

High-Voltage Direct Current Line Conductor Optimization

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EPRI Project Manager

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ABSTRACT

Overhead transmission lines are designed to last for 40 years. Many ac lines in service today in North America are 70 or more years old. This survival rate is a result of conservative utility design practices and detailed product specifications. This reliability record has occurred despite a wide range of conductor types and sizes. In the present transmission system, there are far fewer high-voltage direct current (HVDC) lines, but those that have been designed and built have been similarly successful in terms of mechanical and electrical reliability. This report describes the way that pole conductors are selected for HVDC lines and suggests possible subtle improvements.

Keywords

Conductor optimization

HVDC

Transmission line

GLOSSARY

all aluminum alloy conductor (AAAC). Conductor stranded entirely from high-strength 6201-T81 aluminum-alloy wires.

all aluminum conductor (AAC). Conductor stranded entirely from electrical conductor grade 1350-H19 aluminum wires.

aluminum conductor alloy reinforced (ACAR). Conductor whose outer strand layers consist of 1350-H19 aluminum wires reinforced by a core stranded from high-strength 6201-T81 aluminum-alloy wires.

aluminum conductor composite core (ACCC). Conductor whose outer layers consist of fully annealed aluminum (1350-0) strands (usually trapezoidal in shape) reinforced and supported at high temperature by a single carbon hybrid epoxy composite core.

aluminum conductor composite reinforced (ACCR). Conductor whose outer layers consist of “thermal-resistant aluminum-zirconium alloy” wires (IEC 62004) reinforced by a core stranded from aluminum oxide reinforced aluminum wires.

aluminum conductor invar reinforced (ACIR). Conductor whose outer strand layers consist of thermal-resistant (AT1) or super thermal-resistant (AT3) aluminum-zirconium alloy wires reinforced by an Invar steel core.

aluminum conductor steel reinforced (ACSR). Outer strand layers consist of conventional “full-hard” 1350-H19 aluminum wires reinforced by a core of high-strength steel wires. The steel wires are normally galvanized to prevent corrosion with the aluminum strands.

aluminum conductor steel supported (ACSS). Outer strand layers of fully annealed aluminum (1350-0) strands over a core of high-strength steel strands.

ampacity (of a conductor). Maximum constant current that will meet the design, security, and safety criteria of a particular line on which the conductor is used. In this report, ampacity has the same meaning as *steady-state thermal rating*.

annealing (of aluminum wire). Process in which the tensile strength of copper or aluminum wires is reduced at sustained high temperatures.

EHV-AC lines. Extra high voltage ac lines are normally defined as being between 250 and 550 kV.

electrical clearance (of line). Distance between energized conductors and other conductors, buildings, and earth. Minimum clearances are usually specified by regulations.

extra high strength (EHS) steel (core wire). Extra high strength steel wires for aluminum conductor steel supported or gap-type conductor steel reinforced.

gap-type conductor steel reinforced (GTACSR). Conductor whose outer layers are stranded with thermal-resistant (AT1) or super thermal-resistant (AT3) aluminum-zirconium alloy wires reinforced with a stranded steel core. There is a grease-filled gap between the inner aluminum layer and the steel core.

high-strength (HS) steel (core wire). High strength steel core wires for aluminum conductor steel reinforced.

HV (ac) lines. High voltage ac lines are normally defined as being between 50 and 250 kV.

International Annealed Copper Standard (IACS). International standard for wire conductivity.

International Electrotechnical Commission (IEC). International standards organization that publishes production standards for bare overhead conductors.

Invar steel. Steel core wire made with high nickel content (38%) to reduce the thermal elongation coefficient.

knee-point temperature. Conductor temperature above which the aluminum strands of an aluminum conductor steel reinforced conductor have no tension or go into compression.

maximum allowable conductor temperature (MACT). Highest temperature for which electrical clearances are adequate and annealing is acceptable.

rated breaking strength (RBS). Calculated value of composite conductor tensile strength that indicates the minimum test value for stranded bare conductor. Similar terms include ultimate tensile strength (UTS).

ruling (effective) span. Hypothetical level span length in which the variation of tension with conductor temperature is the same as in a series of suspension spans.

self-damping conductor (SDC). Aluminum conductor steel reinforced type conductor in which the aluminum strands are trapezoidally shaped and sized such that there is a small gap between layers to allow impact damping of Aeolian vibration.

super thermal-resistant zirconium-alloy aluminum wire (AT3). Aluminum-zirconium alloy wires that have stable mechanical and electrical properties after continuous operation at temperatures of up to 210°C (see IEC 62004).

thermal rating (ampacity). Maximum electrical current that can be safely carried in overhead transmission line (same meaning as *ampacity*). Some thermal ratings have a time duration associated with them such as “4-hour emergency rating.”

thermal-resistant aluminum conductor steel reinforced (TACSR). (AT1) aluminum-zirconium alloy wires reinforced by a conventional stranded steel core. The steel core wires are typically aluminum-clad or have a Mischmetal coating capable of withstanding high temperatures.

thermal-resistant zirconium-alloy aluminum wires (AT1). Aluminum-zirconium alloy wires that have stable mechanical and electrical properties after continuous operation at temperatures of up to 150°C.

trapezoidal (aluminum) wires (TW). Aluminum strands that are trapezoidal in cross section.

twisted pair conductor (TP or T2). A conductor in which two ordinary round stranded conductors are twisted around each other to enhance mechanical stability in wind.

ultra high voltage (UHV) lines. Ultra high voltage ac lines are normally defined as being above 550 kV.

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

weight (conductor). This report generally describes conductor weight per unit length in lb/ft or kg/m.

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

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1

OVERVIEW

Overhead transmission lines are designed to last for a lifetime of 40 years. Many AC lines in service today in North America are 70 years old or more. This survival rate is a result of conservative utility design practices and very detailed product specifications. This reliability record has occurred in spite of a wide range of conductor types and sizes. Within the present transmission system there are far fewer HVDC lines but the ones that have been designed and built have been similarly successful in terms of mechanical and electrical reliability. The goal of this report is to describe the way pole conductors are selected for HVDC lines and to suggest possible subtle improvements.

The classical conductor selection process is described in many technical papers published over the last hundred years and has typically been applied to very large projects with Extra High Voltage AC (EHV-AC) lines. The process amounts to calculating the total present worth of revenue required for materials, labor, right-of-way, and electrical losses over the life of the line. The optimal conductor is that which yields the minimum total present worth of revenue required.

As shown in Figure 1-1, there is typically no well-defined sub-conductor diameter which is optimal; rather there is a range of diameters which yield low total costs.

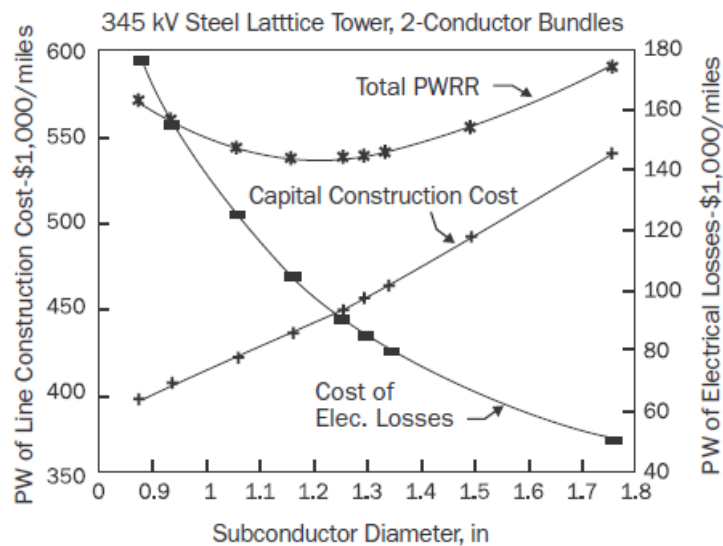


Figure 1-1
Cost as a function of conductor diameter

It is also typically found that similar total costs and environmental effects can be generated with the use of different numbers of sub-conductors per phase bundle, structures, and phase arrangements.

With EHV AC lines, it is unusual to combine the economic analysis of the line with the cost of associated substations since most substation equipment is not only associated with a single overhead line and because the number and location of substations may evolve over time.

With HVDC lines, the conductor selection process is similar to that used with AC lines but the converter cost is included in the overall optimization and the predicted power flow in the HVDC line is much more certain than for an EHV-AC line.

To optimize the HVDC pole conductors, a preliminary investigation is made concerning the conductor blow-out, electric fields at the edge of right-of-way, structure and foundation loads, etc. for each of the pole bundle choices considered. In addition, the pole bundle must be sufficiently large to carry the power provided by the converters at each end of the line. Over many years, the cost of the converter stations has become less relative to the line cost and the “break-even” line length for which HVDC is more economical than EHV-AC has gotten smaller.

The converter station cost is included in the HVDC conductor optimization for a number of reasons:

- In many cases the cost of the converter stations may exceed the cost of even a long HVDC line.
- The capacity of the converter stations determines the power flow on the HVDC line conductors.
- The losses in the converter stations are not insignificant.

In this report a recent comprehensive CIGRE Technical Brochure 388 “Impacts of HVDC Lines on the Economics of HVDC Projects” is reviewed and the summarized. The brochure describes a comprehensive process by which the HVDC line conductors may be optimized for voltages between ± 300 kV to ± 800 kV, with power capacities ranging from 700 to 6000 MW, and line lengths of 750 km to 3000 km. Generally, it is concluded that the most economical voltage level increases with line length and the converter station power capacity.

TB 388 considers different numbers of sub-conductors per pole bundle, concluding that the optimum number per bundle increases with pole voltage and converter station capacity. This is consistent with EHV-AC lines where typical 345, 500, and 765 kV lines use 1 to 3, 2 to 4, and 4 to 8 sub-conductors per bundle. In the broad optimization studies described in TB 388, the authors only consider the use of low-steel ACSR conductors. Also, only a single structure bi-pole is considered.

The use of all aluminum (AAC, ACAR, and AAAC) and other types of transmission conductors are evaluated in this report as alternatives to ACSR and it is concluded that all aluminum offers significant advantages over ACSR in this HVDC application. The main advantages of all aluminum include:

- All aluminum conductors are easily recycled thus minimizing the environmental impact of their use.
- Compression sleeves and dead-ends are simpler in function and installation.
- Cost of all aluminum conductors and accessories are less than ACSR.
- The tension loads on angle structures and broken wire loads on tangent structures are less leading to reduced structure cost.
- Maximum operating temperature requirements in an HVDC line are modest so that the thermal elongation advantage of ACSR at high temperature is not significant.

Other types of conductors, including HTLS were also considered, but offered higher cost and minimal advantage over ACSR.

2

BACKGROUND ON LINE OPTIMIZATION

High voltage AC or DC overhead transmission lines are constrained in many ways. They must first of all “do no harm”. To this end, the bare energized conductors of the line must remain a “safe” distance from human activity and other conductors that are in the line right-of-way (ROW) and from buildings and objects along the edge the line right-of-way. To this end, the line designer calculates the maximum conductor sags along the line under all foreseeable weather and power flow conditions and the blowout of the conductors toward the edge of the ROW during high winds. The tower attachment height, span lengths, and ratio of conductor bundle diameter to weight is chosen.

