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USE OF HTLS IN NEW LINE DESIGNS

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SUMMARY

Prior to "open transmission access", system planners could usually estimate line-specific, normal and post-contingency electrical loads over the life of new lines. Therefore, on large transmission line projects, it was possible to select conductors to minimize electrical losses and line costs when designing new lines. The advent of renewable generation and open access have made less certain any prediction of normal and post-contingency emergency power flows over the life of new lines. At the same time, the lead time for the connection of new generation is reduced, and highly variable generation by renewable sources such as wind farms has reduced line load and loss factors.

Historically, over 80% of existing transmission lines were designed with ACSR conductors consisting of hard drawn aluminium wires stranded concentrically over a stranded steel core limited to a maximum temperature of less than 100C. In recent years, High-Temperature, Low-Sag (HTLS) conductors capable of operating at temperatures as high as 200°C have become commercially available. While originally used to uprate existing lines, this paper considers the possible advantages of HTLS conductors in certain new line designs where high thermal ratings can be obtained at minimal increase in capital investment or losses.

It is noted that the use of HTLS conductors is particularly advantageous in new lines which have a highly variable normal power flows such as from wind generation, where the line is likely to be subjected to infrequent but high N-1 post-contingency power flows, and in new lines where the uncertainty of predicted normal and post-contingency loads is extremely high.

It is also noted that the use of HTLS conductor is unlikely to be attractive in lines that carry relatively high, nearly constant daily power flows such as HVDC lines and radial lines which carry generation power flow from base-load coal or nuclear power plants.

Both rule of thumb and quantitative line design optimisation methods are discussed. It is shown that the use of HTLS conductor has little or no impact on electrical limitations on power flow, have similar electrical losses to same-size ACSR, and that modest differences in high temperature sag between various HTLS conductor designs have little impact on structure cost.

KEYWORDS

HTLS Conductor, thermal line rating, optimisation, loss factor, high temperature sag

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Conductor Selection for New Overhead Lines [1]

In designing new overhead transmission lines, as discussed in the many practical electrical/mechanical design limitations must be considered:

- The insulators, conductors, structures and foundations must have adequate strength to survive ice and/or wind storms.
- The corona and audible noise produced by the line must not exceed statutory and common-sense maximum levels.
- Electrical clearances to ground, buildings, vehicles, and other lines must be greater than statutory minimums under all weather and electrical load conditions over the life of the line.
- The wind vibration of structures, insulators, and especially conductors must be low enough to avoid damaging the line components.
- The insulator arrangement and shield wires placement must be adequate to minimize phase to ground flashovers due to lightning and switching surges.

The choice of phase conductor impacts most of these widely varied requirements. In about 80% of existing power transmission lines, the phase conductors consist of 1350-H19 aluminium wires wrapped helically around a stranded steel core. ACSR (or ACSR/TW) is available in a wide range of "strandings" where the ratio of steel to aluminium area ranges from 3% to 23%, the diameter varies from 0.6 to 1.9 inches (15 to 48 mm), and multiple conductors can be combined into phase bundles consisting 1 to 8 conductors. ACSR conductors are limited to a maximum continuous operating temperature of about 95C.

The number of conductors in a phase bundle tends to be determined by line voltage, with 1, 2, 3, and 4 subconductor bundles used up to 300kV, 400kV, 500kV, and 800 kV, respectively. For each line voltage, the subconductor diameter can be varied in order to reduce the cost of electrical losses and to reduce corona levels. As the subconductor diameter increases, the structure/foundation loads increase and cost of the line (structures, foundations, conductors, insulators, etc.) increase as well.

For very large projects, the conductor type, diameter, and installed tension can be unique - selected in order to optimize the total capital cost of new lines (i.e. the cost of right-of-way, phase and shield wire conductors, and the structures/foundations required to support them) against the present worth of electrical losses over the life of the line and the thermal capacity of the line.

