLE 4. Summary of DLR monitoring technologies.

Monitoring Technology	Direct		Indirect		Location		Country
	A	B	C	D	Ground	Line	
Ampacimon			X			X	Belgium, France [27], [53], [78], [95], [164]–[167]
SMT	X					X	India [49], [51], [95], [119]
CAT-1		X		X		X	New Zealand, US, Brazil, Switzerland, UK, Finland [27], [37], [49], [78], [95], [160], [168]
Power Donut	X	X	X	X		X	UK, Brazil [27], [49], [53], [78]
Ritherm	X					X	Not applicable [49], [95]
RT-TLMS	X				X		US [37], [49], [53], [95], [169]
Sagometer			X		X		US [27], [37], [49], [95], [160]
TAM							Spain [37], [49]
Thermal Rate	X			X		X	US [27], [49], [53], [95], [119]
Weather Station				X	X		India [27], [49], [95]

- A – Conductor temperature monitoring
- B – Tension monitoring
- C – Sag monitoring
- D – Weather monitoring (Ambient temperature, wind speed, wind direction)

Table 4 compares the available monitoring technologies regarding technique, location, and country that use the technology.

C. COMMUNICATION

Effective communication is essential to the DLR process, continuous data often stems from the need to invest in sophisticated and reliable data acquisition and communication infrastructure. This includes sensor deployment, real-time communication networks, data processing and storage, remote monitoring and control systems, maintenance and calibration [76]. The communication system must be reliable and robust to ensure timely and accurate data transfer and to avoid data drop out despite bad weather conditions or challenging environments. Balancing these costs with the benefits of improved system performance and reliability is crucial for the successful integration of dynamic transmission in renewable energy systems. Technological advancements and increased adoption of dynamic transmission solutions over time may also reduce costs.

Traditionally, the communication of transmission lines mainly employs a wireless public network [170], [171], and its communication modes mainly include general packet radio service (GPRS), code division multiple access (CDMA), and third generation (3G). The advantages of wireless public network communication are low construction cost, simple deployment, and mature technology. Nevertheless, the coverage is limited and vulnerable to communication with low reliability and security. The reliability of the data collected transmission is not guaranteed since the communication system is challenging to repair when it breaks down [171]. The communication channels can be used in DLR, for example, radio, cellular network, satellite, fibre optics and physical media [76]. The development of communication technology is very rapid with other technologies such as Zonal Intercommunication Global-standard (Zigbee), Bluetooth, long-range (LoRa), Narrowband-Internet of Things (NB-IoT) and microwave that can be implemented in transmission line communication [171], [172].

The communications requirement needs to be upgraded as the number of measured parameters increases for sensing and monitoring technologies. It becomes a critical asset as utilities and system operators implement DLR systems for control, dispatch, and market decisions. The communication channel must comply with the NERC's Critical Infrastructure Protection standards to guarantee the reliability of the DLR data, including the cybersecurity of the overall systems. The selection of communication technology depends on several factors, such as distance, bandwidth, monitoring approach, application requirement and cost [76].

D. COMPUTING AND FORECASTING (ANALYTICAL ENGINE)

Computing and forecasting play crucial roles in predicting and regulating power flow in real-time. Advanced algorithms and models are used to simulate the transmission system's behaviour and forecast the impact of environmental changes on line ratings. This system allows the operators to judge the power transfer limits and operational strategies accurately. The forecasting techniques are employed to predict future

