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CONDUCTORS FOR THE UPRATING OF OVERHEAD LINES

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Conductors for the Upgrading of Overhead Lines

Working Group B2.12

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Dedication

The members of Working Group B2.12 would like to dedicate this technical brochure to the memory of Yakov Motlis. Yakov was a member of the working group for many years.

He cared deeply about this work and contributed greatly to its ultimate form and content. Yakov will be missed both for his contributions to our work and, even more, as a friend.

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Foreword

Across the developed world, there is a growing need to increase the power handling capacity of existing power transmission assets. At the same time there is fierce opposition to the construction of new lines on both aesthetic and environmental grounds, and large capital investments in transmission systems are difficult to justify given the rapid growth of unregulated, distributed generation and little certainty that such investments will yield acceptable returns. As a result of these conflicting pressures, increasing the thermal rating of existing overhead transmission lines by the methods described in this brochure is seen as a valid alternative to the construction of new lines.

The methods of increasing the thermal rating of existing lines are as follows:

- 1) Weather data and load profiles can be fed into computer programs whereby probabilistic ratings can be determined. This can be done on a line-specific basis or on a generic, system-wide basis. This can result in increased line ratings on a risk assessment basis [1-4]. The use of such methods, however, is dependent on regulations and statutory requirements for electrical clearances.
- 2) A real-time monitoring system may be used that determines the position of a conductor in space thereby determining the rating of the line in real-time [5-8]. Ratings are typically calculated to avoid exceeding design sags during periods of poor cooling by assuming pessimistic weather parameters. Real-time rating systems allow network operators to take advantage of periods of better cooling, normally increasing the thermal rating of critical circuits.
- 3) The electrical clearances under an existing line can be re-assessed, with the possibility that the rated temperature of the line can be increased with no physical modifications. This is rarely possible. However, in many cases, relatively modest physical modifications, based on a reassessment of clearances, can allow an increase in the line's maximum allowable conductor temperature. Such physical modifications might involve moving suspension clamps, re-tensioning the conductors, raising conductor attachment heights, or adding new structures in long spans.
- 4) The existing conductor may be replaced with a new conductor that has either a lower electrical resistance and/or is capable of operation at higher temperature within the existing line limits on sag and tension (i.e. has reduced high temperature sag).

The methods discussed in this brochure refer to items (3) and (4) above. These are methods exhibiting lower capital cost, minimal visual impact, and easier environmental acceptance than the construction of new lines. Three methods of increasing thermal rating are presented:

- a) Increasing the operating temperature of existing conductors while maintaining adequate electrical clearances.
- b) Replacing existing conductors with lower resistance conductors operating at moderate temperatures.

- c) Replacing existing conductors with conductors capable of operating at high temperatures and exhibiting low thermal expansion.

Methods (a) and (b) above are also discussed in related CIGRE documents [1] and [5]. Reference [1] concerns the use of statistically safe thermal ratings in place of conventional “worst-case” ratings. Reference [5] considers the use of real-time thermal ratings based on measurement of actual weather and line conditions. It is possible to combine these non-physical uprating methods with the physical methods of uprating discussed in this brochure to obtain still greater improvements in transmission line capacity.

In addition, certain factors must be taken into account prior to uprating:

- When uprating existing lines by replacing the conductors, an assessment must be made of the mechanical capability of the existing structures and should only be attempted if the structures are capable of supporting the required loads.
- The use of a larger conductor imposes greater loads on the existing structures and may reduce the reliability of the line unless the structures are reinforced.
- If reappraising the loading criteria for an uprated line, the line designer should consider changing the replacement conductor design, component wire materials, and making changes in the tension limits under both everyday and extreme conditions.

Bare overhead conductors are traditionally made up of nearly pure aluminium wires usually reinforced by steel wires where necessary for physical strength. The conductors described in this brochure are not limited to these basic wire types but are limited to conductors which are commercially available and which have been used extensively in at least certain areas of the world.

No specific economic analyses are described since each reconductoring application is in some sense unique. Technical information and comparisons, however, are made.

This brochure consists of two sections. The first section discusses how limits on conductor operating temperature are related to limits on electrical clearance and loss of strength at high temperature. Based on this methodology, the second section describes the various choices that allow increased line capacity.

We hope that the brochure will be of interest to the electric power industry and make a useful contribution to development of appropriate strategies for increasing the thermal rating of existing overhead lines.

Definitions

AAAC - All Aluminium Alloy Conductor.

ACAR - Aluminium Conductor Alloy Reinforced.

ACSR - Aluminium Conductor Steel Reinforced.

ACSS - Aluminium Conductor Steel Supported - A stranded conductor made up of fully annealed aluminium strands over a core of steel strands.

Ampacity - The ampacity of a conductor is that maximum constant current which will meet the design, security and safety criteria of a particular line on which the conductor is used. In this brochure, ampacity has the same meaning as “steady-state thermal rating.”

Annealing - The process wherein the tensile strength of copper or aluminium wires is reduced at sustained high temperatures.

ASTM - American Society for Testing and Materials.

Electrical Clearance - The distance between energised conductors and other conductors, buildings, and earth. Minimum clearances are usually specified by regulations.

EC (grade aluminium) - Electrical Conductor grade aluminium also called 1350-H19 alloy or A1.

EHS Steel - Also designated S3. Extra High Strength steel wires for ACSR.

GTACSR - Gap- type TAL aluminium alloy Conductor, Steel Reinforced.

HS Steel - Also designated S2. High Strength steel core wires for ACSR.

I.A.C.S. or IACS - International Annealed Copper Standard.

IEC - International Electrotechnical Commission.

Invar Steel - A steel core wire made with high Nickel content to reduce the thermal elongation coefficient.

Knee-point Temperature - The conductor temperature above which the aluminium strands of an ACSR conductor have no tension or go into compression.

Maximum Allowable Conductor Temperature - The highest conductor temperature at which an overhead power line can be safely operated.

RBS - Rated Breaking Strength of conductor. A calculated value of composite tensile strength, which indicates the minimum test value for stranded bare conductor. Similar terms include Ultimate Tensile Strength (UTS) and Calculated Breaking Load (CBL).

Ruling (Effective) Span - This is a hypothetical level span length wherein the variation of tension with conductor temperature is the same as in a series of suspension spans.

SDC - Self-Damping Conductor is an ACSR conductor wherein the aluminium strands are trapezoidally shaped and sized such that there is a small gap between layers to allow impact damping of aeolian vibration.

T2 - Twisted Pair conductor wherein two ordinary round stranded conductors are twisted around each other to enhance mechanical stability in wind.

TACIR - TAL Aluminium Alloy Conductor reinforced with an Invar steel core.

TACSR - TAL Aluminium Alloy Conductor reinforced by a conventional stranded steel core.

TAL – (“Thermal-resistant aluminium”) An aluminium zirconium alloy that has stable mechanical and electrical properties after continuous operation at temperatures of up to 150°C.

Thermal Rating - The maximum electrical current, which can be safely carried in overhead transmission line (same meaning as ampacity).

TW conductor - A bare overhead stranded conductor wherein the aluminium strands are trapezoidal in cross-section.

Uprating - The process by which the thermal rating of an overhead power line is increased.

Weight - This brochure generally uses conductor in weight per unit length. Mass per unit length can be obtained by dividing by the acceleration of gravity (approximately 9.81 m/sec²).

“Worst-case” weather conditions for line rating calculation - Weather conditions which yield the maximum or near maximum value of conductor temperature for a given line current.

ZTAL – (“Super Thermal-resistant aluminium”) An aluminium zirconium alloy that has stable mechanical and electrical properties after continuous operation at temperatures of up to 210°C.

ZTACIR - ZTAL aluminium alloy conductor reinforced by an Invar steel core.

1. - Calculation of Conductor Performance at High temperatures

1.1 Introduction

The thermal rating of an overhead line is the maximum electrical current that yields acceptable loss of conductor tensile strength over the life of the line and which results in adequate electrical clearance in all spans of the line under all weather conditions. Loss of tensile strength is a function of temperature, the degree of cold work during manufacture, and time. Electrical clearance is dependent on conductor sag, which is related to conductor temperature along the line.

Line current is approximately the same in all spans (unless there are “taps”). Air temperature and solar heating are also quite consistent from span to span. Wind speed and direction, however, can vary greatly from span to span along the line. Since the temperature attained by bare overhead conductors with moderate to high electrical currents is very dependent on both wind speed and direction, conductor temperature can vary along the line, both within long spans and from span to span.

Given the line current and weather conditions (air temperature, solar heating, wind direction and speed) at any location along the line, the local conductor temperature may be calculated by performing a heat balance calculation such as that suggested in the CIGRE brochure [9]. However, since wind conditions can vary greatly along the line, especially during periods of low wind, the calculation of appropriately conservative line ratings is less dependent on the details of the heat-balance equations than on the choice of appropriately conservative wind speed and direction to represent worst-case conditions along the line.

Electrical clearance between energized conductors and ground is dependent on the ground profile, the structure attachment heights, the span length, the everyday sag after heavy loading events and the energized conductor’s sag increase with temperature. The sag increase with temperature is determined by the conductor’s thermal elongation and is a complex function of temperature and tension. Sag-tension calculation methods are typically used to estimate the relationship between conductor temperatures and sag-tension. At high conductor temperatures, certain errors and assumptions found in common methods of both heat balance and sag-tension calculations may lead to uncertainty concerning the maintenance of adequate electrical clearance and the avoidance of excessive tensile strength reduction. This section of the brochure discusses some of the major sources of error in each of the component calculations used in line ratings.

In addition, certain factors must be taken into account prior to uprating:

- When uprating existing lines by replacing the conductors, an assessment must be made of the present capability of the structures. Replacing the conductors of an existing line should only be attempted if it has been demonstrated that the structures are capable of

supporting the required loads for the lifetime required of the new conductor system. In some cases, this might involve carrying out repairs or improvements to the structures.

- When replacing conductors, use of a larger conductor imposes greater loads on the existing structures and may reduce the reliability of the line unless the structures are reinforced. When renovating and especially when uprating an existing line, full advantage should be taken of beneficial terrain and foliage conditions, as they exist at each and every span or structure.
- When reappraising the loading criteria for an uprated line, the line designer should not lose sight of the possibilities of both changing the conductor design or materials and, of equal importance, making changes to the usage, or limits of use, that are applied to the conductor. (e.g. Limiting the ratio of tension to weight per unit length (H/w) in order to control Aeolian vibration [10,11] may lead to the application of larger replacement conductors with reduced steel content and lower weight.)

1.2 Thermal Rating Calculations At Elevated Conductor Temperature

Given “worst-case” weather conditions used for rating purposes, the maximum allowable temperature of a line’s energized conductors determines the thermal rating of an overhead line. The maximum allowable sag (for which the minimum ground clearance is maintained) and the maximum allowable loss of tensile strength of this conductor (over the life of the line), determine the maximum allowable conductor temperature. Thus the thermal rating of any overhead line is determined by the relationship of current and conductor temperature.

Figure 1 illustrates this relationship for three different sized conductors with typical “worst-case” weather conditions. Other limitations on power flow may exist. For example, power flow on transmission circuits may be limited by the economic cost of electrical losses, by system stability concerns, or by voltage “drop” along the line.

The relationship between the current and temperature was calculated by the use of thermal rating method described in [9], with typical values for conductor resistance and dimensions. The assumed weather conditions are described in the caption of Figure 1.

From Figure 1, it can be seen that a thermal rating of 1000 amperes is not unique to any conductor aluminium cross-sectional area. It may be obtained by using a conductor with an aluminium cross-sectional area of (A) 800-mm² at a conductor temperature of 70°C, (B) 400-mm² conductor at 100°C, or (C) a 200-mm² conductor at 200°C.

Clearly, if higher electrical losses are acceptable, and limits on loss of tensile strength and maximum sag can be met, the small conductors at higher temperature can yield the same thermal rating as large conductors at more conventional temperatures.