In order to minimize inventory and simplify maintenance, utilities typically "standardize" on one or two conductor diameters used depending on whether the predicted line power flow levels are low or high.

Impact of HTLS Conductor on Line Design

High temperature low sag (HTLS) conductors [2] [3] [4] were developed primarily to allow the operation of existing transmission lines at higher conductor temperature without needing to replace or extensively modify the existing line structures. As a consequence, the thermal rating of the existing line could be increased to allow higher post-contingency power flow during system emergencies. This is illustrated in **Figure 1**.

As explained in CIGRE TB 244 [5], not all HTLS conductors produce the same reduction in sag at high temperature. In particular, HTLS conductors with a carbon or ceramic fibre core may be required in re-conductoring existing lines with very little clearance margins and HTLS conductors with annealed aluminium rather than zirconium aluminium, may not be strong or stiff enough to be used in routes which experience high wind and ice loads.

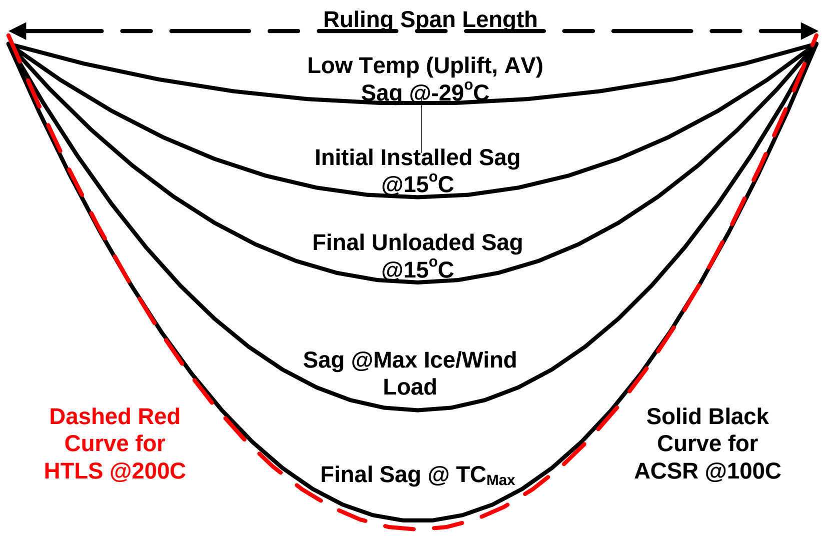

Figure 1 - How HTLS conductors limit sag at high temperature

For new lines with conventional ACSR conductor, the maximum allowable conductor temperature is normally limited to 95°C or less to avoid annealing [6] the 1350-H19 aluminium wires. In older lines, the MACT was typically kept below 75°C being as low as 40C in some unusual designs. As shown in **Figure 2**, if a new line is still being designed with a MACT less than 75°C, the simplest way to increase the line's thermal rating is to raise it to 95°C. Raising the MACT of these two ACSR conductors from 50°C to 75°C and from 75°C to 95°C produces increases in line rating of 100% and 35%, respectively.

