Methodology to assess phasor measurement unit in the estimation of dynamic line rating

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Abstract: This paper presents a methodology to analyse the influence of both atmospheric variations in time and space and the error in synchrophasor measurements to estimate conductor temperature along an overhead line. In this methodology, expressions to compute the error propagation in the computing of temperature as a consequence of measurement errors and load variations are proposed. The analysis begins by computing overhead line’s thermal and mechanical parameters using simulations of load and atmospheric conditions. The weather in each span is interpolated using nearby weather stations. Having computed thermal and mechanical parameters, values of resistance, inductance and capacitance of the overhead line modelled by means of a equivalent circuit are estimated, with the purpose of quantifying the sensibility of electrical parameters to changes in conductor temperature. Additionally, this analysis allows the identification of the temperature in each span along OHLs. Subsequently, the average conductor temperature is estimated using simulations of synchrophasors through the relationship between resistivity and temperature. This estimated temperature is compared with the temperature computed using atmospheric conditions in order to obtain the maximum error. This error is contrasted with the acceptable error margins. Thus, during the planning stage, this methodology can be used to assess PMU as a method of computing conductor temperature.

1 Introduction

Power systems are facing new challenges in operation, control and planning. To better face these challenges, it is necessary to optimize assets capacity, because they have reached their limits as a consequence of new loads and sources [1]. These new loads and sources increase congestion and risk, especially in overhead lines (OHLs) [2]. Thus, to push limits in OHLs, new technologies and methods have been developed with the aim of improving their capacity, reliability, safety and economic operation [3]. Among these technologies is Dynamic Line Rating (DLR) which has the ability to compute conductor’s ampacity in real time, based on current weather [4]. Rating in medium and short OHLs is commonly determined by catenary sag [5], a limit given by a maximum temperature in the conductor. Hence, DLR is typically used for this kind of OHLs.

Traditionally, line ratings are fixed according to extreme climate conditions that rarely happen. However, thanks to development of information technologies, it is possible to compute online OHL’s rating, via measurements of atmospheric conditions and current intensity. Two types of measurements for DLR have been defined, they are called direct and indirect [6]. The indirect method uses weather stations near to the OHL whereas direct methods use sensors of mechanical tension, temperature, sag or measurements derived from these three variables. Devices used in direct methods are located directly in the OHL, making it difficult to put them into operation and requiring maintenance. Despite this, DLR has low costs and it is fast to implement, if compared with other methods used to increase OHL’s ampacity [7]. Additionally, DLR is useful when it is necessary to increase the capacity between 10% and 30%, particularly for wind power integration [8], given the relationship between wind speed, power generation and cooling. In brief, DLR increases the capacity of OHL most of the time, achieving asset optimization.

The use of PMUs allows the estimation of OHL’s conductor thermal capacity in real-time. This method is considered as DLR technology, with the advantage that it uses an existing infrastructure capable of guaranteeing the functioning and reliability of DLR system [9]. With PMU, conductor rating is estimated using impedance of OHL’s equivalent circuit [10, 11], because of impedance changes according to conductor temperature. This temperature impacts state estimation [12] and load flows [13], thereby affecting losses, bus voltages, protections schemes [14] and OHL ampacity, among others.

The use of PMU for DLR is based on the computing of OHL’s average conductor temperature. However, conductor temperature varies along OHL, as a consequence of atmospheric variations in the different spans. Reference [15] presents a methodology for incorporating temperature variations along OHLs. This methodology consists of dividing line in segments based on temperature gradients obtained from measurements along the conductor. In same way, in reference [16] critical spans for monitoring OHLs are estimated by means of weather forecasting models, considering climate variations in time and space. However, there is not literature on the assessment of the error obtained by using resistance to compute OHL’s conductor temperature.

