Converting AC power lines to DC for higher transmission ratings

One way of avoiding transmission bottlenecks caused by a shortage of suitable right-of-ways is to convert overhead power lines from AC to DC. This option allows the power transmission rating to be more than tripled and the specific transmission losses to be substantially reduced without having to widen the right-of-way. What is more, such conversions cost only a third to half the cost of building a new DC line. Several examples of 330-kV AC line conversions illustrate these benefits.

Increasing competitiveness in the electric power market is forcing utilities to look more closely at the benefits of long-distance energy transmission. Several European power suppliers, for example, have considered joining together to build a 1,800 km long transmission line with a rating of 4,000 MW, running east to west across the continent. A feasibility study showed that high-voltage DC transmission would have special advantages for such a line [1]. Converter stations of the type that would be needed are already being operated successfully all over the world. An example is the Radisson station in Canada **1**, which belongs to the multi-terminal HVDC transmission system linking Quebec and New England (USA) [2].

One way of overcoming the present shortage of suitable right-of-ways for long-distance power transmission is to convert existing AC lines to HVDC systems. In such cases, an AC system is turned into an HVDC bipole. Conversions of this kind allow the transmission capability of an existing right-of-way to be increased considerably. For example, for the same line-to-ground voltage the transmission rating can be raised by the factor $\sqrt{2}$ [1]. Since existing towers often allow a increase in the line-to-ground voltage, numerous studies have been carried out in the past to investigate ways of converting AC lines to HVDC lines [3, 4].

To minimize the risk to people living or working in the immediate vicinity of overhead lines, lower limits are being introduced worldwide for the electrical and magnetic fields produced by new lines. The cost of a conversion therefore also has to be considered in this context. Also, it is important to differentiate between the cost of converting from AC to HVDC and those costs arising as a result of stricter regulations.

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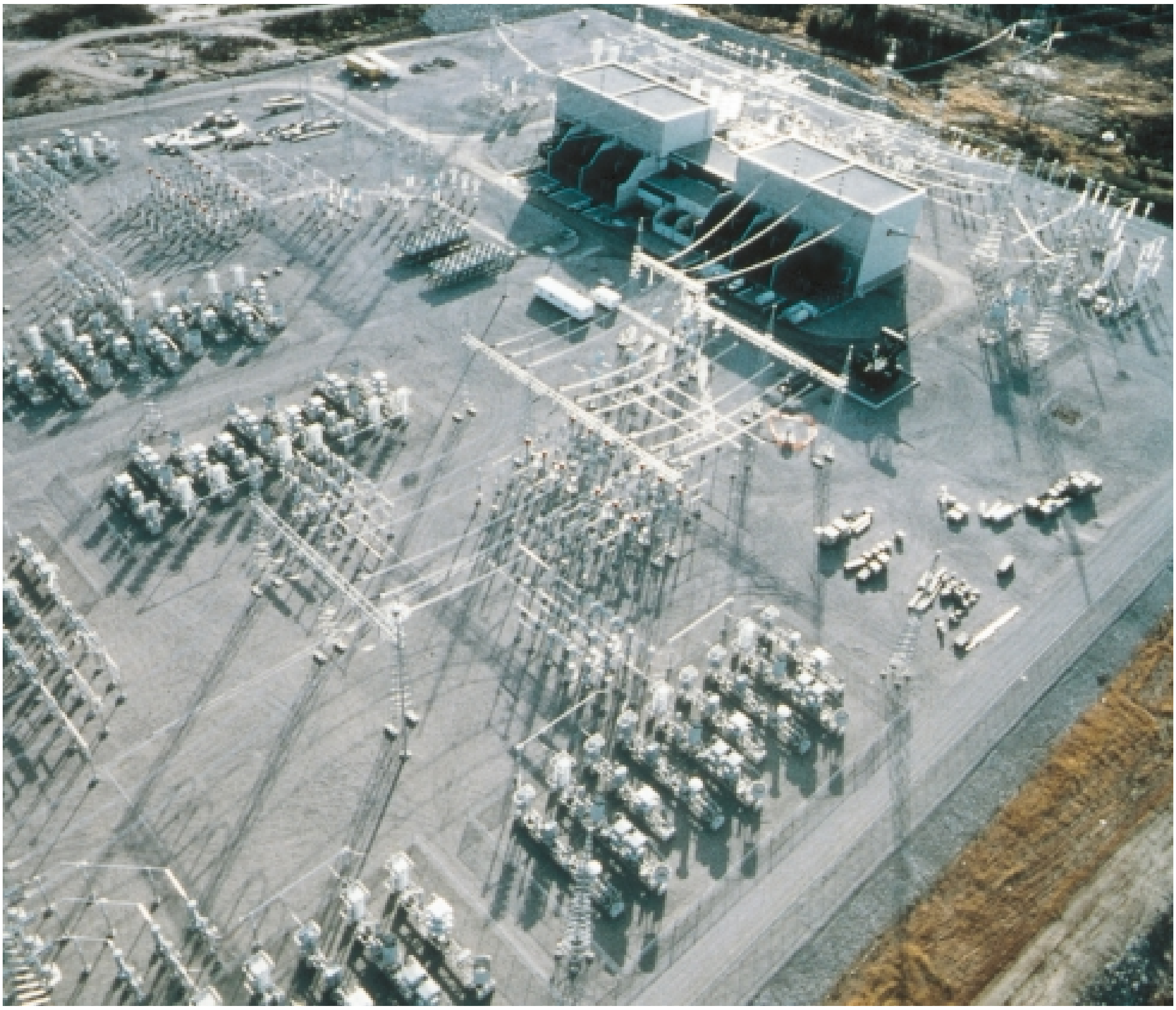
Main features of AC to DC conversions