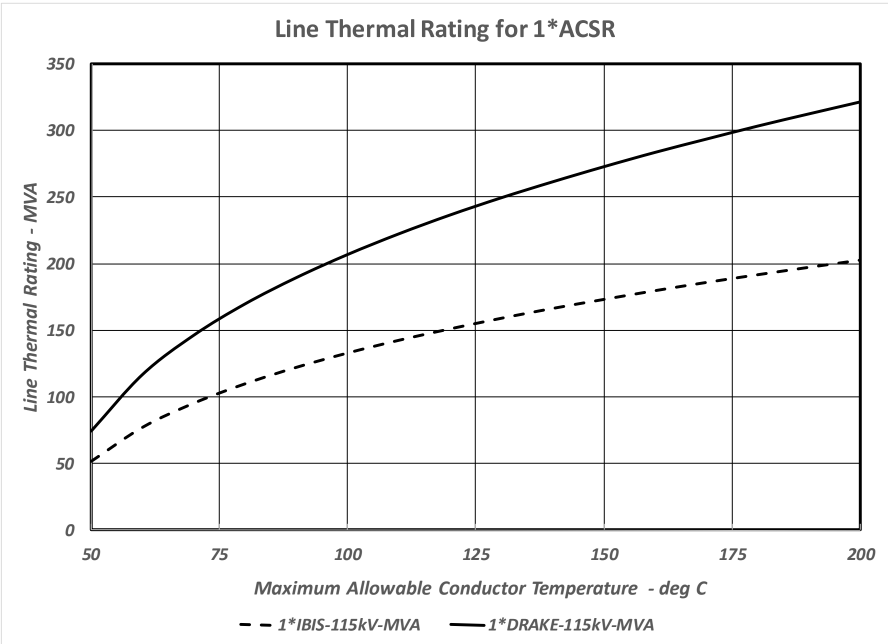

Figure 2- 115 kV Line Thermal Rating vs MACT for Single Ibis (397.5 kcmil) and Drake(795kcmil)

Notice two things about such an increase in the MACT of the line's ACSR conductors: (1) the use of a higher MACT does not increase the electrical losses of the line which are largely due to line currents during normal system conditions not during emergencies and; (2) according to the paper by Douglass [7], the cost of increased structure height required to maintain ground clearance at 100°C rather than 50°C is less than 4%.

To increase the line's MACT beyond 95°C requires either a statistical analysis of weather data and line loading to limit loss of conductor strength, as described in [8], or the use of HTLS conductor which can be used for MACT ranging from 180°C to 250°C depending on the type. As shown in **Figure 2**, substituting an HTLS conductor having the same diameter and resistance, produces an increase in line rating of from 75°C to 200°C and from 100°C to 200°C produces increases in line rating of 100% and 50%, respectively. Given the use of conductors having the same diameter and nearly the same sag is unlikely to require a large increase in structure/foundation costs but, of course, if the HTLS conductor is much more expensive than ACSR, the overall line cost may be higher.

When to Consider HTLS for New Lines

The use of HTLS in new overhead lines is most useful in those design situations where the maximum power flow on the line is much greater than the normal or minimum flow and where the limitation on such occasionally high power flows is due to the line's emergency thermal rating.

The use of HTLS conductor in new line design is not sensible if the maximum power flow on the line is limited to avoid excessive voltage drop (typically less than 5% to 10%) or, for lines with an operating voltage near the system maximum, where power flow is limited to avoid excessive phase shift which can lead to stability problems. In either case, the use of a conductor which is capable of operating at high temperature will have little or no effect on voltage drop and phase shift.

Figure 3 shows that new lines which are relatively short (<100 km), are most likely to be thermally limited while power flow on longer lines is limited by voltage drop and phase shift concerns. Therefore, the use of HTLS conductor is most helpful in the design of relatively short new lines.

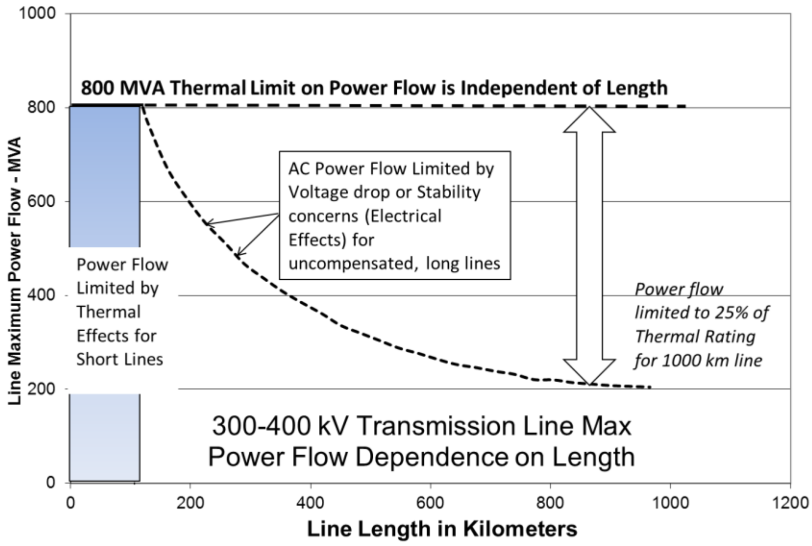

Figure 3 - Power Flow Capacity Limits versus Line-Length

Another major indicator for the use of HTLS conductor in new lines involves the cost of electrical losses over the life of the new line. The calculated electrical losses per annum, depends on:

- The maximum line current with the system operating normally.
- The loss or load factor of the line current
- The electrical resistance of the phase conductors.
- The length of the line.

HTLS conductor, installed in a line where the predicted normal daily load is relatively high ((> 1 amp/mm2) and relatively constant (e.g. loss factor > 0.5) is unlikely to prove economic in comparison to a larger diameter, conventional ACSR with reduced resistance. However, in a new line where the power flow fluctuates widely (perhaps as a result of wind generation) or where the maximum power flow is expected to be the result of relatively infrequent post-contingency loads, the use of HTLS can be an economic solution, keeping the cost of the new line well below that which would result from the use of a much larger conventional ACSR required to meet the maximum power flow while keeping the conductor temperature below 100ºC.

Finally, HTLS conductor might be used in designing new lines for which the maximum power flow is impossible to predict, making its use sort of an insurance policy by building in high thermal capacity at minimal extra capital cost in order to avoid the need for future line re-conductoring or replacement. If power flow on multiple lines within the transmission system are similarly difficult to predict, it may be sensible to consider standardizing new line designs as having HTLS conductors.

Of course, in a technical paper it is inadvisable to discuss the relative cost of HTLS conductors but ACSS or ACSS/TW are generally acknowledged to be the least expensive type of HTLS since the materials used (aluminium and steel) are essentially the same as ACSR and ACSS/TW (in one widely used manufacturing method, ACSS is produced by heat soaking ACSR) and the cost of ACSS is often quite close to that of same-size ACSR. Where true, the only cost penalty in using ACSS in new lines concerns the possible increase in tower height.

Conventional ACSS or ACSS/TW may not have adequate tensile strength to deal with very high ice loads. In this design situation, ACSS with an ultra-high strength steel core may be used or High Temperature (HT) ACSR with zirconium aluminum wires may be used, however, the conductor cost may be up to twice that of ACSS depending on the cost of zirconium aluminum and UHS steel.

In most new line applications, it is difficult to justify the higher cost INVAR or Composite core HTLS conductors since the small high temperature sag savings obtained result in relatively small structure cost savings. Therefore, the most sophisticated and expensive types of HTLS conductor may not be useful in new lines.

Optimising line design

The technical brochure (TB) 638 [9], describes the matching of the overall line design to the function of the line. The function of the line, in the case of AC, is described in terms of the surge impedance loading of the line (SIL) and the thermal rating of the line.

The surge impedance loading depends on the location of the phases, the number of conductors per bundle and the diameter of the bundle. The thermal rating depends on the conductor type and the templating or the design temp. This is the temperature at which the conductor is assumed to be at the height above ground in line with regulations.

The more compact the phases (distance between phases) the higher the SIL. Similarly, the larger the conductor bundle diameter the higher the SIL. The location of the phases affects the tower top geometry or the configuration of the phases in the case of the cross rope or compact cross rope towers. This in turn, affects the initial cost of the line.

The higher the templating temperature, the higher the tower attachment heights or the closer the towers have to be together (shorter span length). This affects the initial cost of the line.

The life cycle cost of the line includes the cost of losses which depends on the resistance of the conductor bundle. This is dependent on the load profile on the line either as a result of generation or load.

In the case of Direct Current transmission (DC), the thermal rating is similar that in the AC case. The SIL is not applicable, however, the corona and audible noise constraints will dictate the optimal location of the pole bundles as well as the diameter, number of conductors per bundle, and the height above ground.