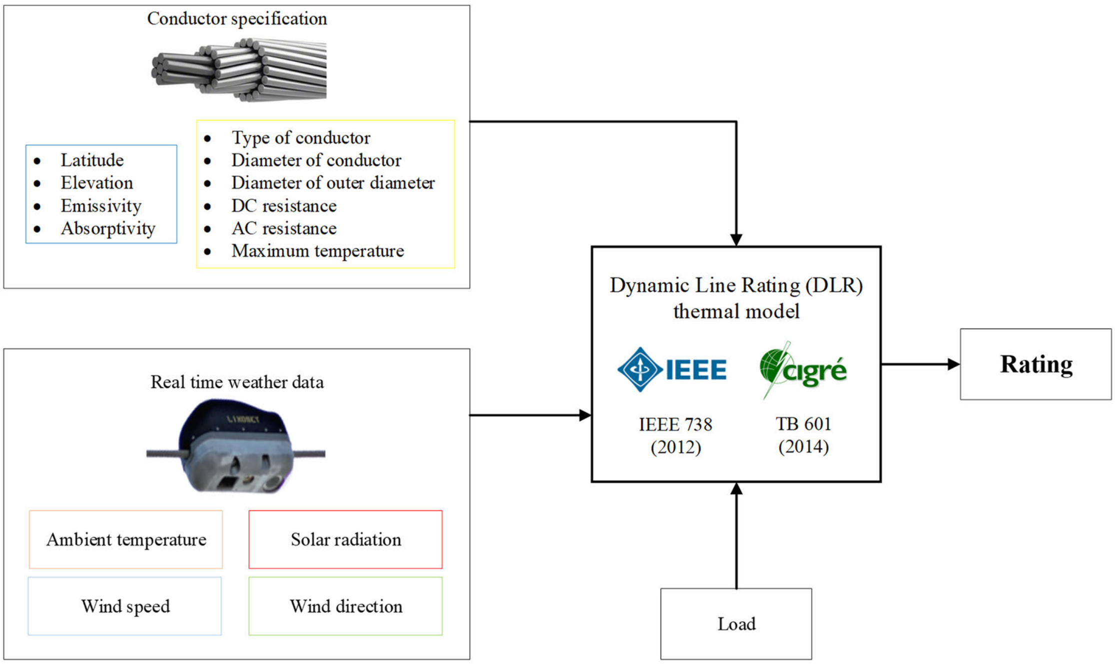

FIGURE 6. DLR calculation process.

TABLE 5. The differences between IEEE and CIGRE standard.

Parameter	IEEE-738 (2012)	CIGRE-TB 601 (2014)
Convective cooling	$q_{c1} = K_{angle} \bullet [1.01 + 1.35 \bullet N_{Re}0.52] \bullet k_f \bullet (T_s - T_a)$	$P_{cf} = \pi \bullet \lambda_f \bullet (T_s - T_a) \bullet Nu_\delta$
	$q_{c2} = K_{angle} \bullet [0.754 \bullet N_{Re}0.6] \bullet k_f \bullet (T_s - T_a)$	
	$q_{cn} = 3.645 \bullet \rho f^{0.5} \bullet Do^{0.75} \bullet (T_s - T_a)^{1.25}$	$P_{cn} = \pi \bullet \lambda_f \bullet (T_s - T_a) \bullet Nu_\beta$
Radiative cooling	$q_r = 17.8 \bullet D_O \bullet \varepsilon \bullet [\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4]$	$P_r = \pi \bullet D \bullet \sigma_B \bullet \varepsilon_s \bullet [(T_s + 273)^4 - (T_a + 273)^4$
Solar heating	$q_s = \alpha \bullet Q_{se} \bullet sin(\theta) \bullet A'$	$P_s = \alpha_s \bullet I_T \bullet D$
Joule heating	$q_j = I^2 \bullet R(T_{avg})$	$P_{J\_NF} = k_j \bullet I^2 \bullet R_{dc} \bullet [1 + \alpha c(T_{av} - 20)]$
		$P_{J\_F} = {I_{dc}}^2 \bullet R_{dc} \bullet [1 + \alpha c(T_{av} - 20)]$

events that may influence line ratings, which include weather patterns and power demand. Forecasting allows the system operator to foresee and manage potential issues before they happen. Forecasting methods can be classified into stochastic processes [173] and deep learning [174].

During this stage, the sensor data communicates with the control centre, which will evaluate it using complex algorithms that use environmental and conductor conditions to compute and forecast the current ampacity of the transmission line in real time. The data is utilized to optimize the transfer capacity and prevent overloading [175]. The complex algorithms employed in DLR are based on standards published by the Institute of Electrical and Electronics Engineers (IEEE) and the Council on Large Electric Systems (CIGRE) for estimating conductor thermal behaviour depending on weather and conductor conditions. Modern technologies utilize artificial intelligence to compute and continually update transmission line ratings in real time. The results are transmitted to transmission system operators to guarantee efficient use of transmission capacity [175]. Many versions of the standards are accessible to determine the line rating of the conductor. Thus, it is crucial to understand each standard's differences and constraints before deciding which standard is suitable based on the available parameters. Figure 6 illustrates the calculation process based on the IEEE and CIGRE standards.

