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RESEARCH ARTICLE

A Novel Thermo-Mechanical Model to Assess the Dynamic Thermal Rating of Multi-Span Overhead Transmission Lines

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Abstract
The power flow limits of transmission lines are set in order to ensure a given level of security to the electric system; their improper definition can reduce system reliability, increase the curtailment of renewable energy sources or create barriers to the free trading of energy.

Unlike the previous literature, the Dynamic Thermal Rating procedure here proposed takes into account not only that the temperature of conductors can vary span by span for different weather conditions, but also the mechanical interaction between spans, due to their different elongation and to the consequent rotation of insulator strings.

The developed tool is able to forecast the time trend of conductor temperatures, tensions, sags and clearances at each span, or to indicate which current can be carried for a given time before a clearance or temperature constraint is violated.

Several case studies compares the results of this novel method with the outcomes of the traditional "ruling span" technique, especially when using High-Temperature Low-Sag (HTLS) conductors, having non-linear behaviour with respect to temperature.

Keywords
Ampacity, Dynamic Thermal Rating, Overhead lines

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1 Introduction

All over the world, increasing the thermal rating of existing overhead transmission lines is considered a valid alternative to the construction of new lines [1, 2].

The thermal rating of a transmission line is the highest current that the line can carry under assigned meteorological conditions, respecting all clearances. The ampacity is limited in practice by the maximum allowed operating temperature: if the temperature limit is exceeded, the distances between conductors and ground decrease to unacceptable values. Assessing the dynamic ampacity of a conductor is then strictly related to the precise calculation of its sag [3, 4].

In this context, Dynamic Thermal Rating (DTR) of transmission lines represents a significant improvement with respect to the traditional steady-state rating criteria, which usually result in standard seasonal ampacities. In fact the thermal time constant of conductors is relatively high (more than 10 minutes) [3]; this fact allows exploiting the dynamic performances of conductors, i.e. currents significantly higher than the steady-state thermal limits, during transient overloads, thus avoiding re-dispatching or the curtailment of Renewable Energy Sources [5].

The margin of dynamic overloading of a power line can be evaluated focusing on the temperature of the conductor; such a temperature can be either evaluated using a thermal model, having as an input weather conditions and power flows [6, 7], or operating a direct measure on the conductor [8].

The analysis of the literature clearly shows that, no matter which method is used to assess the conductor temperature, the dynamic mechanical behaviour of multi-span power lines has been so far investigated under the hypothesis that the horizontal mechanical tension along the line is uniform; this means neglecting the contribution given to the tensions, span by span, by the insulators' strings rotation. This conventional technique is referred to as method of the "equivalent span", or "ruling span technique" [9-11]. Furthermore, this traditional method strictly assumes one uniform conductor temperature over the entire power line, thus neglecting the fact that different spans basically share the same current, but not always the same weather conditions (solar radiation, wind speed). Finally, this method does not consider the vertical components of mechanical tension of conductors, nor the mechanical interactions between adjacent spans due to different conductor stress in each span.

At the same time, a second issue worth investigating is related to the fact that in the last years novel materials have been introduced in order to overcome the maximum operating temperatures of conventional aluminium conductors with steel core (ACSR), generally limited to 90°C [12]. These High-Temperature Low-Sag (HTLS) conductors are generally capable to be operated continuously at temperatures of at least 150 ºC; some of them can be operated up to 250ºC without significant changes in their mechanical and electrical properties. Furthermore, they exhibit low elongation rate with respect to temperature, hence much lower sags with respect to ACSR [12].

The calculation of power lines equipped with HTLS conductors is complicated by the fact that their mechanical characteristics change beyond the so called "knee-point temperature"; at higher temperatures, the tension of the external strand goes to zero and all the strength is carried by the internal one. Above the knee-point temperature, the conductor elongates with temperature at the low sag/temperature rate corresponding to the internal strands material, thus showing a "knee" on a plot of sag versus temperature [13].

As already mentioned, in a multi-span line the mechanical stress is generally different span by span; as a consequence, the knee-point temperature changes span by span, thus introducing a new complexity for the calculation of the sag. Furthermore, the "ruling span" principle considers a single knee-point temperature for all the spans located between two dead-end towers; in lines where HTLS conductors are installed, entails an error that has not been investigated, especially at high temperatures . It's worth mentioning that in conventional bimetallic ACSR conductors this non-linearity can be usually neglected, since knee-point occurs well above the operational temperature of the power line.

