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Development of a Prototype to Maximize Renewable Energy Integration applying Experimental Studies on DLR

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Abstract. The continuous rise in global energy demand has necessitated the adaptation of conventional power systems to meet increasing consumption requirements and to enhance energy transmission capabilities. The transition from a centralized energy model to one based on renewable sources requires a shift from traditionally linear and radial transmission infrastructures to decentralized networks that integrate diverse renewable generation sources.

To ensure optimal performance and reliability in this new paradigm, it is essential to implement more advanced and precise strategies for the control and management of power grid operations. In this context, improving transmission networks becomes a critical factor, as they often represent bottlenecks in the modernization and decarbonization of the energy system.

This project aims to contribute to the optimization of transmission lines, with the objective of maximizing the integration of energy generated by decentralized renewable sources. To this end, a real prototype has been developed to analyze the thermal and electrical behavior of power conductors in real operating conditions. The experimental setup is designed to support the assessment of dynamic line rating (DLR) strategies applied to both conventional and high-temperature low-sag (HTLS) conductors, enabling a more efficient use of existing transmission infrastructure and facilitating the transition towards a more sustainable and resilient energy system.

Key words. HTLS, ACSR, Renewable-Energy Integration, Ampacity, Overhead Lines, Dynamic Line Rating.

1. Introduction

The increasing energy demand necessitates the modernization of conventional electrical systems to enhance transmission capacity, incorporating a decentralized generation model. To achieve greater integration of renewable energy sources, it becomes essential to enhance the transmission capacity of existing power lines or to develop new infrastructure. However, constructing new transmission lines is a highly complex endeavor, often rendered unfeasible by economic limitations, environmental concerns, legal restrictions, and political opposition.

Furthermore, the development of new lines frequently lags behind the growing demand for electricity transmission. Although increasing the voltage level is a viable alternative to boost transmission capacity, such upgrades typically involve complex engineering solutions and substantial financial investment. As a result, optimizing the current-carrying capacity of existing lines emerges as a more efficient, cost-effective, and immediately actionable strategy to meet the evolving needs of the power grid [1].

Fig. 1: Pictures of the conductors testing prototype.

The prototype aims to enhance the efficiency of overhead power lines. By improving transmission performance, the objective is to facilitate a more reliable and sustainable energy infrastructure capable of adapting to evolving energy demands.

The analysis has been approached from an experimental perspective through the development of a fully operational simulation prototype, shown in figure 1, designed to study the behavior of overhead line conductor technologies.

As an initial phase, a comprehensive data acquisition campaign has been carried out over the course of an entire year, resulting in the analysis of more than 300,000 distinct operating states. The system has demonstrated its capability to operate under electrical currents exceeding 1,200 A, thus providing a robust dataset for performance evaluation.

These empirical results have been systematically compared with traditional analytical methods to assess their accuracy, identify inherent limitations, and propose improvements to conventional predictive models. By addressing these shortcomings, the research contributes to the development of more accurate and adaptive grid management strategies, thereby facilitating the reliable integration of decentralized renewable energy sources into the power network.

Following the validation of this initial assessment, the prototype will serve as a platform for evaluating and comparing current and emerging transmission technologies under real-world conditions. Enhancing the efficiency of overhead lines directly contributes to improving the overall performance of the electrical system.

2. Challenges to be faced

For an efficient and sustainable energy transport system, current power grids face several critical challenges:

- The increase in energy demand. Advances in technology, growing social energy demands, consumption patterns and the expansion of electric transportation systems are driving a steady rise in electricity consumption. As a result, electrical networks are playing an increasingly central role.
- The decentralized nature of renewable energy generation. Traditional power systems were structured around large, centralized generation plants distributing energy through an extensive transmission network. However, the shift towards decentralized and diversified energy production has led to a democratization of energy generation [2]. This paradigm shift is primarily driven by integration of renewable sources, which range from large-scale power plants to smaller, distributed generation units.
- The modernization of existing grids is becoming increasingly necessary, not only to accommodate rising demand but also to address the aging infrastructure of current power networks.

The combination of these factors makes transmission lines the limiting element in the generation-transport-consumption equation. When transmission capacity is insufficient, power generation from renewable sources may need to be curtailed, as the system is unable to transport all the electricity produced. Such limitations significantly reduce overall system efficiency, causing major energy losses and severe environmental impacts by restricting the full utilization of renewable energy resources.