The TB 638 [9] suggests the use of indicators to determine objectively, the best line design options. The equations are given below:

The equation referred to for AC and DC is as follows:

$$ATI_{AC} = w_1 LCC + w_2 \frac{IC}{MVA_{sil}} + w_3 \frac{IC}{MVA_{th}} \qquad (1)$$

$$ATI_{DC} = w_1 LCC + w_2 IC * P_{losscorona} + w_3 \frac{IC}{MVA_{th}} \qquad (2)$$

Where

LCC is the life cycle cost
IC is the initial cost
MVAsil is the surge impedance loading
MVAth is the thermal rating of the line
Plosscorona is the power loss due to corona

ATI is the appropriate technology index

The method of determining the scores is described in [9]. It normalizes the parameters to a score out of 10 and this dimensionless score is then added for each term and weighted according to the planner's requirements. An overall score out of 10 is then determined for each design option. The best group of design options are then taken to detailed design.

Example on use of ATI for HTLS conductors

The HTLS conductor option will mainly affect the thermal rating term in the ATI. The initial cost may be slightly higher than the conventional conductors but the thermal rating will be far higher than the conventional conductor option.

The following example is for a 400kV line 60km long using cross rope suspension towers. The HTLS conductor used was ACSS and a conservative initial cost of 15% for the line was assumed using this conductor. It is likely to be less in a real case.

The conductor options are shown in the table below. The ACSS rating is taken at 150^{o}C which is also conservative. The costs are converted from South African Rands at 15ZAR=1USD.

Conductor Bundles	SIL (MVA)	Thermal rating (MVA)	Initial cost (USDX1000)	Initial cost ranking	Life cycle cost including losses (USDX1000)
3 x kingbird	1463	625	6344	1	8067
3 x Tern	1471	649	6989	2	8969
4 x kingbird	1469	688	8031	3	9109

4 x Tern	1475	717	8983	5	9701
3 x Bersfort	1440	691	9655	6	9942
3 x ACSS Tern	1478	933	8038	4	8969

Table 1 Conductor bundle options considered

Using the values in the above table, the following scores are obtained for the indicator (ATI for AC).

Conductor bundles	K1 LCC	Score	K2 IC/MVA	Score	K3 IC/SIL	Score
3 x kingbird	8066.67	3.00	10.15	3.00	4.34	3.00
3 x Tern	8969.33	6.27	10.77	2.53	4.75	3.79
4 x kingbird	9108.67	6.77	11.67	1.83	5.47	5.16
4 x Tern	9701.33	8.92	12.53	1.18	6.09	6.35
3 x Bersfort	9942.00	9.79	13.97	0.08	6.71	7.53
3 x ACSS Tern	8969.33	6.27	8.61	4.17	5.44	5.11

Table 2 ATI scores for options including HTLS

In determining the scores, the 3x kingbird conductor is considered to have a value of 3/10. An arbitrary value is chosen for the 10/10 score and a linear interpolation between the two points determines the remaining scores.

Of interest is the IC/MVA (K2) score which indicates that the HTLS option yields a score of 4.17 which is far higher than the next highest score of 3. This indicates that if thermal rating is the main criteria for the function of the line, that HTLS conductors will result in the best option even with a 15% increase in line cost.

Case studies

Use of HTLS Conductor in Servitude (Clearance) Limited areas.

The following case study if taken from a 400kV line design in Eskom, South Africa, where a portion of the line was limited in servitude. The conductor selected initially was a triple Bersfort bundle. The section with the narrow servitude required a double circuit tower as opposed to the preferred single circuit cross rope tower. The double circuit tower design for triple Bersfort was a heavy self-supporting tower. Engineers then looked to see if they could use a HTLS conductor for the double circuit section (this section was only a few kilometers in length). Analysis was performed using a triple Tern ACSS conductor. It was found that the use of the lighter HTLS conductor allowed for a lighter double circuit tower. Although the HTLS conductor was more expensive than the Bersfort, the use of the lighter tower allowed for an overall reduction in the line cost of around 4%.

