Uprating of Transmission Lines by Means of HTLS Conductors for a Sustainable Growth: Challenges, Opportunities, and Research Needs

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***Abstract*—This paper provides a comprehensive and critical review and evaluation of the technological state-of-the-art of high-temperature low-sag (HTLS) conductors by analyzing research articles, theses, reports, white papers and international standards. The growth of power demand requires new solutions to develop power transmission systems, while facing the issues related to power systems congestion. A possibility to solve the load growth issue is to increase the capacity of existing transmission systems by reconductoring the lines with new conductors, which are able to operate at higher temperatures, while limiting the sag and maintaining or reducing the required clearances, thus having more current carrying capacity than the existing ones. This paper also describes the limitations of such technology and identifies the research needs to fulfill the requirements of the industry and transmission system operators.**

***Index Terms*—Power systems, high temperature conductors, low sag, overhead conductors, transmission lines.**

ACRONYMS

AAAC	All-aluminum alloy conductor
AAC	All-aluminum conductor
AACSR	Aluminum alloy conductor steel-reinforced
ACAR	Aluminum conductor alloy reinforced
ACCC	Aluminum conductor composite core
ACCR	Aluminum conductor composite reinforced
ACSR	Aluminum conductor steel-reinforced
ACSS	Aluminum conductor steel supported
CTE	Coefficient of thermal expansion
DLR	Dynamic line rating
EHV	Extra high voltage
EXB	Expanded bundle
GHG	Greenhous gas emissions
GTACSR	Gapped TAL alloy ACSR
HSIL	High surge impedance loading
HTLS	High-temperature low-sag
HV	High-voltage
KPT	Knee point temperature
LCA	Life cycle assessment
MRSM	Modified ruling span method
NPV	Net present value
RSM	Ruling span method
RTS	Rated tensile strength
SIL	Surge impedance loading
SLR	Static line rating
TACIR	TAL alloy aluminum conductor Invar reinforced
TACSR	TAL alloy ACSR

TAL	Thermal-resistant aluminum alloy wire
(Z)TAL	Thermal-resistant aluminum-zirconium alloy wires
TSO	Transmission line operator
TW	Trapezoidal wire

I. INTRODUCTION

Worldwide electricity demand is growing [1] steadily, which will be maintained in the next decades [2], with an increase around 4% in 2018, rising almost twice compared to the global energy demand [3]. Electricity supply is becoming more important due to the current society development needs [4]. Different factors such as the aging of the current electrical network, load increase, the incorporation of renewables [5]–[7], the increasing presence of electric vehicles [8], the increasing power system decentralization and flexibility [9], or the European market integration [10] are subjecting transmission systems to an increasing pressure. In addition, renewable power sources are often located in remote areas, very far from the consumption nodes, thus adding more stress to the existing power grids [11]. Today, the rate of construction of new transmission lines is well below the rate of increase in electrical power generation, so there is the need to increase the capacity of existing transmission lines [12]–[14]. Overhead transmission lines are the most cost-effective highways for transporting electrical energy between the generating stations and the consumers or between transmission systems [15]. For example, the economic cost of underground cables is between three and ten times the cost of overhead lines [16], [17]. Today, it becomes particularly difficult to construct new lines [18], mainly due to public, social [19], legislative, economic and environmental constraints, specifically those related to land requirements due to the required right of way [14]–[16], since there is scarcity of corridors, particularly in dense populated urban areas [23] and in regions of ecological interest. In addition, fulfilling the regulatory aspects and environmental regulations [24], and obtaining the required licenses [18], [25] is increasingly difficult [26]. The period required between there is the need to install a new line and its coming into service often exceeds the time tolerable by the utility [27]. Therefore, there is an imperious need of increasing the power transferred and optimizing existing grid exploitation [28]. Transmission lines power transfer capacity, i.e., the ability to carry bulk power, mostly depends on different factors such as conductor sag, security limit (maximum voltage phase difference across the line to ensure a synchronous operation) [29], thermal limit, transient stability and voltage stability [30]. Whereas the latter two factors refer to reliability requirements, the thermal limit also affects the safe operation of the line, since it determines line clearance and conductor annealing [31].

To face this growing power demand, there are two main approaches, i.e., the construction of new power lines, or the increase of the capacity of the existing ones. However, as explained, it is often extremely difficult to build new transmission and distribution lines. This problem leads to the energy sector to search a feasible solution to solve saturation problems of electrical lines due to the increased demand and generation of electrical power. It is possible to face this issue by replacing the existing conductors by conductors of larger diameter, but at the expense of requiring extensive structural modifications, this being a very expensive solution [32] and often unacceptable to the public [21].

Instead of constructing new overhead power lines, an interesting alternative is to apply an uprating approach [3], that is, increasing the transmission capacity of existing power lines [33] by rising the voltage, the current or both [20], with minimum or no intervention on the existing structures. A possible solution could be to operate the existing lines at higher temperature [21], by increasing the current carrying capacity (ampacity). When exceeding the thermal limit, due to the annealing effect of the aluminum strands, the conductor tends to increase its ductility and decrease its hardness, thus affecting negatively the sag which facilitates infringing the minimum clearance [34]. Therefore, when increasing the operating temperature, different effects arise, including a drop of the integrity and expected life of the conductors and accessories due to the accelerated ageing, increase in conductor sag and a consequent reduction of clearances, or a rise of Joule losses [35].

Therefore, in most cases, it is not feasible operating the existing lines at higher temperature, due to the abovementioned issues, especially those related to the electrical clearances and sag. Conductors' replacement is the most applied uprating method, which presents several advantages, including cost-effectiveness and market readiness. Although several alternatives are possible, replacement with conductors of larger diameter is not a priority, since this method imposes greater mechanical loads on the existing structures, which could require to be reinforced [12] or even replaced. A good alternative consists in replacing the original conductors with conductors of higher current capacity and higher *H/w* ratio, where *H* is the horizontal tension and *w* the unit weight of the conductor [20]. Thus, the most feasible option seems to be to increase the current carrying capacity of existing lines [12]. Under these assumptions, two options are possible. The first one is to replace the original conductors with conductors having a largest cross-section and higher conductivity, but with equal or inferior diameter, operating at the same temperature. The second option is to replace the existing conventional conductors with HTLS conductors, due to their ability to operate at higher temperature, while keeping the sag constrained [25], [36] without infringing permissible ground clearance [37] because of their lower thermal expansion coefficient [20] and without requiring to reinforce existing transmission structures [38]–[40]. Therefore, HTLS conductors, with an almost identical section of conventional ones, allow improving power grid current carrying capacity, efficiency and reliability [5]. Whereas conventional conductors usually operate below 75ºC, all HTLS conductors can operate continuously at least at 150°C [41], although some of them can operate at 250°C without substantial changes in the electrical and mechanical properties [33]. The main advantage of reconductoring existing lines with HTLS conductors is that they allow increasing the thermal rating of the line with minor modifications of the structures [42]. Therefore, HTLS conductors have great potential for replacing conventional ACSR and AAAC conductors [11]. Although HTLS conductors allow increasing power transfer capability, there are other systems to do so, such as the use of compact transmission lines or high phase order (six phase) systems [43], although such methods require replacing or extensive modifications of the existing structures.

This paper reviews the state of the art in HTLS conductors, since they are the latest technology for reconductoring overhead transmission lines on existing structures while complying with sag limitations due to their excellent technical attributes. They have lower sag and increased current carrying capacity, with similar weight compared to that of conventional conductors, thus allowing to tackle with different transmission line concerns, including high construction costs, delays related to right of way issues or natural environment and environmental related impacts [44]. This review paper intends to make a critical and comprehensive review of such technology, while identifying the pros and cons as well as the challenges to be faced. This review paper is completely based on data and information published in recent technical and scientific publications.

II. Current Uprating Methods For Overhead Transmission Lines

The term uprating refers to increase the electrical features of a power line, such as allowing larger electrical clearances or improved electrical capacity [45], so uprating allows to increase the utilization factor of existing assets [46]. In addition, the electrical clearance is the shortest separation between different energized parts of different phases, or between any energized part and adjacent grounded parts [12], [47], [48]. According to Cigré [12], the ampacity and thermal rating of a conductor indicate the maximum continuous current meeting design, security and safety constraints of the line that contains the conductor.