3. Nowadays solutions

Several approaches exist to increase transmission capacity. One option involves replacing existing lines with alternatives that feature larger conductor cross-sections, a greater number of conductors per phase, or conductors with higher ampacity. Regardless of the chosen solution, overhead transmission lines must be properly designed to ensure that the grid can meet the growing energy demand without incurring significant economic costs associated with new infrastructure construction. The development of new transmission lines is a complex process and is often unfeasible due to economic, environmental, legislative, and political constraints. Additionally, the construction of new lines frequently fails to keep pace with the increasing energy demand [1].

Another method for increasing line capacity involves raising the voltage level; however, these approaches often require more complex and costly interventions, making current capacity enhancement a more advantageous and efficient option [3].

Other solution is the use of High Temperature Low Sag (HTLS) conductors, which are specifically designed to handle higher electrical loads while maximizing the utilization of existing lines [4]. However, recent studies have demonstrated the difficulty of achieving accurate and reliable calculations when conductors are subjected to high operational loads and elevated temperatures [5]. This highlights and reinforces the need for experimental testing, such as the proposed study.

The increase in a line's ampacity has been addressed through two main strategies, improving the calculation accuracy and increasing the ampacity of the conductor.

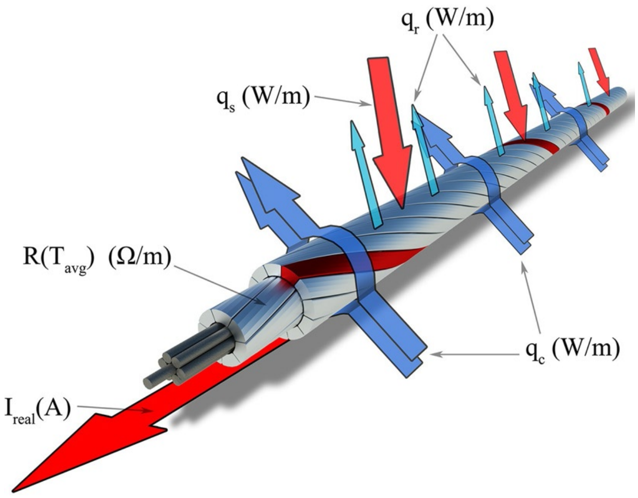

Fig. 2: Representation of thermal exchanges during the operation of a bare conductor in an overhead line.

3.1 Enhancing Accuracy in Conductor Behavior Calculations: Dynamic Line Rating

Traditionally, the stationary ampacity calculation method has been used to estimate conductor capacity. This method incorporates safety margins by considering the most unfavorable operating conditions, which often results in a conservative static ampacity value that is lower than the actual capacity of the line under most conditions.

To overcome this limitation, the concept of dynamic ampacity has been introduced. Dynamic line rating (DLR) enables real-time calculations of transmission capacity based on variable conditions. This approach aims to maximize the utilization of existing networks by implementing non-stationary management strategies, optimizing ampacity dynamically to achieve the highest possible performance for each situation [6].

In any approach for calculating the conductor's capacity, whether through a static or dynamic method, a thermal equilibrium equation is used to analyze the main processes involved in the thermal conditions of the conductor.

Figure 2 schematically illustrates all the thermal processes involved in the equilibrium equation. Some effects, such as the skin effect, have traditionally been overlooked by standard calculation methods due to their minimal impact on the conductor's thermal equilibrium compared to other more significant factors. However, with the advent of new technologies and enhanced calculation precision, it has become crucial to consider all possible factors in order to maximize the overloading of transmission lines efficiently, safely, and sustainably.

The full equation that can be formulated to establish the general equilibrium according to standard calculation methods is as follows:

$$q_j + q_m + q_s + q_i = q_c + q_r + q_w \tag{1}$$

where:

q_j Heat produced by the Joule effect (function of the current)
q_m Magnetic heating
q_s Heat from solar radiation
q_i Heat produced by the corona effect
q_c Convection cooling
q_r Radiation cooling
q_w Evaporation cooling

The calculation standards (IEEE Std. [7] and CIGRE TB 601 Std. [8]) use this proposed heating balance to calculate the ampacity of overhead conductors. The key distinction introduced by these new calculation methodologies is the implementation of dynamic line rating (DLR). Unlike conventional static ratings, DLR continuously adjusts the line's capacity in real-time based on actual environmental and operational conditions.