To limit induced currents and voltages in nearby objects and in people, the electric and magnetic fields that are produced by the lines must remain below prudent levels throughout the life of the line. To limit annoyance of any nearby population, the high electrical stress around the energized conductors must be low enough to avoid excessive corona-induced radio interference or audible noise. In the special case of HVDC lines, the ion currents produced must not be excessive. To ensure this, the designer must choose a conductor “bundle” which is large enough to keep the electrical stresses at a sufficiently low level.

The lines must remain reliable carriers of power throughout their long useful life (up to 80 years) so the insulators must prevent flashovers due to atmospheric contamination, surges that result from switching operations, and, in combination with shield wires, lightning flashes to the line. Also, the distance from the conductor attachment point on the insulators must remain sufficiently far from the structural supports to avoid flashovers. The conductor bundle loads due to construction, broken wires, ice and wind must be calculated in order to choose structures and foundations strong enough to support the conductor/insulator system throughout the long life of the line.

In addition, when these electrical, environmental, and mechanical constraints on line design have been met, the line design is studied in order to minimize the cost of construction and electrical losses. The economic line factors include materials and labor for construction, purchase of ROW, line maintenance, and the cost of electrical losses over the life of the line. The economic analysis of large ac lines normally involves the minimization of the total present worth of revenue required for capital costs and electrical line losses, ignoring associated substation costs. The economic analysis of HVDC lines is more complex because the Converter stations at each end of the HVDC line are included in the analysis. In the HVDC case, the converter stations are sized and dedicated to the power flow on the line. In the AC case, the substation costs are typically shared between multiple lines.

In either case, with ac or dc lines, the electrical losses are directly proportional to the phase or pole resistance (which remains constant throughout the life of the line) and the square of the phase or line current (which typically grows over time).

Most overhead transmission lines are AC. Placed within a predominantly AC transmission system, HVDC lines offer certain advantages and difficulties, particularly with regard to economics and reliable transmission of electrical power. The selection of conductors is essential to the economic and reliable operation of HVDC lines.

HVDC lines are normally employed in one of two situations, either to link two AC systems without the need for frequency coordination or to transmit large blocks of power over long distances. In most cases the HVDC ac-system links are short and conductor optimization is less important. In the other situation, long HVDC lines are added to the existing transmission system in order to move large blocks of power over distances that are difficult to achieve with EHV-AC. In such long lines, the choice of conductor is far more important.

In AC lines, less than 100 km in length, conductors are usually selected from a standardized group which the utility specifies in order to simplify documentation, minimize inventory and reduce maintenance. For long ac lines, the desire to use standard conductors may be overwhelmed by the possible savings with respect to capital cost and electrical losses. This is particularly true for HVDC lines where the great length and high electrical loading of such lines makes the choice of conductor critically important from both a cost and reliability viewpoint.

As has been demonstrated in many studies and reports (for example, CIGRE Electra 137, T-Line Component Costs, 1991), the three main material cost components of an overhead line (ac or dc) are the cost of the conductor system, the cost of the supporting structures, and the cost of ROW with the conductor system being between a third and $\frac{1}{2}$ of the total. The cost of the conductor system is dependent primarily on the conductor area and on the conductor component materials. The cost of the supporting structures is proportional to the conductor OD and the maximum conductor tension. ROW cost for HVDC is not much affected by the line design but rather the pole voltage.

In North America, even some of the largest utilities, may have no HVDC lines or, at most, one or two. There is little or no standardization of HVDC designs.

HVDC lines are usually quite long. For example, the Quebec-New England Phase II ± 450 kV HVDC line carries 2000 MW over 1500 km (930 miles) from northern Quebec to New England.

Long HVDC lines can be operated up to their thermal rating limit. Long EHV-AC lines are constrained to a much lower power flow because of voltage drop and stability concerns. A simple measure of the power flow limit for long EHV-AC lines is their Surge Impedance Loading (SIL). Note in Table 2-1 that the SIL ranges from 20% to 30% of EHV-AC line's thermal rating.

Table 2-1

Surge Impedance Limit compared to thermal rating for overhead lines and underground cable in 60 Hz AC systems

System	XL		XC		Surge Impedance	SIL	Thermal Rating
kV	(Ω /mi)	(Ω /km)	($M\Omega$ -mi)	($M\Omega$ -km)	(Ω)	(MW)	(MW)
Transmission Overhead Line Characteristics							
230	0.75	0.47	0.18	0.29	367	145	440
345	0.60	0.37	0.15	0.24	300	400	1500
500	0.58	0.36	0.14	0.26	285	880	3000
765	0.56	0.35	0.14	0.26	280	2090	8000
Transmission Cable Characteristics							
345	0.25	0.16	0.0060	0.0097	39	3050	2100

When carrying the same power flow with the same phase/pole resistance and the same peak voltage, the HVDC line produces about 75% of the losses of an equivalent HVAC line. On the other hand, the HVDC can be operated up to its thermal rating while the EHV-AC line is limited to less than half its thermal rating. Assuming that the HVDC line can carry 3 times the power flow of the EHV-AC line, the potential losses in the HVDC line can be as much as 5 to 6 times greater.

It should be noted that the thermal ratings in Table 2-1 are estimated for conventional ACSR at a maximum temperature below 100°C. With HTLS conductors, the thermal rating might be twice as high and the AC/DC loss ratio could be much higher than 5 to 6.

The major factors in the selection of conductors for HVDC lines include the following:

- Cost of electrical losses
- Capital cost of conductors and structures
- Mechanical reliability of the line
- Thermal rating

HVDC lines embedded in an EHV-AC system make special demands on the conductors used:

1. Because of the high cost of converters and the lack of an SIL limit on HVDC, HVDC lines are usually operated with higher conductor current densities than EHV-AC lines under system normal conditions. For a long HVDC line HVDC operated near its thermal rating, the losses can be as much as 5 times higher than for an EHV-AC line operating at its SIL limit.
2. Given the large blocks of power typically handled by HVDC lines, there is a need for exceptional electrical load reliability. Yet the surrounding ac system can do little to provide alternate power flow paths in the event of a HVDC line outage. Therefore, certain HVDC lines are designed to allow “single-pole” operation. Given the difficulty of providing alternate power flow paths with the loss of a single pole, there is a strong motivation to use HTLS conductors on such lines to minimize load disruption. Losses are irrelevant in this case given the short time duration.
3. A bi-pole HVDC line allows operation of the line in the event of a pole outage but the remaining pole must be able to handle twice the normal power flow of the HVDC line.
4. Maintenance problems can be consuming given the length and importance of an HVDC line.
5. Given the length of HVDC lines and their importance to system reliability, the conductors should be resistant to corrosion, hardware and spacer wear, and to Aeolian vibration-induced conductor and structure member fatigue.

3

CONDUCTOR BUNDLE SELECTION FOR HVDC LINES

The primary concern when selecting a phase conductor bundle for HVDC lines is that the resulting HVDC line is environmentally acceptable, reliable, and safe. Environmental issues include meeting maximum audible noise and radio interference levels as well as ion current concerns unique to HVDC lines. Reliability issues include avoiding wind-induced vibration fatigue and tensile failure under maximum ice and wind loads. Safety concerns include meeting minimum electrical clearance to ground and buildings at edge of right-of-way.

Environmental issues should be reviewed first, in order to determine the minimum combinations of sub-conductor diameter and number of conductors per bundle which are necessary to meeting environmental concerns with HVDC lines. To some extent, the acceptable bundle is also a function of the pole spacing and the height of conductors above the earth. The pole spacing in the following discussion is held constant at approximately 15 meters as is the height of the phase bundles above ground.

Regarding the economic analysis of HVDC lines, the classic analysis is illustrated in two CIGRE Technical Brochures (CIGRE, 2001 and CIGRE, TB 388, 2009). The older brochure includes an economic analysis of HVDC and EHV-AC, primarily determining the “break-even” line length where the HVDC line is more economic than the EHV-AC alternative. In the newer brochure, while it is still oriented toward developing economic comparisons of HVDC and EHV-AC, there is considerably more discussion regarding the line design and conductor selection.

The 2009 CIGRE brochure covers a wide range of HVDC line designs including voltages from ± 300 to ± 800 kV, power capacities of 700 to 6,000 MW and lengths from 750 to 3,000 km. Loading regions considered were primarily without heavy ice loading. Detailed sag-tension calculations were performed and total line construction costs estimated.

The primary economic analysis considered the annual costs of line and converter station materials and construction as well as line and station electrical losses.

The basic configuration of HVDC line considered in the CIGRE brochure is single circuit bipolar though the results should not be dramatically different than for two adjacent monopolar lines. The cost of structures in the bipolar configuration is undoubtedly lower but the extra cost of the separate structures with the two adjacent monopolar lines may be justified in terms of increased service reliability in certain situations.

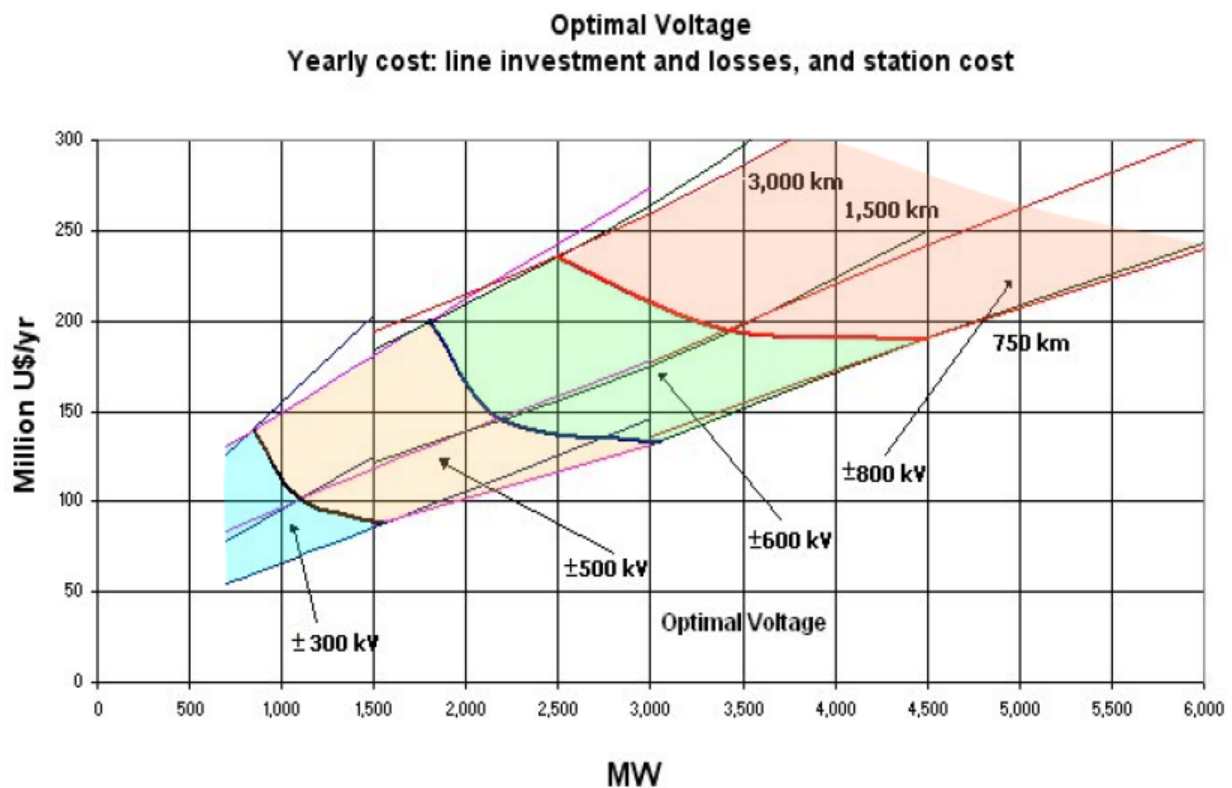
The line cost, C_L , based on a detailed study of 10 lines, was found to obey the following simple equation, where V is the HVDC voltage, S is the aluminum cross-section of each sub-conductor, and N is the number of sub-conductors per pole (a , b , c , and d are derived constants):

$$C_L = a + b \cdot V + S \cdot (c \cdot N + d)$$

By adding the cost of cost of line construction and electrical losses to the cost of converter station capital and electrical losses, the total system cost is obtained for any combination of HVDC voltage and Converter Station power rating. The three straight lines (total cost increases linearly with line length) represent the total cost variation with line lengths of 750 km, 1500 km, and 3,000 km.

