

Aspects to take into account in the application of mechanical calculation to high temperature low sag conductors

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Abstract—Reconductoring with high temperature low sag (HTLS) conductors is an alternative to the traditional uprating methods. The obtained rating increase depends on the mechanical and thermal behaviour of the conductor. In this paper, the HTLS conductors are presented and mechanical calculation methods are analyzed taking into account the special characteristics of these conductors. The widely used graphical method and the recently developed STOC method have been analyzed.

Index Terms— high temperature low sag conductor, overhead conductor, sag-tension, ampacity, uprating

1. NOMENCLATURE

α	coefficient of thermal expansion
θ	temperature
σ	stress
ε	total strain
$\varepsilon^{\text{creep}}$	strain related to creep
ε^{mc}	strain related to metallurgical creep
ε^{gs}	strain related to geometrical settlement
t	time

2. INTRODUCTION

High temperature low sag conductors have been widely used in Japan and North America during the last forty years. Reconductoring with HTLS conductors is an alternative to the traditional uprating methods. The main advantage of HTLS conductors is related to the fact that the uprating is obtained without need to strengthen the towers.

One of the main factors to take into account when choosing between the available uprating methods is the obtained rating increase. The obtained rating increase is related to the maximum allowable temperature of the line, which is usually limited by the sag limit of the line span and depends on the conductor tension limit. The tension is limited by the conductor strength and the maximum tension conditions established by local regulations. The ampacity value depends on the conductor maximum allowable temperature and the assumed weather conditions. The relation between the sag and the conductor temperature is obtained by conductor mechanical calculation and the relation between the maximum allowable temperature and the ampacity by thermal calculation (Fig. 1).

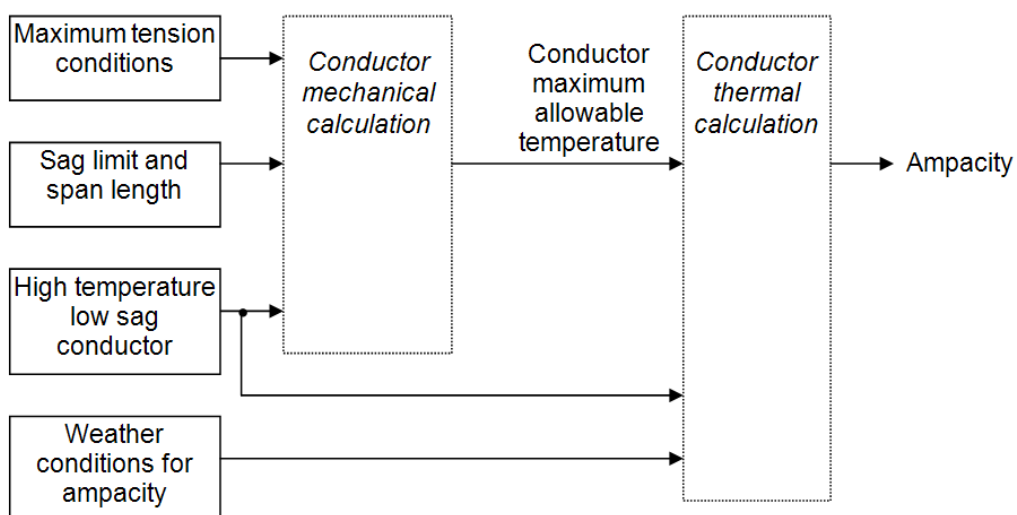


Fig. 1. Ampacity calculation

Conductor mechanical calculation methods, known as sag-tension calculation methods, allow the calculation of conductor sag and tension for different conductor temperature, wind and ice load conditions and take into account the evolution of conductor creep during the line lifetime. The final practical objective of the sag-tension calculation is the calculation of the installation tension taking into account the limits related to sag and tension.

The creep is the permanent deformation of the conductor and it is the result of the addition of the metallurgical creep (ϵ^{mc}) and the geometrical settlement (ϵ^{gs}). The metallurgical creep is related to the microscopic structure of the material and it depends on stress σ , temperature θ and time t . The higher these values are, the higher the metallurgical creep is. In contrast, the strain due to geometrical settlement is supposed to be independent of time. It is dependent on the conductor construction and the maximum tension experienced by the conductor during its lifetime. In [1] the mechanical methods are classified as a function of the way they include the creep in the calculation:

- Methods that do not include the creep
- Methods that include the creep and obtain its value from the experience [2]
- Methods that include the creep and obtain its value from experimental tests [3-4]

The most complete methods are those that consider an independent core and aluminium behaviour and obtain the creep value from experimental tests. These methods allow the calculation of aluminium tension and for this reason they can calculate the knee-point temperature where the aluminium gets slack. Among these methods the most widely used is the graphical method [3] that is implemented in commercial software programs such as SAG10 or PLS-CADD. The graphical method was developed in 1926. It is based on stress-

strain and creep experimental curves. In the case of composite conductors, core and aluminium curves are obtained separately.