Measures to increase the thermal rating of existing overhead lines, involving limited capital investments and public hearings can be classified into three categories [32]; (1) conductor rating increments around 5-20% can be achieved by combining field measurements and improvements related to thermal rating estimation methods such as dynamic line rating (DLR), which allows increasing the current without raising the maximum temperature allowed by the conductor, thus resulting in more operation hours close to the maximum temperature; (2) increases around 20-50% are possible by applying simple changes to the supporting structures, such as raising the suspension points of the conductors by changing the configuration of the insulators (replacing tangent for floating dead-end insulators), or sag modifications by applying retensioning methods; (3) increases above 50% can be achieved by replacing the original conductors with HTLS conductors, while essentially maintaining the original structures [32].

Table 1 shows the different available current uprating methods for overhead power lines. The next paragraphs briefly summarize the current uprating methods summarized in Table 1.

Table 1. Methods for current uprating in overhead power lines adapted from [46].

Strategy	Technique
Reconductoring	Conductor replacement
	Change rating criteria
Deterministic	Increase conductor tension
	Increase conductor attachment height
Probabilistic	Account for actual load profile
	Modify rating criterion
Real-time monitoring	Measurement of sag, tension, thermal and environmental conditions
High surge impedance loading	Changes in conductor bundling and geometry

Conductor replacement by a conductor of higher conducting area (for example replacement of ACSR by AAAC with the same cross-sectional area can improve the thermal rating up to 40% [12]) without increasing the weight or by HTLS conductors, almost avoids applying structural modifications to the supporting structures. This current uprating method is the most applied and effective since it requires minimal changes of the existing structures [46], [49]. Replacement of existing conventional line conductors with HTLS conductors which can operate at higher temperature allows an important increase of the thermal rating and the mechanical reliability. Most HTLS conductors can operate continuously up to 200ºC, while maintaining electrical and mechanical properties and reducing the thermal elongation above 100ºC compared to conventional conductors, thus increasing the thermal capacity by more than 50% [32].

Important rating gains can be obtained when installing conductors of larger cross section, although this strategy may involve structure reinforcement, reconstruction, or replacement, thus resulting in much higher costs and a long line interruption [32].

The deterministic method [46] for current uprating is based on increasing the conductor temperature while keeping ground clearances, by using the weather conditions (solar radiation, ambient temperature, and wind speed and direction) to determine the current rating, considering the maximum permissible conductor temperature [1].

IEEE [50] and Cigré [51] include calculation methods based on the worst-case weather condition. Due to dealing with the worst case scenario, the ampacity value is usually greater than that calculated with the deterministic approach, thus wasting part of the line capacity [52]. The temperature limit for a given clearance or templating temperature, can be raised by increasing the conductor tension and attachment height [45]. The deterministic method is more effective at low templating temperatures, i.e. below 80ºC, when assuming well-known weather conditions and are recognized to be safe [53].

The probabilistic method [46] uses actual weather conditions of the geographical area where the line is located for determining the risk of unsafe conditions and the permissible amount of time for the temperature of the conductor to exceed its limit [53]. Using this method, the level of risk can be kept constant at a defined exceeding level while varying the ampacity [54].

Real-time monitoring methods allow an online monitoring of the actual condition of the line. Different technologies are used for line monitoring, including load cells, temperature sensors, weather stations, radio communications, or GPS. This approach allows applying a dynamic rating [55], which compared to the conservative static rating (rated capacity) provides higher line capability [46], since the dynamic thermal rating is the real-time maximal permissible current of the line [56] based on real-time load conditions [31]. Dynamic rating presents other benefits, allowing to alleviate congestion in transmission lines, facilitating wind energy integration, improvement of power systems reliability and enabling economic benefits [31].

Apart from current uprating methods, other possibilities exist, such as voltage uprating, conversion from ac to dc, or the high surge impedance loading method, which are briefly summarized in the following lines. Voltage uprating is feasible at lower voltage levels, since older 115 kV or 138 kV circuits are designed to generate voltage gradients below the corona limit, so some of these circuits could operate at higher voltages. North American utilities have applied this strategy to uprate lines from 115 kV or 138 kV to 230 kV without changes. It is possible operating these lines at a voltage level restricted only by the voltage gradient on the conductor when applying additional measures, such as insulator modification or limitation of switching surges by means of surge arrestors [32]. Another possibility is to convert an existing ac line to dc [57], [58]. Although this option has been long analyzed, it has been never implemented, although the tripole configuration allows an increase of 37% in continuous rating [32]. Finally, the high surge impedance loading method can be applied to EHV lines [46], in which, due to the presence of a large line inductance, the power transfer capability is reduced, so the rating is below its thermal limit (usually limited to 30% of the thermal capacity [59]), thus limiting the loading below the surge impedance loading (SIL) level. The power transfer capability can be increased by rising the SIL level, i.e. lowering the characteristic impedance of the line [60]. This concept is known as high surge impedance loading (HSIL) and can be developed by using expanded bundle (EXB) and HSIL-EXB configurations, which apply an asymmetrical expanded distribution of sub-conductors in a bundle. The underlying idea is that when increasing the number of subconductors in a bundle, the amount of natural power and the SIL level also increase, due to a reduction of the amount of line inductance and surge impedance [17].

III. Thermal Rating Of Overhead Lines

Overhead lines are operated according to their thermal rating [11], which is defined to limit the loss of tensile strength to ensure satisfactory electrical clearance along all line spans under any weather condition [12]. The loss of tensile strength depends on temperature and time, whereas the clearance depends on conductor sag, which in turn depends on the temperature of the conductor [12]. The clearance limit defines the limit operating temperature of the conductors, or templating temperature [1], i.e. the temperature leading to the minimum ground clearance, which is critical to determine the maximum allowable current in the conductor.

According to Cigré [33], the process to choose a conductor for replacing the original one to increase the power flow on an existing line, is complex. The goal is to increase the thermal rating of the line without replacing the existing foundations and structures, which is usually attained by using a replacement conductor able to operate at higher temperature than the existing one but with the same outer diameter, similar weight and reduced high temperature sag.

Thermal constraints depend on the line current and the environmental conditions, since the temperature and the sag of the conductors depend on such variables [46] and conductors placed at the inappropriate clearance above ground, limit the line's capability for transmitting power [25]. Conductors sag highly depends on temperature, being mostly determined by the thermal elongation of the conductors and the tension to which they are subjected [12]. The rating of overhead lines is mainly limited by the maximum allowable conductor temperature of the conductors to prevent minimum ground clearance [61], or conductor annealing, i.e. the process that reduces the tensile strength of aluminum wires due to sustained high temperature [12]. The temperature of the conductor depends on the instantaneous current level and weather conditions (pressure, temperature, wind speed and solar heating among others), thus resulting in a variable line rating that depends on such conditions [61]. However, the static line rating (SLR) method is often applied for planning purposes and to ensure the safe operation of power lines, which is based on conservative weather conditions [62] regardless of line location or the maximum-allowable temperature of the conductors.

The sag-temperature relationship is stable for conventional ACSR conductors operated below 75°C, but beyond this point this relationship presents anomalies [12]. Above 90°C, ACSR conductors loss their mechanical strength, this reduction being cumulative with time, thus causing sag and reducing clearances between conductor and ground. Therefore, ACSR conductors are limited to operate between 75ºC and 85°C for continuous operation, and between 100ºC and 150°C for emergencies [33].

