Quasi-Dynamic Line Rating spatial and temporal analysis for network planning

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***Abstract*—Electric transmission networks are limited by their ampacity, the maximum current a conductor can carry whilst meeting safety criteria. Ampacity depends on a conductor's ability to dissipate Joule heat and fluctuates with weather conditions. Standard practice sets a single conservative current-carrying limit for each season ('Static' Rating). As a result, transmission networks are performing substantially below their maximum capacity during the majority of their operation.**

This study proposes a methodology to design a Quasi-Dynamic Line Rating (quasi-DLR), based on ampacity simulations using historical weather reanalysis. As opposed to the static rating, this rating varies the current-carrying limit every hour of every month, allowing a higher percentage of a transmission line's capacity to be utilized. The methodology proposed can be applied to an existing transmission line to improve its performance or to a geographical region to aid in network design.

Application of the quasi-DLR methodology on an example transmission line shows significant potential gains in transmission capacity, notably due to ampacity increases in the absence of solar radiation. The example also demonstrates better accommodation of low ampacity events during hot weather, potentially improving the safety of transmission networks. Meanwhile, application of quasi-DLR on a region to evaluate its transmission capacity shows a capacity to reveal potential ampacity bottleneck locations.

All-in-all, the proposed methodology can potentially improve existing and future aerial transmission networks by increasing current capacity and security without adding additional infrastructure.

1. Introduction

Electricity transmission networks face growing energy demand from human activities. Furthermore, several methods of climate change mitigation, such as variable renewable energy sources and electric vehicles, significantly increase power flow during short time periods [5]. On the other hand, installation of additional infrastructure to increase electrical transmission capacity is often economically challenging, technically difficult and socially unwelcome [5]. The current carried by an aerial transmission line is limited by its engineers for safety reasons related to the heating of the conductor. To avoid dangerous accidents, this limit, known as the 'line rating', should ideally always be below the electric cable's current capacity, or 'ampacity', which vary depending on the conductor's properties and oscillates according to seasonal and daily changes in the weather. Ampacity and its dependencies are further discussed in Section 2. The standard practice is to set a single conservative ampere limit for each season ('Summer', 'Winter' and 'Spring\Autumn'), henceforth referred to as 'static' line rating. As this rating is designed to be below the line's smallest ampacity throughout the season, transmission networks are often performing substantially below their maximum capacity [1]. In Section 3, the paper describes the methodology to develop an alternative 'Quasi-Dynamic' line rating, that varies every hour of every month (e.g. January, 13:00, or July, 02:00), according to ampacity simulations based on historical weather data and conductor specifications. The methodology can be applied to an existing line to improve its performance or a region to aid in optimizing future networks. The rating is 'Quasi-Dynamic' as it compromises between the *static* line rating and the *dynamic* line rating, which uses continous forecasting to dynamically adjust the rating [1].

In Section 4, the Quasi-Dynamic Line Rating (qDLR) methodology is applied on an example transmission line and region. The potential improvements observed, and its applications are discussed. Finally, Section 5 summarizes the findings and its importance in the evolving context of increasing electrical consumption and changing weather patterns.

2. Background

As current flows in an electric cable, the Joule effect causes it to heat up. Heating poses a safety concern as it leads to excessive sagging of the conductor, increasing the transmission line's probability of collision with trees and infrastructure, as well as shorting. Thus, an aerial electric transmission line is limited by its *ampacity*, the maximum current an electric cable can carry whilst meeting design and safety criteria to avoid excessive heating [1].

Ampacity can therefore be considered as a measure of a conductor's ability to dissipate Joule heat. In turn, heat dissipation depends on the weather: high temperatures, low wind speeds, and intense solar radiation impede the dissipation of heat from the cable to the surroundings, whilst low temperature, high wind speeds and the absence of solar radiation accelerate heat dissipation. Thus, ampacity decreases significantly on hot summer days, compared to cold winter nights. Likewise, ampacity fluctuates according to cyclical meteorological changes (i.e. day and night, seasons). As the weather varies geographically as well, the effective ampacity of a line at any given time is the minimum ampacity between all its points.