HVDC Voltage, Length, and Power Capacity

The most economic voltage increases with the converter station capacity and the line length. For example, for 2000 MW, ± 500 kV is most economic for lines between 750 and approximately 2,000 km while ± 600 kV is more economic for longer lines.



Legend: Red → ± 800 kV; green → ± 600 kV; pink → ± 500 kV; blue → ± 300 kV
 * station losses cost not included (equal for same station power and different voltage)

Figure 3-1
Total Annual Cost of Converter Stations and Overhead Line as a Function of Voltage and Converter Station Power Rating (MW)

Holding the total kcmil of aluminum per pole constant for a 1500 km long line, Figure 3-2 shows the variation in component cost as a function of increasing voltage and power capacity. Clearly, the converter cost comes to dominate as these factors increase.

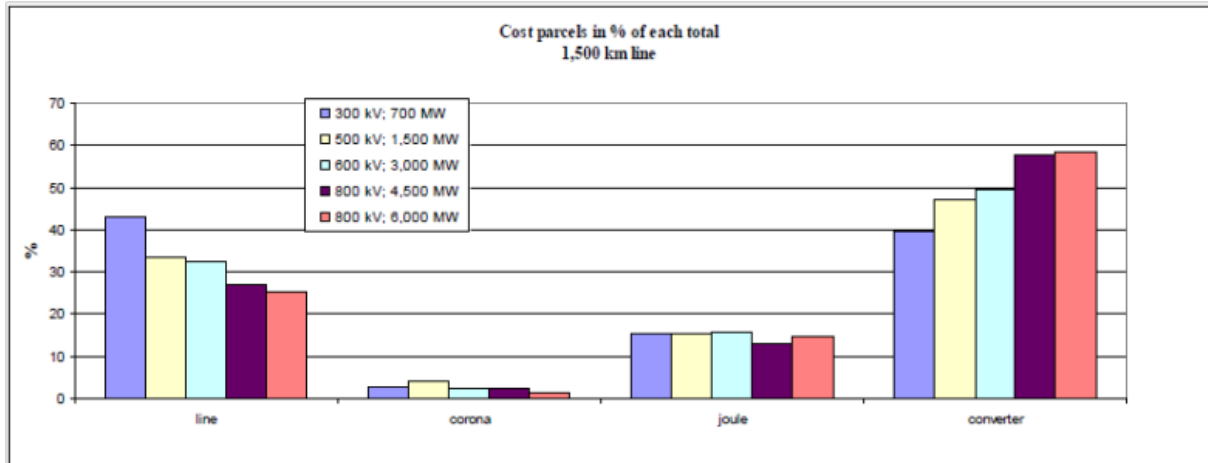


Figure 3-2
Component cost allocation for a 1500 km Line at Voltages of 300 to 800 kV with same resistance per pole.

With regard to conductor selection, the brochure confines itself to various bundled combinations of ACSR conductors with low steel content (that is, Type 7) ranging from 795 kcmil 45/7 Tern to 2515 kcmil 76/19 Joree. Of course, the amount of steel can be adjusted to meet the climatic loading along the proposed line and other types of conductor can be considered.

The brochure evaluated all practical combinations of low-steel ACSR conductors and numbers of such conductor per bundle. The process resulted in the following table which shows the most economical bundles as a function of HVDC voltage.

Table 3-1
Most economic bundle choices as a function of HVDC voltage for a 1500 km long line.

MW	700	1,500	3,000	4,500	6,000
kV	± 300	± 500	± 600	± 800	± 800
conductor/pole	2	2	4	4	5
Aluminum area mm ² (MCM)*	1,155 (2,280)	1,274 (2,515)	1,136 (2,242)	1,274 (2,515)	1,274 (2,515)

It should be noted, that the typical result of such economic optimization studies is to find that variations in bundle area of $\pm 10\%$ have little effect and produce bundles that are essentially similarly economic.

Insulation Analysis

Choosing the diameter and number of sub-conductors per bundle has little impact on most of the line insulation design process. Minimum air gaps, insulator length and configuration, electrical clearance to ground and other conductors, and switching surge levels are not directly affected by the bundle conductor choice.

The bundle choice does influence the wind blowout calculation both in calculating minimum spacing to the structure and, as discussed in the next section, minimum spacing to the edge of the HVDC line right-of-way (ROW). Essentially, as the area of the sub-conductor increases, the swing angle decreases (that is, the ratio of diameter to the weight per unit length decreases). Going from 795 kcmil Tern to 2515 kcmil Joree ACSR, the swing angle for switching surge blowout calculations decreases from 9 to 6 degrees.

Thermal Rating Calculation

The current-carrying capability of the various conductors is calculated using TB 207 with the following weather assumptions and conductor parameters:

- Wind speed 1 m/s
- Wind Angle 45 deg
- Air Temp 35°C
- Altitude 300 to 1000 m
- Solar Emissivity 0.5
- Solar Absorptivity 0.5
- Global Solar Radiation 1000 w/m²
- TC_{max} 90°C (to calculate Max Sag)

The conductors were selected on the basis of minimizing the cost of losses and historically this corresponds to a maximum operating temperature of 50°C to 60°C under worst-case weather conditions or 5°C to 15°C under everyday weather conditions.

The conductors were assumed to be sagged to an everyday tension of 20% RBS unloaded at 20°C air temperature in 450 m spans. The maximum sags ranged from 18 to 22 m as shown in Figure 3-3.

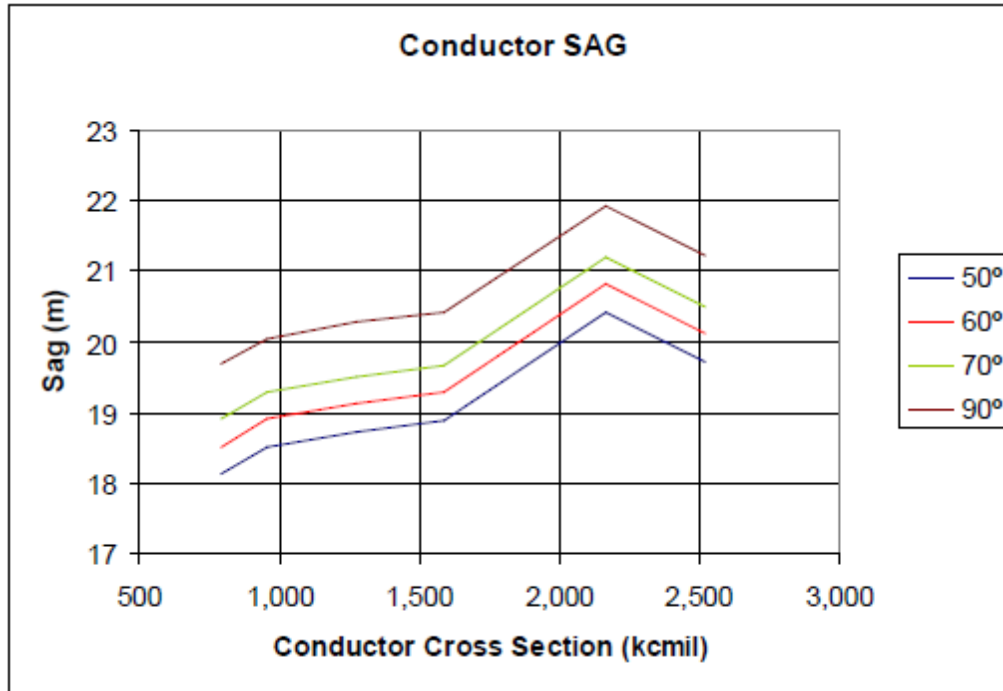


Figure 3-3
Maximum sag in a 450 m span as a function of conductor size and TC_{max}.

Tower Height

Having established the mid-span sag as a function of sub-conductor size, the tower height can be calculated as the sum of the sag (22 m used for all sizes), the clearance distance from pole bundle to ground which is a function of DC voltage ranging from 8m to 20m for voltages from ± 300 to ± 800 kV, the insulator vertical length, and the tower top shield wire supports.

As a result, the tower top heights range from 44 m to 62 m for ± 300 to ± 800 kV.

ROW Width for Mid-Span Blowout

As noted previously, the blow-out angle of the conductor bundles decreases with the sub-conductor size though, as shown in the following table, the difference in blow-out angle for sub-conductor diameters which are within 10%, is small.

Table 3-2
Blow-out angle as a function of sub-conductor area.

Conductor		Swing Angle (degree)
ACSR Code	Section (MCM)*	
Joree	2,515	34.1
Thrasher	2,312	35.1
Kiwi	2,167	36.4
2,034	2,034	37.2
Chukar	1,780	37.0
Lapwing	1,590	39.1
Bobolink	1,431	40.4
Dipper	1,351.5	41.1
Bittern	1,272	41.9
Bluejay	1,113	43.5
Rail	954	45.4
Tern	795	47.5

The resulting single pole structure height at the bundle attachment point ranged from 38m to 51m for line voltages of ± 300 kV to ± 800 kV. The corresponding ROW width ranges from 55-66m to 73-87m with the lower ROW width corresponding to the larger sub-conductors which do not blow out as much. If V strings are used in place of I strings, the ROW dimensions are reduced.

Having established the minimum spacing needed to avoid flashover to the single support structure and to the edge-of-ROW, the line between. The choice of sub-conductor type (for example, high steel ACSR, AAC) can cause some change in the blowout calculation and may impact the minimum ROW width required.

Radio Interference and Audible Noise

Of course, blowout clearance to edge of ROW is not the only constraint on conductor choice. The line must also produce acceptable levels of radio interference and audible noise. The number and diameter of sub-conductors per bundle are an important part of this calculation. The type of sub-conductor will have little direct influence on the calculations but may change the sag used.

Conventional calculations of surface gradient as a function of conductor diameter and number of conductors per bundle were performed. As shown in Figure 3-4, even a single large conductor is sufficient to meet the surface gradient limit at ± 300 kV.