When the maximum allowable conductor temperature is close or above 100°C, then the most suitable option is reconductoring with HTLS conductors. However, when the maximum allowable conductor temperature is below 75°C, there are different possible uprating methods without the need of reconductoring by means of high temperature conductors [33]. According to [12], the ampacity of existing lines can be increased by merging load profiles and weather data, thus obtaining probabilistic ratings by means of a specific software. It is also possible to calculate the rating of the conductor in real time depending on its position in space and the meteorological conditions, to avoid excessive sag. Under some infrequent circumstances, the electrical clearances can be reevaluated, thus increasing the nominal temperature with almost no physical changes in the line, such as conductors re-tensioning, moving the suspension clamps, addition of new towers in long spans, or raising conductor attachment heights. Finally, the conductors can be replaced with new conductors which are able to operate at higher temperature, while offering reduced sag at high temperature, or with conductors with lower electrical resistance [12]. Replacement conductors should present several characteristics, including reduced thermal expansion coefficient, low sag, same or lower outer diameter and same or lower electrical resistance [42].

There are several methods to determine the thermal rating of bare conductors for overhead lines, defining the operational limit of the conductors, which is often calculated based on predetermined environment conditions [11]. SLR is the thermal rating determined under reasonable weather conditions [31], [56]. SLR methods are found in the IEEE [50], Cigré [51] and IEC [63] standards and in Morgan [64], among others. Such methods provide equivalent results when considering similar weather conditions and conductor parameters [32]. These analytical methods are based on the heat balance equation, which takes into account the heat exchange between the conductor and the surroundings. They usually consider mechanisms such as Joule, magnetic and corona heating and convective (natural/free or forced), radiative and evaporative cooling, allowing to perform both transient and steady state analyses. Despite the models apply different simplifications and assumptions, they are suitable for most of the conditions that conventional conductors have to withstand [11]. Convective cooling plays a key role, although most of the models deal with different simplifications of this mechanism [11], and both natural and forced convection are often considered separately during low-wind conditions [34], thus leading to discrepancies among models. It is known that such models are restricted to low temperature conditions, this fact limiting their applicability when dealing with HTLS conductors [2], since they present specific features and operational conditions compared to conventional conductors. According to [2], when the abovementioned models are applied to HTLS conductors, some differences are found among the models, the results indicating a better suitability of the IEEE model to predict the thermal behavior of HTLS conductors.

The foundations of the mathematical thermal models for steady state and transient conditions developed by Cigré [51] are given in (1) and (2), respectively. According to (1), under steady state the heat supplied to the conductor balances the heat dissipated, thus reaching the thermal equilibrium, since there is no heat stored within the conductor.

$$\underbrace{P_{Joule} + P_{Magnetic} + P_{Solar} + P_{Corona}}_{\text{Heating mechanisms}} = \underbrace{P_{Convective} + P_{Radiative} + P_{Evaporative}}_{\text{Cooling mechanisms}} \quad [\text{W/m}] \tag{1}$$

Similarly, under transient conditions, the heat balance equation results in (2).

$$mc\frac{dT}{dt} = P_{Joule} + P_{Magnetic} + P_{Solar} + P_{Corona} - P_{Convectiveg} - P_{Radiative} - P_{Evaporative} \quad \text{[W/m]} \quad (2)$$

m being the mass of the conductor per unit length and *c* the specific heat capacity.

Thermal issues can arise when the cooling rate assumed for the line rating is higher than the actual cooling rate. With favorable air temperature, actual wind speed and solar heating, the SLR is safe. Contrarily, when these magnitudes are unfavorable, the SLR is unsecure, so when the line current equals the static rating, the conductor temperature may exceed the maximum allowable conductor temperature. Therefore, the result of the thermal balance is a critical point to determine the safety level of the line [61].

The thermal rating of the line limit is always changing because of the changing weather conditions [65]. Dynamic line rating (DLR) methods assume that the input parameters to calculate the rating, including the environmental conditions, change continually [31]. Real-time dynamic rating is based on monitoring the weather conditions, so that the observed mechanical state is extrapolated to determine minimum clearances and maximal conductor sag, which are determinant factors to determine the line thermal rating. Weather data is often obtained from local weather stations, from online weather sources [66] or even from sensors installed in the line [59]. With the widespread use of electronic devices, it is now possible an on-line monitoring of key variables such as conductor temperature and sag [67], line clearance, or weather data in the transmission line [59].

IV. Conductors Types For Overhead Power Lines

Electrical conductors play a key role in overhead power lines, since they greatly determine the throughput capacity of the power line [5], while ensuring a reliable and efficient operation of power systems [44]. Bare conductors for overhead transmission and distribution lines are made of virtually pure aluminum wires, which are often reinforced with steel wires to increase the mechanical strength [12]. Conventional concentrically stranded conductors include all aluminum conductors (AAC), all aluminum-alloy conductors (AAAC) and aluminum conductor steel reinforced (ACSR) conductors.

A. Conventional conductors

AAC conductors use almost pure aluminum wires, being mainly applied in urban areas where the supports are close. Conversely, AAAC are composite conductors which include aluminum and aluminum-alloy wires [68]. AAAC conductors present improved mechanical strength and less sag than AAC conductors. Due to the higher resistivity of the aluminum-alloy, AAAC conductors exhibit higher power losses compared to AAC conductors [69]. Fig. 1 shows the cross-section of AAC and AAAC conductors.

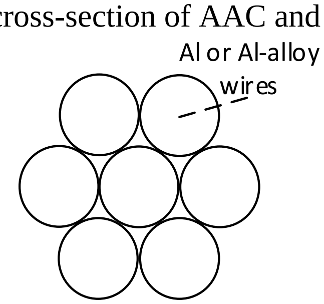

Fig. 1. Cross-section of AAC and AAAC conductors

ACSR conductors have been used during the last century in conventional overhead high-voltage transmission lines, being the most used conductors [70], since they are cost-effective and available from different suppliers [71]. They are composed of hard-drawn (1350-H19) aluminum strands [41] to attain higher tensile strength [44], which are wrapped around the core. Compared to AAC conductors, ACSR conductors present lower ampacity because of the increased electrical resistance due to aluminum impurities [44]. The core is made of galvanized steel wires to increase the tensile strength, thus presenting a relatively high coefficient of thermal expansion at medium temperature, thereby generating a mechanical sag. Due to the additional elongation at medium temperature, the conductor presents additional electrical resistance, thus increasing the temperature, overheating the conductor and increasing power losses, this effect in turn producing more sag and thus treating public safety [21]. The thermal rating of ACSR power lines is restricted either by the annealing of aluminum strands or by the maximum sag [72]. Fig. 2 shows the cross-section of ACSR conductors.

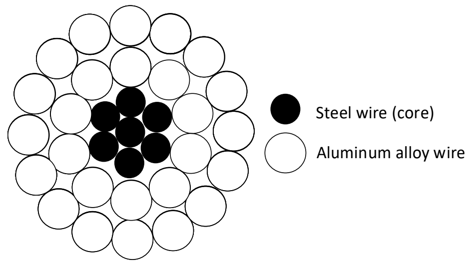

Fig. 2. Cross-section of ACSR conductors

It is known that when exceeding the thermal limits, there is an irreversible ageing of the conductors because of the annealing process, which elongates the conductors, thus increasing the sag and jeopardizing the clearance limits of the tower [34], thus limiting the thermal rating of the line [72]. By rising the current, the temperature of the conductor also increases. Thus, the aluminum wires of ACSR conductors operating beyond the normal operating range 70-90ºC become softer since they start annealing above 90ºC [19], [39], experimenting a loss of tensile strength due a relaxation of the mechanical stress in the microstructure (grain boundaries and lattices), which was attained during the previous cold working process [35], [73]. To avoid this problem, the temperature of ACSR conductors is habitually limited to 75ºC under 0.6 m/s wind speed [74], thus impacting the current carrying capacity [44], although the tensile strength of the steel core is almost not affected below 250 °C [35].

Aluminum alloy conductor steel reinforced (AACSR) conductors are similar to ACSR conductors, with concentrically stranded conductors composed of stranded aluminum alloy wire and a high-strength coated steel core, which like in ACSR conductors, the steel strands may be galvanized (zinc-coated), aluminized (aluminum-coated) or aluminum-clad steel strands [35].