3. Methodology

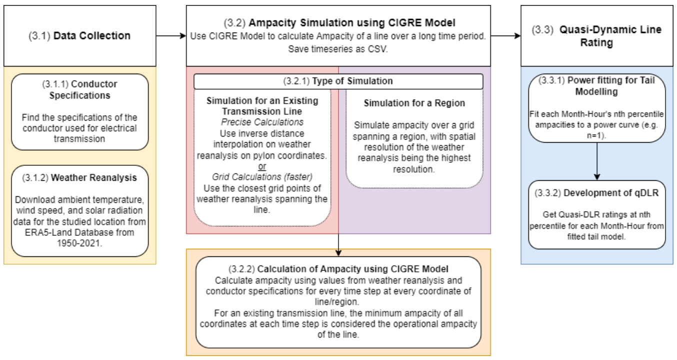


Fig. 1: Methodology to develop Quasi-DLR

As mentioned in Section 1, using the standard static rating, the electric cables are operating well below their capacity most of the time, which limits electricity transmission in the network. The main aim of qDLR is to increase this capacity.

This section describes the methodology to develop the quasi-Dynamic Line Rating, illustrated in Figure 1. The method involves firstly collecting the necessary environmental and conductor data in Section 3-A. Then, the historical time-series of ampacity is simulated on a collection of coordinates forming a grid or a line in Section 3-B. Finally, the tail-end ampacities are fitted to a power model, and the quasi-Dynamic Line Rating is developed in Section 3-C.

A. Data Collection

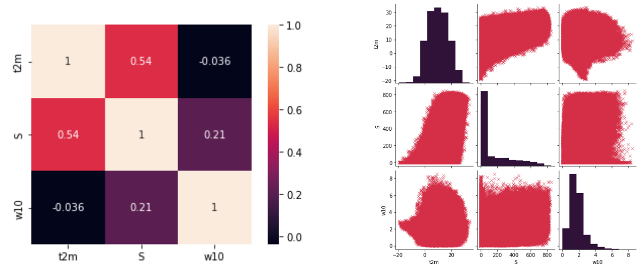
1) Conductor Specifications: In the case of an aluminium-conductor-steel-reinforced (ACSR) cable, several specifications required to calculate its ampacity, namely:

- D $[mm]$: overall diameter of the conductor
- A $[mm^2]$: nominal area
- R_{dc} $[\frac{\Omega}{km}]$: resistance per unit length
- d $[mm]$: non-ferrous diameter of one wire
- α $[\frac{1}{K}]$: temperature coefficient of resistance
- α_s : solar absorptivity of the surface
- ϵ_p: solar emissivity of the surface

D, A, R_{dc}, and d can be found in conductor tables from the provider of the cable. Default values of 0.5 for α_s and ϵ_p can be used in the case of lack of information [2].

2) Weather Reanalysis: There are three weather variables needed for the calculation of Joule heat: ambient temperature, wind speed, and solar radiation (wind direction is also used, but due to its high variability, a worst-case scenario of wind parallel to the conductor is assumed). These are provided by a *reanalysis* dataset, which provides a comprehensive and consistent picture of the weather by combining historical measurements with past forecasts. [3] [4]. The reanalysis used in this paper is ERA5-Land, a dataset showing the hourly evolution of land variables from 1950 to 2021, with a resolution of 0.1° x 0.1° (∼10 km) [3] [4].

The descriptive statistics of the weather from 1950-2021 of the 14 grid points spanning the example transmission line used in can be found in the Table I. The correlation and pairwise relationships between the variables are found in Figure 2. Similar to ampacity, low wind speeds and high solar radiation is associated with higher ambient temperature.