The similarity of both standards (IEEE and CIGRE) is their foundation to calculate the conductor's ampacity for the steady-state and dynamic state. It is based on the thermal balance theory, where heat gain equals heat loss, as stated in equations (1) and (2) for IEEE and CIGRE, respectively [176], [177], [178], [179]. The parameters for weather conditions, such as the amplitude and direction of the wind, ambient air temperature and solar radiation are present in both standards. However, they use different ways to calculate the thermal equation [180], especially for solar heat gain and convective cooling. The IEEE standard has the following form:

$$q_C + q_r = q_s + q_j \tag{1}$$

While the heat balance equation according to the CIGRE standard is presented by:

$$P_c + P_r + P_w = P_s + P_J + P_M + P_i \tag{2}$$

As shown in (1), magnetic heating, corona heating and evaporative cooling are negligible because they have a minor influence on the line rating calculation [181]. Even though corona heating and evaporative heating are included in (2), they are still excluded from the line rating calculation. According to previous studies, the outcomes for both measures are approximately the same, with percentage differences in the range of 5 - 15% [182], [183], [184], [185]. The contrast between the formula between both standards is summarized in Table 5.

According to Table 5, using different non-dimensional parameters is the key difference between the convective cooling standards of IEEE (3) and CIGRE (4). While IEEE only considers Reynold's numbers, CIGRE employs Nusselt's, Reynolds, Grashoff's, and Prandtl's numbers. These parameters make CIGRE more theoretically accurate, provided that the values obtained are precise. CIGRE considers the conductor surface's temperature, while IEEE assumes it to be constant along the conductor's length [186]. However, both standards agree that natural and forced convection can reduce the conductor's temperature [74], [77], [187], [188], with wind speed being the most significant factor. The formulas in both standards depend on wind speed, but unreliable wind speed measurements can lead to significant errors in the conductor's ampacity. Therefore, to increase reliability, both IEEE and CIGRE suggest calculating forced and natural convective cooling and choosing the largest value as the conductor's convection value.

The radiative cooling formula between the two standards shows they are similar. The four main parameters that govern the radiative heat loss are the outer diameter, emissivity, conductor's temperature, and ambient temperature, with constant values such as the Stefan-Boltzmann law and Pi, which are included in both equations. The sensitivity of emissivity depends on the temperature difference between the conductor's maximum operating temperature and the ambient temperature. The relationship between emissivity and temperature difference is directly proportional and corresponds to the radiative cooling rate [77], depending on the conductor's age.

For solar heating, both standards include various terms in their calculations, such as solar declination, the sun's hour angle, and the latitude of the line [182]. The conductor's location can impact global solar irradiance, although it is less significant than wind speed. The CIGRE standard considers other factors such as ground reflection, conductor orientation, and nearby sheltered areas. Both standards recognize that solar radiation depends on the time of day and location [189] and that solar intensity increases with altitude above sea level. The physical characteristics of the overhead line conductor, such as outer diameter and absorptivity, are essential considerations for solar heating. It is worth noting that solar heat gain increases with increasing absorptivity, typically determined by the manufacturer, and varies from 0.2 to 0.9, depending on the conductor's age.

The IEEE standard directly includes magnetic heating in joule heating, whereas CIGRE separates both terms. While both types of heating can increase the conductor's temperature, their sources differ. Joule heating arises from resistance, whereas magnetic heating arises due to magnetic flux phenomena such as eddy currents, hysteresis, and skin effects. Thus, CIGRE separates joule heating and magnetic heating, which depends on the type of conductors (ferrous and non-ferrous) since ferrous conductors include magnetic heating and skin effect.