B. High temperature conductors

HTLS conductors try to solve the issues related to the limited current carrying capacity and sagging when operating at high temperature [21]. The power transfer capability of short overhead lines (< 80 km) is mainly limited by the conductors' thermal rating. For longer lines (< 300 km) the voltage drop limits the power transfer capability, whereas for lines over 300 km, steady-state stability becomes a critical factor [75].

The main benefits of applying HTLS compared to conventional ACSR conductors, is that the firsts can dissipate more heat, present lower coefficient of thermal expansion with an improved tensile strength. HTLS conductors can double the current carrying capacity of conventional ACSR conductors [2], [72], [76], while offering almost the same impedance, although when operating at very high temperatures their electric resistance increases, and thus, the power transfer capability can be reduced [72], so they are often applied in relative short lines [33]. Therefore, the main drawbacks of using HTLS conductors are the considerably higher conductor costs and operating costs because of the increased power losses [71].

HTLS conductors are nowadays installed at line voltages in the range 66-500 kV [42]. Despite their appealing features, some utilities are still hesitant to use HTLS conductors due to their inexpertness in the reliability and long term service behavior under severe operating conditions [77].

HTLS conductors usually have two main components, i.e., fiber core and aluminum wires. Aluminum wires, often with trapezoidal shape, are used for minimizing the interstices between aluminum strands, thus making a better usage of the cross-sectional area compared to round wires. They allow reducing the conductor diameter while obtaining a larger effective cross section area [44], thus increasing the ampacity [21]. Such wires are made of annealed O-temper aluminum, which although is softer than aluminum alloy, presents higher electrical conductivity, thus being more efficient in transmitting electrical power [44]. Fully annealed aluminum wires have the same chemical composition than conventional hard drawn aluminum, but with much less tensile strength, being able to operate continuously beyond 250°C without any loss in electrical or mechanical properties [33]. The core of HTLS conductors is usually made of stranded carbon fiber composite cables. It presents appealing features when compared with the steel core of conventional ACSR conductors, such as flexibility, low weight, lower expansion coefficient, non-magnetic properties, high resistance to corrosion, higher tensile strength [21] and elastic modulus or reduced creep elongation (permanent deformation of the conductor under continuous stress [47]) [44]. Therefore, the mechanical effort of HTLS conductors is supported by the greater tensile and strength properties of the composite core [44].

Since HTLS conductors have very similar physical dimensions to those of conventional ACSR conductors, the same accessories such as joints, clamps or connectors can be used, but it must be ensured that they can withstand the higher temperatures. This requires to develop standardized higher temperature tests for such accessories [5].

According to [12] different types of high temperature conductors can be found in the market, including, (Z)TACSR, G(Z)TACSR, (Z)TACIR, ACSS, ACCR and ACCC conductors, which are reviewed in the following paragraphs.

(Z)TACSR with identical structure than ACSR conductors [33], have galvanized steel wires in the core and thermal-resistant aluminum-zirconium alloy wires, known as (Z)TAL wires. Both TAL and (Z)TAL wires have almost the same tensile strength and conductivity than conventional conductor grade aluminum wires. However, (Z)TACSR are not low-sag conductors, since they present the same thermal elongation performance as ACSR conductors, but the alloy wires anneal above 150ºC for TAL (aluminum alloy wires) and above 210ºC for (Z)TAL (Al-Zr alloy), whereas for conventional ACSR conductors, the aluminum wires anneal around 93ºC [41].

G(Z)TACSR or gap-type conductors, include a small gap between the inner aluminum layer and the steel core, which is filled with heat-resistant grease to minimize the friction between steel wires, as shown in Fig. 3. All the tension in the conductor can be supported by the steel core, thus allowing to extend the low-sag steel core properties over a greater temperature interval [33].

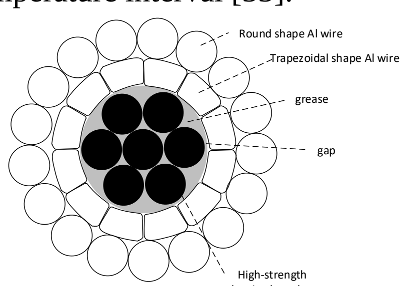

Fig. 3. Cross-section of gap-type GTACSR conductors

(Z)TACIR with identical structure than ACSR conductors, use (Z)TAL wires surrounding the zinc-coated core, this coating layer preventing corrosion between the aluminum and steel wires [33], or aluminum-clad Invar alloy (iron-nickel alloy with reduced CTE) steel wires.

ACSS and ACSS/TW conductors with trapezoidal-wire (TW) are made of fully annealed strands of 1350-0 aluminum, concentrically stranded around a high strength core of stranded coated steel wires, which can be either galvanized, aluminized, or aluminum clad of zinc-aluminum Mischmetal coated (zinc alloy—5% aluminum coating [35]) [33]. The geometry of ACSS conductors is essentially that of conventional ACSR conductors, as seen in Fig. 4. ACSS conductors are available in round or trapezoidal aluminum strands. Due to the low tension of the annealed aluminum wires, the aluminum strands do not creep under normal tension loading, and the thermal elongation is basically that of the steel core [33]. The continuous operating temperature of ACSS conductors is around 200°, but when the core is aluminized is close to 260°C [78], [79].

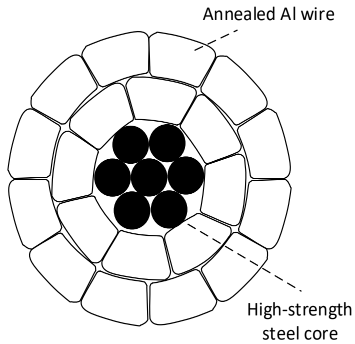

Fig. 4. Cross-section of ACSS/TW conductors

ACCR conductors [21] include a composite core (alumina fibers and aluminum matrix core) and (Z)TAL wires of high electrical conductivity [33], thus showing improved sag and current carrying capacity at high temperature. ACCR conductors have a continuous operating temperature of 210°C [1], [11], although under emergency conditions they can operate up to 240°C. [78]. Fig. 5 shows the cross-section of ACCR conductors.

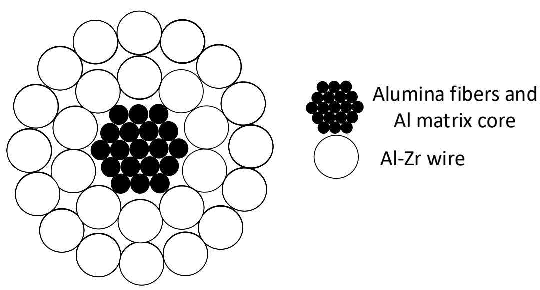

Fig. 5. Cross-section of ACCR conductors

Aluminum conductor composite core with trapezoidal wire (ACCC/TW) is based on a high strength, lightweight hybrid core made of glass and carbon fiber embedded in a resin matrix (see Fig. 6). ACCC/TW conductors allow limiting the sag when operating at high temperature because of the low thermal elongation of carbon fiber, while being able to withstand severe wind and ice loading conditions [33]. This hybrid core is surrounded by helically wound, high conductivity, fully annealed trapezoidal aluminum wires. The low thermal elongation coefficient of the hybrid core ensures good sagging resistance at higher temperature above the knee-point temperature since it exhibits increased stiffness/weight and aspect ratios compared to steel [21]. ACCC conductors offer several advantages, including increased ampacity and reduced transmission losses [21]. Annealed aluminum wires used in ACCC conductors are purer, highly softened and more conductive compared to the ones used in conventional ACSR conductors. Since they have lower mechanical properties, the dynamic and static mechanical loads are mainly supported by the core. ACCC conductors have a continuous operating temperature of 180°C [11].