Tower design

The scope of such a conversion, as it is understood here, covers changes to the conductor arrangement on the tower, the insulator assemblies and the configuration of the conductor bundle, but not to the actual tower structure or to the number of towers (ie, no additional towers have to be erected). As a starting point, it is assumed that the existing overhead conductors will be re-used, although this will depend on their condition. Re-use of the existing conductors has the advantage that the load that the weight of the conductors exerts on the towers does not change. Even so, it may be necessary to reinforce the towers if the conductors have to be hung higher.

Phase-to-ground clearance

Although none of the national or international standards committees, such as the VDE or CENELEC, have as yet specified phase-to-ground clearances for DC lines, a recommendation of the EPRI in the USA [5] provides some help. An important parameter for specifying the clearances is the maximum overvoltage occurring. Field experience shows that, due to the advanced controls being used today for HVDC schemes and because of the resulting insulation coordination, overvoltages to earth of no more than 1.7 to 1.8 p.u. can be expected in the worst case. According to [5], clearances of at least 2.2 m for a transmission voltage of 500 kV and 3.1 m for 600 kV are needed.



The Radisson HVDC station in the Canadian province of Quebec converts AC power from hydro-electric plants into DC power. **1**

If, for example, a 400-kV AC line is converted to an HVDC bipole rated at ±500 kV, the design voltage to earth will increase by the factor 1.46. According to the latest CENELEC draft [6], the phase-to-ground clearance (ie, between conductor and cross-arm) should be at least 2.26 m for AC systems with a maximum operating voltage of 420 kV and a basic insulation level (BIL) of 950 kV. It is therefore possible in principle to convert from AC to DC with a higher design voltage without having to change the structural design of the tower.

Surface voltage gradient

Unlike AC lines, DC lines are characterized by the following phenomena [7]:

- Steady-state ionization forms around the conductors.
- The emitted ions create a space charge around the conductors.
- The most severe radio interference occurs in dry weather conditions.

The space charge acts like a screen and reduces the maximum surface voltage gradient of the conductors. In contrast, the effect of the space charge close to earth is to strengthen the electric field. Corona discharge is always caused by the ionization of neutral air molecules colliding with free electrons accelerating in the electric field. Because of the different velocities at which the positive and negative ions travel, two very different types of corona discharge occur in the region around the conductors. Negative corona discharges occur with a high repetition rate and small discharge amplitudes. Positive corona discharges occur less often, but exhibit higher amplitudes.