A new dynamic thermo-mechanical model for multi-span overhead lines is proposed in this paper to face the two issues mentioned above: a non-linear model for HTLS bimetallic conductors is discussed and the longitudinal mechanical interaction among the spans placed between two dead-end towers was investigated.

2 Thermo-mechanical behaviour of HTLS conductors

In a real power line, thermal and mechanical phenomena interact, but their time constants are very different (about two orders of magnitude). For these reasons, the two phenomena can be decoupled and the solution of the model is subdivided into two steps:

1) the dynamic evaluation of the temperature of conductors over time, based on power flow and weather conditions (span by span);
2) the algebraic evaluation of the mechanical equilibrium of the multi-span line at each time step, the temperature of conductors being known.

The dynamic behaviour of conductor temperature was evaluated using the CIGRE model [6]; the calculations were carried out as a function of line current, conductor thermal properties and meteorological conditions (ambient temperature, solar radiation, wind speed, etc.). All of these parameters, different span by span, were considered variable over time. Conversely to the method proposed in [14], a first-order response model was adopted to connect two consecutive steady-state ratings.

The solution of the thermal problem was found by applying a sample-and-hold procedure to the time trend of inputs (current, solar radiation, intensity and direction of wind, ambient temperature, all sampled for instance every 5 minutes) and consequently studying the time trend of conductor temperature, separately span by span, as sequence of first-order step responses. More details about the thermal model are available in [15] and [16].

The temperatures obtained at each span of the power line were then used, separately at each time step (e.g. every minute), to solve the algebraic mechanical problem.

2.1 Mechanical model of HTLS conductors

HTLS conductors consist of two strands: the internal one is in steel or other high strength materials, like Fe-Ni alloys (e.g. INVAR) or composite materials based on alumina fibre, ceramics and carbon fibre [13]; the external one is typically a thermal-resistant aluminium alloy. Due to the different thermal elongation coefficients of the two materials (the aluminium coefficient is much higher), the allocation of the mechanical stress between the two strands depends on temperature: the mechanical stress of the external section decreases when temperature increases. At the so called "knee-point temperature", the external section stress reaches zero. For higher temperatures, the external conductor would be compressed, if it were not stranded; hence it swells up and its stress remains nil. In these conditions, the conductor's behaviour depends only on the internal section, which has very low temperature-sag rate. Since the conductor behaves differently under and above the knee-point, its performance is not linear with respect to temperature.

The present paper proposes two novel models:

1) the first is oriented to overcome the singularity of the function "stress-deformation" of HTLS conductors and the non-linearity of its derivatives;
2) the second elaborates the traditional "equation of change of state" of the power line, in order to take into account the non-linear HTLS model above mentioned.

2.2 Stress-deformation function

If the internal and the external conductor's strands can slide over each other without significant friction, three main hypotheses can be assumed:

a) in order to sustain the conductor weight, the internal strand (steel alloy) is subjected to traction stress in any operating condition; the stress-deformation behaviour is linear;

b) conversely, the external strand (aluminium alloy) cannot react to compression stress: if compressed, it swells up since stranded, so its tension remains nil;
c) the axial elongation of both strands is always equal, since at each insulator string the clamp constrains the two strands not to slip with each other.

The three assumptions above reported correspond to the following formulation (please refer to the nomenclature placed at the end of the paper):

$$\sigma_i = \frac{T_i}{A_i} = E_i \cdot \left[\varepsilon_{el-i} + \alpha_i \cdot (\vartheta - \vartheta_0) \right] \tag{1}$$

$$\sigma_e = \frac{T_e}{A_e} = \frac{E_e}{2} \cdot \left[(\varepsilon_{el-e} + \alpha_e \cdot (\vartheta - \vartheta_0) + \sqrt{(\varepsilon_{el-e} + \alpha_e \cdot (\vartheta - \vartheta_0))^2 + \xi} \,) \right] \tag{2}$$

$$\varepsilon_i = \varepsilon_e \tag{3}$$

In Eq. (2), ξ represents an arbitrary positive constant, whose value is very small compared with the other terms inside the square root; in practice its value may be 10^{-12} or lower. The presence of ξ guarantees the continuity of the function and of its derivatives, introducing an error that in all operational conditions is largely negligible.