In order to represent the experimental curves with the computer, they are given by 4th order equations that relate the stress σ and the strain ϵ . Initial curves correspond to stress-strain tests and they represent the conductor after one hour creep. Creep curves represent the conductor after ten years creep. These curves are associated to the temperature θ_0 , at which the tests have been carried out. Thermal expansion is considered by a displacement of the curves in the strain axis ϵ .

The reference condition is calculated taking into account the creep experienced by the conductor. Three options are possible. The first option is to consider a continuous metallurgical creep at a certain temperature, usually around 15 °C, during a certain period of time, usually 10 years. The second option is to consider an initial one hour creep associated to a maximum tension condition due to ice or wind loads. The third option considers a continuous metallurgical creep at a certain high temperature, during a certain period of time, usually a few hours. In this case, the creep is evaluated following a study presented in [5-8]. Among the three options, that one that gives the higher creep value is chosen.

Recently, some of the authors have developed the STOC method, a method that suits the special requirements of the HTLS conductors [9]. The method is based on strain summation and separate consideration of core and aluminium creep. One of the main advantages of the method is the flexibility for the consideration of several creep stages and the ability to take into account the influence of previous creep stages. Another advantage is the versatility, as it can be adapted to any type of conductor.

Fig. 2 shows a schematic diagram of the STOC method. All the conditions are calculated

from the reference condition. The first stage corresponds to the installation process where all the installation steps are considered. Then, several creep stages can be considered. Creep is calculated sequentially and temperature and load values are considered. The strain due to creep is cumulative and depends on the previous creep stages.

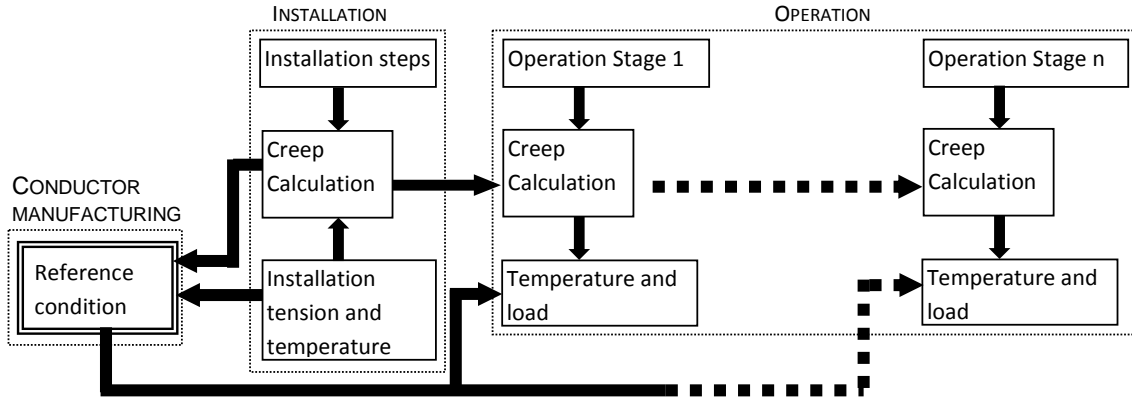


Fig. 2. Schematic diagram of the STOC method

The aluminium and the core creep values are calculated independently. In both cases, the total creep ε^{creep} is calculated as the addition of the metallurgical creep ε^{mc} and the strain due to geometrical settlement ε^{gs} (1).

$$\varepsilon^{creep} = \varepsilon^{mc} + \varepsilon^{gs} \quad (1)$$

It is important to take into account the limitation of the sag-tension calculation methods due to several uncertainties that affect the result [1]. Uncertainties related to conductor weight, end of span effects and flexibility of structures yield a sag calculation error of 1 % to 2 %.

When the conductor is at high temperature, other error sources are the radial thermal gradient of the conductor, the multiple span effects or the effect of the manufacturing temperature [10].

The cooling of the conductor surface gives as a result a radial thermal gradient and a

temperature difference between the conductor core and the aluminium surface. This temperature difference reduces the relative thermal expansion between the aluminium and the core and increases the knee-point temperature. Although this temperature difference is always present, for practical purposes its value is considered negligible [10]. However, for large size conductors and high current values this difference can be important [11]. The temperature difference can oscillate between 10-15 °C.

This paper presents the HTLS conductors and analyzes the mechanical calculation methods taking into account the special characteristics of these conductors.

3. HIGH TEMPERATURE LOW SAG CONDUCTORS

High temperature low sag conductors can work at higher temperatures than conventional conductors. Conventional conductors, such as the ACSR conductor, usually work below 90 °C because the aluminum anneals above this temperature. In order to resist higher temperatures, special aluminium alloys have been developed. These alloys do not lose mechanical strength at higher temperatures and maintain electrical conductivity properties. Among the developed alloys those that are most commonly used are the TAl alloy (Thermal-Resistant Aluminium Alloy), the ZTAl alloy (Super Thermal-Resistant Aluminium Alloy) and the XTAl alloy (Extra Thermal-Resistant Aluminium Alloy or Special Thermal-Resistant Aluminium Alloy). Another option is the annealed aluminium 1350-O, which is annealed above 400 °C in the production process. Hence, its mechanical strength is low but this value will not decrease due to the overhead line operation temperatures. Thermal, electrical and mechanical properties of aluminium are shown in Table I. Besides the aluminium, the core has to be able to work at high temperature.