By neglecting the space charge effect,

Table 1:
Limits for low-frequency electric and magnetic fields

Frequency	Hz	50	16 ⅔
Electric field	kV/m	5	10
Magnetic field	µT	100	300

Table 2:
Limits for DC electromagnetic fields (rms values)

Electric field	kV/m	20
Magnetic field	µT	21,200

a theoretical value can be calculated for the surface voltage gradient of DC lines in dry weather conditions using the same method as for AC lines.

The surface voltage gradient of overhead transmission lines has to be dimensioned according to the permitted radio interference. The electric field intensities recommended for AC lines take account of a 10 dB increase in radio interference when it rains. With DC lines, the radio interference decreases when it is raining. This justifies increasing the electric field intensities for DC lines in comparison with AC lines. Providing the usual limits are introduced to prevent radio interference, the contribution made by corona discharge to the total transmission losses will be negligible.

Creepage distances

According to CIGRE SC 33-WG04, a conservative approach to the problem of creepage distances for DC voltage would be to increase the specific values for AC voltage by a factor of 2. This results in values of about 4.2 cm/kV for lines in a moderately polluted environment. The reserve included in this figure is ample; for example, the ± 600-kV Itaipú bipole line in Brazil has insulators designed with a specific creepage distance of 2.7 cm/kV.

Electric and magnetic fields

The health risk for people living or working within the low-frequency fields produced by power transmission lines is a concern which national and international committees have addressed through an agreement on field values. These values satisfy even the most critical safety criteria, and providing they are observed such electromagnetic fields cannot be considered a hazard to health.

Some of the new data are also used as a basis for legislation. The German federal government, for example, issued a decree in December 1996, based on the recommendations of the International Radiation Protection Association [8] and the German Radiation Protection Commission, which specifies mandatory limits for fields generated by low-frequency systems such as overhead transmission lines. The systems are to be built and operated in such a way that the fields do not exceed the limits given in *Table 1*.

No German legislation exists as yet for DC magnetic fields. However, the tentative standard DIN VDE 0848-4/A3 [9] gives limits which take account of the

330-kV Sapele–Aladja single-circuit AC line, Nigeria (1982) **2**

need to protect even highly sensitive people from such fields (*Table 2*).

Conversion procedure

In the case of multiple-system lines, some of the tower designs in use allow conversion in stages, so that transmission can be continued over that system not actually affected by the work being carried out.

Conversion in stages allows step-by-step matching to growing power demand and reduces the time until start-up of transmission at the increased power level, translating into lower capital investment. This approach helps to raise the energy availability of the line during the conversion.

During the replacement of the first AC system by the first HVDC bipole, the two DC cables are positioned one above the other on one side of the tower. Since the field strengthening effect of the space charge below the positive conductor is much lower than below the negative conductor, it is an advantage to fix the positive conductor to the lower cross-arm.

The next step is to replace the second AC system by the second HVDC bipole. Exchanging the polarities of the conductors vis-à-vis the first bipole will reduce the field intensities in the vicinity of the earth (soil) but increase the electric field at the surfaces of the conductors. If the polarities are left the same, this effect is reversed. The best arrangement for the conductor polarities therefore has to be decided from case to case.

Examples of conversion projects

330-kV Aba-Afam double-circuit AC line, Nigeria (1982) **3**

In general, the cost of converting from AC to HVDC will depend upon the type of AC system involved. The following examples look at the conversion of 330-kV AC lines in Nigeria and give a good idea of the cost of such conversions. More thorough investigations are needed to determine the exact cost of an actual project. To obtain a rough estimate of the cost, it is assumed that the towers of the Sapele–Aladja single-circuit line **2** and the Aba–Afam double-circuit line **3**, both built by ABB, are converted to one and two HVDC bipoles with a transmission voltage of ± 500 kV, respectively. In each case, the towers carry twin

Table 3:
Insulator assemblies for the tower configurations in 4 and 5

Voltage		330 kV AC **4a**	330 kV AC **5a**	± 500 kV DC **4b** and **5b**
Type of insulator		18 glass cap and pin assemblies F12P	20 glass cap and pin assemblies F12P	4×1,500 line posts 40 glass cap and pin assemblies F 1600 P/C 146 DC
String length (insulation only)	m	2.62	2.92	5.84
Creepage distance	mm	8,010	8,900	22,000
Spec creepage distance	cm/kV	2.2 1)	2.5 1)	4.4 2)

1) referred to U_m as per IEC 71, here 362 kV

2) referred to maximum service DC voltage U_{dmax}, here 500 kV

conductor bundles of type ACSR ‘BISON’[1] (DC resistance of sub-conductors = 0.07574 Ω/km), which are to be re-used if possible.

