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Feasibility study for converting 380 kV AC lines to hybrid AC / DC lines

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Summary

The feasibility of converting 380 kV double-circuit AC lines into AC/DC hybrid lines by utilizing one of the circuits as a bipolar DC line has been studied. The aim of the conversion is to increase the power transfer capacity of the lines.

The environmental effects are decisive for determination of the maximum allowable DC voltage level and for selection of the most favourable DC polarity configuration for the converted line. The objective of the feasibility study presented here is to estimate the power transfer capacity that may be attained for the converted line while taking into account the environmental aspects associated with AC/DC hybrid lines, including the mutual influences on the corona effects. The study is confined to the principal environmental influences of the DC line, i.e. the audible noise level in fair weather and the electric fields at ground level.

For the study, it is assumed that the existing conductors be retained, but that the upper phase conductor be split between the two lower phases in order to form a bipolar DC line. For the conversion to DC, the ceramic insulators are to be replaced by composite insulators with appropriate dimensions for the assumed pollution level.

The feasibility study has shown that a conversion of a 380 kV AC double circuit lines to AC/DC hybrid lines is feasible when the environmental effects in terms of fair weather audible noise and electric field effects are adequately considered. The gain in thermal power transfer capacity by the conversion is substantial; the capacity of the DC line is about twice as high as for the existing AC line.

It was found that a DC voltage of about ±450 kV might be the maximum acceptable voltage level with regard to corona and field effects. It was also found that the environmental effects of the remaining AC circuit is not significantly changed by the conversion; the audible noise level in rain as well as the AC electric and magnetic field levels are essentially unaffected.

In order to limit the extent of the feasibility study, the scope was confined to environmental effects in terms of audible noise and electric fields. Other factors might be included in a more comprehensive study, e.g. the effects of the DC line on under-built 220 kV circuits, the lightning performance of the DC line, as well as the radio interference level and corona losses of the DC line.

The final selection of the DC voltage level for a converted line should primarily be based on the audible noise level in fair weather. However, it should be realized that the audible noise generation of dry conductors is rather difficult to predict due to uncertainties regarding the actual state of the conductor surface. The influence of altitude on the audible noise level should also be considered. It is therefore recommended that audible noise measurements be carried out on an AC/DC hybrid test line before settling the DC voltage level for the converted line.

1. Introduction

The feasibility of converting 380 kV double-circuit AC lines into AC/DC hybrid lines by utilizing one of the circuits as a bipolar DC line has ben studied.. The aim of the conversion is to increase the power transfer capacity of the lines.

The goal of the feasibility study presented here is to estimate the power transfer capacity that may be attained for the converted line while taking into account the environmental aspects associated with AC/DC hybrid lines. The study is confined to the principal environmental effects, i.e. the audible noise generated by corona discharges and the electric fields at ground level.

For the study, it is assumed that the existing conductors be retained, but that the upper phase conductor be split between the two lower phases in order to form a bipolar DC line as described in Section 2.

The environmental effects are decisive for determination of the maximum allowable DC voltage and for selection of the most favourable DC polarity configuration. The environmental aspects in terms of corona and field effects are discussed in Section 3, and calculated results are presented in Section 4 for three different DC voltage levels. The selections of the most favourable polarity configuration and a suitable DC voltage level with regard to the environmental effects are discussed in Section 5.

For the conversion to DC, the ceramic insulators are to be replaced by composite insulators. The dimensioning of these insulators for the assumed pollution level is discussed in Section 6.

As a result of the dimensioning of the composite insulators for different DC voltages, together with the required height above ground for the DC conductors, the maximum allowable conductor sag can be determined as described in Section 7. The corresponding maximum conductor temperature is then used to calculate the maximum DC current rating for different ambient temperatures, and the maximum currents are used to estimate the power transfer capacity of the converted line for different DC voltage levels.

2. Hybrid line configurations

The feasibility study is based on a typical double-circuit, twin-conductor 380 kV AC line configuration.. The main dimensions of the line are shown in Figure 2-1.

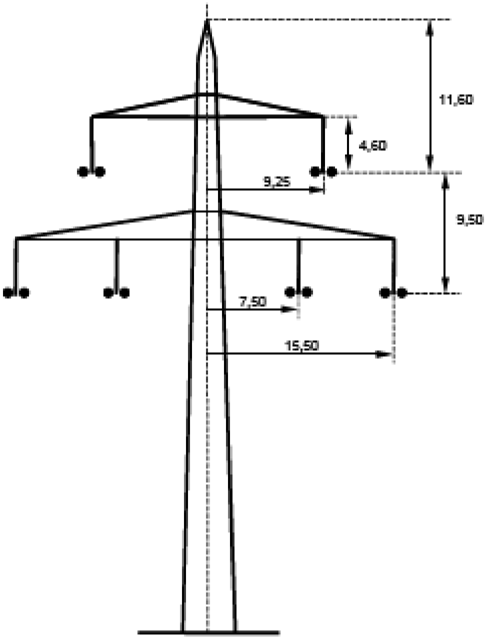


Figure 2-1. Main dimensions of double-circuit 380 kV AC line used for the feasibility study.

There are several possible ways to convert the double-circuit, twin-conductor AC line into a hybrid line. One option would be to keep the conductors and the ceramic insulators in their original positions to form a bipolar DC line with a metallic-return conductor. However, a more efficient way to increase the power transfer capacity would be to rearrange the available conductors by splitting the twin-conductor bundle belonging to the top phase and move the sub conductors to the lower phases to form a bipolar DC line with triple-conductor bundles, as shown in Figure 2-2. The advantage of the latter solution is that triple-conductor bundles allow a higher DC current rating and a higher DC service voltage with regard to the corona effects. The feasibility study is therefore focused on this alternative.