(a) Correlation (b) Pairwise Relationships

Fig. 2: Relationship between Weather Variables

TABLE I: Sample Weather Data from 1950-2021 from ERA5-Land around the French Riviera

	min	25th	mean	75th	max	std
t2m [°C]	-22.78	4.85	10.52	16.23	35.53	7.64
S [W/m2]	0	0	150.89	271.38	1220.81	213.08
w10 [m/s]	0.0013	1.09	1.70	2.08	10.73	0.93

B. Ampacity Simulation

1) Type of Simulation: Two types of simulation can be done: on a specific set of coordinates (wherein lies an aerial electric cable), or on a grid spanning a region. Their respective purposes are to aid in improving the capacity of an existing transmission line, or to optimise the expansion of the electrical network when routing new connections.

Simulation for an Existing Transmission Line: A list of coordinates (denoting the pylons of a transmission line, for example) is provided, and the weather data on each coordinate is gathered using inverse-distance interpolation of the reanalysis dataset (*Precise Calculations*). Alternatively, the grid points of the weather reanalysis spanning the line are used for a faster simulation as there is no need for interpolation (see Figure 3 for reference).

Simulation for a Region: The desired bounding box coordinates are provided, and the ampacity at each grid point of the weather reanalysis is calculated. In the case of ERA5-Land, the ampacity is calculated at a resolution of 0.1° x 0.1° (∼10 km between each point).

2) Calculation of Ampacity using CIGRE Model: The ampacity of each coordinate is calculated based on the CIGRE model for every hour from 1950-2021, for a given maximum allowable conductor temperature, T_{av} [2]. The CIGRE Model assumes the steady-state thermal condition of the conductor. The heat gains and losses considered not negligible by the CIGRE model are solar heating, joule heating, radiative cooling and convective cooling. The power associated with these heat transfers depend on the conductor's specifications and the weather variables mentioned in . By equating the heat gains and losses of the cable (1), it determines the maximum joule heating allowable. From this, the maximum allowable current is deduced (2).

$$P_j + P_s = P_r + P_c \tag{1}$$
$$\text{where } P_j = \text{Joule Heating}$$
$$P_s = \text{Solar Heating}$$
$$P_r = \text{Radiative Cooling}$$
$$P_c = \text{Convective Cooling}$$

The maximum allowable DC current, I_{dc}, can then be calculated by imposing Joule Heating to be equal to net cooling.

$$P_j = I_{dc}^2 R_{dc}(1 + \alpha(T_{av} - 20) \tag{2}$$
$$I_{dc} = \sqrt{\frac{P_r + P_c - P_s}{R_{dc}(1 + \alpha(T_{av} - 20)}}$$

In the case of a simulation for a transmission line, the minimum ampacity of each hour is the line's 'bottleneck', and is considered as the operational ampacity.

C. Quasi Dynamic Line Rating

1) Power Fitting for Tail-Modelling: The power law is used to model the tail-end behaviour for each month-hour. By fitting the historical ampacities, the coefficients a and b which will be used to model I_{ac} is determined (3).

$$I_{ac} = ax^b \tag{3}$$
$$\text{where } I_{ac} = \text{Ampacity (A)}$$
$$x = \text{Percentile}$$
$$a, b = \text{Power Model Coefficients}$$

2) Development of qDLR: Percentiles are the values below which a certain percentage of the data in a data set is found. According to the desired safety, the n_{th} percentile of each month-hour is calculated, where n is close to 1. For example, designing a rating to be at the first percentile (n=1) implies a 1% chance of the transmission line's ampacity being below the rating. If $n << 1$, the power fit may not be feasible. If $n >> 1$, the tail-model is no longer applicable, and the power fit is not appropriate to model the data.