In order to utilize the cross-arms of the towers for a DC voltage of ±500 kV, the distance between the conductors and the tower structures has to be fixed 4b, 5b. The minimum clearance between the conductors and the tower cross-arm for the single bipole is 5.72 m, while for the HVDC double bipole it is 4.83 m. These two figures lie well above the minimum clearance recommended in [5], even for a DC voltage of 600 kV. Also sufficient is the safety margin for the clearance between the top conductor and the bottom cross-arm of the HVDC double bipole.

The higher conductor voltage of the DC lines calls for a larger line-to-ground clearance. Due to this, and because of the longer insulator assemblies, the overhead lines have to be raised by 4.3 and 4.4 m, respectively (dimension M in 4b and 5b. ABB has developed a technology for raising towers which easily allows the height to be increased by this amount [10].

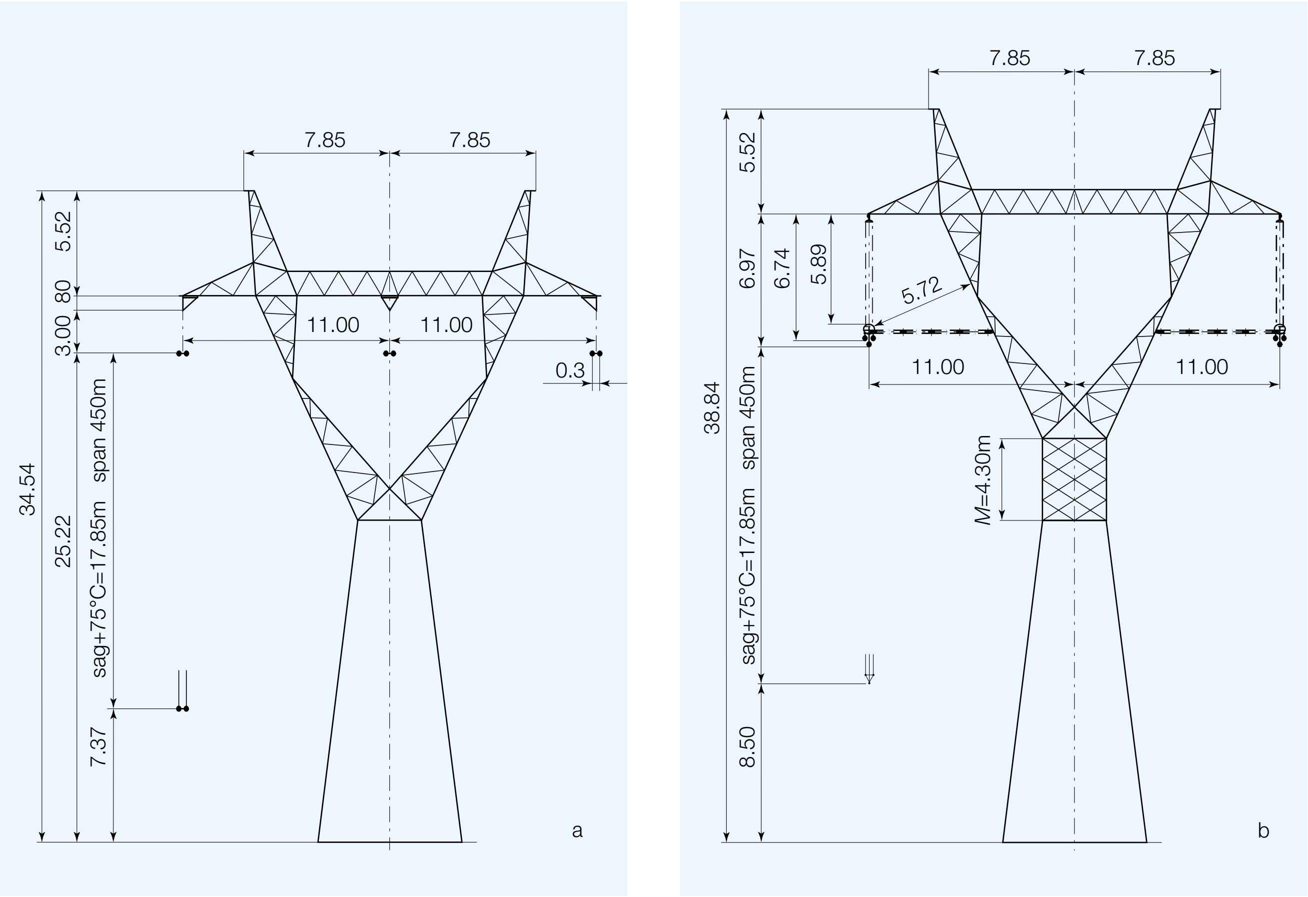
The line suspension length is approximately the same for each type of DC tower. The figure chosen for the specific creepage distance is the maximum value stipulated for a moderate level of pollution. *Table 3* compares the insulator assemblies for the AC and DC line towers.