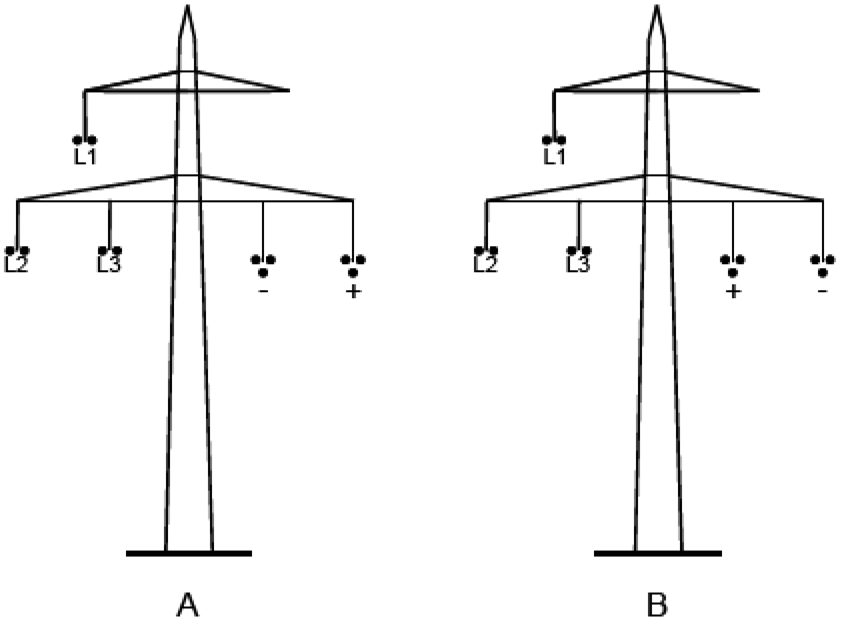


Figure 2-2. Hybrid AC/DC line created by rearranging the upper phase conductor to form triple-conductor bundles for the DC line. Both polarity configurations are shown.

Configurations A and B refer to the two possible polarity configurations of the converted line. Both configurations will be studied with the aim to determine the most favourable configuration with regard to the environmental effects. However, the final selection of polarity configuration will depend on the type of HVDC scheme to be applied: for IGBT based schemes, the polarities remain constant and the most favourable polarity configuration can be applied directly. For thyristor-based schemes, the polarities change with the direction of the power flow, which means that the most favourable polarity configuration should be associated with the most frequent power flow direction.

It is assumed that composite insulators be used on the DC line to keep the insulator length as short as possible in order to maximize the allowable conductor sag while taking into account the specified minimum clearance to ground.

Some double-circuit 380 kV AC line configurations sometimes include one or more under-built 220 kV circuits. The presence of the 220 kV conductors will influence the corona and field effects caused by the DC line, and the corona effects of the 220 kV conductors will be affected by the presence of the DC line. However, in order to limit the number of configurations included in the feasibility study, the effects associated with the 220 kV circuit(s) are not included at this stage.

3. Environmental aspects of AC/DC hybrid lines

The environmental aspects of transmission lines include primarily corona and field effects such as audible noise (AN), radio interference (RI), electric fields and magnetic fields.

Corona and field effects depend on the voltage and current levels, and on the configuration and positioning of the conductors; the voltage gradients at the conductor surfaces are of primary importance to the corona effects, while the positions of the conductors are essential for the electric and magnetic fields at ground level.

For an AC/DC hybrid line, the corona effects depend also on the relative positioning of the DC and AC conductors. The reason is that static charges will be induced on the AC conductors by the electric field from the DC conductors and, in the same manner, time varying charges will be induced on the DC conductors by the electric field from the AC conductors. Thus, the voltage gradient at the surface of the AC conductors will get an additional DC component, while the voltage gradient at the surface of the DC conductors will get an additional AC component. The magnitudes of these additional gradient components depend on the relative positions of the AC and DC conductors. The electric fields at ground level will also be influenced by the relative positioning of the AC and DC conductors since the DC conductors act like ground wires to the AC electric field, and vice versa.

Thus, when converting a double-circuit AC line to a hybrid AC/DC line, the corona and field effects will change in various ways as discussed in the following sections.

3.1 Audible noise

The AN level of an AC line is highest during rain, while it is essentially noiseless in fair weather. On the other hand, the AN level of a DC line is highest when the conductors are dry, since the generation of space charges will inhibit the corona discharge activity during wet conditions. This means that when the line is converted to a hybrid line, the AN level in fair weather will increase. The acceptable AN level in fair weather is therefore essential for the selection of a maximum allowable DC voltage. Audible noise limits are covered in local regulations, where maximum allowable noise levels in the range of 40-50 dBA are mentioned for energy-related installations. International experience with AC lines have shown that the special characteristics of the corona audible noise require that the L_{50} level in rain (exceeded 50 % of the time in rain) should be limited to about 50-55 dBA to avoid public complaints. For DC lines, the situation is different since the AN level is higher in fair weather than in rain. Taking into account the longer duration of fair weather audible noise, it is suggested that the AN L_{50} level in fair weather be limited to 40 dBA. Thus, for the AC/DC hybrid line, the AN L_{50} levels in both fair weather and in rain need to be considered, taking into account the mutual influence on conductor surface voltage gradients discussed above.

3.2 Radio interference

The RI level behaves very much like the AN level with regard to weather conditions, which means that the fair weather RI level may be higher for the hybrid AC/DC line due to the RI contribution from the DC line. However, in rainy conditions, the RI contribution of the AC will increase by about 15-20 dB, while the RI contribution of the DC line will decrease. This means that the maximum RI level of the line, which occur in rainy conditions, will be somewhat influenced by the “hybrid effect”, i.e. the increase in surface voltage gradients on the AC line caused by the presence of the DC line. However, the RI level is not regarded as a principal environmental effect and the RI levels will not be considered further in this study.