2.3 The change-of-state equation of HTLS conductors

The HTLS conductor's stress-deformation model previously described has been combined with the traditional equation of change-of-state [15, 16]. In such equation the contribution of external loads on the conductors, i.e. ice and wind, have been neglected since we are analyzing the behaviour of the conductor at high temperature (from ~100°C to ~250°C). Two more usual hypotheses are adopted in the model:

d) the length of the conductor along a generic span is the sum of the four following quantities: the length over a span of a perfectly rigid conductor under its weight, the elastic elongation, the thermal elongation and the distance variation between the clamps of the span; considering Eq. (3), the second and third quantities may be associated only to the internal strands, whose behaviour is linear;
e) the strength operated by the conductor corresponds to the sum of internal and external actions.

Such assumptions correspond respectively to the following equations:

$$\frac{(p \cdot d)^2}{24} \cdot \left(\frac{1}{T^2} - \frac{1}{T_0^2} \right) - \frac{(T_i - T_{i,0})}{E_i \cdot A_i} - \alpha_i \cdot (\vartheta - \vartheta_0) + \varepsilon_{\Delta l} = 0 \tag{4}$$

$$T = T_i + T_e \tag{5}$$

The model described by Equations (1)-(5) can be applied to each span of a line with suspended insulators.

3 The model of a multi-span line

3.1 Ruling span method and HTLS conductors

A multi-span line is defined as the part of the power line existing between two dead-end towers. Its mechanical behaviour has been traditionally investigated under the hypothesis that the horizontal mechanical tension along the line is uniform; this means that the contribution given to the tensions, span by span, by the rotation of insulator strings is neglected. This technique is referred to as method of the "equivalent span", or "ruling span technique" [9-11].

Starting from a given Every Day Stress (EDS) condition, taking into account equations from (1) to (5) and considering that σ_e, by definition, equals zero at knee point temperature, for a HTLS conductor we obtain:

$$(\vartheta_{kpt} - \vartheta_0) = \frac{T_{kpt}}{E_i \cdot A_i \cdot (\alpha_e - \alpha_i)} \tag{6}$$

By substituting Eq. (6) in Eq. (4) and neglecting $\varepsilon_{\Delta l}$, we finally obtain the equation of change-of-state (7):

$$\frac{(p \cdot d)^2}{24} \cdot \left(\frac{1}{T_{kpt}^2} - \frac{1}{T_0^2} \right) - \frac{(T_{kpt} - T_{i,0})}{E_i \cdot A_i} - \alpha_i \cdot \frac{T_{kpt}}{E_i \cdot A_i \cdot (\alpha_e - \alpha_i)} = 0 \tag{7}$$

Eq. (7) allows evaluating the strength T_{kpt} at knee-point that in turn, once substituted in Eq. (6), identifies the knee-point temperature ϑ_{kpt} of the equivalent span.

In a real line the knee-point temperature is different span by span, since span lengths are different and horizontal stress in not uniform along the line; as a consequence, with the ruling-span method it is not possible to correctly evaluate ϑ_{kpt} span by span. This fact implies that with the ruling-span method the sag calculation is affected by unknown errors.

Furthermore, the ruling span technique strictly assumes a uniform conductor temperature along the entire power line, neglecting the mechanical interactions between adjacent spans. Conversely, in a real multi-span line with different span lengths, longitudinal displacements of strings of insulator arise due to different conductor stress at each span [15].

3.2 The novel mechanical model for multi-span power lines

For each span a set of equations like (1)-(5) can be written; terms $\varepsilon_{\Delta l}$ are not null and can be expressed as a function of the angles formed by insulator strings in the derived condition, with respect to the EDS configuration (where strings are vertical). Such angles constitute, together with terms σ_i, σ_e, ε_{el-i} and ε_{el-e} of each span, the unknown quantities of the mechanical problem.

Further equations are relevant to the axial and rotational equilibrium of the strings of insulators:

$$\begin{aligned} &F_{x,i} + (n_{i-1} \cdot T_{i-1} + n_i \cdot T_i) \cdot sen\frac{\gamma_i}{2} = 0 \\ &F_{y,i} + (-n_{i-1} \cdot T_{i-1} + n_i \cdot T_i) \cdot cos\frac{\gamma_i}{2} = 0 \\ &F_{z,i} + (n_{i-1} \cdot T_{i-1} \cdot tan\,\beta_{i-1} + n_i \cdot T_i \cdot tan\,\beta_i) = 0 \end{aligned} \tag{8}$$

$$\begin{aligned} &[(F_{x,i} \cdot sen\phi_i + F_{z,i} \cdot cos\,\phi_i) \cdot sen\delta_i - F_{y,i} \cdot cos\,\delta_i] \cdot L_i = 0 \\ &[(F_{y,i} \cdot sen\delta_i + F_{z,i} \cdot cos\,\delta_i) \cdot sen\phi_i - F_{x,i} \cdot cos\,\phi_i] \cdot L_i = 0 \end{aligned} \tag{9}$$

The meaning of angles reported in Eq. (8) and (9) is explained in the three following figures.