TABLE I
HIGH TEMPERATURE ALUMINIUM

	Maximum continuous temperature (°C)	Min. electrical conductivity (% IACS)	Min. breaking strength (kg/mm ²)
<i>Al</i>	90	61	16,2
TAI	150	60	16,2
XTAI	230	58	16,2
ZTAI	210	60	16,2
1350-O	400	63	6

The first high temperature low sag conductors were developed in the early seventies in Japan and North America. In Japan, the GTACSR (Gap Type Thermal-Resistant Aluminium Alloy Conductor Steel Reinforced) conductor [12], a gap-type conductor, was developed whereas in North America, the ACSS (Aluminium Conductor Steel Supported) conductor [13], a conductor with annealed aluminium, appeared. In the early eighties, in Japan, the invar was introduced as a new material for the core. As a result, the XTACIR/TW (Extra Thermal-Resistant Aluminium Alloy Conductor Invar Reinforced) conductor was developed and later, with the development of the ZTAI alloy, the ZTACIR (Super Thermal-Resistant Aluminium Alloy Conductor Invar Reinforced) conductor [14]. The GZTACSR (Gap Type Super Thermal-Resistant Aluminium Alloy Conductor Steel Reinforced) conductor, the gap-type conductor with ZTAI alloy, and the ACSS/TW, the ACSS conductor with aluminium trapezoidal wires, also appeared at that time. Recently, in North America conductors with composite core have been developed: the ZTACCR (Super Thermal-Resistant Aluminium Alloy Conductor Composite Reinforced) conductor [15] and the ACCC/TW (Aluminium Conductor Composite Core) conductor [16].

Low sag conductors are based on the conductor behaviour above the knee-point temperature, where the aluminium is slack and only the core is under tension. This occurs due to the higher thermal expansion coefficient of the aluminium. Hence, above the knee-

point temperature the behaviour of the conductor is based on the expansion coefficient of the core, which is lower than the expansion coefficient of the conductor. For this reason, the sag increase with temperature is lower above the knee-point temperature (Fig. 3).

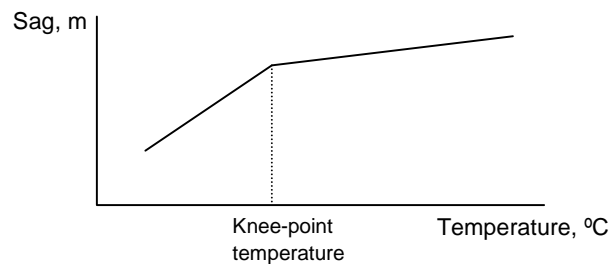


Fig. 3. Knee-point temperature

Therefore, the low sag characteristic is a function of three parameters:

- Conductor expansion coefficient
- Core expansion coefficient
- Knee-point temperature

The lower the values of these parameters are the better the low sag characteristic of the conductor is. Hence, the low sag conductors are designed with low expansion coefficient values and/or low knee-point temperatures. For example, in the case of the gap-type conductors, the aluminium is left slack when the conductor is installed and for this reason, the knee-point temperature is the installation temperature. In the case of the ACSS conductors, the manufacturers recommend a pretensioning during the installation that gives as a result a reduction in the knee-point temperature.

The knee-point temperature is a function of the conductor type, the ratio between the aluminium and the core sections and the span length. The knee-point temperature occurs when the aluminium loses the tension. The lower the ratio between the aluminium and the

core sections is, the lower the tension of the aluminium is. Hence, those conductors with low ratios lose the aluminium tension with lower temperature increases and have lower knee-point temperatures than those with higher ratios. With respect to the span length, the higher the span length is, the lower the decrease in the conductor tension related to the conductor temperature increase is. As a consequence, the decrease in the aluminium tension is lower. Hence, the higher the span length is the higher the knee-point temperature is and vice versa.

4. SAG-TENSION CALCULATION APPLIED TO HIGH TEMPERATURE LOW SAG CONDUCTORS

The aspects to take into account in the sag-tension calculation applied to HTLS conductors are identified and the widely used graphical method and the new STOC method are analyzed.

4.1. Aspects to take into account for the HTLS conductors

The HTLS conductors have special characteristics that complicate the mechanical calculation of the conductor in some cases. For this reason, these characteristics will be identified in order to verify if they are taken into account by the mechanical calculation methods.

4.1.1. Slack aluminium

The HTLS conductors are expected to work above the knee-point temperature. Hence, it is necessary to model the transition in the aluminium tension where the aluminium gets slack. This is achieved only by a method that can calculate independently the core and the aluminium tension.