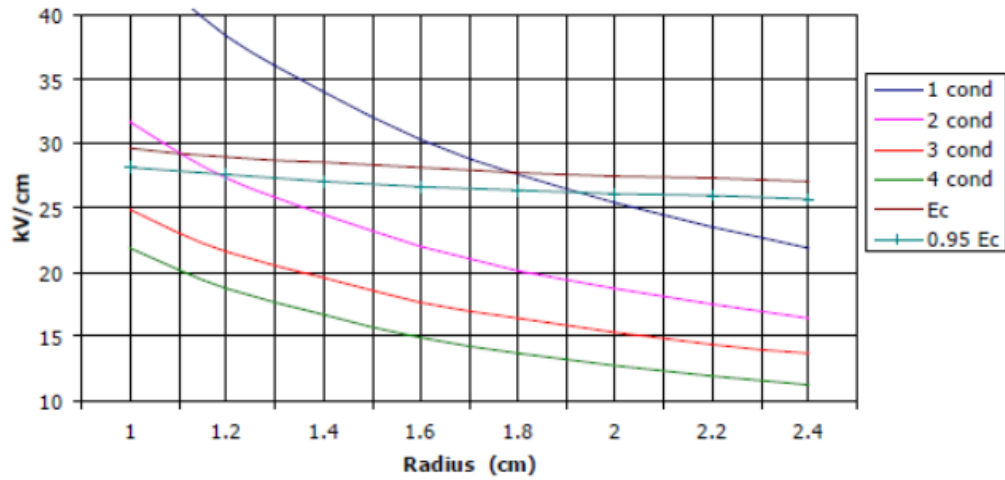


Figure 3-4
Surface Gradient as a function of sub-conductor radius and number of conductors per bundle at ± 300 kV

But similar calculations with the line at ± 600 kV, at least 4 of the largest conductors are needed to meet the surface gradient limits.

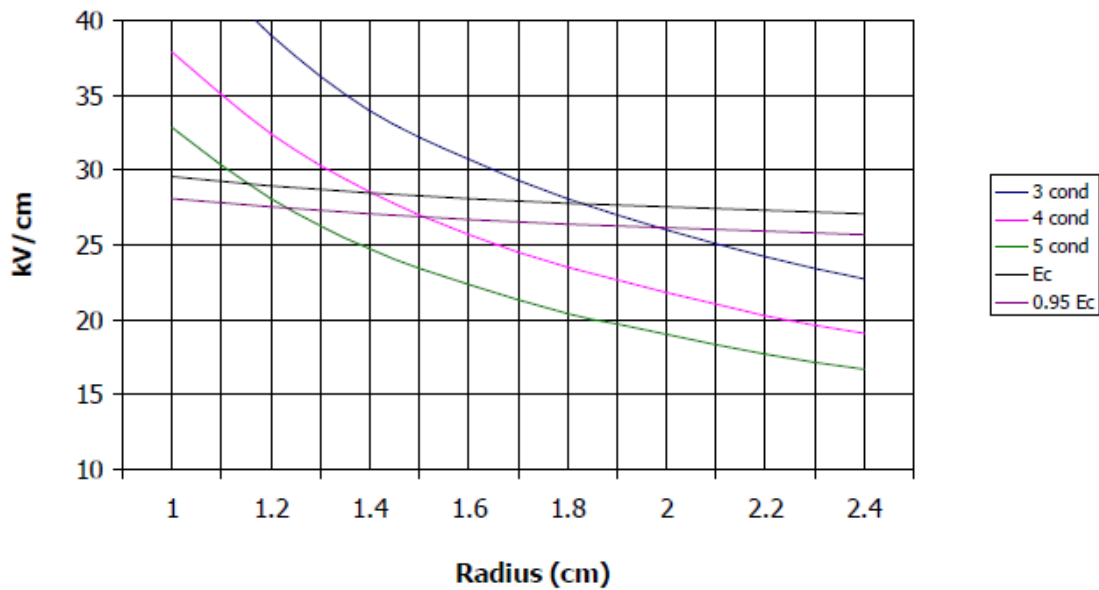


Figure 3-5
Surface Gradient as a function of sub-conductor radius and number of conductors per bundle at ± 600 kV

In terms of minimum ROW width, the various line and conductor bundle configurations were evaluated in terms of radio interference, audible noise, and horizontal “blow-out” clearance. The results are summarized in Figure 3-6 and Figure 3-7 for ± 300 kV and ± 600 kV HVDC lines, respectively.

kV	n	MCM**	I string ROW	V string ROW
±300	1	2,515	70	76
		2,167	130	140
		1,590	155	N (not calculated)
±300	2	2,515	54.7*	48.9*
		1,590	58.7*	56
		795	120	150
±300	3	2,515	54.7*	48.9*
		1,590	58.7*	52*
		795	65.5*	57.7*

Figure 3-6
Minimum ROW width (meters) to meet RI, AN, and Horizontal Clearance minimums at ±300 kV

kV	n	MCM	I string ROW	V string ROW
±600	3	2,515	124	130
		2,312	160	190
±600	4	2,515	76	82
		1,590	90	100
		1,351.5	104	170
		1,113	190	N
±600	5	2,515	65.9*	65
		1,590	70.7*	70
		795	130	240

Figure 3-7
Minimum ROW width (meters) to meet RI, AN, and Horizontal Clearance minimums at ±600 kV

The environmentally acceptable conductor alternatives at each voltage level were studied from a cost viewpoint. Generally, the fewest conductors per bundle resulted in the minimum line construction cost as shown in Figure 3-8.

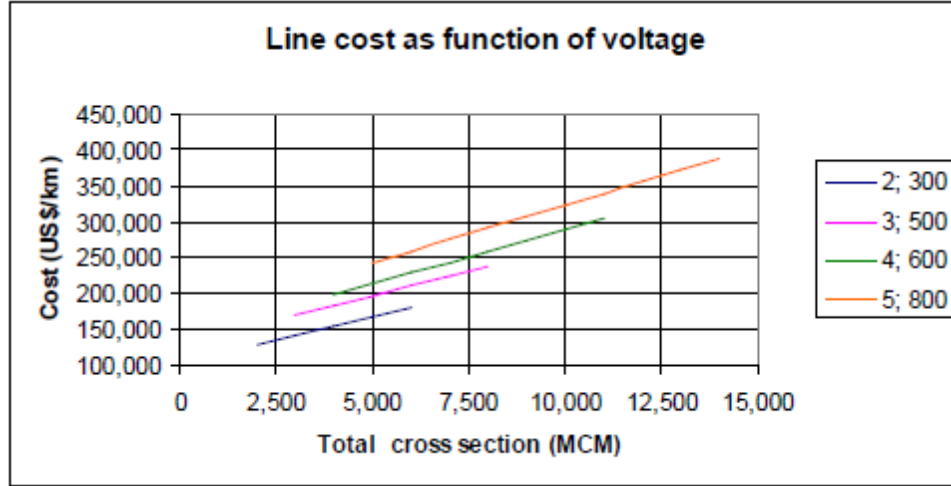


Figure 3-8
Adjusted total line costs (2:300 means a 2-conductor bundle at 300 kV).

Mechanical Design

The most striking thing regarding the calculation of HVDC line losses for this brochure is that the load on the line is assumed to reach the thermal capacity of the line. For a 1500 km HVDC line which has a thermal rating of 3000 MW, the line loading is anticipated to reach an annual peak of 3000MW as soon as construction is complete or within a few years. For a 1500 km 500 kV AC line, the maximum annual line load would be anticipated to be no more than 50% of the line thermal rating even after 10 to 20 years of operation.

On the other hand, it is worth noting that the optimum conductor size is never a sharp, well-defined conductor size. Plots of PW of total revenue required for lines, converters and maintenance typically show shallow minimums such that the difference in PW Total is less than 5% different even when the size of the pole conductor (total kcmil of the bundle) varies over 20%.

Calculation of Line Losses

Corona losses are generally much lower than Ohmic line losses. This is true even in most AC lines which generally carry lower currents than DC lines. Though calculated in this HVDC line analysis, corona losses are about 5% of line losses at all HVDC voltages and are distinctly a secondary consideration in the choice of pole conductors.

The maximum Joule losses are calculated by:

$$L_J = \frac{1}{2} \cdot R_{Bundle} \cdot \left(\frac{P}{V} \right)^2$$

Where:

P = Rated Bipole power in [MW]

V = Pole voltage to ground [kV]

R_{Bundle} = Bundle resistance [Ohms/km]

The loss factor for an HVDC line reasonably assumed to be higher (for example, 50%) than that assumed for an EHV-AC line.

For a 1500 km line length, the total cost breakdown for the most economical combinations of line and converter costs is summarized in

Table 3-3
Most economical total cost of revenue required for converters and 1500 km line as a function of rated power capacity.

MW	700		1,500		3,000		4,500		6,000	
kV	± 300		± 500		± 600		± 800		± 800	
N x MCM	2 X 2,280		2 X 2,515		4 X 2,242		4 X 2,515		5 X 2,515	
	MU\$/yr	%	MU\$/yr	%	MU\$/yr	%	MU\$/yr	%	MU\$/yr	%
line	33,7	42,9	39,7	33,7	56,9	32,4	65,1	26,9	76,0	25,2
corona	1,9	2,4	4,7	4,0	4,1	2,3	5,4	2,2	4,2	1,4
joule	12,0	15,2	17,9	15,2	27,9	15,9	31,5	13,0	44,8	14,8
converter	30,9	39,4	55,6	47,1	86,7	49,4	140,1	57,9	177,0	58,6
US\$/ year/ MW	78,5	100,0	118,0	100,0	175,6	100,0	242,0	100,0	302,0	100,0

Sub-Conductor Selection for HVDC Lines

In section 3 of this report, an good but very conventional process of conductor selection for HVDC lines was followed. Obviously, other calculation methods could be used to determine the corona calculations, the structure costs, and the ion currents and fields along the line, but the general procedure would be the same. Also, of course, the DC voltage might be selected before doing the analysis which would simplify things somewhat. Nonetheless, the procedure followed is generally a valid approach to selecting acceptable combinations of sub-conductor size and number of sub-conductors per bundle.

The only major limitation in the technique described so thoroughly in CIGRE Technical Brochure 388, is that only the most common type of sub-conductor (low steel content, ACSR) was evaluated. In this section of the report, it is assumed that the acceptable combinations of LS ACSR have been identified and that other types of sub-conductors are to be evaluated as alternatives that might provide better reliability or lower costs. If promising alternative conductors are identified, the complete design review process in the preceding section would need to be repeated in order to verify possible improvements in reliability or cost.

Optimal Pole Conductor Choices

HVDC lines are unique relative to most EHV-AC lines in that:

- They are longer than most EHV-AC lines and therefore more expensive.
- They are designed specifically to work with the DC converter stations at each end.
- The optimization (including conductor selection) involves not only the cost of the line itself but also the cost of the dedicated converter stations at each end.
- The emergency load on the HVDC conductors is well defined. It is typically twice the normal current if the line is bi-polar and designed to be operable as a monopolar line.
- The normal load is higher than that of an EHV-AC line because of the high cost of the converter stations and on the line itself.
- There is no need to use utility standard conductors since the typical HVDC line is large enough that the use of unique conductor systems is justifiable.