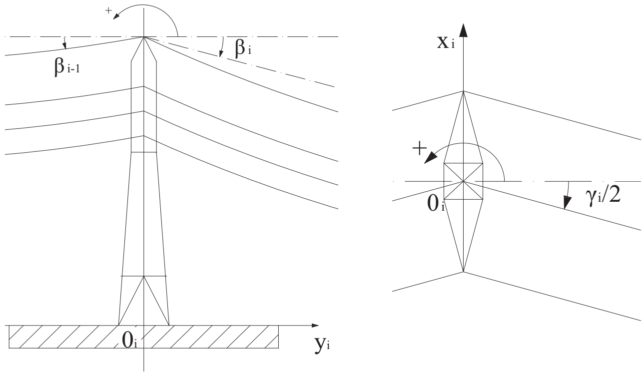

Fig. 1 Lateral and top view of the tower

In case of V-strings, angles ϕ_i are null. Concentrated forces F_i are known. Their components along x and y axes are usually null; $F_{z,i}$ is due to half the weight of the string, half the weight of the conductors at the two sides of the string, plus an external weight if present.

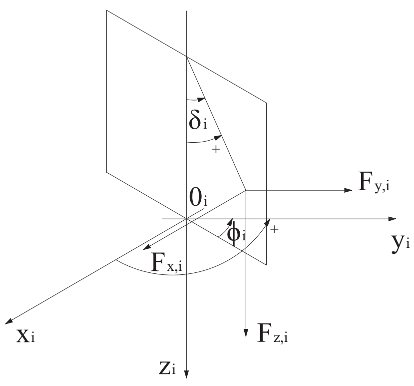

Fig. 2 The string of insulators in a Cartesian coordinate system

4 Case studies

It is worth remarking that in a real line armed with HTLS conductors the knee-point temperature varies span by span because of the rotation of the insulator strings produced by the high temperature of the conductor. From the mathematical point of view, the only simplified method that can be used is based on the ruling span technique; nevertheless such a method assumes that the knee-point temperature is the same for every span.

The aim of the proposed case studies is then to compare the sags obtained through the application of the new model herein proposed, with the traditional ruling span method. To this purpose, different line typologies were investigated: as shown in Figure 3, all the lines share the same total length of 3150m between the two dead end towers, but their 7 spans are different. For the sake of simplicity, all the insulator strings are at the same elevation above the sea level and there are no angle towers. The mechanical data of the conductor are reported in Table 1, together with the EDS conditions assumed for the calculations.

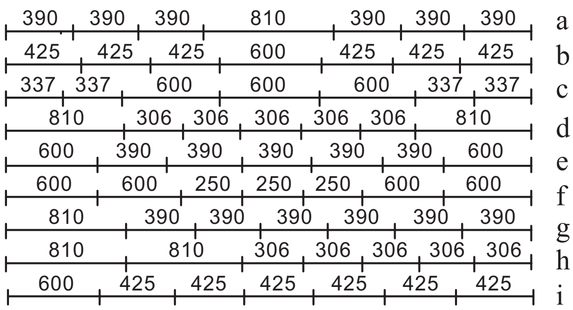

Fig. 3 Graphical visualization of spans

Table 1 Conductor features

Internal layer section	mm²	23.33
Internal layer elasticity	daN/mm²	13620
Internal layer thermal coeff.	°C⁻¹	6.1E-6
External layer section	mm²	137.41
External layer elasticity	daN/mm²	5501
External layer thermal coeff.	°C⁻¹	2.3E-5
Unitary mass	kg/m	0.521
Total conductor's EDS	daN	866
Internal layer conductor's EDS	daN	256
External layer EDS	daN	610
EDS temperature	°C	15
Insulators strings' length	m	1.5

As already said, these case studies are aimed at evaluating the differences between the sags calculated with the ruling span method and with our novel model. The comparison has been carried out at two different thermal conditions: the knee-point temperature evaluated by the ruling span technique, and 180°C. In the first case, in the real line as well as in our complete model, some spans actually operate over their knee-point temperature (typically the shortest ones) and the others under such a temperature; this situation implies that in the spans that operate over their knee-point temperature only the internal conductor's layer reacts to mechanical stress, while in the other spans also the external layer is loaded.