When analyzing the fluctuation in current that influence conductor temperature, it is important to note that sudden changes in current lead to temperature variations with a time delay. The line temperature is in a constant state of flux, depending on fluctuations in electrical load and real-time weather conditions. The proposed equation for this iterations in thermal balance is shown in equation 2.

$$\frac{dT_{avg}}{dt} = \frac{1}{m \cdot C_p} \left[R(T_{avg}) \cdot I^2 + q_s - q_c - q_r \right] \quad (2)$$

where:

q_c Heat loss due to convection (W/m)
q_r Heat loss due to radiation to the surroundings (W/m)
q_s Heat absorbed from solar radiation (W/m)
I Electrical current flowing through the conductor (A)
$R(T_{avg})$ AC resistance at the operating temperature (Ω/m)
T_{avg} Average operating temperature of the conductor $(^{\circ}C)$
t Time variable (s)
C_p Specific heat capacity $(J/kg \cdot K)$

Through this continuous iterative process, the transmission capacity of the line is dynamically adjusted. Ampacity refers to the maximum allowable current a transmission line can carry without surpassing regulatory or safety thresholds, while also ensuring the mechanical integrity of the conductor materials under thermal stress.

Using these calculation methodologies, ampacity is continuously modified based on real-time climatic conditions, conductor type, maximum permissible temperatures, and the conductor's previous thermal state.

By performing these calculations, the grid's operational management becomes more precise and secure, allowing for an optimized increase in transmission capacity and enhanced integration of renewable energy sources. For instance, under high wind conditions, wind power generation increases, necessitating greater transmission capacity in the affected region. Since the conductors experience enhanced convective cooling due to stronger wind currents, their ampacity can be precisely and safely adjusted, allowing for the controlled overloading of the transmission line under these favorable conditions.

3.2 Increasing Ampacity by Enhancing Conductor Transport Capacity: HTLS Conductors

Another approach to increasing ampacity focuses on the conductors themselves. The goal is to develop conductors that can withstand higher current levels while maintaining geometric constraints and avoiding material degradation due to increased operating temperatures. A promising solution is the adoption of HTLS conductors, which allow for significantly higher current flow while maintaining low sag values. By utilizing HTLS conductors, ampacity values can be doubled compared to conventional conductors [9].

The relationship between ampacity, environmental conditions, and the physical and electrical properties of the conductor determines the minimum clearance that a line must maintain from the ground.

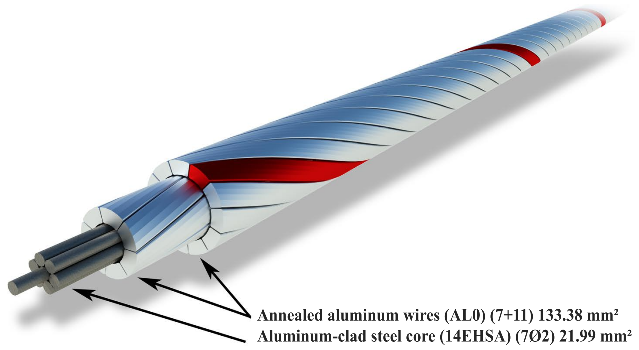

Fig. 3: render of the Nexans ACSS/TW/AW 133/22 conductor to be tested.

High-Temperature Low-Sag (HTLS) conductors have emerged as a key solution for enhancing transmission capacity maintaining existing infrastructure. HTLS conductors do not rely on improved cooling but rather on their ability to endure elevated thermal stresses—operating at significantly higher temperatures—without excessive elongation or mechanical degradation.

Several HTLS technologies have been developed, all characterized by operating temperatures exceeding 150ºC, with some exceeding 200ºC while maintaining structural stability. ACSS (Aluminum Conductor Steel-Supported) conductors incorporate a galvanized steel core, often aluminum-clad or coated with a Galfan layer, surrounded by fully annealed aluminum or aluminum alloy wires in circular or trapezoidal cross-sections to enhance electrical conductivity.

One of the primary challenges in HTLS conductor design is balancing electrical conductivity with mechanical strength. This is achieved by utilizing alloy compositions incorporating elements such as zirconium (Zr) and scandium (Sc), which enhance thermal resistance, increasing mechanical strength and enabling continuous operation at temperatures between 150ºC and 230ºC.

