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Assessment of Dynamic Line Rating for Transmission Planning in the Costa Rican Power System

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Abstract. The continuous growth of electricity demand driven by electrification and the increasing penetration of renewable energy sources pose significant challenges for transmission system planning. In Costa Rica, where electricity generation is largely sourced from renewable resources, conservative planning criteria based on Static Line Rating (SLR) may lead to an underutilisation of existing transmission infrastructure. This paper evaluates the potential benefits of applying Dynamic Line Rating (DLR) to the Costa Rican transmission network using a detailed power system model implemented in ETAP. A 24-hour simulation of a representative day of peak demand is carried out, considering hourly load profiles and comparing system operation under static and dynamic thermal limits. The results show that the application of DLR significantly reduces the number and duration of thermal overloads in critical transmission corridors, particularly those connecting renewable generation areas with major demand centres. These findings indicate that DLR can increase the effective transmission capacity and defer the need for network reinforcements, providing a flexible and cost-effective alternative for transmission planning in renewables-based power systems.

Key words. Dynamic Line Rating, transmission system planning, ampacity, thermal constraints, ETAP

1. Introduction

The sustained growth of electricity demand represents one of the main challenges for transmission systems in the context of the ongoing energy transition. According to the International Energy Agency, global electricity consumption has increased significantly in recent years and is expected to continue rising due to the electrification of transport, the expansion of digital infrastructure, and the increasing use of electric heating and cooling systems [1]. In parallel, the rapid integration of renewable energy sources is introducing higher variability and uncertainty in power flows, placing additional stress on transmission networks.

Traditionally, the expansion of transmission capacity has relied on the construction of new lines or the reinforcement of existing infrastructure. However, these solutions are often associated with high investment costs, long permitting processes, and significant environmental and social constraints. In this context, increasing attention is being given to alternative solutions that enable a more efficient use of existing assets, commonly referred to as non-wire alternatives.

In Costa Rica, these challenges present specific characteristics. The country has historically achieved one of the cleanest electricity generation mixes worldwide, with more than 90 % of its electricity produced from renewable sources in recent years [2]. However, the strong dependence on hydropower makes the system vulnerable to seasonal variations, while the progressive electrification of transport and productive sectors is expected to significantly increase electricity demand. Under conservative transmission planning criteria, these trends could lead to early diagnoses of network congestion and to the need for costly grid reinforcements.

Conventionally, the transmission capacity of overhead lines has been defined using Static Line Rating (SLR), based on conservative assumptions regarding ambient temperature, wind speed, and solar radiation [3]. While this approach guarantees safe operation, it may result in an underutilisation of the actual thermal capacity of transmission lines. As an alternative, Dynamic Line Rating (DLR) allows the adjustment of line ampacity according to real-time or estimated environmental conditions, enabling a more flexible and efficient use of existing infrastructure [4].

Recent studies and pilot projects have demonstrated that DLR can significantly increase transmission capacity, reduce congestion, and facilitate the integration of renewable energy sources [5]. These benefits are particularly relevant in systems with high penetration of variable renewable generation, where power flows may concentrate on specific transmission corridors.

In this context, this paper evaluates the impact of applying Dynamic Line Rating to the Costa Rican transmission network using power system simulations carried out in ETAP. A 24-hour operation of a representative day of peak demand is analysed, comparing system performance under static and dynamic thermal limits. The results provide insight into the potential of DLR to reduce thermal overloads, increase effective transmission capacity, and defer the need for transmission network reinforcements in renewables-based power systems.

2. Background and related work

This section reviews the main concepts and previous work related to transmission line rating, including conventional static approaches, dynamic rating methodologies, and their application in real power systems.

A. Static Line Rating and its limitations

Transmission line ampacity is traditionally defined using SLR, which is based on conservative assumptions regarding worst-case environmental conditions in order to ensure safe operation [3]. While this approach has proven effective in maintaining system reliability, it often leads to an underutilisation of the actual thermal capacity of overhead transmission lines, particularly in regions with variable climatic conditions. In practice, SLR may lead to both safety concerns under extreme weather conditions and inefficient operation under more favourable conditions, highlighting its inherent limitations [6].

As a result, transmission systems planned under static criteria may exhibit apparent congestion even when actual environmental conditions would allow higher power transfers. This conservative approach can lead to premature investment decisions, including the reinforcement or expansion of transmission infrastructure, which may not be strictly necessary under real operating conditions [7].