Conversely, at 180°C all spans certainly operate over their knee-point temperature, so the strength of external strand is null (T=T_i). In Table 2 and 3 the results obtained by using the ruling span techniques are reported.

It's worth remarking that errors are almost always negative in long spans (i.e. the ruling span overestimates the sags) and positive in short ones; furthermore, percentage errors are larger in short spans: the ruling span method gives conservative results in long spans, but may give potentially risky situations for the shortest ones.

Table 2 Ruling span results at knee point

Case	Ruling span [m]	ϑ_{kpt} [°C]	T_{kpt} [daN]	Sag [m] at shortest span	Sag [m] at longest span
a,g	530.75	145	699	14.17	61.13
b,i	463.45	140	671	17.53	34.94
c	504.5	143	689	10.77	34.03
d,h	618.8	150.5	728	8.38	58.69
e	481	141.5	679	14.59	34.53
f	537.7	145.5	702	5.80	33.40

Table 3 Ruling span results at 180°C

Case	T=T_i [daN]	Sag [m] at shortest span	Sag [m] at longest span
a,g	689	14.38	62.02
b,i	659	17.85	35.58
c	678	10.94	34.58
D,h	721	8.46	59.26
e	667	14.85	35.15
f	692	5.88	33.88

It is clear that the ruling span technique takes into account the different span lengths but not their disposition; consequently, cases a and g, b and i, and d and h correspond. The novel complete method is instead able to capture the different order of spans.

In Figure 4 the percentage errors made by the ruling span technique in terms of sags are reported, both at the knee-point temperature of the ruling span and at 180°C.

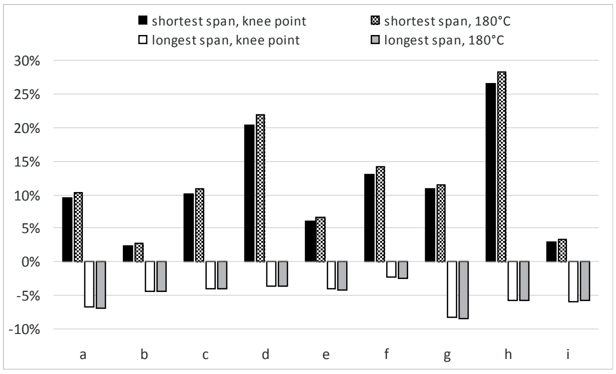

Fig. 4 Sag errors between ruling span and complete method (positive error means that the ruling span technique underestimates sags)

The complete model confirms that, at the knee-point temperature suggested by the ruling span technique, some spans of the line are actually over their real knee-point, others below it. For example, in case h ϑ_{kpt} equals 150.5°C with the ruling span, while ranging from 123.5°C to 158°C in the 7 spans of the complete method.

5 Conclusions

This paper proposes a new thermo-mechanical model able to simulate multi-span transmission lines equipped with high-temperature low-sag conductors.

The calculations performed in the paper demonstrate that, in the presence of HTLS conductors, the use of the traditional ruling span technique result in significant errors when the line is operated around its knee-point temperature. In fact, the ruling span method provides a single, approximated knee-point temperature for all the spans placed between two dead-end towers, while at such temperature some spans are actually under their knee-point (i.e. both strands of the conductor react), other beyond (the external strand is mechanically unloaded). The consequent errors made by the traditional technique in terms of sag are often too large to be acceptable (over 25% for particular geometric configurations).

Moreover, the use of the traditional ruling span technique results in even higher errors when HTLS conductors are operated close to their upper thermal limit, i.e. around 170-180°C. In this case, calculation errors are due to the fact that the ruling span technique always assumes the uniformity of the horizontal strength of conductors along the line: at so extreme temperatures, conversely, the sags and elongations of the spans are so intense that such assumption is no more valid.

The errors made when applying the traditional ruling span technique to lines with HTLS conductors are negligible only if all spans have similar length, since insulator strings remain practically vertical.