If the maximum allowable operating temperature of the existing line conductors is modest, it may be possible to accommodate operation at somewhat higher temperature by re-tensioning the original conductor or by raising attachment positions. In this manner, the line’s thermal rating can be increased without replacing the conductors.

If the increased structural loads resulting from the use of larger diameter replacement conductor are acceptable, it may be possible to increase the thermal rating of the line and to reduce the normal electrical losses by using a larger conductor which has lower electrical resistance.

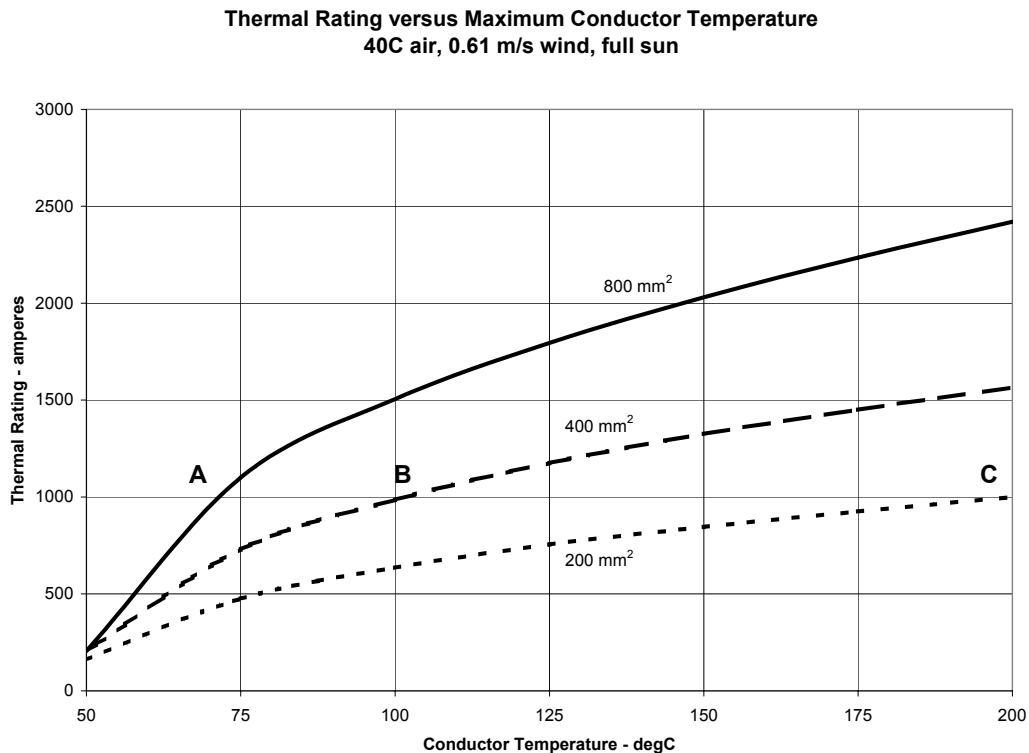


Figure 1 - Line thermal rating as a function of maximum allowable conductor temperature and conductor cross-sectional area

In many cases, however, the operation of existing line conductors at higher temperature is not possible and the use of a larger diameter replacement conductor may require extensive structural modifications that are either prohibitively expensive, physically impossible, or unacceptable to the public. In such cases, the use of a smaller cross-section replacement conductor, tolerant of operation at high temperatures, may be an attractive solution if the cost of electrical losses is acceptable. Of course, the high temperature conductors must also exhibit relatively low sag at high temperature in order to maintain electrical clearances. Some of the conductors discussed in section 2 of this brochure offer the possibility of operating at higher temperature without structural reinforcement.

1.3 Sag-tension Issues at High Conductor Temperature

A line's thermal rating is specified such that its energized conductors remain safely above people and vehicles under the line. As such it is critical that the correct sag-temperature relationship is obtained for all operating temperatures. This relationship is well defined for conductor operated at moderate temperatures (up to approximately 75°C), but it has been found that at higher conductor temperatures, particularly with non-homogeneous stranded conductors such as ACSR, there are anomalies relating to this relationship. This section highlights and explains these anomalies.

For new transmission lines, preliminary sag-tension calculations are performed for structural design. These calculations provide the maximum conductor tension loads. Final design includes stringing sag-tension tables for conductor sagging, as well as final sags at both “everyday” and

maximum design temperatures for line layout design that includes tower spotting and considerations of aeolian vibration etc. at minimum temperature.

In this brochure, we are only interested in the calculation of sag at the maximum allowable conductor temperature. Broader issues of sag-tension calculation are discussed in [12,13,14]. Therefore, our interest centres on both plastic and elastic elongation of transmission conductors at or above maximum allowable conductor temperatures of 100°C.

At high temperature, in lines with unequal suspension span lengths, this brochure considers the possibility that tension equalisation between suspension spans may be imperfect. In particular, in lines with grossly unequal suspension span lengths, sags in short spans may be underestimated and in long spans overestimated. Errors associated with the “ruling span” tension equalisation assumption are investigated.

In the case of non-homogeneous conductors (e.g. ACSR), we are concerned with the composite behaviour at high temperature. In particular, we investigate how compressive or residual forces in the aluminium strands beyond the “knee-point” temperature [15,16] may influence the maximum sag of the conductor.

In order to understand the essential issues at high temperatures, it is important to understand the methods used for sag-tension calculations. This is covered in the following section.

1.3.1 Graphical and linear methods for sag-tension calculations

The graphical method [12], as the name implies, makes use of experimental graphs and equations to represent the stress-strain behaviour of stranded conductors as a function of load, time, and temperature. Separate experimental curves are used to represent the stress-strain behaviour when the conductor is first installed (i.e. the “initial” curve) and after it has been installed for an extended period of time during which it is exposed to ice and wind loading (i.e. the “final” curve).

The linear method, which may also be based on experimental data, represents the stress-strain behaviour of stranded conductor with a single modulus of elasticity. The difference in initial and final unloaded sags is usually estimated based on experience rather than calculated. Generally, the change in modulus (experimental curve slope) between initial and final conditions is ignored in the linear method.

The “strain-summation” method of sag-tension calculation [14] also utilises laboratory test data but offers the opportunity to model multiple load and high temperature events rather than assuming a single loading event.

All of the sag-tension calculation methods are based on finding the intersection of two fundamental types of curves: the equilibrium relationship between conductor tension and elongation arc length (expressed as a percent increase over the span length) and a composite stress-strain curve of the conductor. As the length of the conductor changes with temperature and with time and elevated loadings, the sag-tension is recalculated by shifting the intersection point of the stress-strain curve(s) and their shape.

Figure 2 shows the typical result of sag-tension calculations by any of the methods. This figure illustrates several aspects of any sag-tension calculation:

- There is a permanent elongation of the conductor due to aluminium creep elongation reflected in the difference between the initial and final unloaded sag at 15°C.

- The sag under normal maximum ice and wind loading is less than the sag at high temperature.
- The sag at maximum temperature determines minimum ground clearance (and is sensitive to the thermal elongation behavior of the conductor).

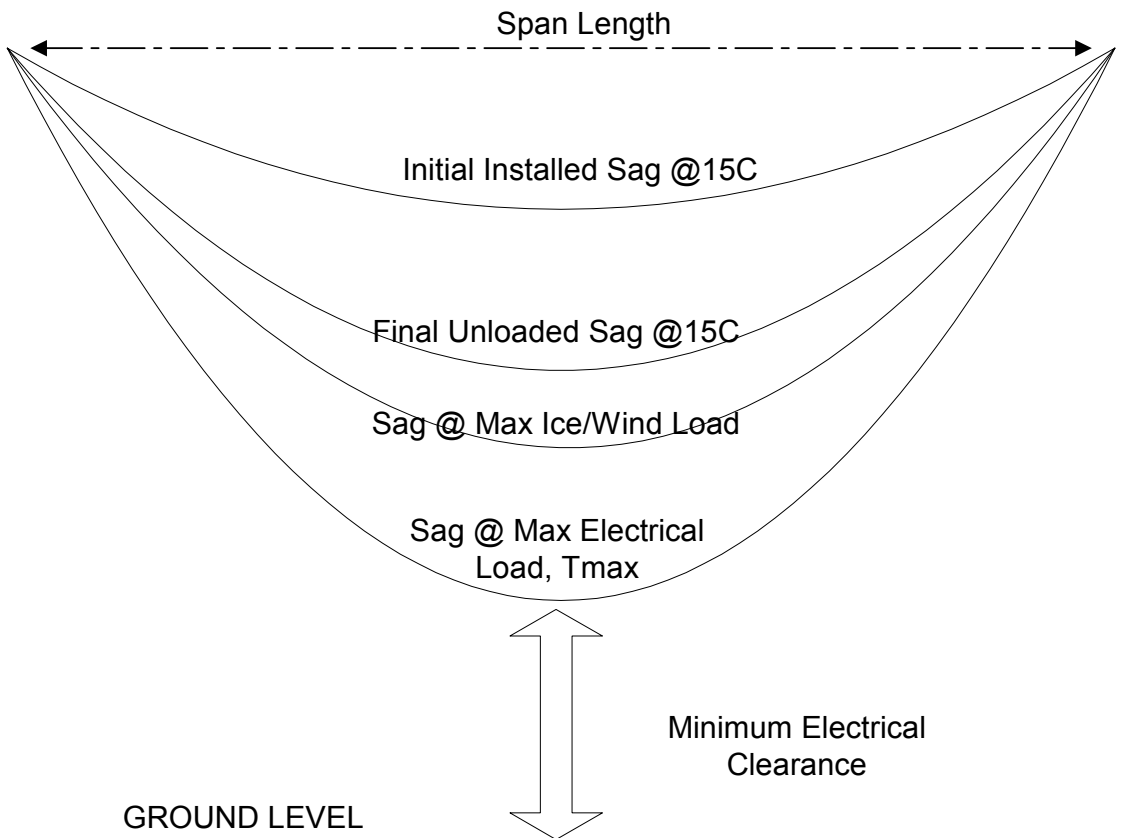


Figure 2 – Typical sag-tension variation with time, mechanical load, and temperature.

1.3.2 Sag-tension corrections for high temperatures.

Essentially all of the calculation methods used for high temperature sags are still based on methods, which have been verified as reasonably accurate at relatively low temperatures only. Recently, field information regarding sags at high temperatures has become available [17]. This information points out the need to correct the traditional calculations as summarised below. It is important to note that the individual error sources are cumulative and that most of them increase the sags. Thus, while any individual error may be of small significance, the combined effect can be profound.

There are several different sources of errors. They can be categorised as those errors that affect high temperature sag calculations for:

- all types of conductor in any single or multiple span line section
- conductors in multiple suspension-span line sections
- non-homogeneous conductors (e.g. ACSR)

1.3.2.1 Errors affecting any high-temperature sag calculation.

At high conductor temperatures, several errors impact sag estimates for all such conductors. These errors reflect the facts that stranded conductors at high temperature are not isothermal, that such high temperatures can influence conventional estimates of modulus and thermal expansion, and that plastic creep elongation of aluminium strands is affected by temperature.

Temperature differences between the strands.

Sag calculations are conventionally made assuming the conductor is isothermal. Actually, the temperature difference between the centre of the conductor and its surface is a function of the current density, the number of layers, the tension and the conductor diameter [18, 19]. For example, a current density of 2.5 A/mm² causes a surface temperature of 99°C and core temperature of 101°C in 403 mm² ACSR “Drake.” On the other hand, in a 1092 mm² ACSR “Bluebird” which has a much larger diameter, a somewhat lower current density of 2.0 A/mm² causes a surface temperature of 122°C and a core temperature of 126°C.

The correction for sags in non-steel core conductors is relatively straightforward. The sag correction consists of using average conductor temperature instead of surface temperature. The resulting sag increase in a 300 m span varies from a few centimetres for small conductors to over 10 cm for large conductors at 100°C. For steel-cored conductors, the situation is more complex because the temperature difference between the steel and aluminium wires also shifts the knee-point temperature upwards.

Effect of temperature on elastic modulus and coefficient of thermal expansion.