E. VALIDATION

The last step of the DLR process is validation, which involves verifying the accuracy and effectiveness of the system. This significant step ensures the reliability and accuracy of the DLR system to provide accurate information for real-time grid operation. The malfunction of monitoring sensors due to age or weather conditions could lead to incorrect readings. Real-time detection of anomalies in the sensor data during analysis can enhance confidence in decisions made based on the data [72], [115]. The accuracy of the models used in the analytics may vary based on the input range, requiring the validation of both models and sensor data. It is possible to use sensitivities that can restrict the variation of weather data parameters affecting transmission line ratings. More steps must be taken to diagnose and identify the causes of system failures. Addressing these issues could be crucial in establishing long-term trust in DLR technologies [72], [115]. It is an ongoing process that that compares the ampacity calculated by DLR with actual line temperature and sag measurements. Another way is by comparing the DLR predictions with the calculated ampacity from the SLR method. The lines' reserved margin can be known by comparing DLR and SLR values.

Integrating DLR into the control room is the most challenging aspect of implementing this technology, as it involves complex work that may overwhelm operators [115]. One approach to address this is to have the analytic engine calculate information, which can be ready by the supervisory

TABLE 6. Summary of DLR interaction with other flexibility option.

DLR + Flexibility option	Finding
DLR + TS TS – Transmission switching	Reduce overall system dispatch rates by up to 23%, reduce congestion by 44%, enable RE sources by up to 97%, minimize wind power curtailment, and cut system expenses by 6.78% [50], [196], [207]–[210].
DLR + RES RES – Renewable energy source	Improve the grid's security [50], [211].
DLR + ESS ESS – Energy storage system	Reduce the reliability index of expected energy not supplied by 23.6%, minimize the environmental impacts by 10%, scale down the total operational cost and emissions of the multi-area network, and lower utilization of ESS [50], [212]–[214].

control and data acquisition (SCADA) system [190], [191] and displayed to operators. Operators want a maximized but stable line rating that ensures conductor temperatures do not rise excessively, which could cause sagging. DLR depends on wind speed and direction, which can cause noisy data. Thus, filtering is needed to reduce the volatility of information and increase confidence in ratings. It is recommended to use standardization of DLR data with a baseline of expected functionality and performance to integrate DLR into the control room successfully [115].

VI. GRID FLEXIBILITY WITH DYNAMIC LINE RATING

Grid flexibility has become increasingly important in modern power systems due to new challenges, such as integrating intermittent RE sources and transportation electrification. In renewable power generation with large amounts of wind power production, the dynamic nature of wind results in significant power output fluctuations over a short time duration. These power fluctuations have a negative effect on the safe and economic operation of grids and challenge the effective utilization of extra-wind electricity generated in congested transmission networks [192], [193], [194], [195]. DLR is a promising solution to enhance grid flexibility by allowing utilities to dynamically adjust the capacity of transmission lines based on actual conditions. Integrating traditional and flexible resources requires novel methods and control strategies to address the uncertainties in power system operation without compromising power system reliability. Flexibility in the power grid can be achieved through different system stages, such as generation, transmission, and distribution. On the generation side, grid flexibility can be provided by allotting more reserves from conventional power plants to cope with the uncertainty posed by RE sources. Demand-side management and storage options can be deployed on the load side to make the system more flexible, although such technologies are expensive [196].

Energy storage technology can be used to store and stably transmit the power generated with wind energy and can efficiently restrict the fluctuations of wind power, enhance the grid's frequency modulation capacity, provide rapid active power support, improve power accommodation capacity and enable large-scale wind power to be reliably and conveniently integrated into grids [192], [194], [197], [198], [199]. However, effective utilization of energy storage technology in the wind power intermittency mitigation depends on several factors such as installation and maintenance costs, efficiency and maturity of the technology, storage duration, delay time response, ramp rate of the technology, environmental impact and the suitability of the site topology. Consequently, single storage technology cannot provide a total mitigating solution to the intermittency effect of wind power on the grid [200]. Changing the topology using DLR can provide flexibility on the transmission side. Table 6 summarizes the interaction of the DLR with other flexibility options to make the system more reliable, efficient, and cost-effective.