3.3 Electric fields

Electric field limits are covered by local regulations. For the purpose of this study a maximum level allowed below AC lines has been assumed to be 5 kV/m.

In contrast to AC, where limits have been established by international organisations regarding the induced current density in the human body by time-varying electric fields, no generally applied limits exist for the static electric field caused by DC sources. National limits may exist, but information on such limits is sparse. However, one example is a review by the NRPB (National Radiological Protection Board of U.K.), where the effects of DC electric fields on the human body are described in the following way [5]:

"Static electric fields interact directly with the body by inducing a surface electric charge. Indirect effects can also occur when a person is in contact with a charged conducting object, e.g. a car exposed to a static field. At sufficiently high voltage the air will ionise and become capable of conducting an electric current between the charged body and a person in good electrical contact with the ground. A charged insulated person touching a grounded object would receive a microshock (spark discharge). These effects may be painful. However, the threshold static electric field values for such perception will vary depending on the degree of insulation and other factors. Overall, the results of the few studies that have investigated the effects of static electric fields in humans do not suggest exposure is associated with significant health effects (IARC2002). Clairmont et al (1989) exposed volunteers to static electric fields up to 40 kV/m and reported a threshold for perception of around 20 kV/m. This was possibly associated with corona discharge on the tips of hair shafts. Annoying sensations were induced above about 25 kV/m."

Regarding restrictions on general public exposure of static electric fields, NRPB states: *"Where static electric fields cause annoyance, pain from electrostatic discharge or potentially dangerous effects due to arcing, NRPB proposes that steps should be taken to reduce the possibility of these effects occurring."*

The above description of the field effects covers in practice also the possible effects of ion currents at ground level caused by the corona discharges on DC line conductors, since the ion currents will charge insulated objects near the line and may cause discharge effects in the same way as the electric field. The charging effects of electric fields and ion currents on humans and other objects near DC lines is described in detail in [3], and a review of the influence of static electric and magnetic fields on human health is presented in [6]. Since the possible effects of fields and ions near DC lines seem to be more annoying than harmful, it is difficult to establish recommended maximum levels for these quantities. Furthermore, it is an open question whether such limits should refer to the maximum level below the line, or to the level at the edge of right-of-way.

To sum up, when converting a double-circuit AC line into a hybrid line, the changes in the AC electric field are of interest along with the DC electric field and the ion current density.

3.4 Magnetic fields

Magnetic field limits are covered by local regulations. A common figure for the exposure limit value for AC fields is 100 μT and for DC fields 40 mT . Furthermore, the installation limit value for AC fields is 1 µT at a distance from the line where people may reside for prolonged periods of time. However, the installation limit value is not directly applicable to existing installations.

For the AC magnetic field limit, the reference operating mode for the AC line is the thermal limiting current at +40°C, which is set to 1920 A. The magnetic fields generated by the DC line are well below the exposure limit value and are not treated further. The study is therefore limited to determine how the AC magnetic field levels will change after the conversion of the double-circuit AC line into an AC/DC hybrid line.

4. Calculated corona and field effects

The corona and field effects of the two possible hybrid line configurations A and B shown in Figure 2-2 have been calculated in order to find the most favourable configuration with regard to the environmental effects.

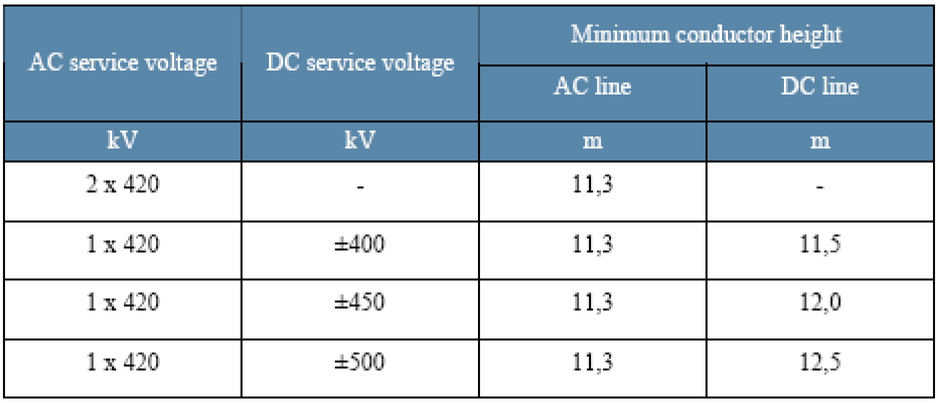
For the calculations, it is assumed that the phase conductors have an area of 600 mm2, a diameter of 31,9 mm and a sub conductor spacing of 400 mm, while the shield wire has a an area of 350 mm2 and a diameter of 24,2 mm. It is further assumed that the AC lines have two sub conductors in each phase, while the DC line has three sub conductors in each pole. The geometrical positions of the conductors at the tower are shown in Figure 2-1.

For the calculation of corona and field effects, the service voltage of the AC line was set to 420 kV with the phase order for the double-circuit line as shown in Figure 4-1. The service voltage of the DC line was varied as ±400, ±450 and ±500 kV in order to study the influence of the DC voltage level on the environmental effects.