Sag calculation programs assume that the final elastic modulus and the coefficient of thermal expansion of aluminium and steel are constants, independent of temperature and stress. Actually, the rate of change of the coefficient of thermal expansion α is a function of the stress and elastic modulus E [20].

For high-carbon steel, the elastic modulus decreases by about 6.5%/100°C and for aluminium, about 5%/100°C. Because of the higher elastic modulus of steel, the resulting sag error is more pronounced for conductors with high steel contents. For example, in a 300 m span of ACSR “Drake”, the effect at 120°C would be a 0.2 to 0.3 m increase in the sag. Such small variations are likely to be of minimal significance in uprating but should be noted.

Creep elongation at high temperatures and increased tension.

The effects of high temperature creep are reasonably well known [21, 22], although there is a relative scarcity of data of creep rates of different strand ratios. High temperature creep occurs for ACSR conductors having a proportion of steel less than 7%. It is important to realise that, contrary to annealing, there is no specific temperature threshold for high temperature creep. It should also be noted that old conductors, which are primarily manufactured using hot-rolled aluminium rods, have a higher creep rate than newer conductors manufactured from the continuous-cast (“Properzi”) aluminium rods that are prevalent today.

Creep rates depend on tension and temperature. For example, assume that a 402 mm² AAC “Arbutus” is installed in a 300 m span and its final sag at 100°C is 12.0 m. If the material is rolled rod, operation at 100°C causes a sag increase of 0.2 m in 10 hours, 0.6 m in 100 hours and 1.1 m in 1000 hours. If the material is continuous cast (“Properzi”), the sag increases will be about 60% of the above values. Even on older existing lines, re-tensioning an existing conductor that has stabilised (“stopped creeping”) will cause additional creep due to the higher tension.

A survey conducted among utilities indicated that the majority of them realise annealing as a potential problem for high temperature operation. For the above example, most utilities would recognise that 1000-hour operation at 100°C causes a small loss of strength (about 2.5% according to [23]). Contrary to this, very few utilities account for the acceleration of permanent creep elongation of aluminium at high temperature. This can commonly cause substantial problems at much lower temperatures than annealing. However, conductor creep is determined by the combination of temperature and tension. As the conductor temperature increases, the tension of line decreases. In consequence, in some cases, high temperature creep is less than room temperature creep. Information on loss of strength due to high temperature can be found in [23].

1.3.2.2 Errors affecting sag calculations in multiple span line sections.

Sags of individual spans in line sections (i.e. between dead-ends) are often calculated using the “ruling span” principle. The ruling span principle assumes that the horizontal component of tension is the same in each suspension span, because the longitudinal swing of suspension insulators equalises the tension differences. In the recent past, it has been recognised that the insulator swing equalises the tension only partially. When the conductor heats, the insulator strings normally swing from short spans into long spans, and the result is that the tension varies more in the short spans than in the long spans. This behaviour and its impact on sags is described in detail in IEEE report [24], which found that most of the presently available multi-span sag/tension programs provided similar results. On the other hand, the results of these programs showed that ruling span method could cause sag errors which could be as much as 1 m in error at 100°C for certain combinations of unequal length suspension spans.

1.3.2.3 Errors affecting sag calculations of “Knee-point” temperature for non-homogeneous (e.g. ACSR) conductors.

The “graphical method” and the “numerical method” for sag calculations assume that there is a definite “knee-point temperature” above which the stress of the aluminium wires is zero. Thus, below the knee-point temperature, the conductor sag/temperature relationship depends on the composite elastic modulus and composite coefficient of thermal expansion, while above the knee-point temperature the behaviour depends on the elastic modulus and coefficient of thermal expansion of steel only. It is now known that:

- There is no exact knee-point. There is typically a range of 10-20°C, within which the conductor properties change from high to low values.
- The coefficient of thermal expansion and elastic modulus below and above the knee-point temperature may differ substantially from theoretical values [17, 25].
- The knee-point temperature is generally higher than assumed by classical calculation methods. There are two different explanations for the reason for the knee-point shift [15, 16]. Although conceptually different, they result in rather similar knee-point shifts and thermo-elastic behaviour above the knee-point. Thus, it has not been possible to judge between the relative merits of the approaches.

Table 1 shows the variation in knee point temperature with conductor steel core size and with span length. The knee-point temperature is not much above summer ambient for high steel content ACSR in short spans. These calculations were made using [12].

Name	ACSR Stranding	Steel mm ²	Span m	Kneepoint Temp [°C]	
				No Alum Compression	20 MPa of Alum Compression
Tern	45/7	28	300	150	156
Condor	54/7	53	300	100	112
Drake	26/7	66	300	70	88
Mallard	30/7	92	300	32	52
Drake	26/7	66	450	74	100
Drake	26/7	66	300	70	88
Drake	26/7	66	200	55	71
Drake	26/7	66	100	42	50

Table 1 - “Knee-point temperatures” for various strandings of ACSR as determined by the graphical method. All have an aluminium strand area of 403 mm²

1.3.2.4 Summary of high temperature sag errors.

The above list of factors causing high temperature sag errors may not be all-inclusive but identifies the most common and the most significant causes of errors. It needs to be stressed that the errors are cumulative and mostly additive (with the exception of the ruling span errors, which can be either positive or negative). Thus, in the worst case, such errors can amount to a sag error that can exceed 2 meters for temperatures above 100°C in 300m spans. It is thus imperative to analyse and correct such errors before operating lines at temperatures in excess of 100°C.

Typical error magnitudes in high temperature sag calculations

	<u>ACSR Drake</u>	<u>ACSR Condor</u>	<u>ACSR Tern</u>
Aluminium area (strands)	403 mm ² (26)	403 mm ² (54)	403 mm ² (45)
Steel area (strands)	66 mm ² (7)	53 mm ² (7)	28 mm ² (7)
Final tension at 20°C	25 800 N	23 150 N	19 100 N
Equivalent span length	250 m	250 m	250 m
Sag at 20°C	4.84 m	5.06 m	5.36 m

Effect of calculation methods on final 120 °C sag:

Calculation assuming constant modulus	7.76 m	7.78 m	8.53 m
Graphical method with no Al compression	7.00 m	7.53 m	8.53 m
Graphical method with typical 20 MPa maximum compression	7.32 m	7.73 m	8.53 m

Additional sag errors at 120 °C :

Temperature difference core/surface	+0.03 m	+0.05 m	+0.06 m
Change of elastic modulus vs. temperature	+0.15 m	+0.11 m	+0.06 m
High temperature creep	0	0	+0.50 m
Multiple span effects	+0.6 to -1.0	+0.5 to -0.9 m	+0.5 to -0.8 m
Effect of core magnetisation losses	0	+ 0.07 m	+0.05 m
Effect of manufacturing temperature	+/- 0.14	+/- 0.12	0

Table 2 - Typical differences in calculated high temperature sag as a function of ACSR steel core size.

Table 2 lists the sag errors produced by different knee-point assumptions. It also includes estimates of sag errors due to other relatively “minor” sources of calculation error including consideration of radial temperature differences between the steel core and outside of the conductor, change in elastic modulus with temperature, non-ideal ruling span effects, etc. Note that the errors due to non-ideal ruling span effects are generally larger than those errors due to the other factors and that sags are usually greater than predicted in the shortest spans and less than predicted for relatively long spans.

1.4 Summary of Conductor Performance at High Temperature

It is economically attractive to increase the thermal rating of an existing line while avoiding the need to replace the existing transmission line conductor. This avoids the cost of buying new conductor, reinforcing existing structures and the loss of service during the line reconductoring. In most cases, the increase in thermal rating that results from operating the existing conductor at a higher temperature is modest but in certain lines even small modifications can cause a substantial increase in rating.

The electrical current in the existing bare, overhead transmission line conductor is limited in order to avoid:

- Permanently reducing the conductor’s tensile strength through annealing of aluminium
- Permanently lengthening the conductor (and thus increasing its sag) by a process of accelerated high temperature creep of aluminium
- Momentarily violating regulatory electrical clearances through excessive reversible sag increase at high conductor temperature.

If it is necessary to reductor an existing line (either because there is not sufficient electrical clearance or because the existing conductor is in poor condition), it may be economically (and sometimes environmentally) attractive to use a replacement conductor that does not require the extensive reinforcement of existing structures. This normally requires that the replacement conductor be operated at temperatures well above the annealing temperature of ordinary aluminium (90°C) and presents a number of difficult calculation issues that are not normally encountered in conventional line design.

Section 1 of this brochure discusses some of the primary concerns about high temperature operation of transmission line conductors. These concerns involve the accuracy of sag calculations at temperatures that may, at least occasionally, exceed 100°C. Non-homogeneous conductors such as ACSR present a particular challenge. Sag calculation errors may result from the following:

- Incorrect modelling of thermal elongation of non-homogeneous conductors, such as ACSR, above their knee-point temperature.
- Permanent elongation of aluminium strands when tension and/or temperature are above everyday levels.
- Temperature differences between the core and the surface of conductors at high current densities.
- The failure of tension equalisation at high conductor temperatures in lines having large span length variations.
- Increased effective electrical resistance due to core magnetisation losses in steel core high temperature conductors.

While the preceding Section of this brochure presents some estimate of the order of magnitude of sag errors due to these factors it does not provide definitive answers to all the questions.

2. - Conductors for Increased Thermal Rating of Overhead Transmission Lines

2.1 Introduction & Summary of Conductor Use Survey

The first task of CIGRE TF B2.12.1 was to conduct an international survey of utilities to determine the identified needs for higher temperature operation and the related present practices. Responses were received from 71 utilities in 15 countries. They indicated that although the present practices had wide differences, the anticipated needs showed very similar trends.

The survey confirmed that the vast majority of the installed conductors today are ACSR (82%), although some European countries show preferences for AAAC and ACAR conductors in their newer lines. Special conductors of many types exist [26, 27] which reflects the need for local solutions to regional problems. Regionally, some of these special conductors have been used enough to be considered “normal” there. Examples are TW, SDC, ACSS and T2 conductors in North America, and TACSR, GTACSR, and ZTACIR in Japan and Asian countries (these conductor types are defined in the “Definitions” section).

Most utilities in the world operate their lines under normal conditions at temperatures up to 85-100°C, with emergency temperatures which are usually 10-25°C higher, but some utilities use temperatures of up to 120°C normal and up to 150°C emergency. The calculations used in thermal ratings of the lines are generally quite similar, and usually follow reasonably closely the recent CIGRE Standard method [9], or the closely related IEEE Standard 738 [28]. With a few notable exceptions, ratings are calculated using deterministic assumptions of a high ambient temperature, full solar radiation and a low wind speed. Most utilities assume wind speeds of 0.5-0.6 m/s, but a number of utilities have recently increased the wind speed assumption to 0.9-1.2 m/s.

The survey showed that most power utilities have felt the pressure to increase line ratings. The majority of the responses indicated that their company had, in the recent past, increased the maximum operating temperatures of existing lines, changed the weather assumptions used to calculate line ratings, and/or reconducted or re-tensioned lines. A significant minority had either applied special conductors or used real-time rating methods to increase ampacity. These trends are expected to continue in the future.

The respondents were asked to rank their interest in the future information needs of conductors. The highest interest (78% combined “Very High” and “High”) was given to “Better information on high temperature sags of present conductors” and “Information on high temperature creep or annealing of present conductors.” “Conductors with reduced sag at high temperatures” (75%) and “New conductors for higher operating temperatures” (65%) followed closely.

The survey clearly showed that there is a need to operate existing lines at higher temperatures. On the other hand, the individual responses showed a marked reluctance to drastic changes in materials. A significant number of responses indicated that new conductor materials should not drastically affect line design or maintenance. A large number of respondents also indicated that

the acceptable premium price for new conductors was quite limited, except in very special cases (such as river crossings and congested urban areas) where the cost of alternatives (such as expensive rerouting or underground cables) was very high.