This paper proposed a methodology which consists in analysing, through simulations and analytically, the influence of measurement errors and atmospheric variations in time as well as space in the estimation of conductor temperature when PMUs are used. This methodology can be used to assess PMU for computing OHL’s conductor temperature. This in order to ensure that the estimated temperature error does not exceed acceptable margins. This paper is organized as follows: Section 2 discusses multiphysics behaviour of OHLs when changes in weather or load occur. In section 3, the proposed expressions to compute error propagation are addressed when synchrophasors are used. Section 4 describes the OHL under study and the interpolation method used to compute atmospheric conditions along an OHL. In section 5, the impact of weather over conductor temperature is computed in each ruling span and compared with the temperature calculated using PMU measurements. Finally, Section 6 analyses the error in estimation both OHL resistance and temperature when PMU measurements are used, taking into account measurement accuracy and load variations.
2 Multiphysics Phenomena - Background

During operation, OHLs are under influence of thermal, mechanical and electrical phenomena [17]. Figure 1 shows the relationship between these physical phenomena. At first, a heat transfer \( Q \) is presented as a product of a heat gain (mainly by Joule effect \( P \)) and solar radiation \( (S) \) and a heat loss (radiation and convection). That heat transfer is determined by the current intensity \( |i_{\text{rms}}| \), conductor properties and by atmospheric conditions (ambient temperature \( (T_a) \), solar radiation, and wind speed and direction \( (\vec{v}) \)). Heat transfer affects the conductor temperature \( (T_S) \), leading to a variation in the horizontal component of conductor mechanical tension \( (H) \), as a result of changes in conductor length \( (\ell) \) and in catenary sag \( (D) \). Additionally, changes in \( T_S, D, \ell \) impact both electric field \( (\vec{E}) \) distribution and conductor electrical conductivity \( (\sigma) \). These variations reflect in the values of voltage \( (v) \) and current intensity \( (i) \) in OHL’s. Finally, these three physical phenomena affect the OHL’s RLC parameters, given that these parameters depend on line geometry and conductor properties.

2.1 Thermal phenomena

CIGRE [18] and IEEE [19] standards are commonly used for computing temperature in OHL conductors. These standards are based on the heat balance equation. For thermal steady state, eq. (1) is used,

\[
Q_J + Q_S = Q_C + Q_R
\]

where \( Q_J \) is the heat gain from the Joule effect, \( Q_S \) is the gain from solar radiation, \( Q_C \) is the loss for convective cooling and \( Q_R \) is the loss for radiative cooling. The gain from magnetic heating and corona heating, as well as the losses due to evaporative cooling, are commonly ignored.

From eq. (1), the conductor temperature \( T_S \) and the maximum current intensity can be computed, provided that atmospheric conditions, current intensity and conductor properties (resistivity, temperature coefficient of resistance, solar absorptivity of surface, solar emissivity of surface, diameter, among others) are known.

2.2 Mechanical phenomena

Temperature variations in conductors result in changes in their length and on forces that act on catenary. To model this behavior, numerical or analytic formulations can use. Numerical methods such as Finite Elements are not commonly used for DLR, because of they require specialized software and large computational resources when compared with analytical approximations. As an analytical method, the state change equation (2) approximates the mechanical tension in an OHL stringing section using the ruling span method [20, 21].

\[
\frac{EA(r_m g s)^2}{24} = H^2 \left[ H - H_{T_{\text{ref}}} + \frac{EA(r_m g s)^2}{24H_{T_{\text{ref}}}} + E\alpha t \left(T_S - T_{\text{ref}} \right) \right]
\]

Equation (2) relates the tension \( H_S \) at a temperature \( T_S \) by means of a known \( H_{T_{\text{ref}}} \) at a known temperature \( T_{\text{ref}} \), where \( E \) is the modulus of elasticity of the conductor, \( A \) is the conductor cross section, \( g \) is the gravitational constant, \( m_c \) is the conductor mass per unit length, \( r_m \) is the equivalent ruling span length, and \( \epsilon_t \) is the coefficient of thermal expansion. \( \epsilon_t \) is a function of the stress and the elastic modulus. This dependence has a considerable influence at high temperatures [21], however in this research it is assumed constant, because the temperatures assumed in the simulations are below of 25 °C. Finally, as the values of \( H_{T_{\text{ref}}} \) and \( \epsilon_t \) vary over time, a continuous estimation of these value is necessary.