Other HTLS technologies improve mechanical performance using invar-based alloys, such as those found in TACIR and ZTACIR conductors. Invar, a nickel-iron alloy with an extremely low coefficient of thermal expansion, is coated with aluminum and combined with heat-resistant aluminum alloy wires. GAP-Type HTLS conductors, such as GAP-Type Aluminum Conductor Steel-Reinforced (G(Z)TACSR), feature a grease-filled gap between the steel core and the outer thermal-resistant aluminum alloy layer. This gap allows mechanical stress absorption, ensuring that the core handles mechanical loads while the aluminum wires focus on electrical transport. Another HTLS category includes aluminum composite reinforced conductors (ACCR), which employ a metal-matrix composite core composed of aluminum fibers embedded within a pure aluminum matrix. These conductors incorporate heat-resistant aluminum alloys or annealed aluminum (ACCR, ACMR) to mitigate thermal effects on the outer layers, enabling stable operation at temperatures exceeding 210ºC. Composite aluminum core conductors, such as Aluminum Conductor Composite Core (ACCC), feature a modified epoxy resin composite core reinforced with carbon fiber and glass fiber layers. The core is surrounded by heat-resistant aluminum alloy wires, ensuring structural durability and efficient high-temperature performance.

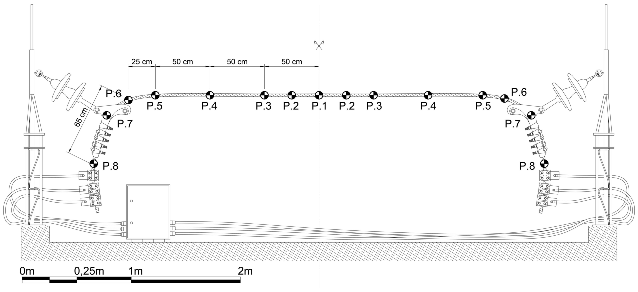

Fig. 4: Elevated plan of the real installation. The figure includes the location of the thermal control points used for testing the conductors.

For the validation of the simulation prototype, an advanced-generation ACSS-type HTLS conductor was selected for testing. Over the course of one year, extensive data collection was conducted, yielding approximately 300,000 measurements. The conductor, shown in Figure 3, was subjected to real-world operational conditions to assess its performance and thermal behavior. This dataset provides valuable insights for evaluating the accuracy of existing predictive models and identifying potential improvements in transmission efficiency.

4. The Prototype

The simulation prototype has been developed to study overhead conductors under the same environmental conditions as real transmission networks in order to maximize the decentralized power generation integration. This prototype enables the analysis of different conductor behaviors, identifying potential areas for performance improvement to advance toward safer and more efficient systems.

The installation was designed based on a two-dimensional CAD model, which provides a detailed layout for analyzing and evaluating the dimensional constraints of both the conductors and their accessories. Figure 4 presents a scaled drawing of the completed installation, including a graphical scale to illustrate the overall dimensions of the developed model.

Once the theoretical requirements are known, the physical assembly of the simulation and testing prototype was carried out. In summary, the prototype is used to analyze and collect fundamental parameters required for numerical calculation and analysis.

These parameters are classified into two main categories, starting with the environmental parameters, such as temperature, solar radiation, and wind properties. The second category are the conductor-specific parameters, including current, reflectivity, and surface temperature.

The system continuously monitors and stores all relevant meteorological data to enable a comprehensive thermal behavior analysis of the conductors, collecting measurements every minute. Also the prototype has been calibrated and contrasted with other measuring instruments like contact sensors or thermal cameras, as shown in Figure 5.

The prototype is located on the rooftop of the University of Cantabria building, placed in Santander at coordinates (43.47261, -3.7992). The testing setup is distributed across two main areas. The first area is on the outdoor rooftop, where the current loop is installed with the test conductor exposed to the local weather conditions, as shown in Figure 1.