2.2 Increasing Line Capacity (Thermal Rating) With Existing Conductors

Line thermal ratings can be increased without replacing the existing line conductors in one of two ways: the maximum allowable conductor temperature may be increased; or a probabilistic rating can be determined. Whatever the method, an increase in capacity of the line will allow operation at higher current levels, and increased electrical loading will result in increased average operating temperature of the phase conductors, their connectors, and support hardware. Since this approach is often taken on older lines, mechanical reliability is a significant concern.

It should be noted that the selection of less conservative weather conditions for thermal rating calculations without a thorough engineering analysis of line ratings is a potentially dangerous but economically attractive process. Increasing the thermal rating on lines without such analysis will inevitably lead to an increased utilisation and an increased probability of sag clearance violations. Generally, this method is not valid and can be dangerous to public safety.

2.2.1 Maintaining electrical clearances.

If the maximum allowable conductor temperature is to be increased, then the corresponding maximum conductor sag will increase and existing electrical clearances will decrease. A careful physical review of the line under everyday conditions is required for the computation of revised line clearances at the new higher temperature. With steel-reinforced aluminium conductors (e.g. ACSR), the thermal elongation rate at high temperature must also be re-evaluated as discussed in later sections of this brochure.

If the electrical clearance corresponding to the new higher conductor temperature is determined to be above the appropriate legal minimum at all points along the line, then no modifications need be undertaken. Verification of adequate sag should be undertaken after establishing higher ratings without physical modification of the line. The calculation of clearances at high conductor temperatures should consider the possible permanent elongation of aluminium conductor due to extended operation at high temperature.

If electrical clearances corresponding to the new higher conductor temperature are inadequate, then either the support points must be raised, the conductor tension increased, suspension clamp positions changed, or conductor length reduced. All such physical modifications must be carefully considered and strain structures reinforced if these conductor changes increase the maximum conductor tensions.

2.2.2 Limiting loss of tensile strength.

For conductor temperatures above 90°C, hard-drawn aluminium and copper strands will lose significant tensile strength (“anneal”) over time [23, 29]. Copper wires may also anneal at lower temperatures although the rate is very slow. Temperatures below 300°C do not affect the tensile strength of steel strands. Aluminium conductors having a steel core (ACSR) also experience loss of composite strength if operated above 90°C but, since the strength of the steel core is unaffected, the reduction in tensile strength in the aluminium strands is of less concern than for phase conductors made entirely of aluminium or copper strands.

Aluminium strands made from rod made by the continuous casting process are less susceptible to annealing than those drawn from “rolled rod.” Since the rod source for an existing stranded conductor may be unknown, it is conservative to assume “rolled rod” as the source of aluminium wires.

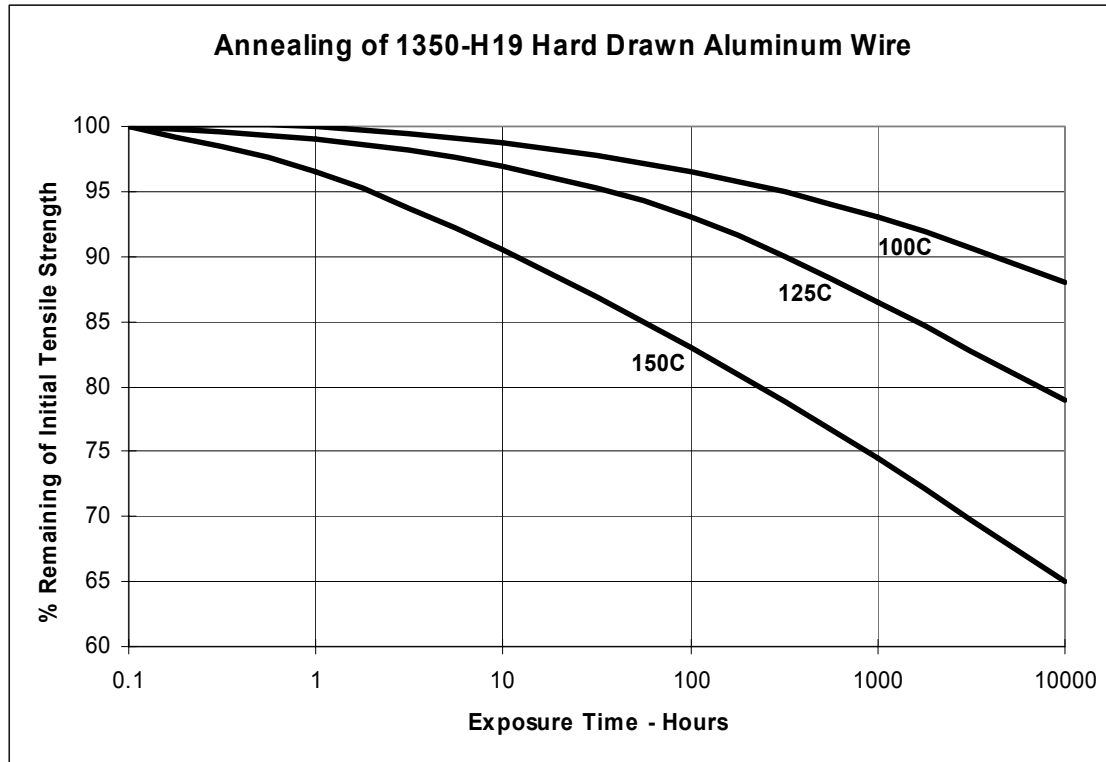


Figure 3 -Typical annealing curves for aluminium wires, drawn from “rolled” rod, of a diameter typically used in transmission conductors [13].

The conductor temperature must remain above 90°C for an extended period of time for the reduction of strength to become significant. For example, with reference to Figure 3, an all aluminium conductor at 100°C must remain at that temperature for 400 hours to lose 5% of its tensile strength. This loss of tensile strength is cumulative over the life of the line so routine emergency operation at 100°C may be unacceptable over time even though individual events may persist for no more than a few hours.

As the conductor temperature increases, the rate of annealing increases rapidly. At 125°C, an all aluminium conductor will lose 5% of its tensile strength in only 30 hours. For aluminium strands drawn from continuous cast rod, the loss of strength in these two high temperature-time combinations is negligible.

The loss in tensile strength, at temperatures above 100°C (above 125°C for wire from continuous cast rod) may be limited by using “limited time” ratings where high currents are allowed only for brief periods of time. As noted in many references, the presence of a steel core, which does not anneal, reduces the loss of strength for ACSR conductors.

2.2.3 Avoiding connector failures.

Unless an increase in rating is preceded by a careful inspection of the energized conductors, connectors, and hardware, the higher operating temperatures will result in a reduction in reliability. As described in reference [30], the detection of “bad” compression splices prior to their failure during emergency loadings is not simple. Regardless of the probability of mechanical failure a connector is usually considered failed if it operates at a temperature in excess of the conductor.

There are two types of connectors: low tension and full tension splices. Low tension connectors include compression and bolted types and are used at strain structures in “jumpers” and other locations where the full rated mechanical load of the conductor will not develop. Full tension splices are found in span and at termination points of line sections.

One of the greatest challenges in increasing the line capacity without replacing the conductors concerns evaluating the connectors. This is the result of a number of factors:

- The workmanship of old connectors is problematic.
- There may be a variety of existing connector types to evaluate.
- Infrared temperature measuring cameras are ineffective at normal electrical load levels.
- Corrosion in connectors is hard to detect.

As a result of these uncertainties, an effort should be made to identify old connectors that are likely to fail under increased electrical loads. This can be done with infrared or resistance checks [30]. If the condition of existing connections is uncertain, then shunts or mechanical reinforcement should be considered in order to avoid mechanical failures at high current loading.

2.3 Increasing Line Thermal Rating Capacity by Conductor

Replacement

Conductor replacement can be a very effective method of increasing the capacity of a transmission line. Depending on the type of conductor already in place, the temperature for which it was originally designed, and the desired new operating temperature, significant enhancements in both thermal rating and reliability can be achieved at a cost that may be very much less than that of building a new transmission line. This does, however, assume that very few, if any, structural modifications are required to enable the towers to accommodate the new conductor. There is a wide variety of conductors in use worldwide, and any specific choice for a particular project will depend on the circumstances and conditions applicable to that project.

Replacing the conductors of an existing line can only be attempted on a line that has demonstrated over a period of years that it has some reserve of strength to resist the weather-related loads that have occurred. The reliability of a line that has exhibited frequent structural failures is unlikely to improve as a result of reconductoring.

Increasing the ampacity of an existing line by use of a replacement conductor larger than the original (having lower resistance) will increase both ice and wind loads and tension loads on existing structures. A larger conventional conductor, imposing greater loads on the existing structures, may reduce the reliability of the existing line unless the structures are reinforced.

Increasing the ampacity of an existing line by use of a replacement conductor having nearly the same diameter as the original conductor but capable of operation at higher temperature (within existing sag clearance and loss-of-strength constraints) may avoid the need for extensive reinforcement of suspension structures. Section 2.3.4 of this brochure considers several different types of high-temperature, low-sag conductors that can be used to increase the ampacity of existing lines with a minimum of structural reinforcement.

2.3.1 Replacement conductors for operation at moderate temperatures (<100°C).

This section of the brochure describes two broad categories of replacement conductor. Each is suitable for operation at moderate temperatures (<100°C). The first category includes conductors using alternative materials to those used in ACSR. These are AAAC and ACAR conductors which both make use of aluminium alloy in their construction [31, 32]. AACSR (Aluminium Alloy Conductors Steel Reinforced) also make use of aluminium alloy but only give a benefit over standard ACSR where they make use of high temperature alloys such as TAL and ZTAL, and are therefore not described in this section. The second category includes replacement conductors with alternative stranding arrangements to the standard round-wire construction. These conductors include those with compacted constructions and those designed to resist wind-induced motion. These types of construction are applicable to conductors of all material types, including those designed for high operating temperatures.

2.3.1.1 All Aluminium Alloy Conductor (AAAC).

For transmission lines strung with ACSR, designed, for relatively low temperature operation (50 to 65°C), restringing with AAAC can offer a significant improvement in thermal rating. AAAC conductors have a higher strength to weight ratio than ACSR and, if strung to a similar percentage of rated breaking strength (RBS), can be rated for higher temperature operation than ACSR, without exceeding design sags. It should be noted however, that stringing to a similar percentage of RBS would result in a much higher ratio of horizontal tension (H) to unit weight of conductor (w), which can cause problems for lines sensitive to aeolian vibration. In the United Kingdom, where favorable terrain and/or vibration dampers allow stringing at relatively high H/w values [9, 10], AAAC has been used extensively for the uprating of ACSR lines. AAAC is also widely used in other countries for the construction of new lines.

The alloy used in AAAC is, most commonly, a heat-treatable aluminium-magnesium-silicon alloy, designated by IEC 60104. There are many tempers available, varying in strength and conductivity. Conductivities range between 52.5% and 57.5% IACS (EC grade Aluminium has a conductivity of 61% IACS), while strengths vary between 250 MPa and 330 MPa. As a rule of thumb, the higher the conductivity of the alloy, the lower the strength, and vice versa.

Aluminium alloy conductors (295 MPa, 56.5% IACS) have been widely used in the UK to replace ACSR (“Zebra”, 400mm² nominal aluminium area, 54/7 x 3.18mm strands). Comparing properties, an AAAC with the same diameter as Zebra will be 3.5% stronger, 18.5% lighter and have a 5% lower DC resistance. Matching either the resistance or the strength of Zebra gives similar results, but with a slightly smaller conductor. If climatic conditions and tower capabilities permit the use of a larger conductor, then an AAAC with the same unit weight as “Zebra” will be 24% stronger, have a 20.5% lower DC resistance, but have a diameter almost 10% larger.

Where the AAAC can be strung at a similar percentage of RBS to ACSR, thermal rating increases of up to 40% can be achieved with a conductor of the same diameter and 50% with a conductor of the same weight. This may require additional mechanical damping since the H/w ratio of the AAAC will be higher than the ACSR that it replaces. There are no ferromagnetic or transformer effect losses with AAAC.