Table 3-4
Adequate pole conductor bundles chosen for economic analysis

Voltage (kV)	n conductors	MCM*	Code
±300	2	2,167	Kiwi
	4	1,780	Chukar
±500	2	1,272	Bittern
	3	1,590	Lapwing
	4	2,167	Kiwi
±600	3	1,272	Bittern
	4	1,780	Chukar
	6	2,167	Kiwi
±800	6	954	Rail
	5	2,167	Kiwi

4

ALTERNATE SUB-CONDUCTOR CHOICES

With HVDC lines, the resistance of any sub-conductor is simply related to the conductor cross section area and to the conductivity of the wires. No skin effect or complex magnetic coupling through ACSR's steel core occurs. Replacing the steel core of these low steel ACSR conductors with aluminum will yield lower resistances. Given the conductivity of steel, its presence can be ignored in calculating resistance.

Similarly, trapezoidal strands could be used in place of round strands to decrease resistance but in ACSR, the use of trapezoidal aluminum wires requires a similar enlargement of the steel core in order to keep the strength to weight ratio the same. For all aluminum conductors, increasing the cross-section area while leaving the diameter unchanged does not change the strength to weight ratio (sag-tension behavior) but of course it increases the vertical bare conductor loads on structures.

By replacing the steel core with a composite, the high temperature sag can be reduced and the line rating increased without altering the structure loads. In light loading areas, the structure height may also be decreased.

Homogeneous Bare Stranded Conductor Types

In a recent CIGRE TAG 4 survey, over 80% of the overhead transmission lines around the world used ACSR conductors. Similarly, in most HVDC lines including the designs considered in Technical Brochure 388 are low-steel content ACSR. Given the size of the sub-conductors found to be optimum in the HVDC study described in 388 there is no apparent need for high steel content ACSR conductors. They would simply be more expensive and raise the cost of tension structures. On the other hand, it appears that there may be multiple advantages to the use of one of the various types of all aluminum conductors that have been used in AC or DC overhead lines:

The major advantages of all aluminum bare stranded conductors include the following:

- No electrolytic corrosion occurs even in aggressive sea coast environments over long periods of time. The concern over loss of sacrificial zinc coating on steel core wires over the life of the line is removed.
- Installation procedures and compression connectors are simpler to apply and avoid the various problems with two-part compression connectors.
- No money need be spent on a steel core which is not required for mechanical reliability.
- High temperature clearances are more reliable because there is no knee-point behavior to consider.
- The conductor is lighter than ACSR and maximum design tensions on strain structures will be reduced.

There are also some disadvantages to their use:

- They present a lack of flexibility regarding mechanical properties if entirely made of the same type of aluminum (though ACAR allows one to adjust the tensile strength by changing the stranding within a given cross-section area).
- In AC transmission lines, their low temperature limits (for example, 90°C continuous) yields concern that occasional high current emergency events could reduce the tensile strength and permanently increase sags, requiring replacement.

This last limitation is less severe for HVDC lines where the most likely high loading event is operation in single pole mode.

All-Aluminum Conductor (AAC)

AAC is manufactured entirely with 1350-H19 aluminum strands. It is a relatively inexpensive conductor since it has no steel core. 1350-H19 aluminum is available from multiple suppliers, for use in ACSR. It has relatively high conductivity (61.2% IACS), good corrosion resistance since it is also used in ACSR and very light weight per unit length. It is limited to use in overhead lines with either relatively short spans or in regions with very mild loading conditions.

It should not be operated above 100°C, for more than very short emergency loadings, since it loses tensile strength due to annealing and it should not be operated continuously at temperatures above 50°C because of accelerated metallurgical creep at high temperatures. These concerns are much less important in lines having short spans in urban areas where it is widely used.

All-Aluminum Alloy Conductor (AAAC)

AAAC is manufactured with 6201-T81 heat-treated aluminum alloy strands. These strands have the same stiffness as 1350-H19 but lower conductivity (52.5% IACS) and twice the tensile strength. Outside of the United States, similar high-strength aluminum alloys are called “Aluminum-magnesium-silicon alloy” (IEC 60104) and have similar but not identical properties.

The strength to weight ratio is twice that of AAC and comparable to strong ACSR. It can be used in lines with long spans and moderately heavy loading conditions. AAAC offers the combination of high tensile strength and excellent corrosion resistance. Its electrical conductivity is 52.5% IACS, lower than that of 1350-H19 (62.1% IACS). To produce stranded conductors with the same resistance as AAC, AAAC conductors have somewhat higher cross-sectional areas and diameters.

AAAC Conductors have been used extensively in both the English and French 400 kV systems. They are also used in many ex-British and French colonies. One of the limitations of AAAC is prone to wind vibration induced fatigue. The other major limitation is that it cannot be operated continuously or even for limited periods of time at temperatures over 100°C without a reduction in strength and possibly permanent increases in sag.

Aluminum Conductor Alloy Reinforced (ACAR)

ACAR consists of a mix of 6201-T81 and 1350-H19 strands having the same strand diameter. ACAR allows the designer to balance mechanical and electrical properties. Because the 6201 and 1350 strands are equal in diameter, they can be interchanged to optimize the properties of ACAR for each particular application. An example of this flexibility is the increase of the relative number of 6201 strands to achieve a strength-to-weight ratio matching that of a wide range of ACSR conductors. These conductor exhibit excellent corrosion resistance and utilize simple termination hardware making them excellent choices for many transmission line applications.

Use of All Aluminum Transmission Line Conductor – US Experience

AAC and ACAR conductors as well as low strength ACSR (for example, 36/1, 45/7, 84/19, 72/7) are in widespread use in the United States. In recent years (since the mid-1980's) few new lines have been built and much of the conductor sold has been for re-conductoring existing high voltage lines.

The primary argument in favor of AAC is economic. The conductor is less expensive than ACSR and the strain structures required to support it are also less expensive since the maximum tensions are lower. It requires no special installation or termination procedures (a single piece compression splice/dead-end can be used) and AAC/TW offers the lowest electrical losses possible for a given conductor diameter. The use of all aluminum conductor is attractive in coastal and industrial/urban areas where corrosion is a concern.

The primary objection to the use of AAC is high-temperature operation. This is a concern primarily in high-voltage rather than extra-high voltage lines and in re-conductoring existing lines rather than in new lines. In EHV lines (AC or DC), AAC is an economic alternative to ACSR and has proven itself to be a reliable transmission line component.

A key aspect of whether AAC is an acceptable choice for this application involves estimating the Aeolian vibration levels and possible resulting aluminum strand fatigue that may result. This report assumes that installing AAC conductors in the desired configuration at 25% of breaking strength results in vibration levels that can be controlled by easily acceptable and inexpensive methods such as dampers and spacer-dampers.

In areas that are not subject to severe ice loading or to hurricane force winds, AAC and ACAR have been used successfully primarily in extra high voltage (EHV) AC where the need to limit corona effects requires relatively large diameter conductors even in bundles. The Keystone Project, for example, is a single circuit 500 kV line having 2 conductor bundles (see Table 2) of ACSR. Each sub-conductor is 46 mm in diameter. With self-supporting steel lattice structures, this line goes up the east coast of the US from Virginia to New York. It was built in the 1970's and has been very reliable over the last 40 years.

Table 4-1 contains a number of examples of 500 kV ac transmission lines built in the US with all aluminum conductors. From this table one can see that all aluminum conductors have been used in quite a wide range of regions. PP&L and AEP are not on either coast and these lines are in hilly terrain (though not mountainous). All of these lines are subject to both ice and wind loads though not to the most severe ice loadings such as are found in mountainous areas and in Canada.

Table 4-1
Examples of lines which used all aluminum phase conductors in the US

Utility	Voltage	Sub-conductor type	Stranding/ Area-mm2	Span Length [m]	OD [mm]	UTS[kN]	SagTen@15C %UTS [m/kN]	Damp/ Spacer Damp
VEPCO 1973	500 Single	ACAR	2 - 84/7 1263	365	46.3	280	15% 14.6/41.0	2/none
PSE&G 1978	500 Single	ACAR	2 - 54/37 1263	335	46.3	280	16% 10.6/45.8	1,2 or 4/none
PP&L 1980	500 Single	ACAR	2 - 54/37 1263	395	46.3	280	25%@15C 17.6@125C 117@Med	1/none
PG&E 1974	500 single	AAC	2 – 61 1167	450	44.5	280	28%@15C 19.8@55C 107@Med	1/none
Louisiana P&L 1966	500 single	ACAR	3-24/13 519	335	29.6		20%@15C	1/none
AEP 1970	500 Single	ACAR	2 – 42/19 1013	400	41.9		16%@15C 69@0C	2/span

AAC is most common in the Western coastal states (CA, OR, WA), the arid Southwest (NM, AZ), and in the heavily populated mid-Atlantic states (NJ, MD, NY, CN).

The percentage of all aluminum conductor sales in the United States is less than 5%. It is more commonly used in lower voltage power distribution lines than in high voltage transmission lines. AAC is more commonly used in coastal areas and in urban areas where spans are relatively short. The manufacturers and suppliers stock only a few sizes of AAC.

In regions with severe corrosion problems, the use of all aluminum conductor eliminates concerns over the process of electrolytic corrosion between the aluminum and steel reinforcing core strands. Obviously, other approaches to corrosion protection have been effective in most cases (aluminum clad steel core wires, grease filling the interstices of the stranded conductor, heavy zinc coatings on steel core wires) but all are more expensive than normal ACSR while AAC is less expensive.

It is interesting to note that there have been numerous vibration fatigue failures in ACAR and AAAC (6201-T81) lines which were installed to EDS values used for ACSR. This seems consistent with the recent CIGRE technical publications which suggest that the catenary constant is a better vibration indicator than %EDS. On the catenary constant basis, 25% UTS at 15C with AAC is comparable to 17% for 54/19 ACSR and 20% for 42/19 ACAR. On a %EDS basis it is easy to see why ACAR had more vibration fatigue problems than AAC.

Extensive studies were made in the 1990's using software which was developed prior to PLS-CADD. Bryan White, a well regarded structural consultant, performed many studies to evaluate line construction cost as a function of conductor type. Bryan concluded that AAC was the cheapest solution in most regions, the exception being areas with very heavy ice loading.

Power Technologies also performed “typical span” studies of line cost for various types of conductors in the 1980’s. The conclusions were similar; AAC and ACAR were less expensive than lines built with ACSR except when the steel content was very low.

Virginia Power constructed one of the first 500 kV lines (perhaps the first commercial 500 kV line in the world) in 1963 using 5005 alloy conductor (5005 has slightly higher tensile strength and somewhat lower conductivity than ordinary AAC). The line used a 2 conductor bundle with sub-conductor area of 1038 sq.mm. Total line length of the loop was almost 500 km. The design tension was 18% final at 16 °C. One Stockbridge damper was applied per sub-conductor in each span with standard non-damping spacers. The line is still in operation without any vibration damage. The project is described for example, in IEEE Transactions Paper 64-126, by Harold Adams and J.D. Shaw.

The use of AAC conductors on the BPA system has been common since the mid-70's where their application makes sense in terms of strength to carry anticipated extreme loads (25 mm glaze ice and 384 Pascals wind [96 km/hr]) and tower cost versus conductor cost.

When AAC was being seriously considered by BPA as standard conductor options it was recognized the steel core in many previous conductors used by BPA was very expensive (both in conductor cost and increased sag) and provided very little value as the towers would not develop their ultimate strength.

BPA has limited use of AAC at 500 kV but the AAC option is common on 230 kV and 115 kV lattice steel, tubular steel and wood pole H-frame. The sizes vary from 278 mm² (18mm OD) to 1220 mm² (40 mm OD) with about five standard conductors of various sizes in the standard family. There is also a standard ACSR family based on TW strands with about six conductors of various sizes. For single and twin (2) conductors, the standard dampers for BPA are Stockbridge type and for triple (3) and quad (4) bundles, BPA uses spacer-dampers.