B. Dynamic Line Rating: principles and approaches

DLR has been proposed as an alternative approach that adjusts line ampacity according to real-time or estimated environmental variables such as ambient temperature, wind speed and direction, and solar radiation [8]. By considering the actual cooling conditions of the conductor, DLR enables a more accurate assessment of the available transmission capacity, improving system flexibility, enhancing the integration of renewable energy sources, and reducing congestion.

Different approaches to DLR can be identified in the literature. Sensor-based methods rely on direct measurements of conductor temperature, sag, or tension, providing highly accurate real-time ampacity values [9]. Weather-based methods estimate ampacity using meteorological data, either measured locally or obtained from numerical weather models. In addition, forecast-based approaches allow the prediction of line ratings ahead of time, enabling their integration into operational planning and market applications. Each of these approaches presents different trade-offs in terms of accuracy, implementation complexity, and cost [8].

C. Applications and international experience

Several studies and pilot projects have demonstrated the potential benefits of DLR in different power systems. Applications in the United States and Europe have reported significant increases in transmission capacity, allowing higher integration of renewable energy sources and deferring investments in transmission reinforcements [10], [11]. These benefits are particularly relevant in systems with high penetration of variable renewable generation, where power flows may concentrate on specific transmission corridors [12].

In recent years, several transmission system operators have implemented DLR in real-world environments. In the United States, multiple pilot projects and large-scale deployments, particularly those led by the Bonneville Power Administration, have demonstrated that DLR can significantly increase the utilisation of existing transmission assets and reduce operational constraints, enabling more efficient system operation under varying environmental conditions [13]. In Europe, the Belgian TSO Elia has reported successful deployments of DLR technologies, highlighting their ability to enhance real-time monitoring of overhead lines and improve operational decision-making [14]. Similarly, the Italian TSO Terna has implemented DLR systems in several transmission lines, reporting that dynamic ratings can increase line capacity by approximately 10–30% under favourable weather conditions, while simultaneously reducing renewable energy curtailment and improving network reliability [15]. Beyond Europe and North America, DLR has also been successfully applied in other regions such as Chile, where it has been used to alleviate transmission congestion and facilitate the integration of large-scale renewable generation in critical corridors [16]. These international experiences highlight not only the technical feasibility of DLR but also its growing role as a cost-effective solution to enhance grid flexibility, optimise asset utilisation, and support the transition towards more sustainable power systems.

In addition to real-world implementations, several studies have evaluated the impact of DLR through simulation-based approaches. Early analyses based on standard test systems have shown that DLR can effectively increase transmission capacity and alleviate thermal constraints, enabling higher levels of renewable energy integration without requiring network expansion [17]. More advanced studies have further demonstrated that incorporating DLR into stochastic optimisation frameworks can increase transmission capacity utilisation, reduce renewable energy curtailment, and lower overall system operation costs by enabling higher power transfers under favourable environmental conditions [18]. Furthermore, these studies highlight that the benefits of DLR become more pronounced when uncertainties in both renewable generation and meteorological conditions are explicitly considered, reinforcing the value of forecast-based approaches in modern power system operation.

Despite the growing international experience with DLR, its application in tropical and renewable-dominated power systems remains relatively limited in the literature. Most existing studies and real-world implementations have focused on regions with temperate climates and well-established transmission infrastructures. In this context, the Costa Rican transmission network represents an interesting and relevant case study, given its high share of renewable generation and its increasing electricity demand. This work contributes to this area by evaluating the potential impact of DLR on transmission planning in Costa Rica through power system simulations, providing insights into its applicability under different climatic and operational conditions.

3. Methodology

The analysis is based on a detailed model of the Costa Rican power system implemented in the commercial software ETAP [19]. The model was derived from previous studies of the Central American interconnected system and adapted to represent the main transmission corridors, substations, and generation units of Costa Rica. Particular attention was given to accurately representing the topology of the high-voltage network, as well as the geographical distribution of generation and demand. Operational data provided by the Costa Rican Electricity Institute (ICE) [20], including the hourly load profile of a representative day of maximum annual demand, were used as the basis for the simulations. This approach ensures that the analysis reflects realistic operating conditions and captures the behaviour of the system under peak stress scenarios.

The methodological procedure consisted of three main stages. First, a base case was evaluated using SLR, where transmission line ampacities were defined according to conventional static planning criteria. These limits were assumed to be constant over time and based on conservative environmental conditions, as typically considered in transmission planning practices. Hourly load flow simulations were conducted to identify the onset of thermal overloads as system demand progressively increased. This step allowed the identification of critical transmission elements and the saturation level of the network under static conditions. In addition, it provided a reference scenario against which the impact of alternative approaches could be assessed.