4.1 Minimum height of DC conductors

Corona and field effects are usually determined at mid span with the lowest conductors positioned at their minimum height in accordance with the ground clearance regulations. The effect of conductor sag is neglected, i.e. the conductors are assumed to be at their minimum height along the entire span. According to local regulations, the minimum height for AC conductors is 7,5 m + 0,01 m per kV of the nominal system voltage, i.e. 11,3 m for a 380 kV line. There are no special regulations for DC lines; therefore the same rule was provisionally applied also to the DC line by using the DC line-to ground voltage in the formula above. This means that the minimum height of the DC line is varied when calculating the corona and field effects of the two polarity configurations at the three different DC voltage levels. The minimum heights used for the lowest AC and DC conductors are shown in Table 4-1.

Table 4-1. Minimum height of lowest conductor for double-circuit and hybrid lines.



AC service voltage	DC service voltage	Minimum conductor height	
		AC line	DC line
kV	kV	m	m
2 x 420	-	11,3	-
1 x 420	±400	11,3	11,5
1 x 420	±450	11,3	12,0
1 x 420	±500	11,3	12,5

The reference position for the calculated corona and field effects was chosen as 50 m horizontally from the line centre. This position is roughly 40 m from the nearest conductor, which is the closest distance of to be considered.

For the calculation of corona and field effects of the existing AC double-circuit line, the phase order of the AC circuits are shown in Figure 4-1.

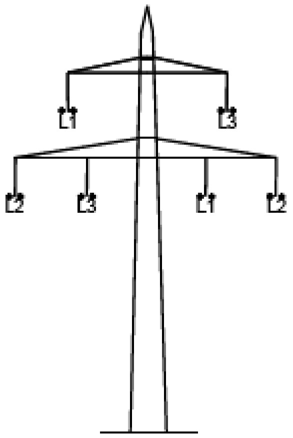


Figure 4-1. Phase order of the existing double-circuit 380 kV AC line.

4.2 Audible noise

The AN levels were calculated within 50 m from the line centre using the methods developed by Bonneville Power Administration (BPA) for AC and DC lines [1], as well as for AC/DC hybrid lines [2].

The method for hybrid lines takes into account the additional voltage gradient components induced mutually on the conductor surfaces by the AC and DC electric fields, as discussed in Section 3. In contrast to ordinary prediction methods for AN, which use the r.m.s. or DC values of the conductor surface voltage gradients for calculating the corona effects of AC and DC lines, the method for hybrid lines uses the peak voltage gradients to account also for the induced DC and AC voltage gradient components.

The L50 AN levels were calculated for both rain and fair weather conditions, since the AN level generated by the AC line is high in rainy weather and low in fair weather, while the opposite is true for the AN level generated by the DC line. It should be noted that the major generation of AN from a DC line is caused by the positive conductor.

The calculated AN levels for the existing double-circuit lines and for the two hybrid line configurations are shown in Table 4-2 and Table 4-3 for the reference distance to the line centre. The AN levels are calculated at a height of 1,5 m above ground. The levels are given for the side of the line where the highest level occurs depending on line configuration and weather condition. The calculated lateral profiles of the AN levels within 50 m from the line centre are shown graphically in Appendix A.

The precision in the calculated AN levels is estimated to be ±2-3 dBA. Thus, the accuracy indicated in the tables is merely for the purpose of comparison between the two polarity configurations. Furthermore, it should be realized that predicted AN levels below 40 dBA are uncertain due to the influence of ambient noise sources.

Table 4-2. Calculated AN L_{50} levels for AC double-circuit line and AC/DC hybrid line in rain.

AC service voltage	DC service voltage	AN L_{50} level at 50 m from line centre		
		AC double-circuit line	AC/DC hybrid line	
			Conf. A	Conf. B
kV	kV	dBA	dBA	dBA
2 x 420	-	50,4	-	-
1 x 420	±400	-	50,0	50,0
1 x 420	±450	-	50,3	50,3
1 x 420	±500	-	50,6	50,6

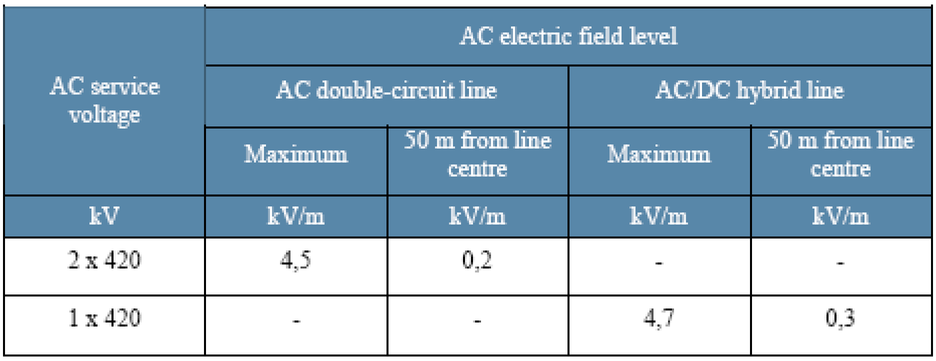
Table 4-3. Calculated AN L_{50} levels for AC/DC hybrid line in fair weather.

AC service voltage	DC service voltage	AN L_{50} level at 50 m from line centre	
		AC/DC hybrid line	
		Conf. A	Conf. B
kV	kV	dBA	dBA
1 x 420	±400	33,1	33,2
1 x 420	±450	37,1	37,2
1 x 420	±500	40,9	40,9

4.3 Electric fields

The AC electric field caused by the AC line was calculated for a height of 1 m above flat ground using the BPA Corona and Field Effects Program, version 3. Note that for the hybrid line configuration, the DC conductors act like ground wires when calculating the AC electric field. As in the calculation of corona effects, the voltage of the AC line was chosen as 420 kV with the phase order shown in Figure 4-1. The calculated electric field levels for the existing double-circuit line and for the hybrid line are shown in Table 4-4 in terms of the maximum levels and the levels at the reference distance to the line centre. The latter are given for the side of the line where the highest level occurs depending on the line configuration. Lateral profiles of calculated AC electric fields within 50 m from the line centre are shown graphically in Appendix B.