PG&E is located in northern and central California with four major environmental loading conditions:

- California Light: -3C, 384 Pascals, no ice.
- Intermediate: -18C, 288 Pascal wind, and 6mm glaze ice
- California Heavy: -18C, 288 Pascal wind, and 12mm glaze ice
- Extra Heavy: -18C, 288 Pascal wind, and 12mm glaze ice

In light loading areas, PG&E typically installs AAC for both transmission and distribution lines. In other areas, ACSR is the standard conductor. Out of a total of approximately 18,000 circuit-miles of transmission line of voltages from 60 to 500 kV, approximately 9400 circuit-miles is AAC. At 500 kV, PG&E has several lines totaling approximately 1100 circuit-miles constructed between 1965 and 1978 with a two-bundle 2300 kcmil, 61 strand AAC in light loading areas.

The selection of all-aluminum conductors is based on economics. Its high conductivity-to-weight ratio makes it a good choice where only moderate strength is required. They find that it lowers the cost of both the conductor and the structures. The conductor cost is lower without the steel

core. In addition, the dead-end structures do not have to be as stout because the conductor tensions are lower and the tangent structures can be designed for somewhat smaller transverse loads because the diameter is smaller for the same crosssectional area.

PG&E's experience is that AAC and ACSR have similar service lives, though ACSR is more prone to corrosion in our coastal areas. AAC has pretty good corrosion performance. Standard design limits used by PG&E for spans up to 550 m are:

- Maximum tension, initial: 45%
- 60 degree F, initial: 35%
- 40 degree F, final: 25%

In summary, PG&E has found AAC to be an economical and reliable conductor in light loading areas.

Conclusions of Studies

The conclusion of these studies is that the most economic pole bundle at ± 300 kV is two large (1590 to 2515 kcmil) sub-conductors and at ± 600 kV is 4 or 5 large sub-conductors. Given these acceptable pole conductor bundles, the type of conductor can be varied so long as the diameter, resistance, and high temperature sag of the sub-conductor is not greatly altered.

In new HV, EHV, and UHV AC lines, conductor selection is often driven by the desire for standardization. For example, the utility may standardize on a 345 kV line design which utilizes a phase bundle of 2-Rail ACSR conductors. This allows standardization of installation procedures, hardware, construction equipment and structure/foundation designs. It may well be true that the use of a larger sub-conductor may in standard designs is justified. It may be economic analysis, physical reliability, and ease of field repairs after outages. Very often, a power utility will choose a "standard conductor or bundle" to allow minimization of inventory and simplification on emergency repairs rather than to find the absolute minimum present worth cost.

With HVDC over head lines, conductor selection and optimization are driven primarily by economic issues since HVDC lines are typically much longer than AC lines, involve far fewer terminals, require much larger capital investment, and carry much higher power flow currents than AC lines. HVDC lines are unique and they offer the opportunity to optimize conductors with little need to coordinate inventory with most other lines.

Electrical losses are typically far more important in HVDC lines than in AC since HVDC lines are longer and carry much higher currents than AC lines. The reason for high power flow and great length is the cost of the terminal equipment.

It is possible to argue that HVDC lines should be designed to be far more mechanically reliable than AC lines since the loss of an HVDC line involves far greater system disruption than the loss of even a UHV AC line, which can be compensated for by the increased loading of other AC lines.

The major issues involved in HVDC conductor optimization are the type of conductor and the size of conductor. In particular, the possible use of all aluminum conductors and high-temperature, low-sag conductors should be evaluated.

A critical part of conductor selection concerns the interaction of the HVDC line with the enclosing AC transmission system. Given the much higher HVDC power flows and the inability to use the HVDC converter capacity in the AC network, the loss of a DC circuit can have a much larger impact on system load reliability than the loss of an EHV circuit. On the other hand, the availability of an HVDC terminal near a load center can improve overall load reliability.

It is clear that the value of HVDC lines is a function of how they are considered in system planning studies. Their unique capabilities—load flow control, much higher power flow densities, single pole operation, etc.—make for a very complicated impact on system reliability.

Compacted ACSR Sub-conductors

ACSR is the most commonly used type of overhead conductor internationally. One of the key reasons is that its strength and modulus can easily be adjusted over a wide range.

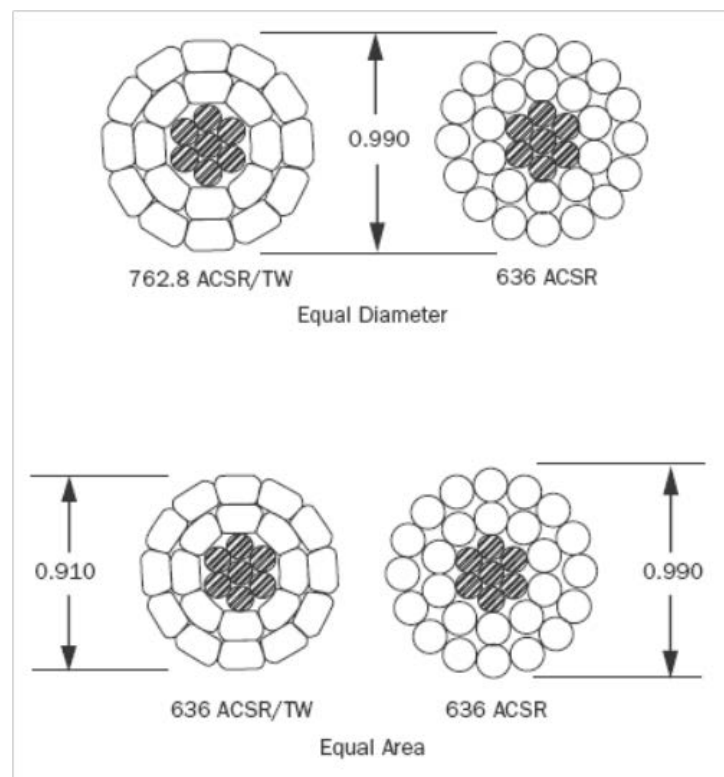


Figure 4-1
Comparison of equivalent ACSR conductors with round and trapezoidal aluminum wires

The same comparison can be made with all aluminum conductors. It is unlikely, however, that the use of trapezoidal wire will have a large impact on the selection of optimum size when designing a new transmission line.

Table 4-2
Comparison of equal area and equal diameter equivalents to 636 kcmil, 26/7 Grosbeak ACSR

Conductor	Grosbeak	Grosbeak/TW	Wabash/TW
Outside Diameter [inches]	0.990 (100%)	0.908 (91.7%)	0.990 (100%)
Alum Area [kcmil]	636.0 (100%)	636.0 (100%)	762.8 (120%)
Rdc@20C [Ohm/mi]	0.1411 (100%)	0.1408 (99.8%)	0.1174 (83.2%)
Rac@25C [Ohms/mi]	0.1451 (100%)	0.1446 (99.7%)	0.1212 (83.5%)
Rac@75C [Ohms/mi]	0.1733 (100%)	0.1727 (99.7%)	0.1446 (83.4%)

In any transmission line, the phase conductors are subject to a myriad of mechanical, thermal, chemical, and electrical constraints. Traditionally, large EHV and UHV AC line projects involve a process of selecting an appropriate conductor which balances the present worth of electrical losses over the life of the line against the present worth of capital investment, while meeting limits on environmental effects and requirements for emergency load rating. In shorter AC lines, conductors are selected from a very limited group of standardized types and sizes in order to limit inventory requirements and simplify maintenance.

Given the great length and capital cost of most HVDC lines, the relatively high system normal electrical power flow, and the critical need for high mechanical and electrical reliability, the process of conductor selection is critical and time spent in the process of selection and optimization is easily justified both technically and economically.

Use of High-Temperature Low-Sag Conductors

Many quite different HTLS conductors are commercially available. These conductors offer substantially lower sags at conductor temperatures above that for which it is initially sagged. At high temperatures both physical and electrical properties are stable, even when operated continuously at temperatures as high as 240C.

HTLS conductors have primarily been used to re-conductor existing overhead lines when a large increase in the line's thermal rating is required but the original structures and foundations are to be re-used without extensive reinforcement.

When applied to new EHV-AC lines, HTLS conductors offer a number of advantages which can offset their higher cost. In particular, given a conductor size which is near-optimum in terms of the overall line cost or chosen for the sake of standardization, an HTLS conductor provides much higher emergency power flow thermal capacity than conventional ACSR. This may allow the utility to avoid the need for future thermal upgrades given the uncertainty of future power flows on HV AC lines due to the open access operation of the system. If the additional cost of the HTLS conductor is small (for example, ACSS), then the cost may be offset by savings from lower tower heights or longer spans because of reduced sag at high temperature.

HVDC lines are operated separately from the AC power system in the sense that their power flow does not suddenly increase in response to the loss of major facilities in the AC system such as EHV lines or generating stations. The flow on HVDC lines is limited by the converter station capacity and controllable so the concern regarding high post-contingency power flows (and using HTLS to deal with it) does not exist for HVDC lines.

Given the length of HVDC lines and their greater cost, it is doubtful that the use of HTLS conductors would be justified in new HVDC lines, even considering their reduced sag at high operating temperatures.

HVDC for Renewable Generation

There have been many claims that HVDC is an ideal medium over which to move renewable generation over long distances. Large blocks of power from extensive wind farms in remote areas of North Dakota could be brought 1000 to 1500 km to population centers near Chicago by means of an HVDC line.

HVDC has undeniable advantages over EHV-AC over long distances where converter costs are less of a limitation. The limitation to this argument involves the load factor of photo-voltaic or wind generation. It is low. Therefore, for much of the time, the power flow over this long expensive HVDC line is much lower than the converter and associated line's capacities.

While it seems likely that the low load factor of renewable generation makes it difficult to justify the use of HVDC, if it could be justified it may be that the use of HTLS sub-conductors could be helpful, especially a less expensive HTLS conductor such as ACSS.

5

CONDUCTOR SELECTION EXPERIENCE

An important factor in any overhead line design process is experience. Transmission lines last for 40 to 80 years and difficulties that appear after 30 or more years are notoriously difficult to foresee. This is especially difficult to obtain with regard to HVDC lines since few utility line designers have designed more than one in their career.

Therefore, this chapter is an important part of the overall process of HVDC conductor optimization in that it provides a summary of line design experience to supplement the other more analytical recommendations in the report.

Questions Posed to HVDC Asset Owners

With some variation in order to reflect a particular HVDC line design, the following questions were posed to a number of HVDC asset managers:

- If the line has bundled pole conductors, have there been any problems with the spacers wearing out?
- Have there been any conductor wind vibration or damper fatigue problems?
- Would the use of a larger original conductor have been advantageous by reducing corona problems or by providing higher thermal capacity?
- Have there been any unusual mechanical failures or excessive maintenance issues that can be traced to the selection of pole conductors/connectors/hardware?
- If you were building a new HVDC line, would you use the same kind of conductors or a different type (for example, AAC, AAAC, HTLS, etc.)?
- Have you increased the operating voltage of the line during its life? If so, did you need to replace the original conductors?