4.1.2. High temperature metallurgical creep

Although there are some differences among the HTLS conductors they have some common characteristics. One of them is the capability to work at high temperature. The temperature values the conductors reach and the time that spend at those temperatures depend on the exploitation characteristics of the line. Anyway, these conductors are expected to work at higher temperature values than conventional conductors, which only reach high temperature values in emergency situations. Metallurgical creep increases with temperature. Hence, it is expected that the HTLS conductors experience higher creep deformation than conventional conductors that work at lower temperatures.

Following the creep calculation equations given in [4], Table II shows the relation between the creep at a certain temperature and the creep at 20 °C. The results show that the influence of the temperature is higher in the aluminium than in the steel. However, for both materials the influence is considerable. For example, at 100 °C, the creep is 11 times higher for the aluminium and 5 times higher for the steel.

TABLE II
HIGH TEMPERATURE METALLURGICAL CREEP

θ (°C)	Creep relation respect to 20 °C (%)	
	$\frac{\varepsilon^{fm}(\theta)}{\varepsilon^{fm}(20^{\circ}C)}$	
	Aluminium	Steel
50	2.5	1.8
75	5.2	3
100	11	5
125	23.3	8.2
150	49.4	13.5

4.1.3. Variable thermal expansion coefficient

The thermal expansion coefficient of the invar core changes with temperature. This behaviour can be modelled by two constant values and a change from one value to the other at a certain temperature. In the case of galvanized invar, the thermal expansion coefficient

changes its value at 100 °C. Below this temperature the thermal expansion coefficient value is $2.8 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ and above this temperature the value is $3.6 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$.

4.1.4. Relative displacement between the core and the aluminium in the gap-type conductors

The gap-type conductors allow a relative displacement between the core and the aluminium during the installation of the conductor. In this way, the aluminium gets slack during the installation and the knee-point is forced to be the temperature of installation. Once the second compression clamp is installed the longitudinal movement is limited in both ends and it is not possible a relative displacement between the core and the aluminium. Hence, after the installation, there is no difference between the behaviour of a gap-type conductor and a conventional ACSR conductor.

In the case of the gap-type conductors, although once installed the core and the aluminium lengths are the same, the total core and aluminium deformation values are different. This occurs only in the case of the gap-type conductors. The reason is related to the relative displacement between the core and the aluminium. Once installed, only the core has tension. Hence, without tension, the core length is shorter than the aluminium length. The length difference depends on the span length and the installation tension.

4.1.5. Installation creep

Although the conductor creep starts at the beginning of the installation process, in practice, the important value is the creep developed after the installation is completed (Fig. 4). The creep developed during the installation affects the creep developed after it. The higher the creep developed during the installation the lower the creep developed after it. Hence, a correct estimate of the creep developed during the installation is desirable.

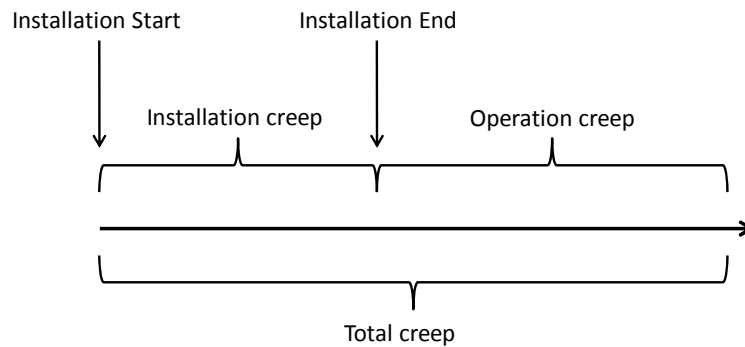


Fig. 4. Creep evolution in time

The installation of the gap-type conductor is more complex than the installation of the conventional conductors. The installation comprises several steps where both the aluminium and the core are subjected to higher tension values with longer duration than in the conventional conductor installation. Hence, the creep developed during the installation is higher. In one of the steps, approximately the 70 % of the installation final tension is applied to the aluminium for a few minutes. In another step, installation final tension is applied to the core for a few hours (up to 24 hours).

In the case of the ACSS conductors, it is recommended to apply a pretensioning during the installation process. A high tension value, around 50 % of the breaking tension, is applied to the conductor during 10 minutes. The objective is to produce a considerable permanent deformation due to geometrical settlement.

4.1.6. Aluminium compression

Some researchers developed a theory with respect to the transition process where the aluminium gets slack [17]. They determined that before the aluminium gets slack, it experiences a compression that is around 10 and 15 MPa for most of the conductors. Hence, due to this effect, the knee-point temperature where the aluminium gets slack is increased.

4.2. Graphical method applied to the HTLS conductors

4.2.1. Slack aluminium

The graphical method allows modelling the loosening of the aluminium because it makes and independent core and aluminium tension calculation.