The conductor length per phase \( (\ell) \) can be computed using OHL geometry and tension \( (H) \) by means of

\[
\ell = \frac{h^2 + \left[ \frac{2H}{m_c g s} \sinh \left( \frac{m_c g s}{2H} \right) \right]^2}{\cos \left( \frac{m_c g s}{2H} \right) - 1}
\]

where \( h \) is the vertical distance between support elevation points (inclined spans) and \( s \) is the span length.

Finally, the OHL sag \( (D) \) is computed by

\[
D = \frac{H}{m_c g} \left( \cosh \left( \frac{m_c g s}{2H} \right) - 1 \right)
\]

2.3 Electro-Magnetic phenomena

The electrical parameters of the \( \pi \) equivalent circuit (fig. 2) by which the Electro-Magnetic phenomena can describe are used for modelling OHLs with medium length. These parameters are influenced by variations both in load and weather as follows.

The equivalent conductor resistance \( (R) \) varies according to temperature \( (T_S) \) and conductor length \( (\ell) \). These variations can be described by

\[
R_{T_S} = R_{T_{\text{ref}}} \left( 1 + \alpha (T_S - T_{\text{ref}}) \right) \cdot \frac{\ell_{T_S}}{\ell_{T_{\text{ref}}}}
\]

where \( \alpha \) is the resistance temperature coefficient. This equation is valid as long as the conductivity of material is in the linear zone regarding temperature dependence, which occurs in the normal operation of OHLs.

Fig. 1: Multiphysical phenomena in OHLs as a result of heat transfer

Fig. 2: Mechanical and thermal variables that influenced RLC parameters of an OHL modelled by \( \pi \) equivalent circuit
The equivalent inductance \( L \) depends on conductor’s arrangement, distances among them, and length of phase conductor. This parameter can be computed using

\[
L = 2 \cdot 10^{-4} \ln \left( \frac{GMD}{GMR} \right) \cdot \ell \tag{6}
\]

where \( GMD \) is the geometric mean distance and \( GMR \) is the geometric mean radius.

The length of phase conductor and the average distance \( h_{avg} \) between conductor and ground influences the equivalent capacitance \( C \). To calculate \( C \) from geometry, eq. (7) can use \([5]\),

\[
C = \frac{0.05556 \cdot 10^{-6}}{\ln \left( \frac{k_1 \cdot GMD}{GMRc} \right)} \ell \tag{7}
\]

where \( k_1 \) depends on \( h_{avg} \). Reference \([22]\) uses (8) for computing \( h_{avg} \),

\[
h_{avg} = \frac{\sqrt{(2h_M - D_{avg}) D_{avg}}}{\log \left( \frac{h_M + \sqrt{(2h_M - D_{avg}) D_{avg}}}{h_M - D_{avg}} \right)}
\]

where \( D_{avg} \) is the average sag and \( h_M \) is the conductor height at the tower. This expression takes into account sag variation which is function of temperature.

### 3 Error Propagation

In this paper, expressions to compute error propagation are proposed, provided that PMU measurements are used to estimate conductor temperature. The sensibility on the computation of temperature using resistors \( R \) is considered as the most critical connection in the country \([3]\), which connects geothermal plants and the substation Brennimelur, and it is considered as the most critical connection in the country \([23]\). This OHL connects geothermal plants and the substation Brennimelur, and it is considered as the most critical connection in the country \([23]\). As shown in fig. 3, BR1 connection crosses mountains, valleys and the sea, and it was built with three different types of conductors; therefore, temperature variations along the conductor occur. Given these characteristics, DLR is an option to increase the reliability and capacity of BR1-OHL.