When the AC system overhead lines are to be re-used, the most effective way to reduce the surface voltage gradient of the DC lines is to increase the number of sub-conductors and place the conductors further apart. In the case of triple bundles, the combination of these two measures leads to an acceptable maximum electric field of 29.6 kV/cm for a DC voltage of 500 kV (*Table 4*). Triple bundles allow full re-use of the existing overhead lines.

When quadruple bundles are used, the surface voltage gradient can be reduced to 24.6 kV/cm. This design is an option when the power to be transmitted is higher than about 2,300 MW. Use of

Tower configuration of the Sapele–Aladja line before and after conversion **4**

a *Before: 330-kV single-circuit AC line with twin bundles (BISON)*
b *After: ±500-kV DC bipole with triple bundles (BISON)*
M *Increase in tower height: 4.3 m*



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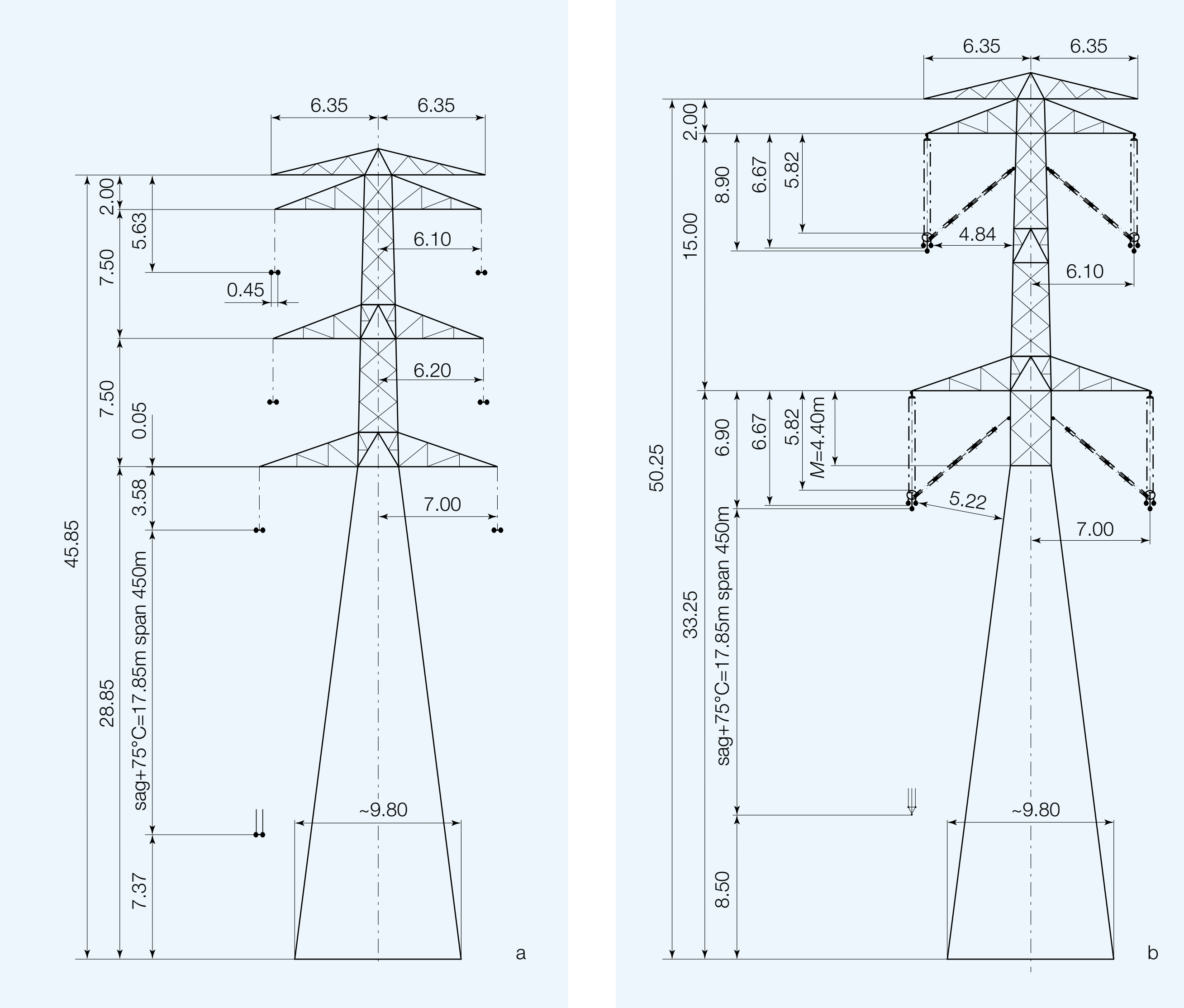
[1] The ‘BISON’ conductor as per British Standard BS 215, part 2, corresponds to the type Al/St 380/50 conductor in DIN 48 204.