Additionally, remote transmission of electricity, especially in the case of wind power generation may experience delays and faults [201] and interference with radio systems and aligned antenna positions, etc. The issues such as delays, faults, and subsequent power losses associated with remote electricity transmission from wind power generation sites often stem from the need to invest in robust and reliable infrastructure such as fault detection and correction systems [202], [203], [204], [205], maintenance and repairs using durable equipment can help minimize the need for frequent visits as remote locations may be difficult to access, making routine maintenance and repairs more challenging and costly [206].

Also, advanced communication technologies for remote monitoring and control [215], [216], [217], [218], which may require additional investment communication technologies [219]. Balancing these considerations is crucial for optimizing the economic viability of remote wind power projects while ensuring a consistent and sustainable power supply. Note that technological advancements and economies of scale may contribute to cost reductions in remote wind power transmission solutions over time [220], [221]. In terms of interference and distortions that can be caused by wind turbines (WTs) due to electromagnetic effects on the transmitted signals in the near radiocommunications such as fixed radio links [222], [223], aeronautical navigation systems [224], broadcasting services [225] and radars [226]. Even though critical interference incidents are rare, if the potential impact is detected before the installation of the wind farm, locations and dimensions of wind turbines can be modified to avoid or at least minimize interference effects.

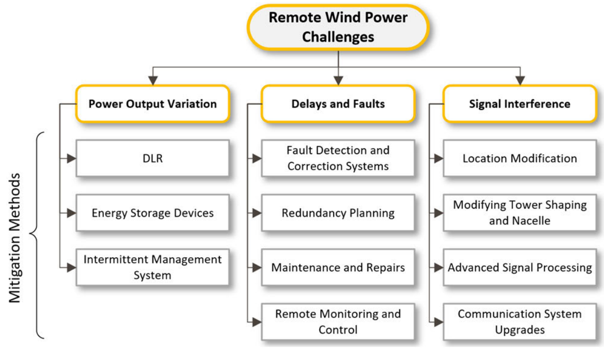

FIGURE 7. **Mitigation of challenges related to remote wind energy.**

However, if they arise after installation, locations and dimensions of WTs can be adapted to prevent, or at least minimize, the necessary post-installation corrective measures, which are typically cost-prohibitive or technically challenging. Also, another mitigation measure can be used to reduce the WT interference effect by modifying careful shaping of the tower and nacelle with different dimensions, using advanced signal processing [227], and choosing a model or communication system upgrades [228]. The above-mentioned challenges and their mitigations are summarized in Figure 7. In any case, the preventive measurement costs are lesser than corrective measurements and prevent public opposition to wind energy development [229]. These wind energy challenges and related compromised costs can be discussed in detail in separate research work.

VII. CONCLUSION

In conclusion, this paper has emphasized the importance of grid optimization and various methods to increase ampacity and voltage. DLR is the best grid optimization option. The OHL conductors' section has provided insights into the factors influencing conductor line rating, including weather and conductor conditions and the range of line rating methodologies available. The discussion on DLR benefits, limitations, considerations, case studies, and standard considerations has given an overview of the status of DLR development worldwide, including a comparison of DLR development in Malaysia with other countries. It is worth noting that there may be unique challenges and considerations for implementing DLR in Malaysia as it is located in a tropical region and experiences hot and humid weather throughout the year with variations in ambient temperature and rainfall.

The DLR process section has explained the process in detail, from line identification to integrating DLR into the control room. The communication system must be reliable and robust to ensure accurate real-time data transfer and to avoid data loss in case of bad weather conditions or challenging environments. Technological advancements and increased adoption of dynamic transmission solutions over time may reduce implementation costs. In addition, the review of the calculation parameters of DLR showed that the CIGRE is more theoretically accurate than the IEEE standard.

The section on grid flexibility with DLR has highlighted how DLR can enhance grid flexibility along with other flexibility options and discussed the future direction of DLR development. This review paper has provided researchers in this study area with valuable information and insights to advance the grid's flexibility and resilience in the face of energy transition and climate change. Further research is needed to explore new and innovative ways to optimize the grid and improve DLR technology to meet the ever-growing demands of the modern power system.

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