AAAC generally has good corrosion performance. The lack of a steel core removes the possibility of galvanic corrosion taking place, such as is possible in ACSR. However, corrosion is still possible, especially in coastal regions, and it is often standard practice to use greased AAAC to prevent corrosion by salt aerosols.

2.3.1.2 Aluminium Conductor, Alloy Reinforced (ACAR).

ACAR combines strands made from aluminium alloy, typically the same as that used for AAAC, and EC grade aluminium. This allows the properties of the conductor to be optimised for a particular application. By increasing the amount of EC grade aluminium used, the conductivity of the conductor is increased, though at the expense of strength. Likewise, if the number of alloy strands is increased, the mechanical strength of the conductor is increased at the expense of conductivity. Again, as with AAAC, the benefits of using ACAR conductors to replace ACSR conductors will depend on allowable stringing tensions.

2.3.1.3 Shaped-wire conductors.

Overhead line conductors are normally constructed from helically wound wires with a circular cross section. This results in a conductor cross-section containing fairly large inter-strand voids, with ~20% of the total cross-sectional area of the conductor being air. By using wires with a trapezoidal shape, conductors can be constructed with an increased proportion of metal within their cross section. Compacted conductors can be homogenous like AAAC/TW, with all strands except the king wire being of trapezoidal shape, or non-homogenous like ACSR/TW, with a round-wired, steel core surrounded by trapezoidal aluminium wires. However, the strands that make up shaped-strand conductors need not be trapezoidal. One conductor design has mosaic (“Z”) shaped strands that effectively lock together.

Shaped-wire conductors have a larger aluminium area and thus lower resistance than a normal round strand conductor with the same outside diameter. When reconductoring an existing line with shaped-wire conductor, the increased weight of the conductor will result in slightly higher tower loads, but climatic loads due to wind and/or ice will not be increased, as these are a function of diameter. For wind-only loading conditions, loads may actually be lower, as the aerodynamic properties of the surface result in a lower drag coefficient at high wind speeds. One example of shaped-wire conductor that achieves a low drag coefficient is one that has an oval cross-section, the orientation of which varies along its length, giving a “spiral-elliptic” shape. [33]

Furthermore, shaped-wire conductors have been shown to possess slightly better characteristics of energy absorption of vibration, due to the higher surface area of the contacts between strands of adjacent layers which results in lower inter-strand contact stresses [34, 35].

2.3.1.4 Motion-resistant conductors.

Shaped-wire conductors have also been used to reduce the effects of wind-induced motions. Such conductors include “self damping” (SDC) conductor, which incorporates small gaps between the successive layers of strands, allowing energy absorption through impact [36, 37]. Another conductor which resists motion is the “T2” conductor, consisting of two standard round conductors wrapped about one another with a helix approximately 3 meters long [38]. This resists motion due to its aerodynamic characteristics and is widely used in the United States.

Existing lines are normally designed or reconducted with T2 or SDC in order to improve their resistance to ice galloping flashovers and to aeolian vibration. At least theoretically, T2 can be made with any of the conductors discussed in this section, possibly including those designed for operation at high temperature.

2.3.2 Conductors for operation at high temperature (>100 °C).

This section presents comparative information for four basic types of transmission conductor – TACSR (or ZTACSR), GTACSR (or GZTACSR), TACIR (or ZTACIR), and ACSS. Each is stranded with a combination of aluminium alloy wires for conductivity, and reinforced by core wires of steel. The steel core wires are coated to prevent corrosion between the steel and aluminium. The properties of the various alloys and tempers of aluminium and the similarly various types of high strength steel core wires are compared in Tables 3 and 4. For example, TACIR is manufactured with layers of TAL aluminium alloy wires over an Invar steel core and ACSS is available in both round wire and trapezoidal wire constructions with standard strength or high strength core wires.

Any of the four types of conductor is capable of operating continuously at temperatures of at least 150°C. Some of the conductors can be operated as high as 250°C without significant changes in their mechanical and electrical properties. Each conductor type has certain advantages and disadvantages, which are discussed briefly in this brochure.

2.3.2.1 Conductor materials.

These conductors, designed for high temperature operation, consist of various combinations of the aluminium and steel wire materials listed in Tables 3 and 4.

Zinc-5% Aluminium Mischmetal coated steel wire is capable of operation at higher temperatures than normal galvanised steel wire (i.e. 250°C instead of 200°C). Invar steel wire has a notably lower rate of thermal expansion when compared to ordinary galvanised steel core wire but has somewhat lower tensile strength and modulus.

Type of Aluminium		Conductivity (%IACS)	Min. Tensile Strength (MPa)	Allowable Operating Temperature(°C)	
				Continuous	Emergency*
Hard Drawn	1350-H19 (HAL)	61.2	159 - 200	90	120
Thermal Resistant	TAL	60	159 - 176	150	180
Extra Thermal Resistant	ZTAL	60	159 - 176	210	240
Fully Annealed	1350-0	63	59 – 97	200 – 250**	250**

Table 3 - Characteristics of Aluminium and High Temperature Aluminium Alloy Wires.

**Emergency operating temperature is not well defined but it is generally agreed that the emergency temperature should not apply for more than 10 hours per year.*

***Fully annealed aluminium strands can operate at temperatures in excess of 250°C but are normally limited to lower temperatures because of concerns about connectors and steel core wire coatings.*

TAL and ZTAL aluminium wires have essentially the same conductivity and tensile strength as ordinary electrical conductor grade aluminium wire but can operate continuously at temperatures up to 150°C and 210°C, respectively, without any loss of tensile strength over time. Fully annealed aluminium wires are chemically identical to ordinary hard drawn aluminium, have much reduced tensile strength, and can operate indefinitely at temperatures even higher than 250°C without any change in mechanical or electrical properties.

For the purpose of this brochure, where a conductor construction referred to could be made up using either the ZTAL or the TAL alloy, it is described as (Z)TAL.

	Min. Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Coef. of Linear Expansion ($\times 10^{-6}$)
Galv. Steel HS Galv. Steel EHS	1230-1320 1765	206	11.5
Alum. Clad (AC) 20.3% I.A.C.S.	1103-1344	162	13.0
Zinc-5%Al. Mischmetal Standard HS	1380-1450 1520-1620	206(Initial) 186(Final)	11.5
Galv. Invar Alloy	1030-1080	162	2.8-3.6

Table 4 -Characteristics of Steel Core Wires for use in overhead conductor.

2.3.2.2 High temperature conductor constructions.

TACSR and (Z)TACIR are stranded in the same fashion as ordinary ACSR. Their electrical and mechanical properties are simply the result of their composite aluminium and steel wire properties.

ACSS can be stranded using either round or trapezoidal shaped aluminium wires. In either design, the conductor depends primarily on the steel core wires for mechanical strength.

The unique installed properties of G(Z)TACSR are the result of both its wire properties and its construction. The innermost layer of (Z)TAL wires is trapezoidal and a small gap to the core is left to allow installation with tension applied to the steel core only.

2.3.3 Application of high temperature conductors.

The advantages and disadvantages of each of the high temperature conductor designs are summarised in the following section. A comparison of their sag behaviour as a function of operating temperature is also presented. The comparison is not exhaustive but rather presented in order to clarify the way in which each conductor combines material and construction innovations to allow operation at high temperature within the confines of adequate electrical clearance.

2.3.3.1 (Z)TACSR

(Z)TACSR has the same construction as conventional ACSR, with galvanised steel wires for the core and (Z)TAL wires (thermal-resistant aluminium alloy wires with zirconium added) surrounding them. Table 3 shows basic characteristics of (Z)TAL wires.

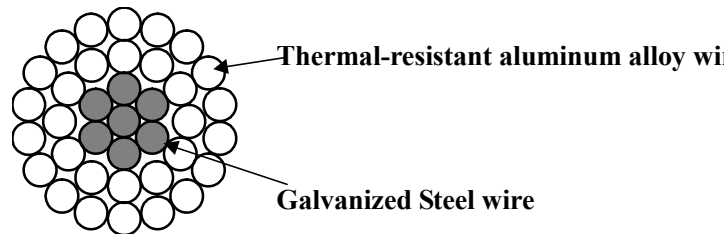


Figure 4 - Cross-section of TACSR Conductor

(Z)TACSR conductor is, in almost all respects, identical to conventional ACSR conductors. The aluminium alloy used in (Z)TACSR has a slightly higher electrical resistivity than standard hard-drawn aluminium, but in all other respects the two conductors are almost identical. Unlike the conductors described below, (Z)TACSR is not, by design, a low-sag conductor. It has the same thermal elongation behavior as ACSR. The main advantage of (Z)TACSR is that its aluminium alloy wires do not anneal at temperatures up to 150°C for TAL and 210°C for ZTAL (Temperatures above 100°C would cause annealing of the aluminium strands in standard ACSR).

(Z)TACSR can therefore be used to uprate existing lines where some additional clearance is available. Steel-cored conductors (and other non-homogeneous conductors) have what is known as a “knee-point.” This is a temperature above which the higher thermal expansion rate of aluminium causes all the stress of the conductor to be borne by the steel core. Beyond this knee-point temperature, therefore, the conductor experiences a sag increase due to the expansion of steel alone. This new expansion coefficient will be lower than that for the conductor at lower temperatures, resulting in relatively low sag increases when operated at high temperature. Standard ACSR exhibits this property, but usually at a temperature beyond the annealing limit. The TAL alloy of TACSR allows this behavior to be exploited. At present TACSR is currently used in place of conventional ACSR in more than 70% of the transmission lines in Japan.

2.3.3.2 G(Z)TACSR

Gap-type conductor [39] has a unique construction. There is small gap between steel core and innermost shaped aluminium layer, in order to allow the conductor to be tensioned on the steel core only. This effectively fixes the conductor’s knee-point to the erection temperature, allowing the low-sag properties of the steel core to be exploited over a greater temperature range. The gap is filled with heat-resistant grease (filler), to reduce friction between steel core and aluminium layer, and to prevent water penetration.

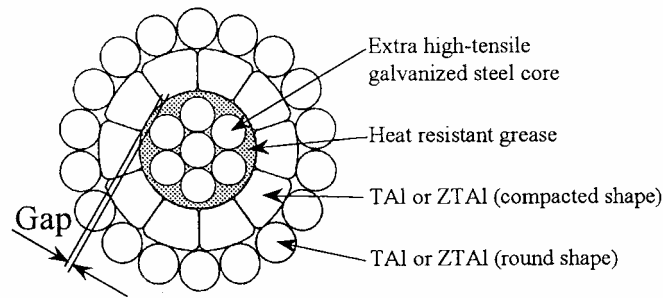


Figure 5 - Cross-section of GTACSR conductor

Table 6 compares the properties of “Zebra” ACSR with 440 mm² G(Z)TACSR. When compared for a given thermal rating, the G(Z)TACSR will be able to reduce the sag as compared with the conventional ACSR.

During installation of G(Z)TACSR, the aluminium layers of conductor must be de-stranded, exposing the steel core, which can then be gripped by a come-along clamp. The conductor is then sagged on the steel core, and after compression of a steel clamp, the aluminium layers are re-stranded and trimmed, and aluminium body of the dead-end clamp compressed. Although this special erection technique is different from that employed with conductors of standard construction, the compression splices and bolted suspension clamps are similar. In addition, in order to assure proper performance of this conductor, a special type of suspension clamp hardware must be installed every three suspension spans.

2.3.3.3 (Z)TACIR

As with (Z)TACSR, (Z)TACIR [40] has a conventional stranded construction (identical to ACSR), making use of material innovations to give properties allowing the conductor to be operated at high temperatures. In place of the steel strands of (Z)TACSR, it has galvanised or aluminium-clad invar alloy steel wires for the core and (Z)TAL wires surrounding them. Table 3 shows basic characteristics of TAL and ZTAL wires. ZTAL resists annealing up to a continuous temperature of 210°C.