#### 4.1 Test Line

BR1 has a rate voltage of 220 \([kV]\), a length of 59.4 \([km]\) and it is suspended at 172 towers divided in 30 tension sections shown in table 1. In this work, each stringing section is approached to a ruling span \([21]\). Different types of conductors are used on the OHL; their properties are shown in table 2. Weather conditions for static rating are: ambient temperature \( T_a = 10 \,[^\circ C] \), wind speed and attack angle \( \theta_a = 0.6 \angle 90^\circ \,[m/s] \) and solar radiation \( S = 0 \,[W/m^2] \) for an allowable conductor temperature \( T_G = 40 \,[^\circ C] \).

#### 4.2 Weather Nowcasting

To compute conductor temperature in each ruling span, this work assumes that atmospheric conditions do not change along each ruling span. Thus, atmospheric conditions were interpolated through biharmonic splines, evaluating the points located in the middle of each ruling span using records and location of weather station and the function \texttt{griddata} of Matlab\textsuperscript{®}. An accurate model of weather nowcasting is beyond the scope of this paper, because of this work only seeks to analyse the influence of weather variations as well as PMU measurement errors on estimation of conductor capacity. There are sixteen weather stations close to BR1-OHL; their names and locations are shown in table 3. The measure records from these stations are available online at the Icelandic Met Office webpage. For DLR, it is recommended to take 10 or 15 min average and standard deviation of samples \([24]\). However, as the aim of this paper is to evaluate the performance to use PMU for DLR, the atmospheric conditions between 2016-04-18 00:00 and 2016-04-18 21:00, with
samples taken every three hours, were considered. As example, temperature and wind interpolations for the date 2016-04-18 21:00 are shown in fig. 4. Given the climate characteristics of Iceland, solar radiation is neglected \cite{23} and normally the Icelandic Met Office does not report this parameter.

5 Impact of atmospheric variations

To analyse the impact of atmospheric variations on the BR1-OHL capacity, thermal, mechanical and electrical variables were calculated for each ruling span using weather interpolation and OHL geometry. Figure 5 shows the flowchart for computing the values of these variables \(T_S, \ell, S, H, R, L, C\). Afterwards, in order to evaluate PMU performance, these results are compared with the values computed using synchrophasors simulations. These simulations are assumed at the ends of the OHL. Thus, with the phasor simulations of \(v_{ik}, i_k, v_{im}, i_m\) and with \(13\) and \(14\), the average temperature \(T_S\) is computed through the estimation of circuit parameters of fig. 2.

Table 1 BR1 OHL - Stringing sections characteristics

<table>
<thead>
<tr>
<th>Ruling Span</th>
<th>Conductor Type</th>
<th>Capacity [MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>470-AL3</td>
<td>304 289 387 440</td>
</tr>
<tr>
<td>2</td>
<td>470-AL3</td>
<td>304 230 395 302 308 392 410 337 336 359</td>
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<tr>
<td>3</td>
<td>470-AL3</td>
<td>304 436 398 457 340 277 188 432 268 187 331</td>
</tr>
<tr>
<td>4</td>
<td>470-AL3</td>
<td>304 421 343 394 408 308 397 414 313 376 435</td>
</tr>
<tr>
<td>5</td>
<td>470-AL3</td>
<td>304 435 436 405 208 394</td>
</tr>
<tr>
<td>6</td>
<td>470-AL3</td>
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<tr>
<td>7</td>
<td>470-AL3</td>
<td>304 416 433 405 431 395 444 408 428 391 367</td>
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<td>8</td>
<td>470-AL3</td>
<td>304 353 342 349 375</td>
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<td>9</td>
<td>470-AL3</td>
<td>304 379 453 317 299 411 328 450 418 416 308</td>
</tr>
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<td>10</td>
<td>470-AL3</td>
<td>304 388 389 446 429 433 293 377 446 372 446</td>
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<tr>
<td>12</td>
<td>470-AL3</td>
<td>304 387 389 294 224 241 455 272 398 414 366</td>
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<tr>
<td>13</td>
<td>470-AL3</td>
<td>304 398 354 252</td>
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<td>304 426</td>
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<td>22</td>
<td>470-AL3</td>
<td>304 202 909 159</td>
</tr>
<tr>
<td>23</td>
<td>470-AL3</td>
<td>304 380 290 362 378 388 349 303 280 341</td>
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<td>24</td>
<td>470-AL3</td>
<td>304 377 182</td>
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<tr>
<td>25</td>
<td>470-AL3</td>
<td>304 270 284</td>
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<td>28</td>
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<tr>
<td>29</td>
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<td>304 468 329 289 580</td>
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<tr>
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<td>305 222 349 337 287</td>
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<td>31</td>
<td>2x774-AL3</td>
<td>305 441 249 288 349</td>
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<td>32</td>
<td>2x774-AL3</td>
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<td>33</td>
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<td>34</td>
<td>2x774-AL3</td>
<td>305 8 470-AL3 304 304 387 389 294 224 241 455 272 398 414 366 398 354 252</td>
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<td>35</td>
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<td>36</td>
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5 Impact of atmospheric variations