4. Results

The methodology described previously in Section 3 is applied to design a Quasi-DLR at the 1^{st} percentile to a 225kV line (ID: LINGOL61ZVA10) in the French Riviera, managed by the electricity transmission system operator of France, Réseau de Transport d'Électricité (RTE). The coordinate locations of LINGOL61ZVA10's pylons, provided by the RTE, and the grid points of the weather reanalysis spanning the line can be seen in Figure 3. Supposing that the designer of a transmission line would like to set the new rating of LINGOL61ZVA10 at the n^{th} percentile of the line's historical ampacity, where $n = 1$). For the purpose of the study, it is assumed that:

- The static rating is also set at the historical ampacity's n^{th} percentile (where $n = 1$), for comparison. For simplicity, *Summer* consists of June, July and August, *Winter* consists of December, January and February, and the rest are *Spring/Autumn*.
- The transmission line uses a continuous aluminium-conductor-steel-reinforced (ACSR) cable of type 'DRAKE', the specifications of which are shown in Table II.
- The maximum allowable cable temperature is 75 °C.

TABLE II: Conductor Specifications of DRAKE

Name	Area	Strands (aluminum)	D (Al)
DRAKE	402.83 mm2	26	4.44mm
Strands (steel)	D (steel)	Overall D	Rdc
7	3.45 mm	28.11 mm	0.07197Ω/km

A. Minimum Ampacity

With the assumptions mentioned above, the ampacity of at every pylon coordinate of LINGOL61ZVA10 is calculated for every hour from 1950-2021. The minimum ampacity of each coordinate calculated is shown in Figure 3. A bottleneck can be observed in red around the minimum, denoted by a star. Assuming that the transmission line is a continuous conductor, the operating capacity is limited by the minimum ampacity of all its coordinates. Figure 3 thus demonstrates that the difference in weather patterns from location to location, even at a local level, can create a significant difference in transmission capacity.

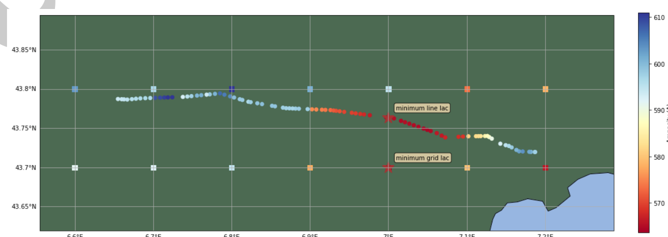


Fig. 3: Minimum Ampacities of LINGOL61ZVA10 Transmission Line

B. Tail Modelling

The power law is used to model the 1^{st} percentile for each month-hour combination. The average r^2 for all month-hours is 0.94, demonstrating an apt fitting. Examples of the fitting in night and day of winter and summer are shown in Figure 4.

For $n > 1$, the data approaches a linear trend. On the other hand, for $n < 1$, there may be a lack of historical weather data to simulate enough ampacities for appropriate modelling as there are around 30 instances of the same month-hour in one year and 71 years available in the weather reanalysis (1950-2021), thus around 2130 instances of each month-hour. This allows for only 21 data points at the 1^st percentile. At the 0.1^{th} percentile, there are only 2 instances, which is insufficient for modelling. Therefore, if the designer desires a stricter rating, he/she may use the 1^{st} percentile as a generous guideline.