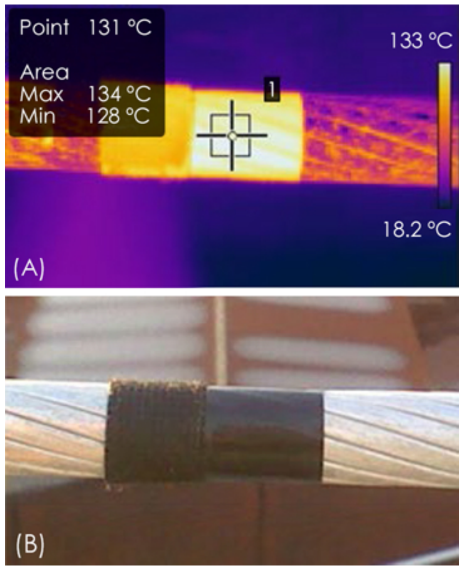

Fig. 5: Picture of the temperature measurement points installed on the prototype. (**a**) The upper figure was captured using a thermal camera. (**b**) The lower figure is a conventional photograph.

Close to the conductor is placed the meteorological measurement instrumentation, along with the elements necessary for the testing procedure. The remaining components are housed in an indoor room just below the rooftop level, where the data storage systems, autotransformer, and the monitoring and control equipment are located.

Electrical components of the prototype: As an initial configuration, the prototype includes a conductor from Nexans, specifically the model `Nexans ACSS/TW/AW 133/22` for the first test. The current loop is closed using four RVK-240 mm^2 Cu-(0.6/1 kV) copper conductors, each capable of carrying a maximum current of 415 A. This results in a total loop current capacity of 1660 A, which is higher than the rated current of most HTLS conductors.

The copper conductors are connected to the high-capacity conductor using high-current terminals, clamps, and aluminum-based conductive grease. The prototype includes two structural mounts that hold the fittings, which include 20 kV insulation-rated insulators. These ensure proper electrical isolation between the loop and the metallic supports and comply with standards UNE-EN 62217, UNE-EN 61109, and the Spanish High Voltage Electrical Line Regulation (REBT LAT).

The current loop is powered by four power toroidal transformers arranged in parallel inside an outdoor cabinet. For integration into the loop, the copper conductors pass through the center of the toroidal cores, using their internal diameter to position the RVK conductors. Thus, the current loop is responsible for inducing high ampacity, raising the conductor's temperature to its operational limit, and enabling performance analysis under extreme real-life weather and electrical loading conditions.

The power supplied to the four toroidal transformers is manually controlled via an autotransformer located in the lower indoor room. This device regulates the voltage feeding the toroidal transformers, which share the same supply due to their parallel connection.

Measurement and monitoring instrumentation: The Data Logger is installed in the control panel located one floor below the test prototype and is responsible for collecting data from all sensors. Sensors are strategically positioned across the prototype based on the nature of the parameter being monitored. These parameters are categorized into environmental conditions and conductor-specific parameters.

Environmental parameters include:

Ambient temperature (T_a),
Solar radiation (R_s),
Wind speed (W_s),
Wind direction (W_{dir}).

Conductor parameters include:

Conductor current (I),
Surface temperature of the conductor (T_s).

For wind speed and direction measurement, a two-axis HD52.3D ultrasonic anemometer is used. These are static ultrasonic anemometers capable of accurately capturing wind characteristics. The weather station also includes a pyranometer to measure solar radiation in real-time. A pyranometer quantifies solar energy flux incident on a given surface, measured in W/m^2, and consists of a glass dome and a thermoelectric sensor.

Thermal sensors used in the prototype are two PT-100 sensors, calibrated through 0–5 V output transducers for real-time data acquisition and continuous monitoring. To monitor the induced current in the prototype loop, a split-core current transformer is used. This transformer provides real-time current readings, which are integrated with the rest of the monitoring data.

To power and protect the instrumentation and monitoring system, an isolation transformer is installed.

Auxiliary equipment: In order to perform initial system checks, commissioning, and calibration of the permanent monitoring instrumentation, several measurement devices have been used. The thermal camera is a Flir E40 Thermal Imaging Camera, used to capture thermographic images, collect thermal data and monitor conductor temperature variations. Testo 435-4 Multifunction Meter, to measure ambient temperature and conductor surface temperature and Proinsa Clamp-Meter (Model 3511937) capable of measuring currents up to 1000 A.

5. Main Contributions

The main contributions of the prototype lie in its ability to establish a real-world testing platform for evaluating the operational conditions of overhead conductors, replicating scenarios comparable to their integration within a decentralized system comprising both renewable and conventional energy sources.