4.2.2. High temperature metallurgical creep

The graphical method uses the equation (2) given in [5-7] and adopted in the IEEE Standard 1283 [8] for the determination of high temperature creep above 90 °C. This equation relates the metallurgical creep ε^{mc} , the stress σ , the temperature θ and the time t .

$$\varepsilon^{fm} = K \times \left(\frac{100 \times \sigma}{\sigma_{ult}} \right)^\alpha \times \theta^\varphi \times t^\mu \quad (2)$$

The values of the K , α , φ and μ coefficients are defined as a function of the aluminium and the core area relation and the aluminium wire manufacturing system (hot rolled or Properzi-continuous cast). If the conductor has high core content (the aluminium area is lower than 13 times the core area) the high temperature creep is neglected (common case). In this case, $\varphi = 0$. The influence of high temperature is only taken into account when the conductor has low core content (the aluminium area is higher than 13 times the core area). This case is more unusual, e.g. ACSR Rail.

The calculation of the high temperature creep is based on one equation. This equation gives as a result the creep of the conductor, without making any difference between the core and the aluminium creep. Furthermore, the equation is the same for all the conductors. At ambient temperature there are different curves for the core and the aluminium and these curves are obtained for each type of conductor. Hence, it is reasonable to think that at high temperatures a similar procedure would be adequate too.

4.2.3. Variable thermal expansion coefficient

The graphical method does not consider different thermal expansion coefficient values as a function of the temperature. The value of the thermal expansion coefficient is the same in all the temperature range. The solution adopted for the invar core conductors is conservative because the highest coefficient value is chosen for all the temperature range. Hence, in the case of the galvanized invar core, the value adopted is $3.6 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$. This simplification gives as a result an error in the calculation.

4.2.4. Relative displacement between the core and the aluminium in the gap-type conductors

When a gap-type conductor is installed the steel core supports the entire load and the aluminium is slack. Hence, in the initial stress-strain curves the steel virtual tension is the same as the conductor tension σ_{inst} and the aluminium tension is zero (Fig. 5). In the graphical method, in the case of the gap-type conductors the aluminium curve intersects the horizontal axis in the ϵ_{inst} strain value that corresponds to the strain in the steel curve when the stress is σ_{inst} . In other words, the aluminium curve is moved to the right a certain value that depends on the installation tension and the related strain. Actually, what occurs is that without tension the aluminium length is longer than the steel length. The longer length is represented as a fictitious permanent deformation of the aluminium.

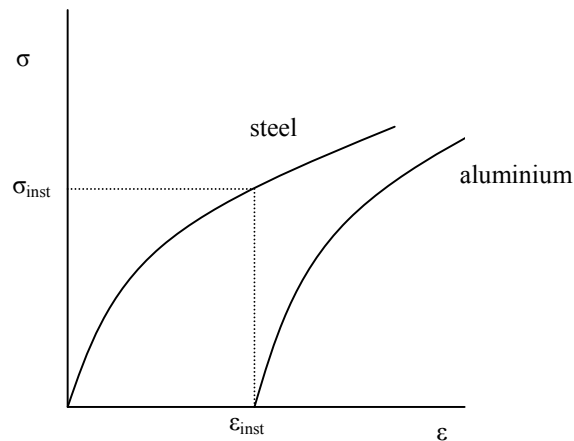


Fig. 5. Displacement of the aluminium stress-strain curve in gap-type conductors

4.2.5. Installation creep

The graphical method calculates the installation creep from the initial stress-strain curves that represent one hour creep. In some cases, this does not represent the actual creep developed during the installation.

In the case of the gap-type conductors the installation comprises several steps where both the aluminium and the core are subjected to higher tension values with longer duration than those given by the graphical method (Fig. 6). On the one hand, the steel core is supporting the installation tension for a few hours and for that reason the metallurgical creep is higher than that corresponding to one hour creep. On the other hand, as in the installation process the aluminium supports tension, it experiences geometrical settlement. Hence, once installed, below the maximum tension supported during the installation, the aluminium behaviour is linear. The graphical method is not able to take into account these issues.

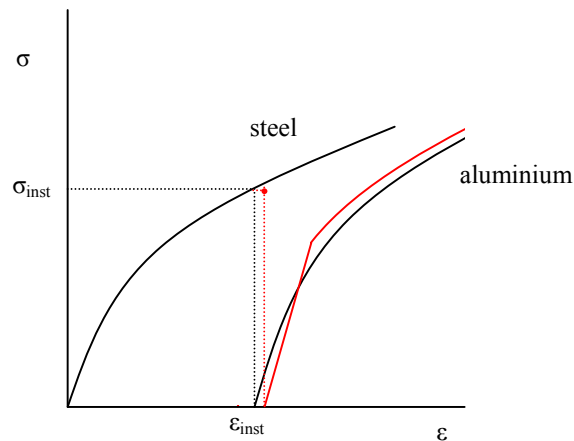


Fig. 6. Stress-strain curves and actual behaviour

The graphical method is not able to model the pretensioning either. Hence, it is not able to model the pretensioning recommended for ACSS conductors. For this reason, an artifice is used in order to model the pretensioning. The pretensioning is modelled as a fictitious wind load.

4.2.6. Aluminium compression

The graphical method gives the option to include or not to include the aluminium compression. If it is included, the value of the maximum compression value can be specified.