Table 4-4. Calculated AC electric field for AC double-circuit line and AC/DC hybrid line.



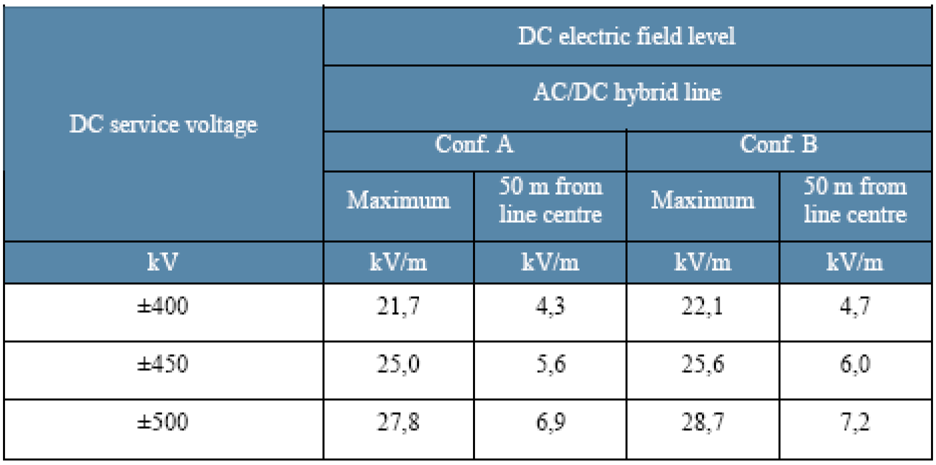
AC service voltage	AC electric field level			
	AC double-circuit line		AC/DC hybrid line	
	Maximum	50 m from line centre	Maximum	50 m from line centre
kV	kV/m	kV/m	kV/m	kV/m
2 x 420	4,5	0,2	-	-
1 x 420	-	-	4,7	0,3

The electric field generated by the DC line was calculated using the AnyPole program developed by BPA. The program is based on the calculation methods described in [3] and takes into account field enhancing effects from space charges caused by corona discharges on the DC conductor surfaces. This means that the DC electric field level is not proportional to the voltage level, as in the case of AC electric fields. The AnyPole program provides the approximate L10 levels (exceeded 10% of the time) in fair weather during no-wind conditions, as found from comparisons of calculated results with measured long-term levels [4]. Standard values were used for the corona onset surface voltage gradients, i.e. 14 and 13 kV/cm respectively for the positive and negative conductors. Note that AC conductors act like ground wires when calculating the DC electric fields. The voltage of the DC line was varied as ±400, ±450 and ±500 kV.

The calculated electric field levels for the two AC/DC hybrid line configurations are shown in Table 4-5 in terms of the maximum levels and the levels at the reference distance to the line centre. The latter are given for the side of the line where the highest level occurs depending on the line configuration. Lateral profiles of calculated electric fields and ion current densities within 50 m from the line centre are shown graphically in Appendix B.

The accuracy of calculated the DC electric field levels in the presence of space charges is controversial. As noted in [4], the calculated levels agree fairly well with measurements on one side of a bipolar DC line, but not so well on the other side. The precision indicated in the table is therefore merely intended for comparison between the two polarity configurations.

Table 4-5. Calculated DC electric field for AC/DC hybrid line.



DC service voltage	DC electric field level			
	AC/DC hybrid line			
	Conf. A		Conf. B	
	Maximum	50 m from line centre	Maximum	50 m from line centre
kV	kV/m	kV/m	kV/m	kV/m
±400	21,7	4,3	22,1	4,7
±450	25,0	5,6	25,6	6,0
±500	27,8	6,9	28,7	7,2

4.4 Magnetic fields

The AC magnetic field caused by the AC line was calculated at a height of 1 m above ground for a symmetrical load current of 1920 A in each circuit. The phase order used for the double circuit line is shown in Figure 4-1. The calculations were performed using the BPA Corona and Field Effects Program, version 3.

The calculated AC magnetic field levels for the existing AC double-circuit line and for the AC/DC hybrid line are shown in Table 4-6 in terms of the maximum level and the level at the reference distance to the line centre. The latter are given for the side of the line where the highest level occurs, depending on the line configuration.

Lateral profiles of the calculated magnetic field levels generated by the AC line within 50 m from the line centre are shown graphically in Appendix B.

5. Selection of polarity configuration and maximum DC voltage

The most suitable polarity configuration and the maximum allowable DC service voltage for the hybrid line may be determined on the basis of the calculated levels of corona and field effects in Section 4 along with applicable limits and recommendations discussed in Section 3. It is suggested to put the highest priority on the audible noise level generated by the DC line in fair weather, and a somewhat lower priority on the DC electric field effects. The reason for choosing the audible noise level in fair weather as the primary environmental parameter is that people living in the vicinity of the line will be exposed to this noise source during a major part of the time. Furthermore, the high-frequency content of the corona noise is easy to distinguish from other noise sources, and may therefore cause complaints also at comparably low levels.

The reason for basing the selection entirely on DC corona and field effects is that the environmental effects of the AC line is only marginally affected by the conversion from a AC double-circuit line to an AC/DC hybrid line. From Table 4-2 it is seen that the audible noise level in rain at 50 from the line centre will change by less than 0,5 dBA, and the changes in AC electric and magnetic field levels are also small, as seen from Table 4-4 and Table 4-6.