In this case the HTLS provided a lighter conductor option for the same thermal rating as the heavier Bersfort conductor bundle. As the line section in question was relatively short, the voltage-drop and losses were not a limiting criteria. The use of the ACSS allowed for a cost saving by using a lighter tower design.

CREZ 345 kV Line in Texas, USA [10]

320 km of new 345 kV double circuit line was built in northern Texas to connect two regions where wind farm development is being encouraged, to the rest of the Texas transmission system. The region in North Texas is shown in Figure 4.

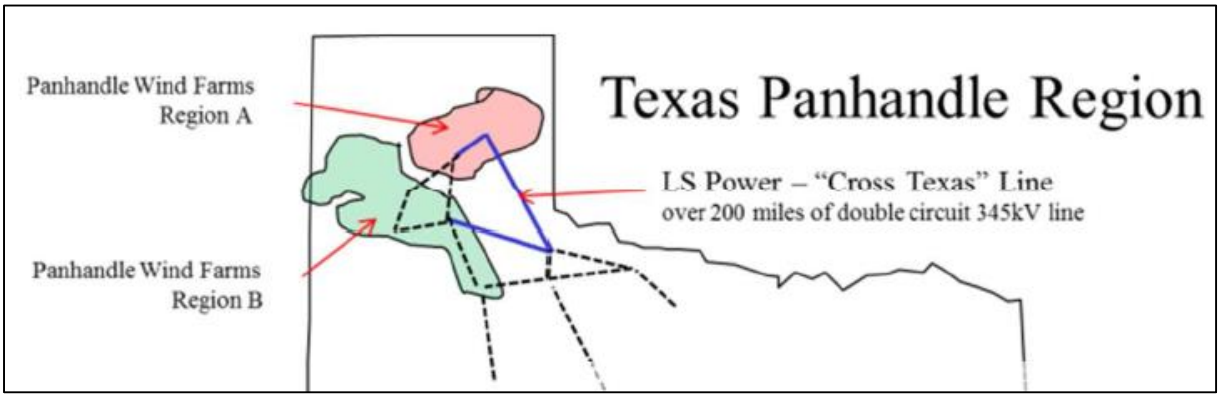

Figure 4 - Layout of new 345 kV Double Circuit Line

The line consists of 1300 structures, both lattice and steel pole ranging from 25 to 60 meters tall with two Falcon (54/19, 805 mm2) ACSS subconductors per phase. The subconductors are each 39 mm in diameter.

Given the assumed rating conditions of 40oC air temperature, 0.61 m/s wind perpendicular to the conductor, 1000 m elevation, emissivity=absorptivity=0.5, and a MACT of 200oC, the thermal rating of each subconductor is 2360 amperes. The thermal rating of each circuit of this line is therefore 2820 MVA !

In the US, a two conductor bundle is commonly used at 345 kV, with ACSR subconductors that range from 28 mm to 40 mm in diameter. For the same rating assumptions and an ACSR subconductor MACT of 95oC, the thermal rating of a typical 345 kV line ranges from 1075 MVA to 1640 MVA.

The main design motivation for the use of ACSS in this line involves load uncertainty. That is, the line was built prior to the development of the extensive wind farms. Therefore maximizing the thermal capacity of the new line reduces the probability of needing to update the line in the near future.

AES Electropaulo Application of HTLS Conductor [11]

AES Electropaulo in Brazil needed a new double circuit 138 kV line between two grid 230kV substations to provide transfer capability between the two stations and provide service to three intermediate substations. While the lines were insulated for 138 kV, one of them operated at 88 kV. Nominal construction for the line would have been a bundle of 2 x 636 MCM (318mm^2) ACSR conductors providing capacities of 308 MVA at 88 kV and 482 MVA at 138 kV. The line length is approximately 9.45 km.