In the data given for PLS-CADD, the manufacturers of the ACCC/TW conductors, the gap-type conductors and the invar core conductors recommend neglecting the aluminium compression. The manufacturer of the ZTACCR conductor recommends including the aluminium compression and recommends the value of 8.6 MPa as the maximum compression value.

4.3. STOC method applied to the HTLS conductors

4.3.1. Slack aluminium

The STOC method models the knee-point because the core and the aluminium tensions are calculated independently. Furthermore, as the knee-point changes as a function of the creep deformation and the method calculates this deformation for all the defined stages, the knee-point is modelled for each stage.

4.3.2. High temperature metallurgical creep

The creep is calculated sequentially and the temperature and the load values are considered inside every creep stage. The metallurgical creep depends on the stress σ , the temperature θ and the time t . The higher these values are, the higher the metallurgical creep is. As given in [18], the metallurgical creep in conductor wires follows the law given in (3), where K , Φ , β and μ are constant coefficients. These coefficients are derived from experimental tests.

$$\varepsilon^{mc} = K \times e^{\Phi\theta} \times \sigma^\beta \times t^\mu \quad (3)$$

Hence, the method takes into account the conductor temperature in the metallurgical creep calculation. Besides, in contrast with the graphical method, the high temperature metallurgical creep calculation makes an independent core and aluminium calculation. Furthermore, the method allows modelling the combined effect of high temperature creep, creep at lower temperature and creep due to wind and ice loads.

4.3.3. Variable thermal expansion coefficient

The invar core thermal expansion coefficient varies with the temperature. The STOC method takes into account this variation. The deformation due to thermal expansion is a function of the conductor temperature θ and the reference temperature θ_0 . If the conductor

temperature θ is higher than the θ_v temperature where the invar core thermal expansion coefficient changes its value, the total deformation is calculated as the addition of the deformation below and above this θ_v temperature (4).

$$\varepsilon_{core}^{\theta} = \alpha_{core1} \times (\theta_v - \theta_o) + \alpha_{core2} \times (\theta - \theta_v) \quad (4)$$

4.3.4. *Relative displacement between the core and the aluminium in the gap-type conductors*

The relative displacement between the steel and the aluminium is modelled by two independent reference lengths for the core and the aluminium. These reference lengths are calculated from the core and the aluminium deformation values at the end of the installation process. The difference between the core and the aluminium deformation values is because the core is under tension whereas the aluminium is slack. The reference lengths are defined for a reference condition without tension and creep deformation. Hence, the core reference length is lower due to the higher deformation value at the end of the installation process.

4.3.5. *Installation creep*

The method allows modelling in detail the creep experienced by the conductor during the installation. The method calculates the metallurgical creep and the geometrical settlement for both the core and the aluminium.

In the case of the gap-type conductors, the creep experienced by the aluminium during the installation is calculated. Although at the end of the installation the aluminium is slack, during the installation process the aluminium is under tension. With respect to the core, the number of hours the core is at rest under full installation tension is taken into account.

The method can model the installation stage where the conductor is at rest under full installation tension not only for gap-type conductors but for any conductor and with any

duration. In contrast, the graphical method considers always one hour period of full tension during the installation.

In addition, the method is able to model the pretensioning. Hence, it is suitable for modelling the pretensioning recommended for ACSS conductors.

4.3.6. Aluminium compression

The method models the aluminium compression during the transition process where the aluminium gets slack. The calculation algorithm limits the aluminium tension to a minimum value depending on the defined aluminium compression value.

4.3.7. Differences between the STOC method and the graphical method

Table III shows the main differences between the graphical method and the STOC method.

TABLE III
DIFFERENCES BETWEEN THE GRAPHICAL METHOD AND THE STOC METHOD

	Graphical	STOC
High temperature metallurgical creep	Whole conductor creep by (2). Same coefficients for all the conductors	Independent core and aluminium creep by (3). Coefficients in function of the conductor type
Pretensioning during the installation	It is not included and it is modelled as a fictitious wind load	It is included
Gap-type conductor installation	Aluminium creep is not modelled. Steel is assumed to be at rest during a fixed period of one hour	Aluminium creep is modelled. Steel is assumed to be at rest during a configurable duration
Conductor at rest during the installation	Fixed period of one hour	Configurable duration
Creep stages	Only one stage: choose between ambient temperature metallurgical creep, high temperature metallurgical creep and creep due to wind or ice loads	Several stages are calculated sequentially: interaction between metallurgical creep and creep due to wind or ice loads
Thermal expansion coefficients	Constant	Variable with the temperature

4.4 Application example

In order to quantify the difference between the STOC and the graphical method, a case of a line span including long term creep has been calculated. The span length is 350 m and the

conductor is the ZTACIR Hen. The installation tension is 1681 kg (15 % RTS) and it has been carried out at 15 °C. The initial sag is 10.85 m.