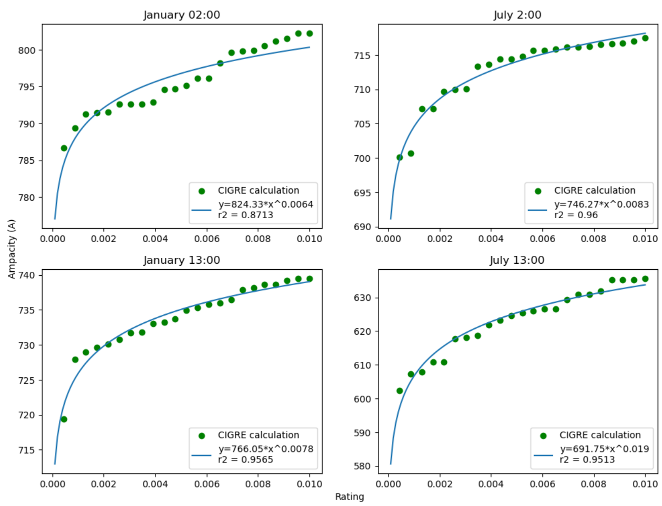


Fig. 4: Tail modelling for Quasi-Dynamic Line Rating

C. Quasi-Dynamic Line Rating

Using the tail-models developed in Section 4-B, the qDLR is set at the 1^{st} percentile for each month-hour. These ratings compared to the equivalent static rating at 1^{st} percentile are shown in Figure 5 and the percentage difference in ampacity is shown in Figure 6.There is an overall average gain in current capacity of 3.8%, a maximum increase of 14% (June 06:00), and a maximum decrease of -6.6% (September 11:00). Two notable differences are the ampacity gains during nighttime and losses during early afternoon.

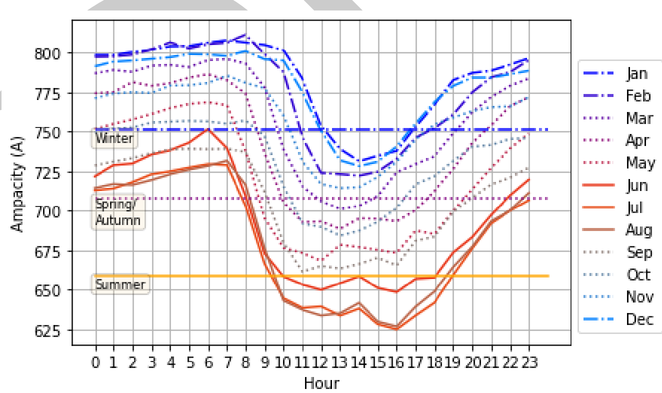


Fig. 5: Quasi-DLR Rating of LINGOL61ZVA10 at 0.01

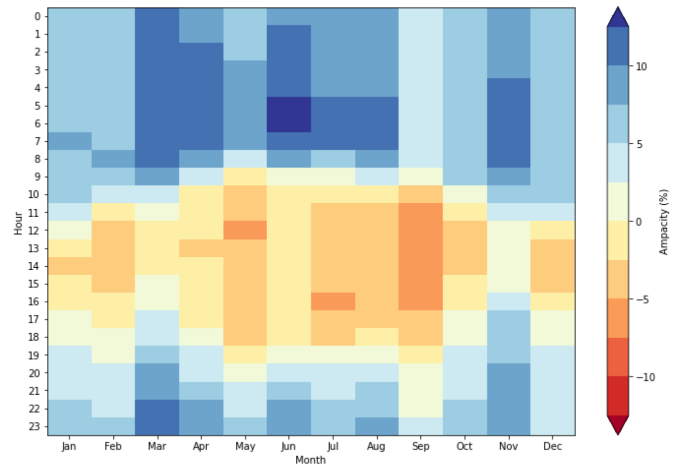


Fig. 6: Difference between Standard Quasi-DLR Rating

1) Day and Night: There are significant transmission capacity increases during nighttime, as the lack of solar radiation accelerates heat dissipation. Especially during spring and summer, the ampacity can increase by almost 15% during the night, seen in blues in Figure 6. A steep descent and ascent in ampacity can be observed during sunrise and sunset respectively in Figure 5, further demonstrating the influence of solar radiation on ampacity.

2) Early-Afternoon Heat: qDLR consistently fall below the static rating during hot early-afternoons, as seen in the orange regions of Figure 6. Using a Quasi-Dynamic Line Rating can thus allow for more careful consideration of short daily periods of extreme heat, ensuring higher security of the network. Instances of abnormally low ampacities could become more relevant in some regions due to the climate context.