The initial study presented a comprehensive analysis of how various parameters influence the thermal behavior of overhead conductors, especially under high-current operating conditions. These parameters include conductor diameter, ambient temperature, wind speed and direction, surface temperature, and electrical resistance. The findings are crucial for understanding the thermal dynamics involved in Dynamic Line Rating (DLR) systems and for enhancing the secure and efficient integration of renewable energy sources into the electrical grid.

Therefore, the implementation and commissioning of this simulation prototype opens the door to experimentally validating both emerging and existing energy transmission technologies. The integration of these technologies can be optimized to maximize the renewable energy mix and improve overall grid efficiency, thereby reducing losses and enabling the connection of an increasing number of distributed energy generation centers.

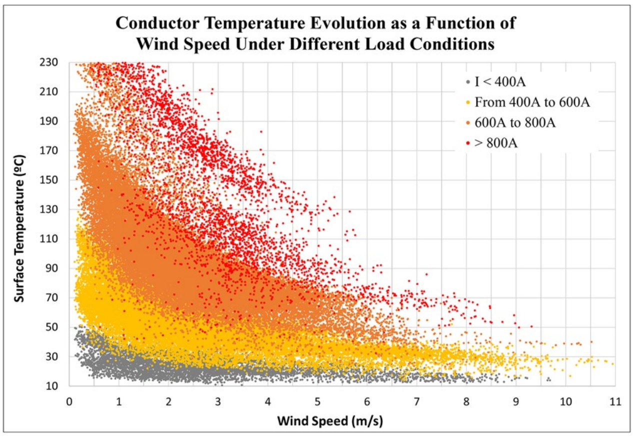

Fig. 6: Conductor Temperature Evolution as a Function of Wind Speed Under Different Load Conditions

Among other aspects, the first test includes data collected over an entire year, with more than 300,000 data points analyzed wich validates the prototype work system. Phenomena such as rainfall and specific forced convection effects caused by wind flowing in quasi-parallel directions to the conductor have been thoroughly examined and compared against standard calculation models. These findings offer valuable insights into future directions for improving transmission line calculation methodologies. Throughout the ongoing and future tests using the simulation prototype, the objective is to shed light on the key parameters that should be considered and improved in current conductor rating methodologies.

One of the parameters under investigation is the conductor diameter, which has been shown to significantly impact thermal performance. Larger diameters enhance heat dissipation due to the increased surface area, resulting in lower surface temperatures for a given current level. This geometric factor directly influences the conductor's ampacity, as improved cooling allows for higher current transmission without exceeding critical thermal thresholds.

The effect of wind on overhead conductors is also being thoroughly analyzed, with particular relevance for power transmission in areas surrounding wind farms and in regions where wind conditions are dominant. By evaluating wind speed and direction under realistic test conditions, the potential for dynamic overloading of transmission lines is assessed. Initial test results have shown that wind is one of the most influential environmental variables, with a high impact reducing the temperature with high wind speeds, as shown in figure 6. Both speed and direction dramatically affect convective cooling. Winds that strike the conductor perpendicularly provide the most effective cooling. Even moderate wind speeds at optimal angles can result in significant reductions in surface temperature, increasing the thermal margin and thus the current-carrying capacity of the line. In contrast, low wind speeds or suboptimal angles significantly diminish cooling performance, leading to increased thermal stress on the conductor.

Another parameter of particular interest, especially in regions with high solar irradiance and photovoltaic energy production, is the combined effect of solar radiation and ambient temperature. Ambient temperature plays a crucial role in determining the surface temperature of the conductor. Higher ambient temperatures reduce the thermal gradient between the conductor and its surroundings, thereby decreasing the efficiency of heat exchange with the environment. As a result, conductors can reach higher operating temperatures under otherwise identical electrical and meteorological conditions, potentially limiting the allowable current and overall system performance. The surface temperature itself is a key indicator of conductor performance. It integrates the effects of all thermal inputs and losses, including Joule heating, solar radiation, and convective/radiative cooling. An increase in surface temperature corresponds to higher AC resistance, due to the temperature dependence of conductor materials. This rise in resistance creates a feedback loop where elevated temperatures lead to greater power losses through resistive heating, further increasing the temperature unless sufficient cooling is present.

In summary, the combined influence of physical and environmental variables must be taken into account for accurate modeling of conductor ampacity. Understanding and quantifying these interactions is crucial for developing more efficient, safe, and adaptive power transmission systems, particularly under the growing demand for renewable energy integration and dynamic operating conditions.