The maximum tension conditions evaluated are those established in the Spanish regulation. The maximum tension condition in Spanish lines above 1000 m above sea level considers ice load at -20 °C. Besides, a high temperature operation of the line is expected. In order to model the effect of different operation temperatures, the conductor temperature is assumed to be 15 °C for 6 months, 30 °C for 3 months, 60 °C for 2 months and 120 °C for one month every year.

The graphical method calculates in parallel and independently the ambient temperature metallurgical creep, the high temperature metallurgical creep and the geometrical settlement related to the maximum tension condition:

- The ambient temperature creep assumes a conductor temperature of 15 °C for 10 years. As a result, the final sag at 15 °C is 11.08 m.
- The high temperature creep evaluates the creep developed while the conductor is above 90 °C. However, as the conductor has a high steel content (in the case of the ZTACIR Hen conductor the aluminium area is 2.8 times the steel area) the high temperature creep is ignored.
- The maximum tension condition is assumed to happen just after the installation is completed. The conductor tension at the maximum tension condition is 3685 kg. As a result, the final sag at 15 °C is 11.19 m.

Once the three creep values are calculated, the graphical method chooses the worst condition. In this case, the maximum tension condition results in the highest conductor deformation due to creep.

The STOC method evaluates sequentially the ambient temperature metallurgical creep, the high temperature metallurgical creep and the geometrical settlement related to the maximum tension condition. Hence, this method models their interaction. The maximum tension condition is assumed to happen 5 years after the installation. The flexibility of the method allows choosing the moment the maximum tension condition happens. This can be useful for the calculation of the creep in lines in operation when the actual maximum tension situations are known. In order to calculate the metallurgical creep, the conductor temperature is assumed to be 15 °C for 6 months, 30 °C for 3 months, 60 °C for 2 months and 120 °C for one month every year. Figure 7(a) shows the evolution of the calculated sag at 15 °C and Figure 7(b) shows the evolution of the tension. As a result, the final sag at 15 °C is 11.49 m. This value is higher than the obtained by the graphical method due to the interaction of the different stages.

One of the advantages of the STOC method is that it allows analysing the evolution of the creep. For example, in Figure 7 it is observed that the metallurgical creep is higher at the beginning of the operation. At the end of the line lifetime, the deformation due to metallurgical creep is negligible. It is also observed that the ambient temperature creep basically affects the aluminium (decrease in aluminium tension and increase in core tension) whereas the high temperature creep basically affects the core (decrease in core tension and increase in aluminium tension) because at high temperature the aluminium is slack. With respect to the geometrical settlement, it is observed that it basically affects the aluminium (decrease in aluminium tension and increase in core tension). Besides, the decrease in tension due to metallurgical creep before the maximum tension condition happens gives as a result a lower maximum tension value and lower geometrical settlement. The conductor tension at the maximum tension condition happening 5 years after the

installation is completed is 3603 kg while its value is 3686 kg when it occurs just after the installation.