D. Grid Simulations

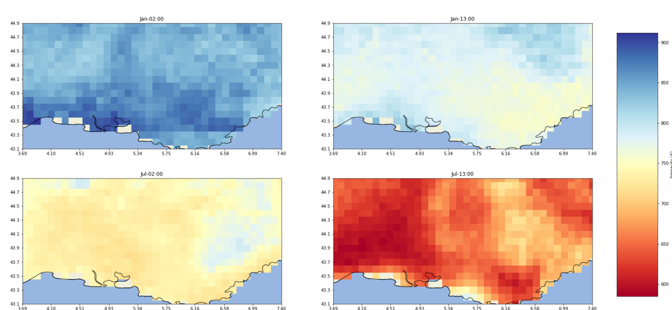


Fig. 7: Examples of quasi-DLR of Provence-Alpes-Côte d'Azur Region of France

The methodology also allows for simulations over a region, in the form of a grid. As discussed in Section 4-A, and demonstrated by Figure 3, ampacity varies geographically. An example qDLR is done over the French region of Provence-Alpes-Côte d'Azur, seen in Figure 7, at the resolution of the historical weather dataset (0.1° x 0.1°). The applied regional quasi-DLR revealed ampacity bottlenecks. For example, in summer afternoons (exemplified by July 13:00, Figure 7), a low-ampacity region, not present during other times of the year, can be observed around (43.4°, 6.3°).

Descriptive statistics of the change in ampacity from one grid coordinate to its 8 nearest neighbours (in cardinal and ordinal directions) can also be seen in Table III. In general, the change in capacity (A/km) is not excessively dramatic, with an average and standard deviation of 0.62 and 0.85 respectively. However, points with dramatic gradients can pinpoint bottlenecks, such as where the minimum gradient occurs, where the change in ampere capacity reaches 6.21 A/km. Such information could potentially optimise the design of future transmission lines, by route-planning around or employing less-resistant conductors on bottleneck coordinates.

TABLE III: Change in Transmission Capacity in Provence-Alpes-Côte d'Azur (A/km)

mean	min	25%	50%	75%	max	std
0.62	-6.21	-0.47	-0.01	0.45	4.28	0.85

5. Conclusion

Transmission networks need higher capacities to keep pace with the rapid evolution of electricity production and consumption. This paper proposes a methodology to develop a Quasi-Dynamic Line Rating for individual lines, which varies the current-carrying limit for every month-hour based on ampacity simulations using historical weather re-analysis. The methodology can be applied to a set of coordinates representing an existing line, or a grid spanning a geographical area.

The study tested the methodology on an example transmission line in the South of France. The rating proposed showed an increase in transmission capacity over the equivalent 'static' rating, whilst also increasing its security by safeguarding against low-ampacity events during hot weather. On the line considered, Quasi-DLR showed a maximum of 14% increase of the rating during periods of absence of solar radiation. During the early-afternoon, the qDLR generally decreases, with a minimum of -7% capacity, safeguarding the line from extreme heat. All in all, the example demonstrates that the Quasi-DLR can be used to improve the capacity of existing transmission lines.

The methodology was also applied to an example region, the French Provence-Alpes-Côte d'Azur. The results show qDLR's ability to reveal geographical current capacity bottlenecks, which could be utilised in the design or reinforcement of transmission networks.

In conclusion, this paper proposes a methodology to develop a Quasi-Dynamic Line Rating which could potentially improve current and future aerial transmission lines by increasing their capacity and security without the need for expensive network expansions or reinforcements.

Acknowledgment

to finalise

References

[1] Michiorri, Andrea, et al. "Forecasting for Dynamic Line Rating." Renewable and Sustainable Energy Reviews, vol. 52, 2015, pp. 1713–1730., https://doi.org/10.1016/j.rser.2015.07.134.

[2] CIGRE WG 22.12, The thermal behaviour of overhead conductors. Sections 1 and 2., vol. 144. ELECTRA , 1992.

[3] Muñoz Sabater, J., (2019): ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 23-Feb-2020), 10.24381/cds.e2161bac

[4] Muñoz Sabater, J., (2021): ERA5-Land hourly data from 1950 to 1980. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 23-Feb-2020), 10.24381/cds.e2161bac

[5] Bruckner T., I. A. Bashmakov, Y. Mulugetta, H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H. B. Nimir, K. Riahi, N. Strachan, R. Wiser, and X. Zhang, *2014: Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.