5.1 Selection of polarity configuration

As can be seen from Table 4-3, the calculated audible noise level in fair weather is practically independent of the polarity configuration at 50 from line centre. However, the calculated levels below the line are somewhat lower for configuration A, as can be seen when comparing Figure 10-3 and Figure 10-4 in Appendix A. The calculated levels of the DC electric field for configuration A is also somewhat lower than for configuration B, as can be seen in Table 4-5. It is therefore suggested that configuration A be selected from an environmental viewpoint.

5.2 Selection of maximum DC voltage

The calculated audible noise levels in fair weather for configuration A are shown in Table 4-3. It can be seen that ±450 kV as well as ±500 kV may be feasible as a maximum service voltage level for the DC line, taking the limit of 40 dBA discussed in Section 3.1 into account. However, it should be considered that people living near the line might experience that the existing line, which has been practically noiseless in fair weather under AC voltage, may become somewhat noisy in fair weather conditions after the AC/DC conversion. It is also important to realize that audible noise generation of dry conductors cannot be predicted to thesame accuracy as for wet conductors under rain. In dry weather, the corona discharge activity is more dependent on the actual state of the conductor surface in terms of dust and pollution collection, which may vary with the environmental conditions of the area and also show seasonal variations. This is indicated in [1], where it is proposed to add or subtract 2 dBA for the summer and winter seasons, respectively, to obtain the L50 level in fair weather.

Based on the above discussion, and taking into account the effect of altitude on the audible noise level, it is suggested to select ±450 kV as the maximum service voltage level for the DC line from an environmental point of view. At this voltage level, the maximum DC electric field level is also compatible with the recommendations discussed in Section 3.3

6. Insulator dimensioning

Composite suspension insulators are well suited for the DC line when converting the AC double-circuit line to an AC/DC hybrid line. Their main advantage is that for the same connecting length, their pollution performance is superior to that of glass or porcelain insulators, mainly due to the hydrophobic properties of the composite insulators [9].

The porcelain long-rod insulators for the existing AC line have a connecting length of approximately 4,17 m (i.e. the connecting length of three long-rod insulator units plus the size of the intermediate hardware) according to insulator drawing no. 24.2150.07.021. The total creepage distance is 7380 mm according to insulator drawing 101610.00.08.

To determine the dimensions of the DC insulators for the hybrid line on a statistical basis, the following information was used in accordance with the statistical dimensioning method developed by STRI [13]

- A pollution performance curve used to describe the insulator performance. The 50% flashover voltage was determined as a function of the Salt Deposit Density (SDD) from DC pollution tests performed earlier by STRI on composite insulators to be used on DC lines for 500-800 kV.
- The Equivalent Salt Deposit Density (ESDD) representing the pollution conditions in the environment of the hybrid line. Since no measured ESDD levels were available for the region of interest, the statistical ESDD level (exceeded in 2% of the pollution events) was chosen as 0,02 mg/cm2. This values was based on the creepage distance of the existing porcelain long-rod insulators (7380 mm). The chosen ESDD level is in the lower range of the medium pollution severity class according to the revised version of IEC 60815.
- The acceptable pollution flashover rate is 0,1 per year for a 100 km line assuming ten pollution events per year.

The results of the statistical insulator dimensioning calculations are summarized in Table 6-1 for DC service voltage levels ±400, ±450 and ±500 kV in terms of the required connecting length of the DC composite insulators.

The porcelain long-rod insulators on the existing line have the same creepage length independent of altitude. It is therefore assumed that the calculated DC insulator lengths presented in Table 6-1 can also be used without adjustment for the altitude.

Table 6-1. Required insulator lengths for composite DC insulators.

DC service voltage	DC insulator connecting length
kV	m
±400	3,4
±450	3,8
±500	4,2

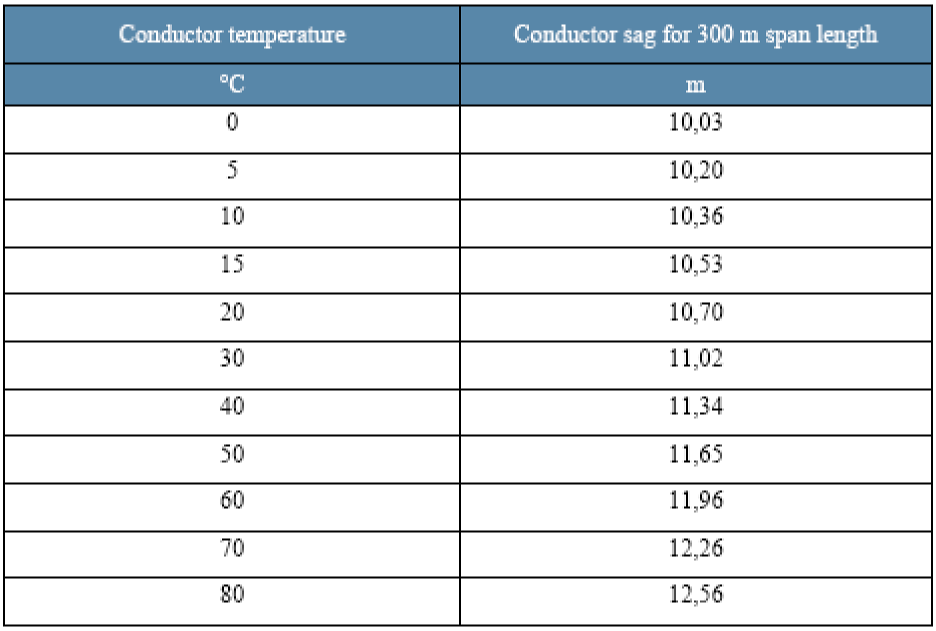
7. Power transfer capacity

When one of the AC circuits is converted to a DC line, the existing insulators will be replaced by composite suspension insulators with a length that depends on the DC voltage level, as discussed in Section 6. Consequently, the height of the conductor attachment points at the tower will change with the selected DC voltage level. The specified minimum clearance to ground varies also with the DC voltage level, as discussed in Section 4.1. This means that the maximum allowable DC conductor sag and the corresponding maximum allowable DC conductor temperature will also vary with the DC voltage level, in order to maintain the specified minimum ground clearance. The influence on the resulting power transfer capacity of the DC line is discussed in the following sections.