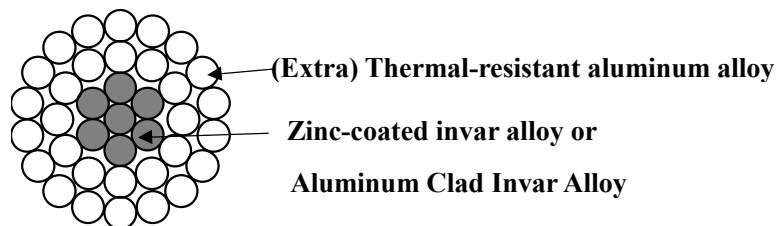


Figure 6 - Cross-section of (Z)TACIR conductor.

Invar is an iron-nickel alloy (Fe—36%Ni) with a very small coefficient of thermal expansion. The typical properties of invar wire are shown in Table 4. The coefficient of thermal expansion of invar wire is around one third that of galvanised or aluminium-clad steel wire.

The installation methods and accessories for the conductor are virtually the same as those used for conventional ACSR. A slight lengthening of compression type accessories is required only to

satisfy increased current carrying requirements.

2.3.3.4 ACSS and ACSS/TW (Originally designated SSAC)

Aluminium Conductor Steel Supported (ACSS) is described in [41] and Shaped (Trapezoidal)-Wire Aluminium Conductor Steel Supported (ACSS/TW) is described in [42]. ACSS consists of fully annealed strands of aluminium (1350-0) concentric-lay-stranded about a stranded steel core. ACSS is not available in conductors with a single strand steel core.

The coated steel core wires may either be aluminised, galvanised, zinc-5%aluminium Mischmetal coated or aluminium clad. The steel core is available in either standard strength or high strength steel. The “high strength” steel has a tensile strength about 10% greater than standard steel core wire. In appearance, ACSS conductors are essentially identical to standard ACSR conductors. ACSS is typically available in three different designs: “Standard Round Strand ACSS”, or with “Trapezoidal Aluminium Wire” in constructions with equal area or equal diameter to conventional round wire constructions. Special high strength constructions are also available.

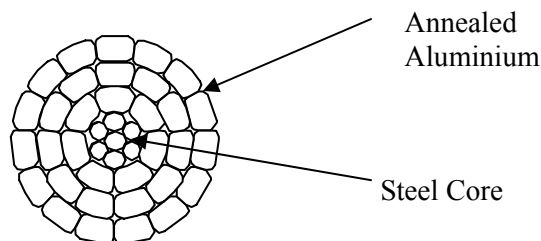


Figure 7 - Cross-section of ACSS/TW conductor.

In all designs, the use of annealed aluminium strands yields much higher mechanical self-damping than standard ACSR of the same stranding ratio.

Because the tensile strength of annealed aluminium is lower than 1350-H19, the rated strength of ACSS [43] is reduced by an amount dependent on the stranding (e.g. 35% for 45/7, 18% for 26/7, 10% for 30/7) compared to similar constructions of ACSR. In fact, a 45/7 ACSS conductor, with standard strength steel core wire has about the same rated breaking strength as a conventional all aluminium conductors made with hard drawn aluminium wire. The reduced strength of ACSS can be offset by using extra-high strength steel core wires, by using a higher steel core area, or by doing both.

Since the tension in the annealed aluminium wires is so low, the thermal elongation of ACSS is essentially that of the steel core alone. Similarly, given the low tension in the aluminium strands, ACSS does not creep under everyday tension loading. ACSS/TW constructions behave in the same manner as ACSS but have the added advantages [44] of reduced ice and wind loading and reduced wind drag per unit aluminium area.

2.3.4 Comparison of high temperature low-sag conductors

The essential advantage of reconductoring existing lines with high temperature conductors is that the line's thermal rating can be increased with minimal modification of existing transmission line structures [45]. *To limit the need for structural modification, these high temperature*

replacement conductors must operate at much higher temperature than ordinary bare overhead conductor without exceeding the original maximum sags and without causing a large increase in the original maximum tension and ice or wind structure loads. Increased sag would require raising the existing structures. Increased structure loads would require replacement or reinforcement of dead-end and angle structures and perhaps even tangent structures.

Clearly, replacement conductors that have the following characteristics (relative to the original conductor) are attractive:

- a low thermal elongation rate
- can be installed with less everyday sag
- the same or lower outside diameter
- the same or lower resistance

It is less clear what replacement conductor characteristics best avoid increasing the maximum structure tension loads while maintaining an acceptable level of safety with regard to conductor tensile failure under heavy loads. Also, while certain replacement conductor characteristics may be attractive, it is not obvious that such characteristics are “cost-effective” (i.e. that the additional cost of the special conductor is justified by the increase in line rating). In any event, the choice of replacement conductor is largely influenced by the existing conductor type and line design conditions.

The preceding comments indicate the complexity inherent in choosing a replacement conductor for an existing line. In a document such as this, it is not possible to identify all possible engineering issues. Nor can the cost of replacement conductors and the cost of structure reinforcement and/or replacement be defined for all line uprating situations. However, we can compare the use of commercially available high temperature replacement conductors for three typical but unique Case Studies.

2.3.4.1 Definition of line reconductoring case studies.

In the three Case Studies which follow:

- The original conductors are assumed to be ACSR (but with different steel core sizes).
- The ruling (i.e. “effective”) span length ranges from 275 to 350 meters.
- The original conductor tension limits are 20% RBS unloaded final at 16°C (everyday limit) and 60% RBS under maximum loading conditions.
- The sag “buffer” (or “excess” clearance) at maximum operating temperature varies from 0 to 2 meters.

Also, in order to avoid extensive reconstruction of the existing line structures, the replacement conductors for the three case studies are limited as follows:

- The outside diameter of the replacement conductor can be no more than 5% greater than the original conductor.
- The maximum replacement conductor tension under ice and wind loading cannot be more than 10% greater than the original maximum tension.
- The final unloaded sag of the replacement conductor at its maximum allowable conductor temperature cannot exceed the original maximum conductor sag by more than the sag buffer (0 to 2 meters) in each case study.

A list of the key parameters for each of the three case studies is shown in Table 5.

<i>Reconductor Design Case #</i>	<i>Loading Condition</i>	<i>Span -m-</i>	<i>Original Conductor Stranding and Aluminium Area</i>	<i>Maximum Allowed Increase in Sag Clearance Limit</i>
1	Medium	350	54/7, 428.9 mm ²	Zebra at 75°C plus 2 meters
2	Light	350	45/7, 402.8 mm ²	Tern at 100°C with no excess
3	Heavy	275	30/7, 264.4 mm ²	Bear at 100°C plus 1 meter

Table 5 – Key parameters of Reconductor Design Cases

To avoid uncertainties in the behaviour of the special aluminium alloy wires at emergency temperatures, the manufacturer’s recommendation for continuous operation is applied: 210°C for ZTAL in GZTACSR and ZTACIR, 200°C for annealed aluminium in ACSS and ACSS/TW conductors with heat-resistant steel wire coatings, and 150°C for TAL in GTACSR and TACIR.

ZTACIR and TACIR are assumed to have the same mechanical and electrical properties. The only distinction is that ZTACIR can be operated continuously at 210°C whereas TACIR can only be operated continuously at 150°C (Also, the higher temperature alloy is likely to cost more). A similar observation applies to GZTACSR and GTACSR.

For the three reconductoring case studies, the original conductor sag-tension design calculations are described in the following. Note that the calculations consider permanent elongation due to high-tension events and everyday creep at 16°C for 10 years. The “final” values shown include this elongation. Ice is assumed to be glaze ice with a density of 913 kg per m³. The stress-strain data is derived from experimental curves.

Case Study #1 - Original Conductor Zebra ACSR and Moderate Ice and Wind Loading

ALUMINIUM COMPANY OF AMERICA SAG AND TENSION DATA

Case 1 - Medium loading, 54/7 489mm² (Zebra) ACSR
2 meters "excess" sag

Conductor ZEBRA ACSR/British
Area= 482.9023 Sq. mm Dia=28.575 mm Wt=15.878 N/m RBS= 133002 N
Span= 350.0 m

Design Points					Final			Initial.....		
Temp C	Ice mm	Wind N/m ²	K N/m	Weight N/m	Sag m	Tension N	RTS %	Sag m	Tension N	RTS %
-10.	6.25	190.0	.00	23.346	8.97	39983.	30.1	8.40	42695.	32.1
-18.	.00	.0	.00	15.878	7.80	31265.	23.5	6.94	35116.	26.4
16.	.00	.0	.00	15.878	9.17	26600.	20.0*	8.13	29996.	22.6
50.	.00	.0	.00	15.878	10.47	23338.	17.5	9.34	26130.	19.6
75.	.00	.0	.00	15.878	<u>11.36</u>	21518.	16.2	10.21	23911.	18.0
100.	.00	.0	.00	15.878	12.21	20038.	15.1	11.06	22094.	16.6

* Design Condition

The maximum final unloaded sag at 75°C is 11.36m. The rating of the original Zebra ACSR at 75°C is 805 amperes (see section 2.3.4.3). Assuming that the original line clearance was generous, this maximum can be increased by up to 2 meters in reconductoring so the sag of the replacement conductor may not exceed 13.36m.

The original maximum conductor tension is 42 695 N so the maximum tension of the replacement conductor may not exceed 46 965 N (10% higher) and the diameter of the original Zebra ACSR is 28.575mm so the outside diameter of the replacement conductor cannot exceed 30.00mm (5% greater).

Case Study #2- Original Conductor Tern ACSR and "Light Wind Loading"(the wind pressure is 430 N/m²)

In this case, the original line clearance buffer is small. The maximum final sag of Tern ACSR at 100°C - 13.3 meters - cannot be increased at all. Therefore the maximum final sag of the replacement conductor may not exceed 13.3m. The rating of Tern at 100°C is 1030 amperes (see section 2.3.4.3).

The maximum tension of the original design is 29 699 N so the replacement conductor maximum tension may not exceed 32 670 N (10% higher). The diameter of the replacement conductor must not exceed 28.4 mm.

ALUMINIUM COMPANY OF AMERICA SAG AND TENSION DATA

Case 2 - Light loading, 45/7 410mm² (Tern) ACSR
Sag clearance limited no excess sag buffer

Conductor TERN 430 mm² 45/ 7 Stranding ACSR

Area= 430.5798 mm² Dia=27.000 mm Wt=13.073 N/m RBS= 98306 N

Span= 350.0 m

Design Points					Final			Initial.....		
Temp	Ice	Wind	K	Weight	Sag	Tension	RTS	Sag	Tension	RTS
C	mm	N/m ²	N/m	N/m	m	N	%	m	N	%
0.	.00	430.0	.00	17.484	10.05	26746.	27.2	9.05	29699.	30.2
0.	.00	.0	.00	13.073	9.57	21008.	21.4	8.35	24048.	24.5
16.	.00	.0	.00	13.073	10.23	19661.	20.0*	9.01	22289.	22.7
50.	.00	.0	.00	13.073	11.55	17427.	17.7	10.38	19367.	19.7
75.	.00	.0	.00	13.073	12.47	16168.	16.4	11.35	17743.	18.0
100.	.00	.0	.00	13.073	13.33	15135.	15.4	12.26	16432.	16.7

* Design Condition

Case Study #3- Original Conductor Bear ACSR and "Heavy" Ice & Wind Loading

The original line clearance buffer was moderate. The maximum final sag of the original Bear ACSR conductor at its maximum allowable temperature of 100°C (6.65m) can be increased to 7.65m with the replacement conductor. The rating of Bear ACSR at 100°C is 815 amperes(see section 2.3.4.3).

The maximum conductor tension of the original Bear ACSR is 53.7% of its RBS. The maximum tension of the original design with the relatively strong Bear ACSR is 62307 N so the replacement conductor maximum tension may not exceed 68 540 N (10% higher). The diameter of the replacement conductor must not exceed 24.7 mm.