The proposed line traversed two different areas of the system. First there is a non-urban area where the typical steel lattice towers would be applied. Another section of the line, however, was located in a more populated area, where right-of-way and clearances would be more restrictive. In the early planning stages for the line, the engineering staff decided to use steel poles for the more congested region. In order minimize foundation costs, they desired a conductor system that would develop minimal mechanical loading on the poles and the foundations, yet match the same capacity as the bundle 636 MCM ACSR. They investigated single conductor options to minimize the mechanical loads and were led to the high temperature low sag conductors as an alternative to meet their project requirements.

Evaluating the different options of HTLS conductor available to them, the engineers finalized a design based on a polymer matrix core (ACPR), z strand 469/38mm2 (section) conductor, where; ACPR stands for "Thermal Aluminium Conductor Polymer matrix-Reinforced" as per CIGRE WG B2.48

This single conductor could match the desired 2,000-amp capacity and meet the mechanical load requirements of the structure designs and maintain desired clearances.

The final design was engineered for the typical 636 bundle and lattice towers in the non-urban area and the new design using steel poles and single T-Rail conductor.

The installation of the HTLS conductor was accomplished in a fashion almost identical to standard ACSR conductors. Some special training sessions were held by the manufacturer for the crews; focusing on the installation of the dead-ends and other accessories.

Elia Application of ACPR 850/87-Z [11]

The current 150kV-grid in the coastal region in Belgium is insufficient to answer all its future energy needs. The Stevin project will develop a new 380 kV connection between the coast and the existing 380kV backbone grid. It addresses four major needs, of which the connection of the growing offshore windfarms in the North Sea and the interconnection capability with the UK are the most important.

For the overhead lines, the use of existing corridors has been chosen and the line consists of the following three sections:

1. an existing 380 kV line will be re-conductored with two circuits of HTLS twin-conductors to uprate the line to 3000MVA for each circuit,
2. A new 380kV line will be built in two sections: one more or less parallel to the route of an existing 150-kV overhead line and, in another section, Elia will partly reuse the corridor of an existing 150 kV overhead line. For both line sections, Elia uses a compact 380kV tower design with insulated cross-arms,

In order to avoid the densely populated area of Bruges and a protected bird habitat an underground solution has been selected during the permitting process. It will consist of four parallel 380kV cable links on a route length of about 10km including a double tunnel.

In total, Elia is building four new 380kV and one new 220kV GIS substations in enabling the connections with offshore wind parks, the backbone grid and the transitions between overhead lines and underground cables.

The existing 380 kV line between Zomergem and Eeklo Noord will be re-conductored with HTLS conductors in a twin-bundle configuration so that both circuits will be able to uprate the line up to 3000MVA for each circuit. One of the circuits will be equipped with ACPR 850/87.

For this part of the project, the HTLS-suppliers were asked to propose their solution to re-conductor the line and other lines related to specific requirements. Different solutions (ACSS, ACPR, ACCR, and carbon cored) were examined. Due to a change in Belgian regulations concerning the application of an extreme wind loading criterion in the design, only the compact solutions with a low drag coefficient could allow that the towers be reinforced and not replaced entirely. The Z-shaped wire has been chosen in that case and a TCO analysis has been performed to compare the products.

The conductor will be installed during 2016.

Construction and Standardization Issues

Construction crews are accustomed to the tension stringing of ACSR or AAC. In most companies, the experience with HTLS conductors is far less.