Tower configurations of the Aba–Afam line before and after conversion **5**

a *Before: 330-kV double-circuit AC line with twin bundles (BISON)*
b *After: ± 500 kV DC double bipole with triple bundles*
M *Increase in height: 4.4 m*

quadruple bundles also allows a transmission voltage of 600 kV, resulting in the transmission capability of the line being increased by another 20 percent. The surface voltage gradient would rise to 29.4 kV/cm, corresponding to the value for triple bundles and a DC voltage of ± 500 kV.

To be sure that the design value of the electric field close to the ground (*Table 2*) is not exceeded, the overhead lines have to be raised even further than for the designs shown in **4** and **5**. In the case considered, this measure would even be necessary for the AC line conversion in order to observe the limit for the electrical field given in *Table 1*.

Table 4 compares the transmission losses and transmission power for AC and DC lines. Assuming the same cross-sectional area for the lines (DC lines with triple bundles), the losses will be the same for the same current density even when the skin effect is neglected. Taking the skin effect into account, the line losses for the DC lines are as much as 3.2 percent lower. On the other hand, the transmission powers of the DC lines (single and double bipole) at ± 500 kV increase to 260 percent of the respective figures for the AC single-circuit line and AC double-circuit line.

Although the use of quadruple bundles with the HVDC double bipole line requires 33 percent more conductor material, the transmission capability for ± 500 kV increases to 350 percent of the reference AC power. However, there is only a 30 percent increase in losses.

Table 4:
Comparison of electrical data for a conversion from 330-kV AC to ± 500 kV DC

a) Conversion of a single-circuit line of the type used for Sapele–Aladja

	AC	DC
Voltage	330 kV	± 500 kV
Type	1 system	1 bipole
Conductor	3×2×ACSR 'BISON'	2×3×ACSR 'BISON'
Surface voltage gradient in kV/cm	15.4	28.7
Line height increase in m	0/4	0/2
Max elec field intensity at earth (soil) in kV/m without/with cross-arm raised	8.96/4.6	24.2/17.6
Max mag field intensity at earth (soil) in μT 1)	56.0/29.6	72.0/55.1
Transmission power at approx 1 A/mm^2	437 MVA	1,145 MW
Thermal limit rating	892 MVA	2,340 MW
Losses at approx 1 A/mm^2 over 300 km	21.6 MW	20.9 MW