BPA Experience

The Pacific Intertie goes between the Northwestern US and California. The line was originally put into service operating at ± 375 KV with a 2 conductor bundle of 76/19 2312 kcmil ACSR, arranged horizontally with two DC poles per steel lattice structure.

Comments regarding the pole conductors:

1. There have been no problems with the spacers wearing out. The original spacers were replaced in 2004 (after 34 years of service).
2. There have been no vibration or damper fatigue problems but BPA is planning to replace the existing Stockbridge dampers as soon as a suitable replacement can be obtained.
3. The original 2-Thrasher bundle has had all the thermal capacity needed. Corona performance is adequate.
4. There have been no mechanical failures traced to conductors/connectors/hardware. They had one tower failure due to vandalism: a side guy was cut and the tower tipped over. The steel tower and conductors were undamaged. The guy and some insulators were replaced, and the line was reenergized.
5. BPA is proposing to upgrade the DC Intertie again to 3800MW with ± 565 kV DC from the Celilo (The Dalles, OR) Station with new insulator assemblies on the line, but the same towers and bundle. This would also involve a complete rebuild of the Celilo station. Los Angeles Department of Water and Power (LADWP), BPA's southern partner has already rebuilt and upgraded their Sylmar Station.
6. If they were building a new line, they might use different bundle and sub-conductors. They might use ACSR/TW sub-conductors, but that would also figure into the electrical performance of the bundle also. A larger conductor in a bundle would have provided better corona performance but they have not really had problems with the corona performance to date so it has not been necessary.
7. BPA might go to a 3 conductor bundle for a new HVDC line but since no HVDC has been built for so long, they would need to do a complete review of the line design to evaluate the corona and field effects that DC causes to determine what they would expect to be acceptable performance before choosing a sub-conductor.

Manitoba Hydro Experience

Manitoba Hydro (MH) has two HVDC lines that they designed: Radisson-Dorsey at ± 450 kV and Henday-Dorsey at ± 500 kV. Both are part of the Nelson River Bi-pole line. Each pole has a 2 conductor bundle of 72/7, 1.6 inch OD ACSR, arranged horizontally with two DC poles per steel lattice structure. The lines were originally put into service at a lower DC voltage in 1972. The spans are typically 1500 ft and have not been re-conducted. Dunlop-Metalastik spacer dampers are used.

Comments regarding the pole conductors:

1. Rubber bushings in all spacer-dampers were replaced after 30 years of service. The problem was the loss of damping at approximately -20°C due to crystallization of the rubber insert.
2. No conductor vibration or spacer-damper fatigue problems
3. The use of a larger original conductor might have been advantageous. Existing lines have experienced anomalous flashovers in summer months which might be related to rather high conductor surface gradient (25.1 and 27.2 kV/cm).
4. There have been no mechanical failures that can be traced to the pole conductors/connectors/hardware.
5. If building a new ± 500 kV HVDC line, they might choose a different type of conductor such as the 3-all aluminum alloy conductor bundle being used in the new HVDC line (Bipole III).
6. There have been no major mechanical failures that relate to conductor choice.
7. In the process of choosing a pole bundle for the newest HVDC line, no commercial package was used in the process. The conductor selection study considered approximately 10 different conductor sizes/stranding/types. The task was simplified by the fact that our System Planning gave them two parameters to maintain:
 - minimum conductor diameter of 38 mm to keep the surface gradient level down to 25 kV/cm
 - resistivity equal to 1590 kcmil ACSR (this resulted with us ignoring the line losses)

In the study, they considered only the variable cost components in the following two groups:

- material costs: conductors, towers, foundations, insulators
- construction costs: tower assembly/erection, foundation installation

The $806\text{ mm}^2\text{-A4-61}$ (AAAC) conductor was chosen.

Great River Energy Experience

The Coal Creek–Dickinson HVDC “CU” line is presently operated at ± 410 KV with a 2 conductor bundle of 45/7 1590 kcmil Lapwing ACSR for each pole. The poles spaced 40 ft apart on separate steel lattice structures with typical 1400 ft spans. The poles have at least 35 ft ground clearance and a 160 ft ROW. It was originally put into service in 1979 at which time they installed Stockbridge vibration dampers.

Comments regarding the pole conductors:

1. No re-conductoring of CU has been done.
2. There have been no problems with the bundle spacers wearing out.
3. There were no vibration issues with the shield wires after energization, and dampers were added.
4. The use of a larger original conductor would have been advantageous since they now use a more conservative ampacity rating methodology for ac and dc transmission lines. They are still evaluating actual clearances to ground in the field to determine the line conductor’s ampacity rating in summer.
5. No mechanical failures have been traced to the choice/configuration of pole conductors/connectors/hardware. The line has performed well.
6. If building a new ± 400 KV HVDC line, they would consider the use of a different type of conductor. The line was conservatively designed with high reliability the first criterion. Also, they have very little overload capability due to converter ratings. Thus it is expected that they would look first at larger ACSR conductors to reduce losses.
7. A comprehensive economic study was done to select the dc line voltage and optimum conductor size when the line was designed. It is not known if that study considered the amount of time in monopolar metallic return mode (with attendant higher losses). Also, replacement power costs are much higher today than in the 1970's. It is expected that a line designed today would probably be different than the CU design.

6

CONCLUSIONS

The operating voltage of HVDC lines varies from ± 300 to ± 800 kV. As the voltage of the HVDC line increases, the choice of phase conductor bundle is increasingly concerned with ion current and DC fields. As with AC lines, this implies that the number of conductors per bundle increases with the line's voltage.

The process of selecting an optimum pole bundle for an HVDC line is similar to the process of conductor optimization in an EHV AC line. For a range of pole bundle sizes, the structure and foundation loads, the right-of-way width needed to yield acceptable environmental effects and horizontal clearances during maximum blowout, and the insulation levels required to yield an acceptable level of flashovers in response to lightning and switching surges are calculated. The present worth of the resulting cost of conductor, structures, foundations, insulators and right-of-way are tabulated and added to the present worth of electrical (and corona) losses over the life of the line.

HVDC lines differ from HV AC transmission lines in that the normal power flow is higher and controllable. Given the high cost of the DC converter stations required with the HVDC line, the load factor for such lines is typically 40% to 50% and the level of transferred power is not influenced by the surrounding HV AC system.

Most HVDC lines are designed to be capable of single pole operation. In this case, the power flow is twice the normal bi-polar power flow and the emergency power flow in the in-service pole approaches the pole bundle thermal limit, even when the line is quite long (the reactance effects in HV AC lines do not apply to HVDC lines).

As opposed to most HV AC lines, the power flow of the HVC line is driven by the high cost of the converter stations to be close to the power capacity of the station and the emergency power flow is twice the normal current if the line is designed to operate in single pole mode.

Because the power flow under normal and emergency conditions is particularly well defined for an HVDC line, the process of conductor optimization is more realistic and worthwhile than for an EHV AC line where the normal and emergency power flow is uncertain, especially decades into the future. Because the emergency loading is predictable at the time of design, the use of all aluminum sub-conductors is an attractive choice for HVDC. In the section on experiences, Manitoba Hydro mentions the choice of an all aluminum alloy sub-conductor for their newest HVDC line design.

7

REFERENCES

1. CIGRE Joint WG B2/B4/C1.17, "Impacts of HVDC Lines on the Economics of HVDC Projects", Tech. Brochure 388, August, 2009.
2. Douglass, D.A., Kennon, R.E., "EHV Transmission Line Design Opportunities for Cost Reduction", IEEE Transactions on Power Delivery, Vol. 5, No. 2, April 1990, pp 1145-1151.
3. CIGRE WG 14.20, "Economic Assessment of HVDC Links", Technical Brochure 186, June, 2001.
4. Douglass, D.A., "Economic Measures of Bare Overhead Conductor Characteristics," IEEE Transactions on Power Delivery, Vol. 3, No. 2, April, 1988, pp 754-761.
5. Grant, I.S. and Clayton, R.E., "Transmission Line Optimization," IEEE Transactions on Power Delivery, Vol. PWRD-2, No.2. April, 1917, pp 520-526.
6. Grant. I.S. and Longo, V.J. "Economic Incentives for Larger Transmission Conductors", IEEE PES Paper 81 WM 201, presented at the IEEE PES Winter Meeting 1980.
7. Fritz, E., "The Effect of Tighter Conductor Tensions on Transmission Line Costs", IEEE Transactions Paper, Vol. PAS-79, 1960, pp 513-527.

A

ELECTRICAL LOSSES FOR HVDC LINES

In a recent CIGRE technical brochure on Life Cycle cost calculations, it was concluded that the electrical losses (or carbon equivalent) produced by overhead transmission lines (primarily ac lines) is practically negligible in comparison to the waste heat and carbon gases produced in power generation. Nonetheless, calculation of electrical losses has always been considered in both the design and operation of overhead transmission lines and, in recent years, there is an increased emphasis by federal regulatory agencies on saving energy. In a recent court case in Austria, the judge ruled in favor of using underground transmission cable instead of overhead lines because the cable had lower losses (more aluminum cross-section) per km.

The magnitude of overhead ac line losses was calculated in a recent IEEE Tutorial on losses in overhead ac transmission lines:

- For a 115 kV line having one 795 kcmil Drake ACSR per phase, the electrical losses per mile were estimated to be about 0.06% of the system normal energy delivered (60MVA), increasing to 0.80% per mile during infrequent system emergency loadings of 200MVA.
- For a 500 kV line having 3 1272 Bunting ACSR per phase, the electrical losses per mile were estimated to be 0.01% of the system normal energy delivered (1000 MVA), increasing to about 0.10% per mile during infrequent system emergency loadings (3000MVA).
- Shield wire losses (induced magnetically) were about 1% of the phase conductor losses. Of course, the shield wire induced current in an HVDC line is zero.
- The length of line at which electrical losses equal 1% of the system normal transmitted power is 15 miles for the 115kV line and 100 miles for the 500 kV line.

As is demonstrated in the following discussion, the calculation of losses in a HVDC line is essentially the same as for a EHV-AC line but two aspects of HVDC make losses more important: (1) HVDC lines tend to be longer than EHV-AC because of the absence of electrical phase shift limitations and because they have to be to justify the high cost of the converter stations; (2) The power flow on HVDC lines tends to be higher than EHV-AC for the same conductor bundle both because it can be and because it must be to justify the converter cost.

Calculation of Electrical Losses in HVDC lines

Electrical loss calculations for HVDC lines typically involve a series of straightforward steps, most of which are followed for loss calculations with ac lines:

- The dc resistance of the pole conductors is determined as a function of temperature.
- The current flow in each of the pole conductors is determined over the life of the line.
- The length of the line is established.
- The average weather conditions along the line route are estimated over the life of the line.
- The economic parameters pertaining to the cost of line losses are estimated for the life of the line.

- The various steps are combined to determine the present worth of electrical losses over the life of the line.
- For HVDC lines, there are no electrical losses due to induction in shield wires, whether they are grounded at each structure or insulated.

DC Resistance of Bare Stranded Conductor

Typical transmission conductors are between 0.6 and 1.5 inches in diameter but can be as small as 0.4 inches and as large as 2 inches. The difference between dc resistance and ac (50 Hz or 60 Hz) resistance is quite small except for ACSR with either one layer or three layers of aluminum strands. The difference may be as large as 20% for single layer and 5% for three layer ACSR at high current densities.