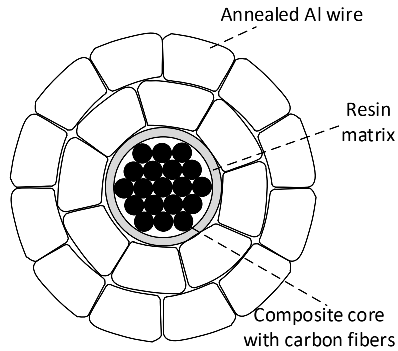

Fig. 6. Cross-section of ACCC/TW conductors

C. Materials for overhead conductors

The materials of both the wires and core have a deep impact on the mechanical and electrical attributes of the conductors [44]. Conventional overhead line conductors are mostly composed of aluminum and steel, although different types are commercialized. While aluminum provides the conductive path, steel provides mechanical strength [2]. Some conductors blend aluminum with zirconium to enable higher temperature operation compared to conventional ACSR conductors, because zirconium permits increasing the annealing temperature. Other materials, including alumina, glass and carbon fiber composites or Invar, are being used in the core of HTLS conductors [2].

Most HTLS conductors use annealed aluminum or O-temper aluminum (1350-O), which presents greater electrical conductivity than that of aluminum wires used in ACSR conductors [79]. However, annealing increases ductility, while reducing hardness and strength. Therefore, the core must support the mechanical load [21].

High temperature conductors are manufactured with the combinations of aluminum wire and reinforcing core materials, which are summarized in Tables 2 and 3, respectively [33].

Table 2. Mechanical and electrical characteristics of aluminum and aluminum alloys used in overhead conductors. Adapted from [33], [73]

Aluminum type	Electrical conductivity (% IACS)	Min. tensile strength (MPa)	Operating temperature (ºC)	
			Continuous	Emergency
Hard drawn 1350-H19	61.2	159-200	90	120
Thermal resistant TAL	60	159-176	150	180
Extra thermal resistant (Z)TAL	60	159-176	210	240
Fully annealed 1350-O	63	59-97	200-250	250

Different core materials such as carbon fiber, polymer composite or glass fiber reinforced in a polymeric base matrix composite exhibit important advantages compared to steel. These cores allow higher mechanical loading while reducing the tensile stress, compared to the conventional steel cores of ACSR conductors with comparable diameter and cross-sectional area. In addition, conductors with composite core are lighter than those made of steel, thus allowing longer spans and reducing the mechanical requirements of the supporting towers [21]. Composite core conductors usually incorporate softened aluminum wires to maximize the conductivity, so at high temperature operation, the core has to withstand most of the mechanical load. The CTE of polymer composite cores is around one order of magnitude below that of aluminum wire, so the CTE of the conductor is mainly determined by the composite core.

The knee point temperature (KPT) is the temperature above it the core withstands the whole conductor tension due to the greater thermal expansion coefficient of the aluminum, so the aluminum wires are slack. At low temperature operation, the conductor tension is shared between the aluminum wires and the inner core. Above the KPT, due the two expansion coefficients, the tension distribution changes, the mechanical behavior being mainly determined by the CTE of the core, so the sag increases less [39]. Since the CTE of the core is lower than that of the aluminum wires, most of the mechanical tension is supported by the core [80], whereas the aluminum layer starts compressing. HTLS conductors are designed to operate beyond the KPT. Below the KPT, HTLS conductors behave similarly to conventional ACSR conductors [2]. However, conventional ACSR conductors operate below the KPT due to the limited temperature operation. The composite core of HTLS conductors presents a reduced CTE (see Table 2), which decreases beyond the KPT, so the sag will be low compared to ACSR conductors of similar diameter [81], thus having beneficial effects such as longer spans, higher operating temperatures or superior current carrying capacity [21], [23].

Table 3. Mechanical and electrical characteristics of materials used in the core of HTLS conductors. Adapted from [33], [73]

Aluminum type	Modulus of elasticity (GPa)	Min. tensile strength (MPa)	Minimum elongation at failure (%)	CTE ($x10^{-6}$)
HS galvanized steel	206	1230-1320	3.5	11.5
EHS galvanized steel		1765		
Al clad 20.3% IACS	162	1103-1344	3	13.0
Mischmetal Zn-5%				
High strength	206 (initial)	1380-1450	3.5	11.5
	186 (final)	1520-1620		
Galv. Invar alloy	162	1030-1080	3	2.8-3.6
Carbon fiber composite	125	2200	2.0	1.6
3M ceramic fiber reinforced aluminum	220	1400	0.64	6

As shown in Table 3, the rated tensile strength of composite core conductors is much higher than that of conductors with steel core [21].

V. Tension And Sag On Transmission Lines

In an overhead power line, the sag is the vertical distance from the midpoint of the span and the straight line connecting the two support points of the conductor [47]. Transmission structures are calculated such that phase to tower and phase to phase clearances must withstand voltage surges, galloping and swinging of conductors during any weather condition [43]. Excessive sagging due to high temperature or insufficient current carrying capacity can lead to a complete blackout [21], so HTLS conductors allow addressing this issue. Therefore, it is of vital importance to develop accurate calculation methods to determine the sag of the conductors.

The creep of a conventional conductor is defined as an accumulative non-elastic elongation under regular every day tensions and temperatures [47], i.e., below 30% rated strength and below 75 °C over 10 years [35]. Permanent elongation results as a combination of the geometric settlement, plastic deformation and the metallurgical creep [28], [39]. In general, in bi-material conductors with cores insensitive to creep, the conductor elongation depends on the creep behavior of aluminum strands and the elastic behavior of the core [28]. The stress due to the geometrical settlement is time independent, although it is affected by the tension at which the conductor is exposed and by constructive aspects of the conductor. The metallurgical creep depends on the material microstructure, stress, temperature and time [39]. When conductor strands creep, the mechanical tensions decrease and sag increases. It could result in issues related to electrical clearances to ground, thus being important to predict high-temperature effects on conductor sag.

A. Sag-tension calculation methods

As explained, aluminum strands expand thermally at a higher rate than that of the steel strands. This effect is combined with an augmented aluminum creep at high temperature operation, so the effect of high-temperature operation on the sag of AAC conductors is superior than that for steel-reinforced conductors. In steel-reinforced conductors, as temperature raises, the conductor tension transfers from the aluminum to the steel core strands, thus decreasing the tendency of the aluminum to creep. The tension in the aluminum strands will decrease when increasing the temperature until the tension in the aluminum strands is totally transferred to the steel strands. Above this temperature threshold (around 75ºC for ACSR conductors with cores with steel content beyond 7.5% by area), the creep in the aluminum strands ends, so only the thermal expansion and the creep of the steel strands further affect conductor sag. Therefore, conductors reinforced with high steel content are less predisposed to high-temperature creep compared to low steel content conductors [35]. Sag-tension models must include high temperature creep when the operating conductor temperature exceeds 75°C in case of AAC and 100°C for ACSR conductors. When high temperature creep is less than normal creep, high temperature creep has little effect on final sag and clearance. Contrarily, when high temperature creep exceeds normal creep, the effects on sag and clearance must be taken into account [35].

According to Cigré [82], mechanical sag-tension methods can be classified depending the method they include the creep as (1) methods not considering the creep; (2) methods considering the creep, which acquire its value from the experience; and (3) methods considering the creep, which acquire its value from experimental tests. Mechanical sag-tension methods are developed to calculate the sag of the catenary and conductor tension considering the evolution of conductor creep along its lifetime, at different conductor temperatures, and under ice and wind loading conditions [39], [82]. The most accurate mechanical methods are those considering independent aluminum and core behaviors, and determine the value of the creep based on experimental tests [82]. Such mechanical methods allow calculating the tension of the aluminum wires, thus calculating the KPT, where the aluminum gets loose. Among these methods, the most widely used is the graphical method [83], which is applied in different commercial software.

The hyperbolic and parabolic equations that define the relationship between span, tension and sag, can be applied to dead-end single level spans. When dealing with several level (or nearly level) spans of unequal length, it is required to develop simple methods for determining a hypothetical level span length for which the tension and sag characteristics can be applied to calculate the tension and sag behavior of all spans.