7.1 Calculations of maximum conductor sag and temperature

The existing double-circuit AC line is designed for a maximum conductor temperature of +80°C. The corresponding conductor sag along with the specified minimum ground clearance determines the height of the conductor attachment points on the tower. The typical conductor sag as a function of conductor temperature for a typical 300 m span length is shown in Table 7-1. The conductor sag information includes only conductor temperatures up to +50°C; therefore, the remaining values up to the maximum temperature +80°C were determined by extrapolation

Table 7-1. Conductor sag vs. conductor temperature for a 300 m span.

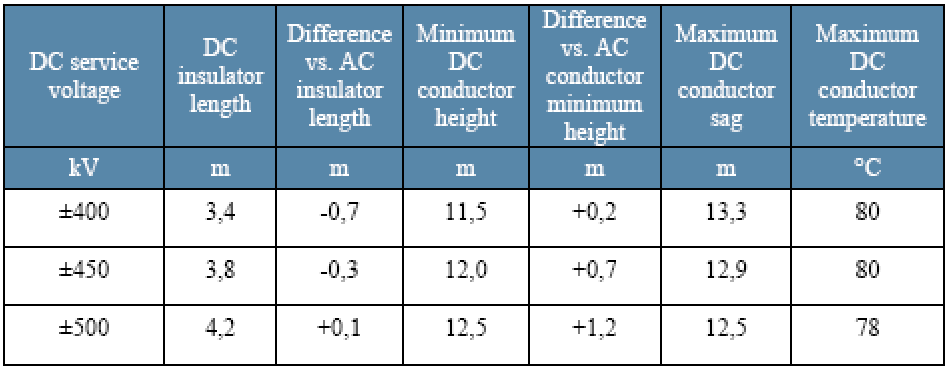


Conductor temperature	Conductor sag for 300 m span length
°C	m
0	10,03
5	10,20
10	10,36
15	10,53
20	10,70
30	11,02
40	11,34
50	11,65
60	11,96
70	12,26
80	12,56

The maximum allowable conductor sag for the DC line was calculated using the DC insulator lengths shown in Table 6-1 and the specified minimum conductor height shown in Table 4-1. The calculated results are shown in Table 7-2 as a function of the DC voltage level. The difference in insulator connection length relative to the existing AC line (4,17 m) is also shown in Table 7-2.

The maximum allowable conductor sag values are used to determine the corresponding maximum conductor temperatures, as shown in Table 7-2. If the maximum allowable sag under DC voltage is larger than for the existing line (12,6 m according to Table 7-1), the maximum conductor temperature is anyhow limited to +80°C.

Table 7-2. Calculated maximum sag and temperature of DC conductors.



DC service voltage	DC insulator length	Difference vs. AC insulator length	Minimum DC conductor height	Difference vs. AC conductor minimum height	Maximum DC conductor sag	Maximum DC conductor temperature
kV	m	m	m	m	m	°C
±400	3,4	-0,7	11,5	+0,2	13,3	80
±450	3,8	-0,3	12,0	+0,7	12,9	80
±500	4,2	+0,1	12,5	+1,2	12,5	78

7.2 Calculation of maximum DC current rating

Using the values of maximum conductor temperature for the DC conductors, the maximum DC current rating was determined using the method described by Cigré [8]. The following weather parameters and conductor surface characteristics were used in accordance with Cigré recommendations for calculating the "base rating" of conductors [12]:

- wind speed: 0,6 m/s at 90º angle
- solar radiation: 1000 W/m2
- emissivity factor: 0,7
- absorptivity factor: 0,8

The physical data for the 600 mm2 aluminium alloy conductor was taken from Table F.33 of EN 50182:2001. The AC and DC resistance of the conductor was used for the calculations of AC and DC current ratings, respectively.

The calculated current ratings are shown in Table 7-3 for ambient temperatures of +10°C and +40°C. The current rating of the existing AC line is shown for a maximum conductor temperature of +80°C, while the current ratings of the DC line are presented based on the maximum conductor temperatures for the 300 m span length shown in Table 7-2.

Finally, the thermal power transfer capacities of the AC and DC lines were calculated and presented in Table 7-3. For the AC line, a service voltage level of 420 kV and a power factor of cos ∏ = 0,90 are assumed. The results in Table 7-3 are visualised in Figure 7-1.

Table 7-3. Calculated maximum current rating and thermal power transfer capacity.

	Service voltage	Maximum DC conductor temperature	Maximum current rating		Maximum power transfer capacity	
			+10°C	+40°C	+10°C	+40°C
	kV	°C	A	A	MW	MW
AC	420	80	2578	1827	1688	1197
DC	±400	80	3891	2759	3113	2207
	±450	80	3891	2759	3502	2483
	±500	78	3801	2652	3801	2652