6. Conclusions

During the development of this experimental prototype, a system has been constructed and validated to analyze the accuracy of the main ampacity calculation methodologies proposed for bare conductors in overhead lines. The main objective is to improve the energy transmission efficiency of the grid and to facilitate the integration of a more diverse, sustainable, and renewable energy mix.

The main conclusions from the system design and the initial associated study are summarized as follows:

- The prototype has been designed with a particular focus on enhancing transmission line performance, incorporating sufficiently high current levels—exceeding 1200 A to enable the evaluation of the latest HTLS technologies such as ACSS conductors.
- The prototype has been validated through an initial comparative study, which will serve as the foundation for the analysis of various conductor types and renewable energy integration systems. The experimental data collection process was successfully carried out and validated, allowing conductors to be tested under high-current and high-temperature scenarios in real meteorological conditions.
- The test installation has been specifically built to sustain very high operating currents, enabling the reproduction of extreme loading conditions in a safe environment. This allows for a more detailed analysis of conductor behavior, with full flexibility to adjust loading conditions according to the researcher's criteria, safely and independently. The system enables the testing of ideal conditions for renewable integration without the operational risks that such trials would pose on a real power grid.
- From the first test campaign and the initial conductor analyzed, potential improvement scenarios were identified, particularly under wind conditions with low attack angles. This paves the way for further exploration into enhancing renewable integration, such as wind energy, for a wide range of conductor types. It will also enable a better quantification of solar radiation impacts on generation technologies like photovoltaics.

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References

[1] M. González-Cagigal, J. A. Rosendo-Macías, A. Bachiller-Soler, and J. C. del-Pino-López, "Reliability assessment of dynamic line rating methods based on conductor temperature estimation," *Electric Power Systems Research*, vol. 233, no. 233, 2024, ISSN: 1996-1073. DOI: https://doi.org/10.1016/j.epsr.2024.110449. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779624003377.

[2] A. Katre and A. Tozzi, "Assessing the sustainability of decentralized renewable energy systems: A comprehensive framework with analytical methods," *Sustainability*, vol. 10, no. 4, 2018, ISSN: 2071-1050. DOI: 10.3390/su10041058. [Online]. Available: https://www.mdpi.com/2071-1050/10/4/1058.

[3] F. Margita, L'. Beňa, W. Malska, and P. Pijarski, "Possibilities of increasing the ampacity of overhead lines using high-temperature low-sag conductors in the electric power system of the slovak republic," *Applied Sciences*, vol. 14, no. 17, 2024, ISSN: 2076-3417. DOI: 10.3390/app14177846. [Online]. Available: https://www.mdpi.com/2076-3417/14/17/7846.

[4] C. O. Ujah, D. V. V. Kallon, D. O. Aikhuele, and V. S. Aigbodion, "Advanced composite materials: A panacea for improved electricity transmission," *Applied Sciences*, vol. 12, no. 16, 2022, ISSN: 2076-3417. DOI: 10.3390/app12168291. [Online]. Available: https://www.mdpi.com/2076-3417/12/16/8291.

[5] J. Riba, "The role of ac resistance of bare stranded conductors for developing dynamic line rating approaches," *Applied Science*, vol. 14, no. 14, 2024, ISSN: 1996-1073. DOI: https://doi.org/10.3390/app14198982.

[6] A. Arroyo, P. Castro, R. Martinez, *et al.*, "Comparison between ieee and cigre thermal behaviour standards and measured temperature on a 132-kv overhead power line," *Energies*, vol. 8, no. 12, 2015, ISSN: 1996-1073. DOI: 10.3390/en81212391. [Online]. Available: https://www.mdpi.com/1996-1073/8/12/12391.

[7] "Ieee standard for calculating the current-temperature of bare overhead conductors," *IEEE Std 738-2006 (Revision of IEEE Std 738-1993)*, 2007. DOI: 10.1109/IEEESTD.2007.301349.

[8] *Guide for thermal rating calculations of overhead lines.* CIGRE TB 601), 2014.

[9] M. Jalilian, J.-R. Riba, and P. Parvizi, "Aluminum conductor steel-supported conductors for the sustainable growth of power line capacity: A review and discussion," *Materials*, vol. 17, no. 18, 2024, ISSN: 1996-1944. DOI: 10.3390/ma17184536. [Online]. Available: https://www.mdpi.com/1996-1944/17/18/4536.