The ruling span method (RSM) allows correcting conductors' sagging while predicting conductor behavior with temperature, creep, and loads within the typical ranges of operation, i.e. 50ºC-70ºC [84]. The RSM has been widely applied to determine the tensions and sags on overhead power lines [85]. It assumes the same temperature for all spans and that once tensioned, conductors tend to slide along the suspension insulators, thus equalizing tension differences, so the horizontal tension component is identical in each suspension span, because the longitudinal swing of suspension insulators. The RSM converts an adjacent sequence of different suspension spans into a single level span. It allows predicting variations of the conductor tension with changing temperature or environmental variables. The RSM produces reasonable results for spans of the same length at the same level at any temperature as well as for spans with similar lengths at different levels at low temperatures [86]. However, the RSM leads to sag inaccuracies when the conductors operate beyond 100ºC [35], especially when dealing with spans of different length in which the tension differences have not been considered [84]. The modified ruling span method (MRSM) was developed to mitigate these issues. The MRSM allows calculating the sags and tensions at higher temperatures along sections with level spans of diverse lengths, while taking into account the effect of the inclination of the suspension strings [87]. In [88] a method to determine the tension and sag for level or non-level multiple span tension sections is presented, which allows evaluating the conditions in which the conductor temperature changes along the section. Finally, a method based on the formulation in [16] is presented in [85], which considers different conductor types in the same tensioning section, while allowing to deal with different temperatures on each individual level or non-level spans, which can be equal or unequal.

References [6], [89] present a method to determine the tension–temperature curve in operating lines by monitoring basic line parameters, such as ambient an conductor temperature, wind speed and mechanical load. In [90] a computer sag-tension program is presented, which is based on measured conductor current and weather conditions. In [25] a method to calculate tensions and sags on a tension section with different level or non-level spans of equal or different lengths at any temperature is presented, which allows dealing with conductor temperature changes along the tension section.

IEEE [35] proposes a set of predictor equations to determine the change in tension and sag for overhead conductors. Most sag-tension models of conductors based on limited laboratory and research works, assume a homogenous radial temperature profile within the conductor, which does not show a substantial radial thermal gradient. However, such limited works in ACSR conductors, indicate a non-negligible thermal radial gradient, which has implications on sag-tension models, since the core could be significantly hotter than the aluminum strands [35], [90]. This temperature gradient is in part due to the radiative and convective cooling on the aluminum strands [39]. According to [91], [92], due to the core materials, HTLS exhibit lower temperature difference between the aluminum strands and the core. For example, radial temperature differences of around 8ºC for ACSR conductors operating below 150ºC are reported in [93] and between 1ºC and 6ºC in case of ACCC conductors. Since the core usually carries most of the conductor tension, especially at high temperatures, the radial thermal gradient suggests potential significant errors or larger tolerances in sag-tension modeling tools [35]. Although other computer codes exist, most of them fail to predict the sag and tension change for multiple layer conductors with reinforced core at high-temperature operation, so further field measurements and research are required in this field [35].

B. Real-time sag monitoring

It is known that sag is a key parameter to ensure an efficient power transmission in overhead power lines. The conductors between two line supports generate a mechanical tension on the transmission tower which must be limited in order to do not damage it, and to ensure an adequate ground clearance. This tension can be limited by controlling the sag, although it changes over time due to the heating effect of the electrical current or changes in the values of weather parameters. Therefore, real-time transmission line sag monitoring is crucial for uninterrupted, safe and efficient power transfer. It is estimated that by monitoring sag and other parameters, transmission line capacity utilization can be raised by 10-30%. Real-time sag measurement also allow the operator taking immediate corrective actions in the case that ground clearance is below the allowable limit [94].

Sag monitoring systems based on global positioning system (GPS) and millimeter wave (mmWave) signals are found in the technical literature. In [95] the performance of two mmWave methods is compared for different practical overhead transmission lines. Whereas the first method is based on a single mmWave transceiver to measure the sag, the second method applies multiple transceivers. It is concluded that the second method offers improved accuracy compared with the first method. In [94] a GPS based system for real-time power lines sag monitoring is proposed. The GPS signal usually contains different inherent error sources such as satellite clock inaccuracies, ephemeris errors, or tropospheric and ionospheric delays among others, which affect the accuracy of the GPS receiver. By applying suitable signal processing techniques such as bad data identification and modification, least square parameter estimation and Haar wavelet transform, GPS receiver accuracy can be substantially improved, thus allowing to perform real-time sag measurements efficiently in overhead power lines.

VI. CONDUCTOR AGEING

Conductor deterioration limits the service life of power lines. The steel core and aluminum strands constituting ACSR conductors tend to corrode due to the direct contact between steel and aluminum [21]. The expected life for conventional ACSR conductors is about 50 years [96], therefore corrosion can be an issue. Overhead power lines are mostly inspected by visual assessment or even from thermal imaging, both from the ground or the air. However, by visual inspection corrosion remains unseen unless in a very advanced stage [97], and the same applies for thermal imaging and for other alternative methods [96]. According to [96], there is not a clear understanding of the corrosion problems and their severity on HV conductors, probably due to important differences among different environments.

Studies regarding corrosion effects on ACCC and polymer composite core conductors are very scarce. In [96] corrosion tests are applied to ACCC and ACSR conductors at room temperature and at 85ºC, concluding that the ACCC conductors undergo less galvanic corrosion than ACSR conductors, in ACCC conductors being the aluminum strands the corroding elements.

There are limited studies and no specific standards for testing the ageing behavior of HTLS conductors. In [98], [99] electro-thermal and mechanical stresses were applied simultaneously for investigating the ageing performance of HTLS conductors and fittings. For HTLS conductors incorporating thermal-resistant aluminum wires, no serious changes were found in the course of the 2000 h tests. However, fittings for conductors incorporating soft aluminum wires revealed an important increase of the measured joint resistances, due to a deterioration of the contact behavior. According to [99], to analyze in detail the ageing effects, more investigations are required, to determine the source mechanisms as well as to study the electrical resistance of the fittings with respect to load and time, and the contact performance of splices and dead-ends.

Apart from the aluminum strands and the supporting core, power transmission conductors usually include compression connections, such as splice connectors, which connect two aluminum bundle segments from different geometrical bundles in a transmission line. The region of the splice connector in a conductor is more sensitive to aging during service because of the material discontinuity and the crimped nature of the connector [100]. Annealed aluminum strands are more prone to suffer from creep deformation, thus leading to relaxation of the clamping stress of the connector and eventually to the separation of the line at the joint. These effects are aggravated with the daily thermal contraction/expansion cycles and when operating at higher temperatures. Finally, the electrical resistance at the contact area tends to increase due to corrosion, oxide deposits, electromigration, inter-diffusion, and fretting phenomena [101]. Such compression connections are commonly applied in HTLS power lines in current carrying fittings including dead-ends, jumper terminals and splices. They usually rely on the contact pressure and the shape of the contact area. However, there is little experience related to the long-term performance in compression connections operating beyond 100°C [102].

VII. COST ANALYSES

Investments in transmission lines require an intensive capital. Since, they have useful lives around 40 years [94], investment decisions have a long-term impact on the power system [26]. Different factors such as the asset life, load growth prediction, planning horizon, value of capital, or a cost benefit analysis among others have a deep impact to increase the utilization of an existing overhead line [33]. The conductor type is also a key decision variable. According to different references, when expanding transmission lines, the use of HTLS conductors allows a profit in the investment cost [76] and reducing the investment time [78].

Reconductoring existing transmission lines with HTLS conductors allow reducing operating costs, because they can offer improved transmission capacity and lower transmission losses, especially when operating below the full capacity [44]. The reduced costs of reconductoring with HTLS conductors are mainly because this possibility does not require constructing new structures [78], thus avoiding new right of way requirements [103], long construction periods and reducing manpower related costs [44]. However, large-scale application of HTLS conductors may be hindered because of relatively higher costs of such conductors compared to the conventional ACSR alternative [104]. Purchase costs of HTLS conductors are around 30% the capital investment required for the transmission line. As stated, HTLS conductors present other drawbacks, including higher voltage drop or increased power losses due to the operation at higher temperature, therefore being almost restricted to short lines [105] or to provide increased flexibility to accept renewable sources generation peaks. However, when the nominal operation of the line does not require the supplementary upgrade ampacity of the HTLS conductors, transmission losses will not increase. This strategy is often applied in North America, where the higher current capacity of HTLS conductors is only used for emergencies [104].