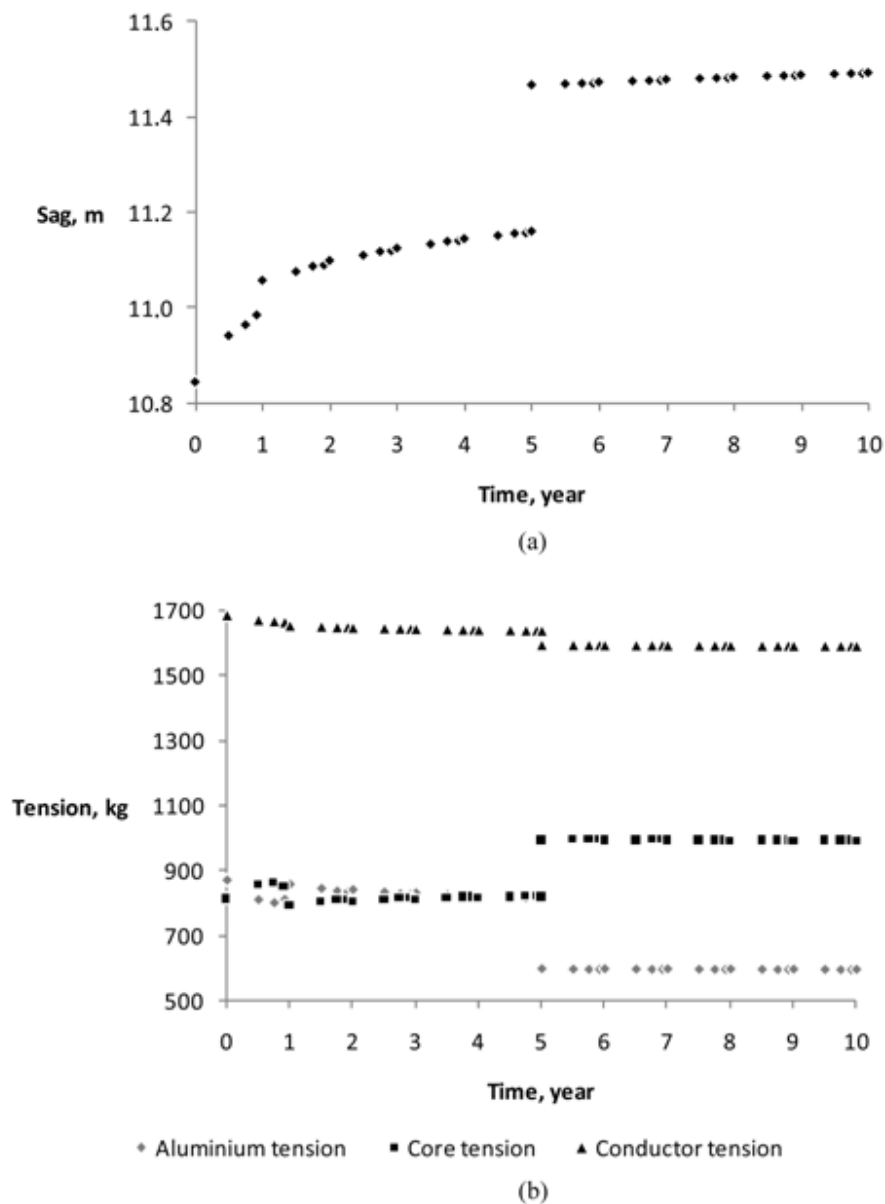


Fig. 7. STOC method calculation results at 15 °C. (a) Sag (b) Tension

The relative difference between the deformation of the core and the aluminium affects the knee-point temperature. Figure 8 shows the sag-temperature relation 10 years after the installation. As the creep deformation of the aluminium is higher than the creep

deformation of the core, the knee-point temperature at the end of the line lifetime is lower than at the beginning. The calculation carried out by the STOC method gives as a result that the knee-point temperature 10 years after the installation is 56 °C (Fig. 9) while just after the installation this temperature is 75 °C.

The influence of the value of the core coefficient of thermal expansion below 100 °C can be observed in Figure 8. The STOC method uses the actual value ($2.8 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$) while the graphical method uses a higher value ($3.6 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$). For this reason, the sag increase is higher for the graphical method.

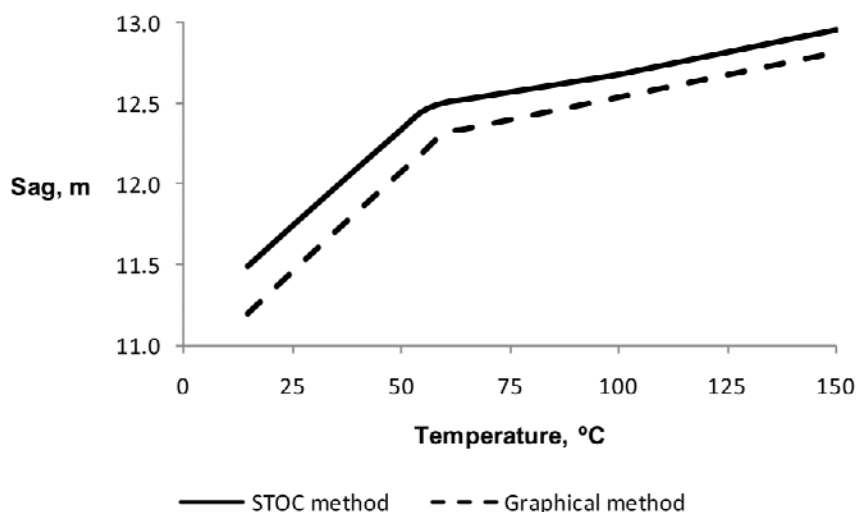


Fig. 8. Sag-temperature relation 10 years after the installation

5. CONCLUSIONS

The application of mechanical calculation methods to high temperature low sag conductors has been analyzed in detail and their limitations have been highlighted.

Firstly, the requirements of the HTLS conductors with respect to the mechanical calculation have been identified. Requirements related to slack aluminium, high

temperature creep, variable thermal expansion coefficient, relative displacement between the core and the aluminium in gap-type conductors, creep during installation and aluminium compression during the transition process have been identified.

The graphical method has been analyzed then taking into account the identified requirements. The limitations of the method on high temperature creep, variable thermal expansion coefficient and installation creep have been identified. Among these aspects the high temperature creep has special significance due to the number of hours the HTLS can work at high temperatures.

The same analysis has been carried out for the STOC method. This method is more flexible and overcomes the limitations of the graphical method. Thus, it allows a detailed modelling of the high temperature creep, variable thermal expansion coefficient and installation creep. Aluminium and core creep are calculated independently. The metallurgical creep in conductor wires follows a law given by some coefficients that establish the relation between creep, temperature and stress. In the literature, only the coefficient values for the steel and aluminium given in [4] are found. Hence, the application of the method requires tests in order to characterize the conductor.

Finally, an application example has been presented to quantify the difference between the STOC and the graphical method. Some of the advantages of the STOC method are related to the capacity to model the interaction between the metallurgical creep and the geometrical settlement and the possibility of analyzing the evolution of the creep in time.

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