ALUMINIUM COMPANY OF AMERICA SAG AND TENSION DATA

Case 3 - Heavy loading, 30/7 264.4mm² ACSR Bear
Max Sag with 1 meter buffer

Conductor BEAR ACSR/British

Area= 326.5800 mm² Dia=23.470 mm Wt=11.952 N/m RTS= 116099 N

Span= 275.0 m

Design Points					Final			Initial.....		
Temp	Ice	Wind	K	Weight	Sag	Tension	RTS	Sag	Tension	RTS
C	mm	N/m ²	N/m	N/m	m	N	%	m	N	%
-20.	25.00	.0	.00	46.051	7.01	62307.	53.7	7.01	62307.	53.7
-20.	12.50	190.0	.00	26.271	5.49	45309.	39.0	5.08	48929.	42.1
-30.	.00	.0	.00	11.952	3.41	33203.	28.6	2.79	40491.	34.9
16.	.00	.0	.00	11.952	4.87	23220.	20.0*	3.73	30338.	26.1
50.	.00	.0	.00	11.952	5.82	19449.	16.8	4.63	24439.	21.0
75.	.00	.0	.00	11.952	6.24	18163.	15.6	5.35	21151.	18.2
100.	.00	.0	.00	11.952	6.65	17030.	14.7	6.08	18623.	16.0

* Design Condition

2.3.4.2 Thermal rating conditions for reconductoring design case studies.

Thermal rating calculations for all three cases are made with the CIGRE method using the same weather and conductor assumptions:

- 0.61 m/s wind perpendicular to the conductor.
- air temperature 35°C.
- Solar heating for 35 degrees north latitude at noon in summer;
- Emissivity = 0.7.
- Absorptivity = 0.9.
- Resistance based on cross-sectional area of aluminium and steel wires accounting for:
 - ❖ stranding effects;
 - ❖ using minimum average conductivity;
 - ❖ ignoring steel core magnetisation;
 - ❖ using generally accepted temperature coefficients of resistance.

2.3.4.3 Comparison of reconductoring alternatives for Case Study #1.

Note – The following chart and table only indicate possible reconductoring alternatives. It is unlikely that all of the high temperature replacement conductors would make economic sense nor that the increase in line rating afforded by each is necessary from a system viewpoint. Nonetheless, the comparison described is technically valid and illustrates some of the advantages of the various high temperature replacement conductors.

Conductor	ACSR	GZTACSR	TACIR	ACSS/TW
Name	Zebra	440	430	Suwannee
Total Area (mm ²)	484.5	491.9	484.5	565.3
Alum Area (mm ²)	428.9	439.1	428.9	486.3
Outside Diameter (mm)	28.62	28.5 (-0.4%)	28.62 (0%)	28.1 (-1.9%)
Rated Tensile Strength (kN)	131.9	146.8 (+11.3%)	121.9 (-7.6%)	147.2 (+11.6%)
Tension @Max Load kN	42.7	44.0 (+3%)	36.7 (-14%)	47.1 (+10%)
DC Resistance @ 25°C ($\mu \Omega$ /m)	68.7	70.0 (+1.9%)	69.9 (+1.7%)	58.6 (-15%)
Conductor Mass per unit length (kg/m)	1.621	1.658 (+2.3%)	1.633 (+0.7%)	1.960 (+20.9%)
Final H/w at 16°C(m)	1659	1797	1522	1720
Cont. Operation Max. Temp (°C)	100	210	150	200
Rating (amps) *	805 @75°C	1890 @210°C	1280 @120°C	1895 @200°C

Table 6 - Characteristics and Thermal Ratings of Replacement Conductors for Case Study #1.

* - Conductor temperature limit due to both sag and manufacturer's continuous operating temperature recommendation.

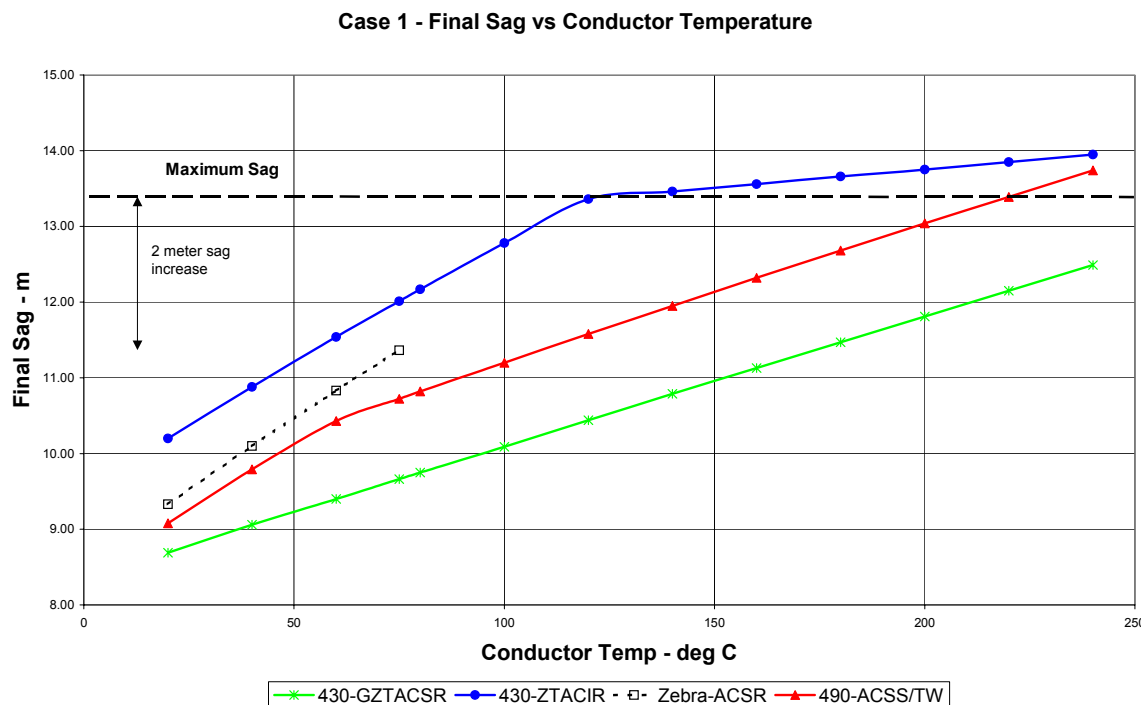


Figure 8 - Sag Variation with Temperature for Original Zebra ACSR and ACSS/TW, TACIR, and GZTACSR Replacement Conductors for Case Study #1.

Reconductoring Calculations for Case Study #1 - Comments

The original Zebra ACSR conductor yielded a final sag of 11.4 meters in the 350 meter “ruling” or “effective” span at the design temperature of 75°C. There is a generous sag “buffer” in the original design and it is assumed that the maximum allowable sag can be increased to 13.4 meters when reconductoring.

As shown in figure 8, the ACSS/TW and GZTACSR replacement conductors can be operated at their maximum recommended continuous operating temperatures of 200°C and 210°C, respectively, without exceeding the sag limit of 13.4 meters. The TACIR replacement conductor (capable of continuous operation at 150°C) is limited to operation at 120°C where it reaches the reconductoring sag limit.

The everyday sag of GZTACSR, and to a lesser extent that of ACSS/TW, is less than that of the original Zebra ACSR. This reflects the higher self-damping of these designs. In contrast, the everyday sag of the TACIR conductor is greater than the original that reflects the lower tensile strength of its Invar steel core.

Other sizes and conductor designs may well give different results.

2.3.4.4 Comparison of reconductoring alternatives for Case Study #2

Note – The following chart and table only indicate possible reconductoring alternatives. It is unlikely that all of the high temperature replacement conductors would make economic sense nor that the increase in line rating afforded by each is necessary from a system viewpoint. Nonetheless, the comparison described is technically valid and illustrates some of the advantages of the various high temperature replacement conductors.

Reconductoring Calculations for Case Study #2

Conductor	ACSR	GZTACSR	ZTACIR	ACSS
Name	Tern	410	400	480 (Cardinal) ACSS/TW
Total Area (mm ²)	430.6	443.6	430.6	545.9
Alum Area (mm ²)	402.8	411.9	402.8	483.4
Outside Diameter (mm)	27.0	26.5 (-1.9%)	27.0 (0.0%)	27.5 (+1.9%)
Rated Tensile Strength (kN)	98.3	121.1 (+23.2%)	85.9 (-12.6%)	124.6 (+26.7%)
Tension @Max Load (kN)	29.7	29.1 (-3%)	22.8 (-23%)	32.6 (+9.8%)
DC Resistance @ 25°C (μ Ω/m)	73.1	74.7 (+2.2%)	74.8 (+2.3%)	59.4 (-21%)
Conductor mass per unit length (kg/m)	1.334	1.408 (+5.6%)	1.341 (+0.6%)	1.827 (+37%)
H/w @16C (m)	1625	1610	1307	1470
Cont. Operation Max. Temp (°C)	100	210	210	200
Rating (amps)*	1030 @100°C	1800 @210°C	615 @65°C	1165 @100°C

* - Conductor temperature limit due to both sag and manufacturer's continuous recommendation.

Table 7 - Characteristics and Thermal Ratings of Replacement Conductors for Case Study #2.

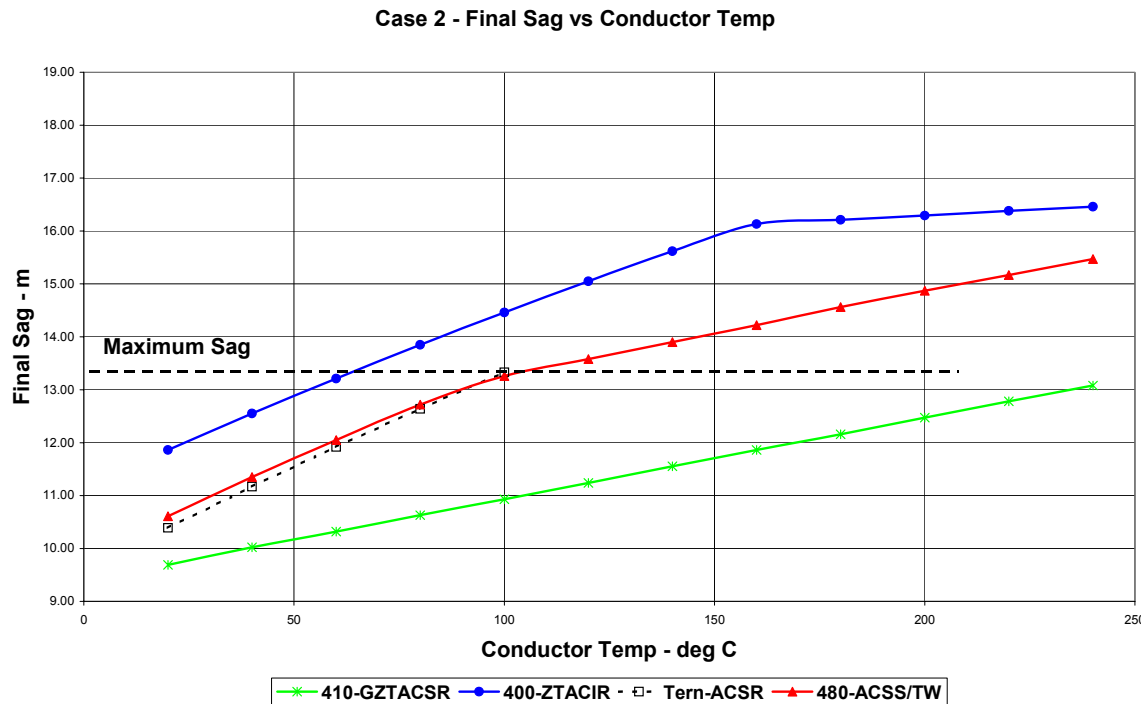


Figure 9 - Sag Variation with Temperature for Original Tern ACSR and ACSS, ACSS/TW, TACIR, and GZTACSR Replacement Conductors in Test Case #2.