Table 4 shows the relative cost of HTLS conductors, including installation and accessories compared to ACSR.

Table 4. Relative costs of conventional ACSR conductors with respect to HTLS conductors. Adapted from [78], [106].

Conductor	ACSR	ACSS	GZTACSR	ZTACIR	ACCC	ACCR
Relative cost	1.0	1.1 to 1.5	2	3.5	5 to 7	10

The uprating of a 11.5 km, single-bundle, double-circuit, 230-kV transmission line was evaluated in [40], in which the capacity was expected to be doubled. The plan was to build new towers using twin-bundle ACSR conductors while keeping the right of way. HTLS conductors can use the existing towers although the suspension structure must be changed. According to [40], demolition, construction and installation costs of ACSRs conductors is in the range of 25-33% of the overall costs, whereas in the case of uprating with HTLS conductors (different types are analyzed), such costs are almost negligible. The costs associated to conventional ACSR conductors are around 9.0% of the project costs, while the costs associated to HTLS conductors depend on conductor type, varying between 5.3% and 12.5%. This study concludes that the costs associated to power losses are the most important ones, being around 67.4 % in case of ACSR conductors and ranging between 86.4% and 93.5% when using HTLS conductors. Table 5 shows the relative costs of uprating a 230 kV transmission line according to [40]. Extra energy loss of HTLS conductors compared to ACSR conductors shown in Table 5 is attributed to the higher temperature operation of HTLS conductors.

Table 5. Relative costs of uprating a 230 kV transmission line [40]

Conductor type	Percent costs			
	Demolition	Construction + installation	Conductor	Energy loss
ACSR	1.1%	22.5%	9.0%	67.4%
HTLS (5 types)	0.4-0.7%	0.7-1.2%	5.3-12.5%	86.4-93.5%

In [107] three uprating projects are considered, with two alternatives each, i.e., using ACSR or ACCC conductors, showing that in all cases it results more economical to upgrade with ACCC conductors by 16.3 - 43.8 % depending on the project characteristics when considering investment and operating costs.

In [108], a 85 km 220 kV line with 150 MVA peak load is analyzed over a time frame of 25 years, concluding that when uprating the ACSR based transmission line with HTLS conductors, savings up to 60 % are expected. This study also concludes that when analyzing different types of HTLS conductors, the costs due to the power losses do not differ considerably compared to the initial costs due to conductor purchasing and installation.

In [80] a 50 km double circuit transmission line is analyzed, with a maximum current of 600 A, predicting important costs reductions (power losses and CO_2 emissions) when uprating with HTLS conductors with respect to uprate the line with zebra ACSR conductors.

In [73] a comparison between a hypothetical 230 kV 100 km transmission line with a maximum capacity of 1 kA with Drake size ACSR conductors and a load ratio of 53% is compared against the same line uprated to 1.6 kA by using ACCC conductors. The study concludes that by using ACCC conductors, line losses can be reduced by around 73 MWh/year, thus obtaining savings around $3.65 million/year, and generation savings of $28.8 million, whereas the cost of reconductoring is much less.

Reference [104] considers six transmission lines to be reconductored by means of HTLS conductors, while analyzing the possible reduction of the operating costs by increasing the thermal ratings. For the analyzed cases, the payback time varies between 7 and 31.5 years. It is known that system operating costs increase with the load, specifically in lines presenting thermal ratings which significantly limit the optimal power flow. Therefore, when increasing system loading and/or the estimated load grow, higher cost reductions and shorter payback times are expected after line uprating.

In [23], the power losses associated to an ACSR equipped line are compared when uprating with ACCC conductors. This study concludes that when both conductors are operated at the rated capacity of the ACSR line, power losses of ACCC conductors are 25% lesser than those using equivalent ACSR conductors [23]. However, when both lines are operated at the maximum current, i.e. the maximum continuous operating temperature, which is 85ºC (902 A) and 210ºC (2114 A) for ACSR and ACCC conductors, respectively, power losses in ACCC conductors are 450% of those of ACSR conductors.

When increasing permissible current to raise line rating, circuit losses will increase considerably due to the increase of the electrical resistance because of the higher operating temperature [109] and the increased current, since power losses depend on the square of the current [104]. However, as explained, when the transmission line operates with low load factors, HTLS conductors can reduce power losses compared to conventional ACSR conductors. Therefore, to limit power losses and the associated economic costs, the operating temperature of conventional ACSR and HTLS conductors should be restricted, since these costs are the most important component among the other components (demolition, construction and installation, conductors purchase, power losses, and land associated costs), particularly for heavily loaded circuits. Therefore, it is recommended to operate the conductors below its nominal current carrying capacity, instead of being operated at high temperature, so that the extra margin of current carrying capacity can be reserved to deal with emergency conditions [40]. When making uprating decisions, the real economic cost of energy losses can be very important, but the importance associated to this cost to make investment decisions differs dramatically among different utility contexts [32].

The gradual penetration of distributed renewable energy sources faces congestion issues, thus impeding possible costs reductions of the electric power and an optimum utilization of the renewable energy sources. Generation peaks generated by renewable energy sources are sometimes not accepted in the system due to security reasons. In some cases, the thermal rating of highly loaded transmission lines can limit optimal generation dispatch. Therefore, this available energy is not used, so the economic benefits for the region are ruled out. However, transmission system operation can be enhanced by increasing the thermal ratings of the limiting transmission paths [29], and thus, line reconductoring with HTLS conductors is a feasible possibility. TSOs often must dispatch the energy produced by renewable energy sources through the existing overhead power lines in order to optimize transmission capacity [24]. The use of HTLS conductors allows increasing flexibility in power operation [103], and along with other strategies applied by the TSO, it may contribute to reduce the electricity's zonal price, reduce the number of constraints of the electricity market, while increasing power system resilience in front of disturbances.

Construction of new power lines or increasing the capacity of existing ones requiring new right of ways involve time consuming legal and regulatory aspects, this process usually requiring more than ten years. Therefore, alternative methods to increase power transfer such as reconductoring existing lines with HTLS conductors using current right of ways are appealing, despite the higher cost of the conductors or extra power losses, which could be offset by power market enhancement [29].

Energy regulatory bodies pursue reliable and low cost electric power supply for the costumers, which can be achieved by minimizing transmission congestions. Therefore, future transmission system expansion must consider possible reductions of the operating costs. Different factors can affect transmission expansion, including load growth, since a suitable transmission infrastructure is required, penetration of renewable energy sources and their impact on the existing power grid, proximity of the power plant to the energy sources, which can decrease generation costs, or ageing of existing transmission facilities, since when reaching the end of life, their transmission capabilities often do not satisfy increased load requirements [29].

According to all aspects reviewed in this section, it can be concluded that reconductoring with HTLS conductors offers many economic advantages, such as minimizing transmission congestions, allowing a smoother penetration of renewables, providing improved flexibility in absorbing generation peaks, reduction of power losses at low load factors, or avoiding new right of ways and the associated delayed legal and regulatory aspects, among others. However, the cost benefits due to the introduction of HTLS technology differs dramatically among different transmission lines and utility contexts, thus being not possible to generalize and hence, an economic study is highly required in each uprating project.

VIII. ENVIRONMENTAL ASPECTS

Economic and environmental limitations are key factors for applying uprating methods when planning new transmission lines [1]. The European energy and climate strategy includes a set of measures for the reducing greenhouse gas emissions and thus fighting the climate change, as well as minimizing energy imports dependence, so renewable sources of energy are fundamental to achieve these objectives [24]. However, the literature assessing the environmental impact of HTLS conductors is extremely scarce. In [107] three uprating projects are considered, with two alternatives each, i.e., using ACSR or ACCC conductors. This study concludes that for the three cases, and for all impact categories analyzed (air quality and sound environment; geology and water resources; landscape and visual impact; flora and line protection corridor; soil morphology; materials and waste) it is more environmentally advantageous to upgrade with ACCC conductors. In [110] the life cycle assessment (LCA) of three 150 kV transmission lines (overhead, land cable and sea cable) are carried out, concluding that there is a clear dominance of power losses for all environmental impact categories.