To analyse the impact of atmospheric variations on the BR1-OHL capacity, thermal, mechanical and electrical variables were calculated for each ruling span using weather interpolation and OHL geometry. Figure 5 shows the flowchart for computing the values of these variables \(T_S, \ell, S, H, R, L, C\). Afterwards, in order to evaluate PMU performance, these results are compared with the values computed using synchrophasors simulations. These simulations are assumed at the ends of the OHL. Thus, with the phasor simulations of \(v_{ik}, i_k, v_{im}, i_m\) and with \(13\) and \(14\), the average temperature \(T_S\) is computed through the estimation of circuit parameters of fig. 2.


\[
Z = \frac{v_k^2 - v_m^2}{v_m i_k - v_k i_m} \tag{13}
\]

\[
Y = \text{Im} \left( \frac{2}{v_k + v_m} \right) \tag{14}
\]

The current intensity \(i_{km}\) used to compute the OHL parameters is given by

\[
i_{km} = i_k - \frac{v_k Y}{2} \tag{15}
\]

PMU values were simulated with SIMULINK® as follows: a power flow for circuit of fig. 2 is run initially assuming design values of resistance, inductance and capacitance under rate conditions,
$v_k = 220 \text{[kV]}$, $S = 304 \text{[MVA]}$ and $PF = 0.9$. Afterwards, an iterative script was implemented changing the RLC values of $\pi$ model according to (5), (6) and (7), with the aim of updating the electrical parameters considering the changes in conductor temperature. This script runs until the current intensity computed through the load flow is equal to the current $i_{km}$ used for calculating the resistance from (5). As simulations results, fig. 6 shows variations of the $\ell$, $X_L$, $Y_C$, $R_i$, $D$ and $T_S$ parameters for each weather sample. These values are of the entire OHL except $D$ which is the sag of the ruling span number 8. This span was chosen because of it has the highest variation within samples, approx. 1.3 [m]. Thus, weather influence over the sag can be determined.

In fig. 6a are shown the values both of current intensity $i_{km}$ and of voltage $v_m$ obtained for each sample. The maximum variation of the entire phase conductor length is less than 0.02%, which corresponds to 9 [m]. This means that the OHL inductance is not affected as a consequence of typical atmospheric variations. Therefore, the phase conductor length can assume constant, as shown in fig. 6b. In the same way, the variation between the maximum and minimum value of the equivalent capacitance is less than 0.2%, making negligible the influence of the sag ($D$), as shown in fig. 6c. On other hand, the resistance changes up to 3.5%, as shown in fig. 6d. In this fig., the average conductor temperature ($T_{S_{avg}}$) is computed using the resistance, obtaining a maximum and minimum of 6.7 [°C] and 2.6 [°C], respectively. In all samples, the differences between $T_{S_{avg}}$ and $T_{S_{max}}$ exceed the acceptable error margin for critical spans of 4 [K] (10% of 40 [°C]) proposed in [6]. The maximum temperature ($T_{S_{max}}$) and minimum temperature ($T_{S_{min}}$) were obtained by computing the temperature from weather in all ruling spans and taking the highest and lowest of these values.