b) Conversion of a double-circuit line of the type used for the Aba–Afam project

	AC	DC	DC
Voltage in kV	330	± 500	± 500
Type	2 systems	2 bipoles	2 bipoles
Conductor	6×2×ACSR 'BISON'	2×3×ACSR 'BISON'	2×4×ACSR 'BISON'
Surface voltage gradient in kV/cm	16.4	29.6	24.6
Line height increase in m	0/3	0/1	0/1
Max elec field intensity at earth (soil) in kV/m without/with cross-arm raised	8.2/5.0	21.1/18.2	23.5/20.0
Max mag field intensity at earth (soil) in μT 1)	40.5/25.0	51.4/44.2	68.0/58.5
Transmission power at approx 1 A/mm^2	873 MVA	2,291 MW	3,054 MW
Thermal limit rating	1,783 MVA	4,680 MW	6,240 MW
Losses at approx 1 A/mm^2 over 300 km	43.2 MW	41.8 MW	55.8 MW

1) for thermal limit rating

The losses specified for the AC line are only valid for transmission distances of not more than 300 km. For AC lines operated over longer distances, the losses (and cost) incurred by the power factor correction which is required also has to be reckoned into the equation. With DC transmission, the transmission losses increase by the losses occurring in the converter stations, these being equal to about 1.4 percent of the transmission power.

An advantage of converting long AC lines into DC lines is that the thermal limit rating can be fully exploited. This particularly increases the availability of double bipole systems. In the event of a DC line failing, the remaining bipole system can easily transmit double the power. Long AC lines, on the other hand, often cannot be loaded to their thermal limit rating as this would make them unstable.

Cost of conversion versus cost of a new line

The basic cost of converting a line from AC to DC stems from the following:

a) *Dismantling and mounting the conductors*
  - Replacement of the insulator assemblies
  - Tower and foundation reinforcements, possibly required due to higher cantilever forces, overhead lines being hung higher, or additional sub-conductors

Additional costs can be incurred as a result of:

b) *Older conductors having to be replaced as they cannot be re-used.*
  - Extra cost of conductor material as a result of the bundle conductors having more sub-conductors

c) *Overhead lines having to be raised* to comply with the latest regulations applying to electric field intensity

Any comparison of the cost of converting from AC to DC with the cost of erecting conventional AC lines should only take account of the expenditures incurred as a direct result of the line being used to transmit DC. Conversion costs resulting from the higher demands made on mechanical strength – both for AC and DC lines – should not be attributed to the conversion as such. The extra cost of raising the overhead lines in order to comply with lower field value requirements will have to be borne whether replacing AC lines by new AC lines or converting from AC to DC. They can therefore be neglected when comparing the costs.

A rough estimate of the costs as fractions of the total is given below:

Conversion according to a)
  approx ⅓ of the cost of erecting a new DC line
in addition, according to b)
  approx ⅐ to ⅒ of the cost of erecting a new DC line, depending on the configuration of the conductor bundle (quadruple or triple bundles)
Conversion according to c)
  approx ½ of the cost of building a new line

In view of the possible extra costs, it should be considered from case to case whether a new line would make more sense than a conversion.

The absolute cost of erecting a new line varies strongly from country to country, since it depends mainly on labour costs and on the type of terrain crossed by the line. In West European countries, the cost of building a single bipole DC line using the kind of tower shown in 4 is about US$ 210,000 per kilometer. For a double bipole DC line with towers as in 5, the figure is about US$ 325,000 to 360,000 per kilometer.

Results

In principle, existing overhead AC lines can be converted to overhead HVDC lines. For transmission voltages of ±500 kV, such a conversion can increase the AC power level by a factor of more than 2.5 for the same current density. This presumes re-use of the existing conductors and an unchanged tower design. The specific transmission losses are reduced by more than half.

The roughly estimated cost of conversion would in the best case be equal to only something more than one third of the cost of building a new DC line in compliance with the regulations in force today. The cost will be higher when the existing conductors are so old that they cannot be re-used. A completely new line is also an attractive proposition in such cases because of the gain in transmission power it brings with it.

The regulations governing the mechanical loading of overhead lines and the requirements in terms of electric and magnetic fields were recently revised. More stringent requirements result in additional costs whether modifying existing AC lines or converting from AC to DC. For this reason, any comparison of the resultant cost of converting a line or of building a new one with the cost of previously built lines should be looked at more closely and not just be taken at its face value.

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