HTLS conductors have the ability to reduce line losses especially at low load factors due to the improved electrical conductivity of the annealed aluminum often used in such conductors, which in turn reduce fuel consumption and GHG emissions, thus promoting clean energy delivery. This is an important benefit of HTLS technology, since most of the countries have approved GHG reduction initiatives, whereas governors, regulators and policy makers consider these benefits as high-value topics. HTLS conductor technology also allows a smoother power system operation, especially in terms of capacity adaption due to the extra ampacity margin that this technology offers, thus providing increased flexibility in power system operation [24]. Capacity adaptation is nowadays an important issue, mainly due to the gradual increase of renewable energy resources in the electricity generation mix [111] as illustrated in Table 6.

Table 6. Electricity generation mix for some Europe countries, EU27 and USA for year 2018. Adapted from [111]–[113]

Country	**Total (TWh)**	**Solid fuels (%)**	**Oils (%)**	**Natural gas (%)**	**Nuclear (%)**	**Other non RES (%)**	**Hydro (%)**	**Wind (%)**	**Solar (%)**	**Other RES (%)**
Austria	68.4	5.3	1.0	14.5	0.0	1.0	60.1	8.8	2.1	7.2
Belgium	74.4	3.1	0.2	32.1	38.3	1.8	1.8	10.0	5.2	7.3
Germany	639.9	37.2	0.8	13.0	11.8	1.1	3.8	17.1	7.1	8.0
Denmark	30.3	21.6	0.9	6.8	0.0	2.3	0.0	45.8	3.1	19.4
Greece	53.1	32.3	10.4	26.4	0.0	0.5	10.8	11.8	7.1	0.6
Spain	273.6	14.1	5.3	21.1	20.3	0.4	13.4	18.6	2.9	3.9
Finland	69.8	14.4	0.4	6.0	32.6	0.7	19.0	8.3	0.1	18.4
France	579.8	1.8	1.0	5.3	71.0	0.4	12.1	4.9	1.8	1.5
Ireland	31.1	13.6	0.4	51.4	0.0	1.0	3.0	27.8	0.1	2.7
Italy	288.4	10.7	3.8	44.5	0.0	0.8	17.5	6.1	7.8	8.7
Luxembourg	2.2	0.0	0.0	8.9	0.0	3.5	60.7	11.6	5.4	9.9
Norway	146	0.1	0.0	1.8	0.0	0.1	95.2	2.6	0.0	0.1
Portugal	59.5	20.1	1.9	26.2	0.0	0.4	22.9	21.2	1.7	5.7

Sweden	163.0	0.9	0.2	0.2	42.0	1.0	38.1	10.2	0.2	7.3
United Kingdom	329.9	5.3	0.3	39.8	19.7	1.5	2.4	17.2	3.9	9.9
EU27	2933.9	21.5	2.2	16.7	25.9	0.7	12.6	10.9	3.7	5.7
USA	4209.1	27.2	0.6	34.9	19.2	0.5	7.0	6.5	2.3	1.8

Many countries have ambitious renewable energy targets by the coming years. Such an ambitious goal will require higher levels of power operation flexibility, where HTLS conductors may be a suitable choice given their adaptive capabilities.

IX. Identified Research Needs

This section summarizes the research needs identified from the extensive literature review, to address the concerns and issues facing HTLS technology.

(1) Stranded conductor sag estimates is an area to be further investigated. Most sag calculation codes assume that stranded conductors are isothermal, and the CTE and the final elastic modulus of aluminum and steel strands are constant values. However, stranded conductors cannot be regarded as isothermal at high temperatures, whereas both the elongation of the aluminum strands under plastic creep and the CTE are regarded as temperature dependent at high temperature operation, the last one also depending on the elastic modulus. Data related to creep rates for conductors of different strand ratios is also relatively scarce [12], so more tests to collect such data are required.

(2) Thermal models of multilayer conductors with reinforced cores for high temperature operation is another area to be further studied. Existing thermal models are restricted to low temperature operation, thus limiting the applicability of such models for HTLS conductors. To fulfill this gap, more experimental data and research is required, specifically for multi-layer conductors operating above 175ºC. Since the core usually carries most of the conductor tension, especially at high temperatures, the radial thermal gradient can lead to larger tolerances or significant errors on existing sag-tension models [35]. Therefore, improved models including the effects of the radial thermal gradients within the conductors are required. They should also take into account the decrease of the mechanical strength of aluminum wires, or the accelerated aging of the steel core.

(3) Power conductors are typically associated to splice connectors, dead-ends or jumper terminals, which produce hot spots due to the electrical resistance at the contact area. Thus, the contact region in the conductor is more prone to aging. These connections are also applied in HTLS power lines in current carrying fittings including splices, although there is little experience related to the long-term performance in compression connections operating beyond 100°C, so much research work and experimental analyses are required in this area.

(4) Studies related to the corrosion and ageing behavior of HTLS conductors, fittings, splices and dead-ends are very scarce, and there are no specific standards for this purpose [99]. It is a recognized fact that more research is required to study the source mechanisms and effects of ageing, as well as the evolution of the electrical resistance of the fittings, splices and dead-ends with time and load.

(5) Cigré has elaborated a guide [41] to provide assistance in the qualification of high temperature conductors, trying to fill the need to standardize the requirements for testing the conductors before being accepted for ordinary use. Qualification tests depend on the materials, since metallic, fiber reinforced metal composites, or polymeric materials must be evaluated using different standards. In addition, the properties (elastic modulus, tensile strength, CTE, creep, density or, conductivity) and thus the response of the materials depends on the operating conditions, so the behavior under increased temperatures may not be evaluated by applying the current standards [41]. So, there is a need to adapt current tests designed for conventional conductors working at low temperatures, to the requirements of HTLS conductors. Although some of the standard mechanical and electric tests can be directly applied to HTLS conductors, other ones need to be further elaborated or adapted. Among them highlight the fault current test, temperature cycle test, the cold

temperature test, or the sag and temperature performance test, for which there is no specific standard. In addition, all line accessories, including spacers, vibration dampers, dead-ends, or repair hardware must have specific tests for high temperature operation, to ensure they perform well when operating at high temperature [41].

(6) It is also required to develop standardized high temperature tests and thermal models for HTLS accessories [4] such as joints, clamps or connectors, in order to ensure that they can withstand the higher operating temperatures.

(7) Finally, it is also required to conduct LCA studies regarding the environmental impact of reconductoring existing power lines with HTLS conductors against other solutions, since at the authors best knowledge, there are virtually no works dealing with this topic. LCA allows identifying the benchmark for environmental improvements, since it can be applied to develop new products taking into account the environmental footprint.

X. Conclusion

This paper has performed a deep literature review of the current status of HTLS conductors which are being applied to increase the current carrying capacity of existing overhead power lines, due its beneficial aspects, technology readiness and maturity. The main benefits of applying HTLS conductors instead of conventional ACSR conductors, is that the first can dissipate more heat, while presenting lower coefficient of thermal expansion with an improved tensile strength. Therefore, they can operate above 200°C, whereas the capacity of the existing lines in some cases can be doubled, compared to conventional conductors operating below 100°C. However, the higher electrical resistance due to the high temperature operation may produce higher power losses. Therefore, the main drawbacks of using HTLS conductors are the considerably higher conductor costs and operating costs because of the increased power losses, thus being recommended operating below the nominal current carrying capacity to restrict the operating temperature and the associated Joule losses. The costs associated to power losses are a key point when making investment decisions.

This work has also highlighted different aspects of this technology for further improvement, thus identifying the main research needs to address the concerns and practical limitations that HTLS technology is facing. The identified needs are related to further improvements of thermal and sag-tension models, the assessment of the long-term performance of accessories for HTLS conductors, the need to study the source mechanisms and effects of ageing of conductors and fittings at high temperature operation, the need to develop specific standard tests for high temperature operation, and finally, the lack of LCA analyses for a detailed assessment of the environmental impacts of this technology.

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