As a consequence of using different conductors in BR1-OHL, the value of $T_S$ in each ruling span varies, even if the weather does not change along it. In this work, this is considered by using the following procedure: an equivalent temperature ($T_{S_{equiv}}$) is computed with (16) using the resistance ($R_{equiv}$) calculated with (5).

$$T_{S_{avg}} = \frac{R_{equiv} - \sum_{i=1}^{N} R_i (T_{ref}) + \sum_{i=1}^{N} R_i (T_{ref}) \cdot \alpha_i \cdot T_{ref}}{\sum_{i=1}^{N} R_i (T_{ref}) \cdot \alpha_i}$$

(16)

With this equivalent temperature and supposing initial values of average ambient temperature ($T_{avg}$) and solar radiation, an equivalent cooling heat is computed. With this parameter, an equivalent wind speed ($\bar{v}_{equiv}$) is calculated [25] along entire OHL. With these new atmospheric conditions, the temperature in each ruling span ($T_S$) is calculated, thus the resistivity of each conductor is considered. However, as $T_a$ is originally guessed, it is necessary to adjust this value via iterations until the difference between the

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Fig. 6: Variation of the parameters of the BR1-OHL for each weather sample

a) Current intensity ($i_{km}$) flowing through the OHL and voltage at end $m$ ($v_m$).

b) Inductance (reactance) and phase conductor length.

c) Capacitance (admittance) and sag of ruling span number 8.

d) Resistance, average temperature and, maximum and minimum temperature along the OHL.
shows both the temperature and the error calculated with a typical accuracy of 0.3% was assumed for measurement simulations. Random errors were simulated with Matlab assuming as three times the standard deviation (σ) of the conductor temperature. Moreover, the critical ruling span changes for each weather sample, and the acceptable error margin of (Δ[K]) is exceeded between the different critical spans, as shown in Fig. 8b. The critical span was assumed as the span with the highest temperature.

### 6 PMU Measurement Error Impact

#### 6.1 Impact on the accuracy

In this section, conductor’s temperature is estimated considering errors in PMU measurements. Measurement errors were simulated assuming a random normal distribution of error with mean zero and standard deviation approximated to 1/3 of meter accuracy. A typical accuracy of 0.3% was assumed for measurement simulations for both current and voltage [26]. The angle between phasors was taken without error; this is analysed in [27]. Additionally, the estimation algorithm proposed in [10] was implemented in order to reduce the error in the computing of OHL resistance and average conductor temperature.

For each weather sample, 1, 000 simulations were run by adding normal random errors to PMU measurements of \( v_k, i_k, v_m, i_m \). Random errors were simulated with Matlab. Figure 9a shows the measurement error impact on the resistance estimation, obtaining an uncertainty of approximately 16%. The uncertainty in this work is assumed as three times the standard deviation (σ). This uncertainty is equivalent to an error within ±0.6 [Ω], considering a normal distribution with a mean between 3.6 [Ω] and 3.7 [Ω]. Thus, the error in the estimation of the equivalent resistance per unit length (\( R_{equiv} \)) is within ±10 × 10^{-3} [Ω/km]. This error propagates to the computing of temperature, reaching errors within ±38 [K], as shown in Fig. 8b.

In the case studies, the 470-AL3, 6469-AL3 /134ST4A and 774-AL3 conductors, which are used in BR1-OHL, the errors calculated by (10) are within ±37 [K], ±34 [K] and ±36 [K], respectively. These values are close to the values shown in Fig. 9b. The differences are due to the use of \( R'_{equiv} \) for computing the standard deviation (σ).

#### 6.2 Impact of load on the estimation of conductor temperature

As voltage and current magnitudes depend on load and OHL impedance, the latter influence the resistance estimation, and therefore, the computing of conductor temperature. A simulation like the one of the previous section is carried out for the weather sample 2016-04-18 21:00, changing the load between 0.1 and 1 [pu] and the power factor (PF) between 0.1 and 0.95. The simulation results are shown in Fig. 10. The standard deviation (σ) was calculated with the 500 runs for each set of loads and PFs. In the estimation of the equivalent resistance (\( R_{equiv} \)) and the computing of conductor temperature (\( T_S \)), the minimum standard deviation was 0.027 [Ω] and 1.0 [K], respectively, for a power factor of 0.1 and a load of 1 [pu]. The maximum standard deviation was 2.41 [Ω] and 172 [K] for a power factor of 0.95 and a load of 0.1 [pu].