Reconductoring Calculations for Design Case Study #2 - Comments

The GZTACSR conductor can be operated to its continuous operating limit of 210°C while meeting the sag clearance limit. The ACSS/TW replacement conductor is limited to a maximum temperature of only 100°C where it reaches the line's ruling span sag limit of 13.3 m. The TACIR replacement conductor is not useful in this case since it cannot be operated at a temperature in excess of 65°C.

Note the relatively high knee point for the ACSS conductor due to the light environmental loading conditions. This indicates that pre-stressing the ACSS conductors might result in higher maximum operating temperature and higher ratings.

The everyday sag of GZTACSR is less than the original Tern ACSR. This reflects the higher self-damping of this conductor design. In contrast, the everyday sag of the TACIR is greater than the original. This reflects the lower tensile strength of its Invar steel core. In this case the everyday sag of the ACSS/TW replacement conductor must be slightly greater than that of the original Tern in order not to exceed the maximum tension limit of 32 668 N (10% above the original).

Other conductor sizes and designs are likely to give different results.

2.3.4.5 Comparison of reconductoring alternatives for Case Study #3

Note – The following chart and table only indicate possible reconductoring alternatives. It is unlikely that all of the high temperature replacement conductors would make economic sense nor that the increase in line rating afforded by each is necessary from a system viewpoint. Nonetheless, the comparison described is technically valid and illustrates some of the advantages of the various high temperature replacement conductors..

Reconductoring Calculations for Case Study #3

Conductor	ACSR	GZTACSR	TACIR	ACSS/TW
Name	Bear	260	260	400 (Scoter/TW)
Total Area (mm ²)	326.6	317.6	326.6	397.4
Alum Area (mm ²)	264.4	261.3	264.4	Area
Outside Diameter (mm)	23.5	22.6 (-0.4%)	23.5 (0%)	24.2 (3%)
Rated Tensile Strength (kN)	116.1	123.5 (+3.4%)	98.5 (-15.2%)	132.1 (+14%)
Tension @Max Load (kN)	62.3	62.3	49.3 (-21%)	67.8 (+8.8%)
DC Resistance @ 25°C($\mu \Omega$ /m)	109.3	115.3 (+3.4%)	113.3 (+1.6%)	89.8 (-18%)
Conductor mass per unit length (kg/m)	1.219	1.188 (-2.3%)	1.227 (+0.7%)	1.48 (+22%)
H/w @16C (m)	1943	1512	1250	2237
Cont. Operation Max. Temp (°C)	100	210	65	100
Rating (amps) *	815 @100°C	1230 @190°C	705 @85°C	1490 @200°C

* - Conductor temperature limit due to both sag and manufacturer's continuous recommendation.

Table 8 - Characteristics and Thermal Ratings of Replacement Conductors for Design Case Study #3

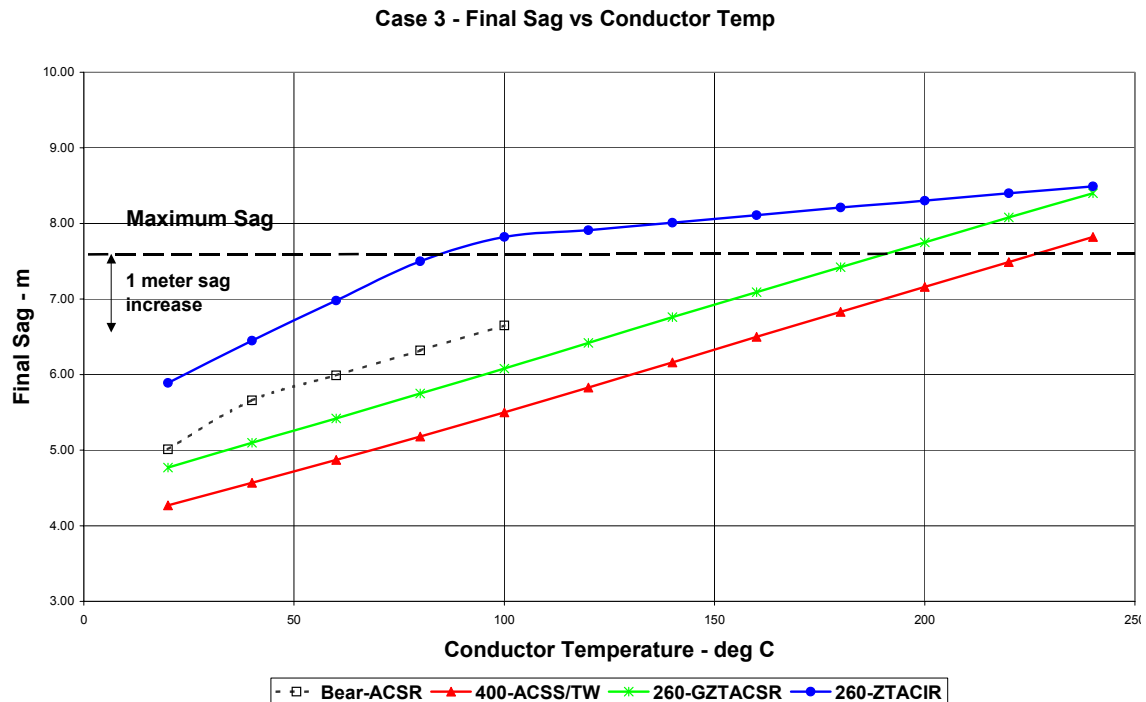


Figure 10 - Sag Variation with Temperature for Original Bear ACSR and ACSS, ACSS/TW, ZTACIR, and GZTACSR Replacement Conductors in Design Case #3.

Reconductoring Calculations for Case Study #3 - Comments

There is quite a difference in the calculated sag versus temperature variation for ACSR Bear according to calculation method - Japanese linear method, the traditional graphical method and the graphical method including aluminium compression. The calculated ruling span sag at 100°C differs by almost 1 meter.

The Japanese linear method, which yields the largest sag is shown in Figure 10.

Given the sag limit of 7.6 meters (6.6 + 1 m), only the ACSS/TW replacement conductor is able to operate at its maximum continuous temperature limit. The maximum operating temperature of all the other replacement conductors is determined by sag.

The GZTACSR conductor can be operated to 190°C, however, which is quite close to its continuous operating limit of 210°C. The TACIR conductor can only reach 85°C, however, for which its thermal rating is less than the original Bear conductor.

Note the relatively low knee point temperature for the ACSS/TW and TACIR conductors due to the heavy loading conditions that cause a relatively large amount of permanent elongation in the aluminium strands.

As in the other three case studies, the everyday sag of GZTACSR is less than the original Bear ACSR (reflecting the higher self-damping of this conductor design) and the everyday sag of the TACIR is greater (reflecting the lower tensile strength of its Invar steel core). The ACSS/TW conductor has the lowest everyday sag of all. The sag of the ACSS/TW replacement conductor is determined by limiting the initial unloaded tension at 16°C to 35% of RTS.

Other conductor sizes and designs are likely to give different results.

2.4 Summary of Conductors for Increased Thermal Rating

Increasing the thermal rating of an existing line is a complex design problem. The initial decision involves power system analysis by utility planners. The result of the analysis is to establish the need for and the timing and magnitude of the needed increase in existing line thermal rating. This initial system study should also provide the line designer with guidance concerning the frequency of occurrence of high current loads.

Given this information, the line designer should perform a thorough physical inspection and analysis of the existing line. The first two sections of this brochure describe most of the activities required and many of the pitfalls involved in determining the possibility of increasing the existing line thermal rating by operating at a higher design temperature.

If this analysis leads the engineer to conclude that the thermal rating of the existing line cannot be increased to meet the system requirements while continuing to assure the public safety, then replacement of the existing line's conductor is perhaps required.

The appropriate choice of replacement conductor type and size depends on the following parameters:

1. Cost of electrical losses.
2. The frequency and magnitude of high current loads.
3. Purchase and labor costs of replacing the existing conductors.
4. The cost of structure reinforcement.
5. Availability of replacement conductor.
6. Likelihood of vibration fatigue problems.
7. Severity of ice and wind load conditions.
8. Cost/Benefit ratio of increased capacity.
9. Availability of additional right-of-way.

Replacing the conductors of an existing line can only be attempted on a line that has demonstrated over a period of years that it has some reserve of strength to resist the weather-related loads that have occurred. The reliability of a line that has exhibited frequent structural failures is unlikely to improve as a result of reconductoring.

Increasing the thermal rating of an existing line by use of a replacement conductor larger than the original (having lower resistance), will increase both transverse ice and wind loads and tension loads on existing structures. A larger conventional conductor imposing greater loads on the existing structures may reduce the reliability of the existing line unless the structures are reinforced.

Increasing the thermal rating of an existing line by use of a replacement conductor having nearly the same diameter as the original conductor but capable of operation at higher temperature (within existing sag clearance and loss-of-strength constraints) may avoid the need for extensive reinforcement of suspension structures. The second section of this brochure considers several different types of high temperature, low sag conductors that can be used to increase the thermal rating of existing lines with a minimum of structural reinforcement.

ACSS, (Z)TACIR, and G(Z)TACSR are commercially available high temperature low sag conductors intended specifically for reconductoring existing lines. Comparisons of these conductors are presented for three typical but not exhaustive line designs. The various conductors are all capable of operation at temperatures up to and somewhat in excess of 200°C. The most attractive choice of replacement conductor depends on the design conditions of the existing line. All are potentially a solution when the line thermal rating is to be increased by more than 50%.

3. - Conclusion and Recommendations

Demand for electricity in many developed countries is no longer growing at the rates once experienced. With low growth rates, justification for the construction of new overhead line routes is very difficult as, in theory at least, the network is having to accommodate very little increased power flow.

However, while demand is changing relatively slowly, the markets for electricity are changing very rapidly. A result of this rapidly changing economic environment is that the power flows across transmission networks are also changing rapidly, often due to changes in the geographical location of generation. Transmission lines that were once required to carry only moderate loads are now causing thermal constraints on the system due to their inability to handle the new power flows. With new lines becoming increasingly difficult and costly to build, uprating has become an area of great importance to transmission companies.

Since structural modifications are expensive, and it is difficult to obtain approval for them, the focus of uprating studies has been on the conductor system. The ACSR conductors typically used for the initial installation are being changed for new, high-performance conductors. This brochure is intended to provide the information necessary to aid decisions relating to conductor replacement.

A number of conductors are covered, ranging from the use of homogeneous aluminium alloy conductors for relatively low temperature operation, to steel-cored conductors utilising high-temperature (“thermal resistant”) aluminium alloys that can resist annealing at temperatures up to 150 to 210 degrees Celsius. Constructions vary greatly, too, from the standard stranding of TACSR to compacted, trapezoidal-strand conductors and the gap-type conductor, with its mechanically separate core. Given the wide variety of replacement conductors, the process of selection can be very difficult. The suitability of each option is dependent on many factors, which will vary from project to project, and it would be impossible to account for all of them in this brochure. Therefore, summary information only is provided, the intention being simply to inform the reader of the capabilities of each conductor. It is up to the reader to decide which conductor is best suited to an individual application, taking into account the required performance, the design constraints, and the cost implications, in order to arrive at the optimum solution.

As well as the issues relating to conductor choice, there are also several issues relating to the use of conductors at high temperature. Many of the models used in the design process for overhead lines were developed around the use of ACSR conductors at relatively low temperatures, around 50 degrees Celsius or so. The effect of temperature differences between strands, the variability of elastic modulus, increased creep, the potential inaccuracies of the ruling span approach, and the importance of a conductor’s “knee point”, are all covered in this brochure. While a detailed description of how to design a line with a high-temperature conductor is beyond the scope of this brochure, it is intended that the information provided is sufficient to alert the engineer to the possible design pitfalls for high temperature conductors.

Overhead line conductor technology is still developing. The conductors covered in this brochure are all readily available and have been in use for many years. However, new conductors, such as those reinforced with lightweight, high strength composite materials, are being developed and readers should be aware that this brochure is by no means exhaustive.

The intention of this document is to serve as an aid to the decision-making process for upgrading overhead lines. The Task Force hopes that it will provide a useful information resource for transmission line engineers everywhere.

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