Difficulties can arise in constructing new lines with HTLS conductors for a variety of reasons:

1. HTLS conductors such as ACCC and ACSS utilize fully annealed aluminium strands which are more vulnerable to bird-caging during installation. This is shown in the figure 2 below

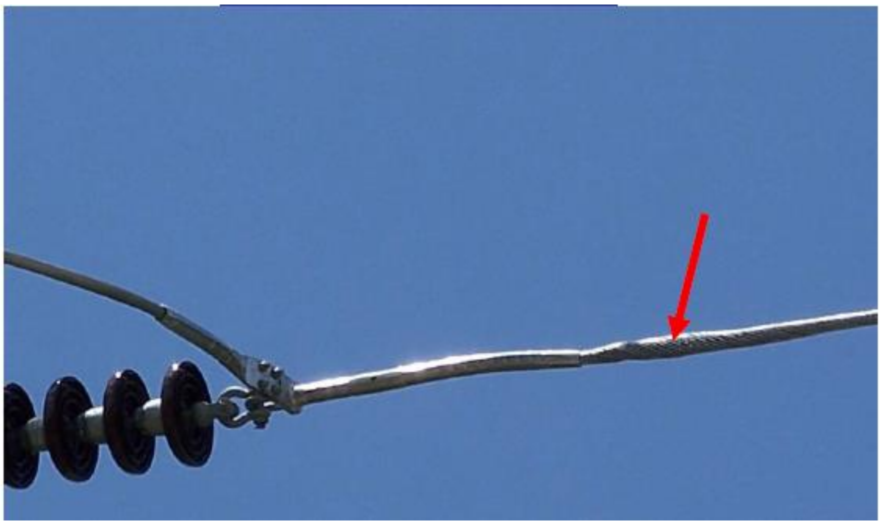

Figure 5 – Bird-caging of Annealed Aluminum Conductor after Compressing Dead-end Courtesy of Ray McCoy, AFL.

2. Pulling annealed aluminium HTLS conductors under tension can be difficult unless the core is part of the tension grip.

3. With bundled conductors, the use of HTLS sub-conductors can cause unequal thermal elongation at everyday temperatures since the knee-point temperature of the sub-conductors may not be equal. As a result bundle spacing can change causing excessive corona and clashing of sub-conductors.

4. Use of composite cores can result in installation damage since these materials are very sensitive to shear stress.

5. Connectors and dead-ends are unique to each type of HTLS conductor. This presents a potential problem of standardization and emergency repairs.

These issues need to be addressed during the selection process to ensure all construction issues are prior to the installation of the conductor. If necessary, a section of line should be constructed to test the installation methods prior to the installation on the main line. The hardware and conductor type need to be matched to ensure correct hardware is applied to the conductor.

If ACSS or ACSS/TW is adequate to meet the design limitations of the new line, stocking of connectors and hardware designed for these conductors can often be used for both ACSS and comparable diameter ACSR which may simplify inventory and line crew training.

Conclusions

HTLS conductors should be considered as an alternative to conventional ACSR in certain new line design situations wherein the new line is:

1. Intended to carry power from a highly variable generation source such as wind turbine “farms”, particularly where the eventual daily peak line power flow is uncertain and the daily and seasonal variations are large.
2. Embedded in an AC transmission system where the line operating voltage is well below the system maximum and the post-contingency power flow may therefore be much higher than the projected daily peak power flow under system normal operation.
3. Relatively short (< 100 miles) and projected normal and emergency loads are very difficult to project with any accuracy due to generation placement uncertainties.

HTLS conductors should not be considered in new line design situations where the new line is:

1. The line load factor is high such as in a radial connection of a new base-load generator.
2. Quite long (>100 miles) and the line voltage equals the system maximum so power flow is limited by electrical effects (stability or voltage drop) rather than thermal rating.
3. Unlikely to experience post-contingency power flows that are more than 150% of the daily peak normal load.

Traditional line design and optimization of new lines can be undertaken for a range of conventional ACSR conductors. Having selected a sub-conductor which meets the limitations on corona, electric and magnetic fields, blowout clearances, and electrical losses over the life of the line, if thermal rating is important, inexpensive types of HTLS can be substituted for conventional ACSR as a way to provide thermal ratings that at least 50% higher for little or no increase in cost of construction or the present worth cost of electrical losses over the life of the line.

Depending on the line requirements other more expensive types of HTLS can be considered. It is possible to investigate the different options using the ATI as explained in TB 638 [9]

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