Given that σR ≈ 1/1km in (10), the uncertainty in the computing of temperature is increased at low power flows. Additionally, if the power factor (PF) is approximated to \( \cos \angle \theta_{km} \) (using \( \angle \theta_k = 0 \) as reference, \( \angle \theta_m \) close to \( \angle \theta_k \) and \( \angle \theta_{km} \) measured with respect to \( \angle \theta_k \)) the uncertainty increases as PF is close to 1. On the other hand, typical ratio between magnitudes of voltage (kV) and current (A) in power transmission systems impacts the measurement error in resistance computing.

The simulation results of this paper were not contrasted with real PMU’s measurements at the same time. However, reference [2] reports results about the use of PMU measurements in the studied DLR method was introduced. Its main advantage is to use simulations and expressions to evaluate the performance of PMU for DLR during the planning stage. For instance, as a result of using this methodology in the case study in this paper, the BR1-OHL temperature obtained was outside the acceptable error margins. Additionally, reference [28] reports high variation including negative values in the computation of the resistance in a real OHL when PMU measurements are used. Both results are consistent to those obtained in this paper. Therefore, using the proposed methodology, the PMU performance could be predicted.

### 7 Discussion

Based on both the weather variations along OHLs and error in PMU measurements, a methodology to assess the use of synchrophasors as DLR method was introduced. Its main advantage is to use simulations and expressions to evaluate the performance of PMU for DLR during the planning stage. For instance, as a result of using this methodology in the case study in this paper, the BR1-OHL capacity cannot be estimated using PMU. Thus, applying this methodology would reduce costs by avoiding future fail implementations. However, provided that a successful result of applying the proposed methodology is achieved, further analysis and validation must be carried out before implementing PMU as DLR method. This analysis should include the presence of uncorrelated data as well as bad data and a more accurate model to describe stringing sections given the limitation of ruling span approximation, mainly at high operating temperatures.

### 8 Conclusions

The changes in the load and the atmospheric conditions along an OHL result in alteration of thermal and mechanical variables, which affect the electrical RLC parameters. This influence is negligible for inductance and capacitance under typical atmospheric and load conditions, as a consequence of the small variation of the line length and...
Fig. 8: Comparison between temperatures computed using weather interpolation and using PMU estimation in each ruling span for different times

(a) Temperature of the conductor - $T_S$

(b) Error between $T_S$ computed using weather interpolation and PMU estimation
Fig. 9: Box plots with the value of both OHL resistance and $T_{S_{avg}}$ estimated using PMU for each sample, assuming an accuracy of 0.3% in simulations of voltage and current measurements

a OHL resistance

b Average temperature of the conductor $T_{S_{avg}}$

Fig. 10: Influence of load on the estimation of both conductor’s resistance and temperature using PMU measurements

a OHL’s resistance

b Average conductor temperature $T_{S_{avg}}$

low impact of the sag on the capacitance. On the contrary, the value of the resistance changes in a non-neglected way.

The use of PMU’s measurements for DLR faces challenges when atmospheric conditions and conductor properties change along OHLs, together with inaccuracy, due to the error propagation in the computation of resistance. Thus, the average value of temperature computed from PMU measurements could not depict the real conductor capacity and jeopardizes OHL, as shown in this paper. This as a consequence of exceeding accepted security margins in critical spans if the temperature computed with synchrophasors are used. Additionally, the estimated conductor’s temperature error can be outside acceptable margins, as a result of the sensibility of temperature with resistance, even if state estimation algorithms are used. For these reasons, a methodology to asset the use of PMU for DLR is proposed. As future research, error minimization techniques that account weather models, PMU and the monitoring of critical spans could potentially improve the estimation of conductor rating.

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9 References