Nomenclature

α_i, α_e	thermal expansion, internal/external strand [°C^{-1}]
A_i, A_e	section of internal and external strand [mm^2]
d	horizontal span length [m]
ε_{Dl}	conductor elongation for clamps movement [p.u.]
ε_i, ε_e	total elongation, internal and external strand [p.u.]
ε_{el-i}, ε_{el-e}	elastic elongation of internal/external strand [p.u.]
E_i, E_e	Young's elasticity, int/ext strand [N/mm^2]
$F_{x-y-z,i}$	concentrated forces, i-th string [N]
L_i	length of the i-th string [m]
n_i	number of conductors per phase of the i-th span
p	conductor weight [N/m]
σ_i, σ_e	stress of internal and external strand [N/mm^2]
J_0, J	conductor temperature (initial/derived) [°C]
J_{kpt}	conductor knee-point temperature [°C]
T	total conductor strength [N]
T_i, T_e	strength of internal and external strand [N]
T_{kpt}	conductor strength at knee-point temperature [N]
ξ	arbitrary positive constant [p.u.]

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References

[1] Popović, D. P. "An efficient unified methodology for steady-state security assessment of electric power interconnection." *International Review of Electrical Engineering.* 5 (1). p. 241. 2010.

[2] Santos, J. R., Exposito, A. G., Sanchez, F. P. "Assessment of conductor thermal models for grid studies." In: *Generation, Transmission & Distribution, IET*. 1 (1). pp. 155-161. January 2007. DOI: 10.1049/iet-gtd:20050472

[3] Adapa, R., Douglass, D. A. "Dynamic Thermal Ratings: Monitors and calculation methods." In: *Power Engineering Society Inaugural Conference and Exposition in Africa, 2005 IEEE.* pp. 163-167, 11-15 July 2005 DOI: 10.1109/PESAFR.2005.1611807

[4] Heckenbergerová, J., Hošek, J. "Dynamic thermal rating of power transmission lines related to wind energy integration." In: *Environment and Electrical Engineering (EEEIC), 2012 11th International Conference on.* pp. 798-801. 18-25 May 2012. DOI: 10.1109/EEEIC.2012.6221484

[5] Giuntoli, M., Poli, D. "Optimized thermal and electrical scheduling of a Large Scale Virtual Power Plant in the presence of energy storages". In *Smart Grid, IEEE Transactions on.* 4 (2). pp. 942-955. June 2013. DOI: 10.1109/TSG.2012.2227513

[6] CIGRE TF B2.12.3, TB 324, "Sag-tension calculation methods for overhead lines." 2007.

[7] "IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors." In: IEEE Std 738-2006 (Revision of IEEE Std 738-1993). pp.c1-59, Jan. 30 2007. DOI: 10.1109/IEEESTD.2007.301349

[8] Musavi, M., Chamberlain, D., Li, Q. "Overhead conductor dynamic thermal rating measurement and prediction." In: *Smart Measurements for Future Grids (SMFG), 2011 IEEE International Conference on.* pp.135-138, 14-16 Nov. 2011. DOI: 10.1109/SMFG.2011.6125755

[9] Keselman, L. M., Motlis, Y. "Application of the ruling span concept for overhead lines in mountainous terrain." In: *Power Delivery, IEEE Transactions on.* 13 (4). pp. 1385-1390. Oct 1998. DOI: 10.1109/61.714512

[10] IEEE WG on Thermal Aspects of Overhead Conductors, "Limitations of the Ruling Span Method for Overhead Line Conductors at High Operating Temperatures." IEEE PWRD 0-12-1997.

[11] Keshavarzian, M., Priebe, C. H. "Sag and tension calculations for overhead transmission lines at high temperatures-modified ruling span method." In: *Power Delivery, IEEE Transactions on.* 15 (2). pp. 777-783. Apr 2000. DOI: 10.1109/61.853019

[12] Zamora, I., Mazon, A. J., Eguia, P., Criado, R., Alonso, C., Iglesias, J., Saenz, J. R. "High-temperature conductors: a solution in the uprating of overhead transmission lines." In: *Power Tech Proceedings, 2001 IEEE Porto.* Vol. 4. pp. 6. 2001. DOI: 10.1109/PTC.2001.964808

[13] CIGRE B2-AG-06, "Types and Uses of High Temperature Conductors."

[14] CIGRE TF B2.43, TB 601, "Guide for thermal rating calculations of overhead lines." 2014.

[15] Bassi, F., Giannuzzi, G., Giuntoli, M., Pelacchi, P., Poli, D. "Mechanical behaviour of multi-span overhead transmission lines under dynamic thermal stress of conductors due to power flow and weather conditions." In: *International Review on Modelling and Simulations, IREMOS*. 6 (4). August 2013.

[16] Bassi, F., Giannuzzi, G., Giuntoli, M., Pelacchi, P., Poli, D. "Thermo-mechanical dynamic rating of OHTL: applications to Italian lines." In: *CIGRE Session 2014*. Paris, 24-29 August 2014.