In the second stage, a DLR approach was applied. Due to the absence of real-time meteorological measurements or monitoring systems installed on Costa Rican transmission lines, dynamic ampacity values were estimated based on reference data reported in the literature. In particular, hourly variations of line ampacity were adapted from previous monitoring studies and adjusted to represent realistic operating conditions. These profiles were selected to reflect typical variations in ambient temperature, wind speed, and solar radiation, which are the main factors influencing conductor thermal behaviour. Although this approach does not capture site-specific conditions, it provides a representative approximation of the potential variability of line ratings. These dynamic limits were then implemented in ETAP to reassess system operation under the same demand conditions, ensuring a consistent comparison with the base case.

Finally, the performance of the transmission network under SLR and DLR was compared using several indicators, including the number of overloaded lines, the duration and severity of thermal violations, and the relative increase in effective transmission capacity. In addition, qualitative observations regarding the spatial distribution of congestion and the utilisation of key transmission corridors were considered. This comparative analysis provides insight into the potential benefits of DLR for transmission planning in the Costa Rican power system, highlighting its capability to improve network flexibility and defer the need for infrastructure reinforcement.

4. Results

The results were obtained from hourly power flow simulations carried out for a representative maximum-demand day. A 24-hour time horizon was analysed, and system operation under SLR and DLR was compared using the same demand profile. This approach allows a consistent evaluation of the impact of dynamic ratings on system performance under identical loading conditions, isolating the effect of line ampacity variations from other operational factors.

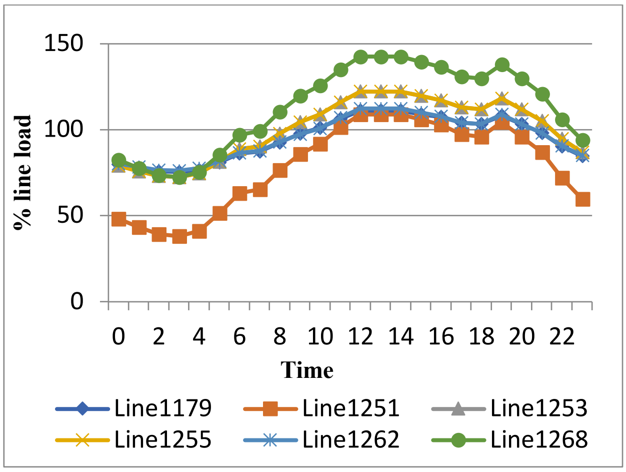

Fig.1. Loading levels of critical transmission lines during the maximum-demand day (SLR case)

Under static thermal limits, Fig. 1 shows the hourly evolution of the loading level of the most heavily loaded transmission lines. As system demand increases throughout the day, several lines progressively approach their thermal limits, reflecting the limited flexibility of the network under conventional static criteria. Loading levels rise during the morning hours and reach their highest values around midday and early afternoon, following the demand profile. Peak loading conditions are observed between approximately 12:00 and 15:00, when some lines operate significantly above 105% of their thermal capacity, indicating the presence of sustained thermal constraints during periods of maximum demand. These results highlight the existence of congestion in key transmission corridors, which may limit the ability of the system to accommodate additional power transfers under static operating conditions.

Fig. 2 presents the same loading profiles for the most heavily loaded transmission lines when DLR is applied. Compared to the static case, the use of DLR leads to a noticeable reduction in line loading levels during almost the entire day, reflecting the increase in available ampacity under favourable environmental conditions. This reduction is particularly evident during peak demand hours, when the system experiences the highest stress levels. For all analysed hours except 11:00, the loading of the most critical lines is reduced with respect to the SLR case, and several lines that exceeded their static thermal limits operate within acceptable loading levels. This indicates that DLR can effectively relieve congestion in critical transmission paths by dynamically adapting the allowable current to real operating conditions. At 11:00, however, the dynamic ampacity is slightly lower than the static rating, resulting in a localized increase in line loading during that hour. This behaviour reflects the inherent variability of DLR and highlights the importance of considering adverse weather conditions in operational planning.