The dc resistance of helically-stranded, bare overhead conductors is primarily a function of the total cross-sectional area of aluminum (or other conducting material) wires and the electrical resistivity of the wire material.

DC Resistance Based on Wire Cross-sectional Area

Ignoring for the moment the helical nature of the wires used in bare overhead conductor, that is, assuming the wires are straight and parallel, and assuming that the wires are at 20°C, the dc resistance (R_{dc}) of the stranded conductor is:

$$R_{dc} = \frac{\rho_v}{A}$$

Where ρ_v = resistivity of wire material [16.946 Ohm-cmil/ft @20°C for 1350-H19 aluminum]

A = total circular mil area of all the wires

The equation works equally well in SI units where the resistivity is 0.028172 mm²/m and the total wire area is in mm².

For a two component conductor such as ACSR, the dc resistance is the parallel combination of the steel core resistance and the resistance of the outer aluminum layers:

$$R_{dc_{total}} = \frac{\frac{\rho_1}{A_1} \cdot \frac{\rho_2}{A_2}}{\frac{\rho_1}{A_1} + \frac{\rho_2}{A_2}}$$

For a 795 kcmil (402.8 mm²), all aluminum conductor, with 1350-H19 aluminum at 20°C, the dc resistance (with infinite lay length) is:

$$R_{dc}(20C) = \frac{0.028172}{402.8} = 0.06994 \text{ Ohm} / \text{km} = 0.1125 \text{ Ohm} / \text{mile}$$

For a 795 kcmil, 30/7 ACSR conductor, the dc resistance of the aluminum layers at 20°C is the same as for 795 kcmil AAC since the aluminum area is the same.

For ordinary Class A galvanized steel core wires, the resistivity is 0.21552 mm²/m (129.64 cmil/ft). Given the steel core area of 185.5 kcmil, the dc resistance of the steel core is approximately:

$$R_{dc}(20C) = \frac{129.64}{185,500} = 6.989E - 4 \text{ Ohm} / \text{ft} = 3.690 \text{ Ohm} / \text{mile}$$

The total resistance of the ACSR conductor is:

$$R_{dc_{total}} = \frac{0.1125 \cdot 3.690}{0.1125 + 3.690} = 0.1092 \text{ Ohms} / \text{mile}$$

The steel core reduces the total dc conductor resistance by approximately 3% and carries about 3% of the total current on the conductor. The steel area of 30/7 ACSR is 23% that of the aluminum strand layers. Since most ACSR conductors have steel core areas less than 30/7, the contribution of the steel core to reducing the composite conductor resistance is less than 3% (for example, for 45/7 ACSR it is about 1%).

According to the Southwire Overhead Conductor Manual (2nd Edition), the dc resistance of 30/7 795 kcmil ACSR is 0.1121 Ohms/mile, 2.6% higher than we just calculated ignoring the helical lay length of the wires.

Accounting for Lay Length

Bare stranded overhead transmission conductors are not bundled but rather helically stranded. With the exception of the center or “king” strand, the length of the other wires is greater than the length of the conductor. Because non-conducting aluminum oxide coats bare aluminum wires, the electrical current in the aluminum wires follows the helix as it moves down the conductor. This must be accounted for in calculating the dc resistance of a stranded conductor.

The length of the wire helix exceeds the length of a straight wire by the following margin:

$$m_{ind} = \sqrt{1 + 9.8696/n^2}$$

Where n = “lay ratio” (length/outer diameter of helical wire which is 13 to 15 for aluminum wires in a typical transmission conductor)

For a lay ratio of 13.5, the length of the helical wire is 1.027 times that of a straight wire. For AAC conductors under 1000 kcmil, ASTM B231 recommends increasing the dc resistance calculated under the assumption of parallel straight wires by 2% to account for helical stranding. For 30/7 ACSR, ASTM B232 recommends increasing the dc resistance of the aluminum layers by 2.75% and the steel core by 0.4%.

Applying these multipliers to the previously calculated dc resistances for 30/7, 795 kcmil ACSR, the dc resistance is:

$$R_{dc}(20C) = 1.02 \cdot 0.1125 \text{ Ohm / mile} = 0.1148 \text{ Ohm / mile for AAC}$$

$$R_{dc_{total}} = \frac{1.0275 \cdot 0.1125 \cdot 1.004 \cdot 3.690}{1.0275 \cdot 0.1125 + 1.004 \cdot 3.690} = 0.1121 \text{ Ohms / mile for 30 / 7 ACSR}$$

This agrees exactly with the dc resistance value cited earlier, taken from the Southwire Conductor Reference manual.

Trapezoidal [Aluminum] Wire (TW)

Traditionally, bare overhead conductors have been stranded from round wires. In recent years, the use of trapezoidal aluminum wires has become commonplace. As shown in Figure A-1, bare overhead conductors with trapezoidal aluminum wires are described as being equal in diameter or equal in area to “equivalent” round strand conductors. In this figure, the round strand conductor is 26/7 636 kcmil Grosbeak ACSR. The TW conductor with **equal** aluminum **area** and reduced outside diameter is called Grosbeak/TW. The TW conductor with **equal** outside diameter and increased aluminum area is called Wabash/TW.

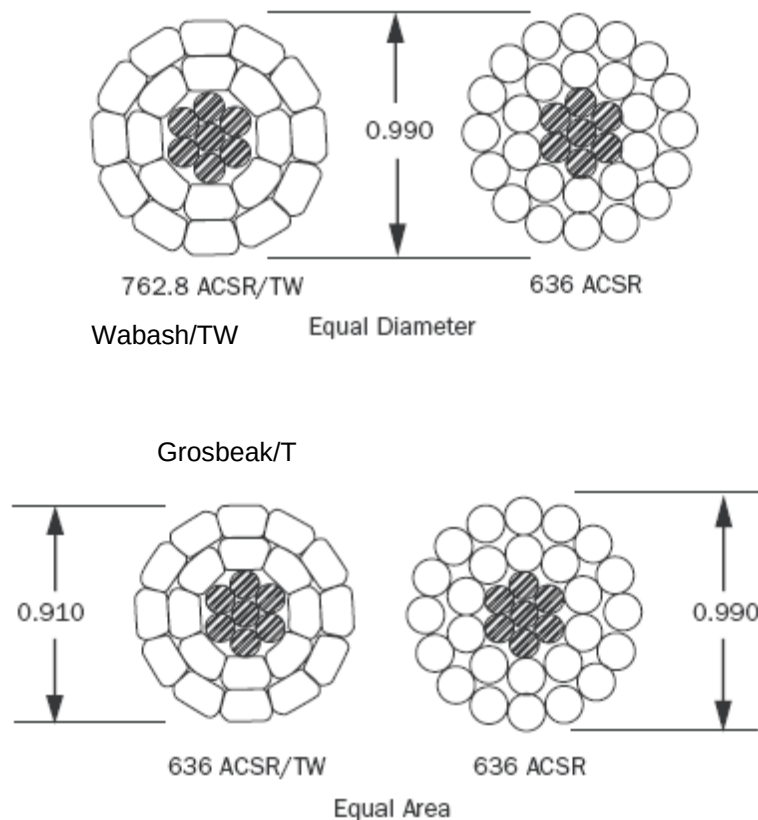


Figure A-1
Comparison of equivalent ACSR conductors with round and trapezoidal aluminum wires.

The impact of trapezoidal aluminum wires on resistance and losses is measured entirely by changes in aluminum area. This can be seen in Table A-1 where conventional “round strand” Grosbeak ACSR is compared to its “equal area” and “equal diameter” equivalents, Grosbeak/TW and Wabash/TW, respectively:

- The aluminum cross-sectional area of Grosbeak/TW is the same as conventional “round strand” Grosbeak therefore the resistance values are the same (as are the weight per unit length, the rated strength, and the ratio of steel core to aluminum area, that is, the conductor “type number”). By using trapezoidal aluminum strands, however, the outside diameter is about 8.3% less which reduces the wind and ice conductor loading.
- The outside diameter of Wabash/TW conductor is the same as “round strand” Grosbeak. Therefore the wind and ice loads on the conductor are the same. Since the aluminum (and steel core) areas are 20% greater, the weight, strength, and offset by a However, the aluminum area and the steel core area are each 20% greater than Grosbeak (larger steel core wires are used to preserve the ratio of steel to aluminum area). Given the increased areas, the resistance is 20% lower, the cost, weight per unit length, and rated strength, are 20% greater. This reduces the electrical losses by 20% and increases the thermal rating by about 10%.

According to the Southwire Conductor Reference Book, the resistance values for these three conductors compare as shown in the following table:

Table A-1
Comparison of equal area and equal diameter equivalents to 636 kcmil, 26/7 Grosbeak ACSR

Conductor	Grosbeak	Grosbeak/TW	Wabash/TW
Outside Diameter [inches]	0.990 (100%)	0.908 (91.7%)	0.990 (100%)
Alum Area [kcmil]	636.0 (100%)	636.0 (100%)	762.8 (120%)
R _{dc} @20C [Ohm/mi]	0.1411 (100%)	0.1408 (99.8%)	0.1174 (83.2%)
R _{ac} @25C [Ohms/mi]	0.1451 (100%)	0.1446 (99.7%)	0.1212 (83.5%)
R _{ac} @75C [Ohms/mi]	0.1733 (100%)	0.1727 (99.7%)	0.1446 (83.4%)

Increase of DC Resistance with Temperature (Below 140 °C)

The dc resistivity of the aluminum and steel wires used in transmission conductors is linear with temperature over moderate temperature ranges. The resistivity of 1350-H19 aluminum wires increases 4.04% per 10 °C for temperatures relative to 20 °C. The resistivity of galvanized steel wires increases 3.27% per 10 °C, also relative to 20 °C.

Up to a conductor temperature in the range of 140°C, the resistance of a bare stranded aluminum conductor can be calculated with the following linear equation:

$$R(T_2) = R(T_1) \cdot [1 + \alpha_1 \cdot (T_2 - T_1)]$$

For example, the dc resistance of 30/7, 795 kcmil, Skimmer ACSR at 140°C can be found by correcting the resistance of the aluminum layers and the steel core for temperature as shown in the following equation:

$$R_{DC}(@140C) = \frac{1.0275 \cdot 0.1125 \cdot (1 + 0.00404 \cdot 120) \cdot 1.004 \cdot 3.690 \cdot (1 + 0.00327 \cdot 120)}{1.0275 \cdot 0.1125 \cdot (1.4848) + 1.004 \cdot 3.690 \cdot (1.3924)}$$

$$= 0.1661 \text{ Ohms/mile}$$

It's worth noting that a simpler method of adjusting dc resistance for temperature is to ignore the change in steel core resistance and simply adjust the composite conductor resistance as though it was entirely aluminum. With that assumption, the dc resistance at 100 °C is:

$$R_{DC}(@140C) = 0.1121 \cdot (1 + 0.00404 \cdot 120) = 0.1664 \text{ Ohms/mile}$$

The error in using the approximate method is only 0.4%.

The preceding dc resistance calculation process involved the following steps:

1. Calculate the dc electrical resistance at 20°C using standard resistivity values for aluminum and steel wires and the total crosssection area of each.
2. Account for the helical stranding of the aluminum and steel wires by a multiplier which increases the dc resistance by between 2% and 3%.

Adjust the dc resistance for temperature, increasing the dc resistance by about 4% for every 10°C that the conductor is above 20°C.

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