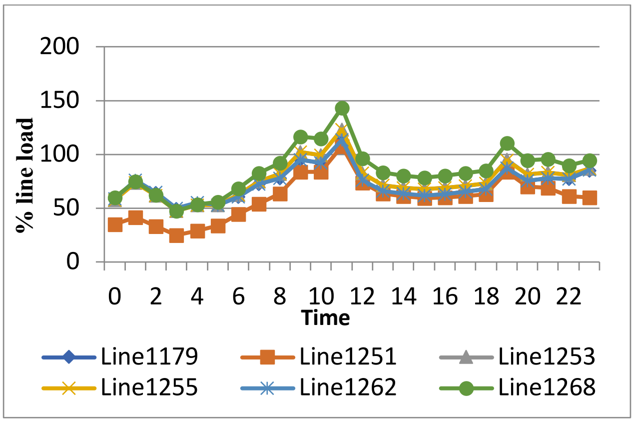

Fig.2. Loading levels of critical transmission lines during the maximum-demand day (DLR case)

Fig. 3 compares the hourly number of overloaded transmission lines exceeding 105% of their thermal rating under SLR and DLR. This indicator provides a system-wide measure of congestion and allows a direct comparison of network performance under both approaches.

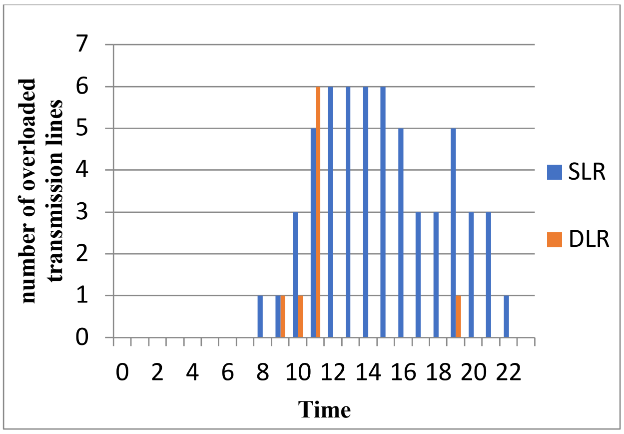

Fig.3. Overloaded transmission lines

Under SLR, thermal overloads appear during a wide range of operating hours and are particularly concentrated during peak demand periods, with up to six overloaded lines occurring between 12:00 and 15:00. These overloads are not only more frequent but also persist over several consecutive hours, indicating sustained stress on the network. When DLR is applied, the number of overloaded lines is substantially reduced for most hours of the day, and thermal violations are completely eliminated during several of the most congested periods. This reduction demonstrates the capability of DLR to increase the effective utilisation of existing transmission infrastructure and to mitigate congestion without requiring network reinforcement. The only exception occurs at 11:00, when the number of overloaded lines slightly increases from five under SLR to six under DLR. However, this increase is limited to a single hour and does not affect the overall improvement observed throughout the day. Overall, the application of DLR reduces both the frequency and persistence of thermal overloads, leading to a markedly improved operating condition for the analysed maximum-demand day and highlighting its potential as a planning support tool.

5. Conclusion

This work evaluated the impact of applying DLR to the Costa Rican transmission system through hourly power flow simulations in ETAP for a representative maximum-demand day. The comparison between Static Line Rating and DLR shows that conservative static thermal limits can lead to an overestimation of transmission congestion and an underutilisation of existing infrastructure, particularly under conditions where favourable environmental factors would allow higher line ampacity.

By incorporating dynamic ampacity limits, a substantial reduction in both the frequency and persistence of thermal overloads is achieved, particularly during peak demand hours, resulting in improved system operability without the need for immediate network reinforcements. The results also indicate that DLR can effectively increase the utilisation of critical transmission corridors, alleviating congestion and enabling a more efficient use of available assets. Although isolated hours may experience limited reductions in dynamic ampacity, the overall system performance is clearly enhanced under DLR, demonstrating its robustness under varying operating conditions.

From a planning perspective, these findings suggest that DLR can serve as a cost-effective alternative or complement to traditional network expansion, especially in power systems with high penetration of renewable generation and growing demand. Its ability to adapt transmission capacity to real-time environmental conditions makes it particularly suitable for systems where variability and uncertainty play a significant role.

Nevertheless, some limitations of this study should be acknowledged. The analysis is based on representative dynamic ampacity profiles derived from literature rather than site-specific meteorological measurements, which may affect the accuracy of the results. In addition, the simulations are limited to steady-state conditions and do not explicitly consider operational uncertainties or contingency scenarios.

Future research will extend the analysis to additional operating conditions, incorporate more detailed and location-specific environmental data, and explore the integration of DLR into more advanced operational frameworks, including probabilistic or security-constrained approaches. This will allow a more comprehensive assessment of the benefits and limitations of DLR in the Costa Rican power system.

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