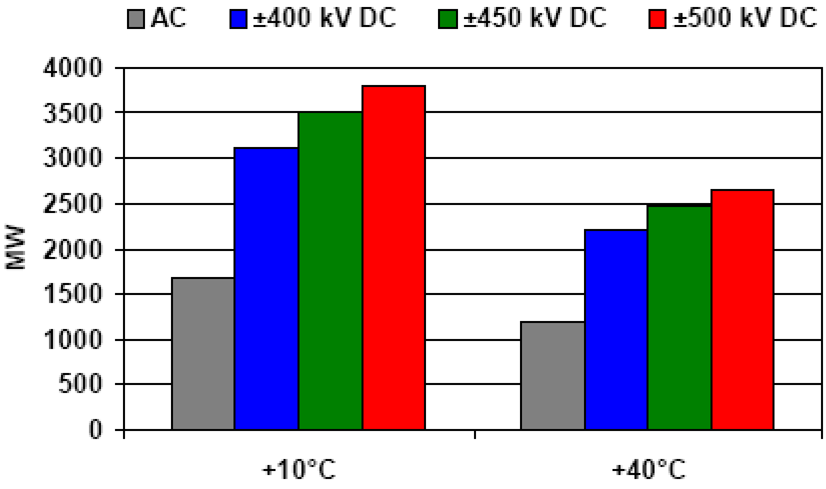


Figure 7-1. Maximum thermal power transfer capacity of the AC and DC lines at ambient temperatures of +10°C and +40°C.

8. Summary and conclusions

The study has shown that a conversion of a 380 kV AC double-circuit lines to AC/DC hybrid lines is feasible when the environmental effects in terms of fair weather audible noise and electric field effects are adequately considered. As seen from Table 7-3 and Figure 7-1, the gain in thermal power transfer capacity by the conversion is substantial; the capacity of the DC line is about twice as high as for the existing AC line.

It was found that a DC voltage of about ±450 kV might be the maximum acceptable voltage level with regard to corona and field effects. It was also found that the environmental effects of the remaining AC circuit is not significantly changed by the conversion; the audible noise level in rain as well as the AC electric and magnetic field levels are essentially unaffected.

The DC composite insulator dimensions have been settled for the assumed pollution severity and the resulting maximum allowable conductor sag of the DC conductors has been calculated accounting for the specified minimum ground clearance. Finally, the corresponding current rating and thermal power transfer capacity were determined for different DC voltage levels.

In order to limit the extent of the feasibility study, the scope was confined to environmental effects in terms of audible noise and electric fields. Other factors that might be included in a more comprehensive study are listed below:

- The effects of the DC line on under-built 220 kV circuits need to be studied to quantify, in particular, how the corona effects of the 220 kV conductors will be affected by the presence of the DC line.
- The lightning performance of the DC line should be studied in order to quantify the influence of tower air clearances and the DC voltage level.
- The radio interference level of the DC line should be calculated to check the compliance with regulations.
- The corona losses for the DC line should be estimated as function of the DC voltage level.

The final selection of the DC voltage level for a converted line should primarily be based on the audible noise level in fair weather. However, it should be realized that the audible noise generation of dry conductors is more difficult to predict than for wet conductors due to uncertainties regarding the actual state of the conductor surfaces. The influence of altitude on the audible noise level should also be considered. It is therefore recommended that audible noise measurements be carried out on an AC/DC hybrid test line before settling the DC voltage level for the converted line.

9. References

[1] Chartier V L, Stearns R D: ”Formulas for Predicting Audible Noise from Overhead High Voltage AC and DC Lines,” IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 1, January 1981, pp 121-129.

[2] Chartier, V.L.; Sarkinen, S.H.; Stearns, R.D.; Burns, A.L.; “Investigation of Corona and Field Effects of AC/DC Hybrid Transmission Lines,” IEEE Trans. On Power Apparatus and Systems, Vol. PAS-100, No. 1, Jan. 1981, pp. 72 – 80.

[3] Transmission Line Reference Book HVDC to ± 600 kV – Prepared by BPA, published by EPRI, 1978.

[4] V.L. Chartier, R.D. Stearns, A.L. Burnes, “Electrical Environment of the Uprated Pacific NW/SW HVDC Intertie,” IEEE Trans. on Power Delivery, Vol. PWRD-4, No. 2, April 1989, pp. 1305-1317.

[5] AF McKinlay, SG Allen et al: “Review of the scientific evidence for limiting exposure to electromagnetic fields (0-300 GHz),” Documents of the NRPB, Vol.15, No. 3, 2004.

[6] http://www.mcw.edu/gcrc/cop/static-fields-cancer-FAQ/toc.html

[7] “CIGRE/IEEE Survey on Extra High Voltage Transmission Line Radio Noise,” IEEE Trans. on PAS, Volume PAS-92, Issue 3, May 1973, Page(s): 1019 - 1028.

[8] “Thermal behaviour of overhead conductors,” CIGRE Brochure No. 207, 2002.

[9] W.L. Vosloo, R. Stephen, P. Naidoo, I. Gutman, D. Muftic, N. Ijumba: “External Insulation Functional Specification for the Upgrade of a 400 kV AC Transmission Line to 500 kV DC”, Conference on “Meeting the Power Challenges of the Future using HVDC Technology Solutions”, July 12-14, 2006, Durban, South Africa.

[10] V. L. Chartier et al., “Effect of High Altitude on High Voltage AC Transmission Line Corona Phenomena,” IEEE Trans. on Power Delivery, Vol. PWRD-2, No. 1, January 1987, pp. 225-232.

[11] Clairmont, B. A.; Johnson, G. B.; Zaffanella, L. E.; Zelingher, S.; “The effect of HVAC-HVDC line separation in a hybrid corridor,” IEEE Transactions on Power Delivery, Volume 4, Issue 2, April 1989 page 1338 – 1350.

[12] “Guide for the selection of weather parameters for bare overhead conductor ratings,” CIGRE Brochure No. 299, 2006.

[13] C.S. Engelbrecht, R. Hartings and J. Lundquist, "Statistical dimensioning of insulators with respect to polluted conditions", IEE Proc. on Generation, Transm. and Distrib., Vol. 151, No. 3, May 2004.

10. Appendix A: Calculated lateral profiles of audible noise

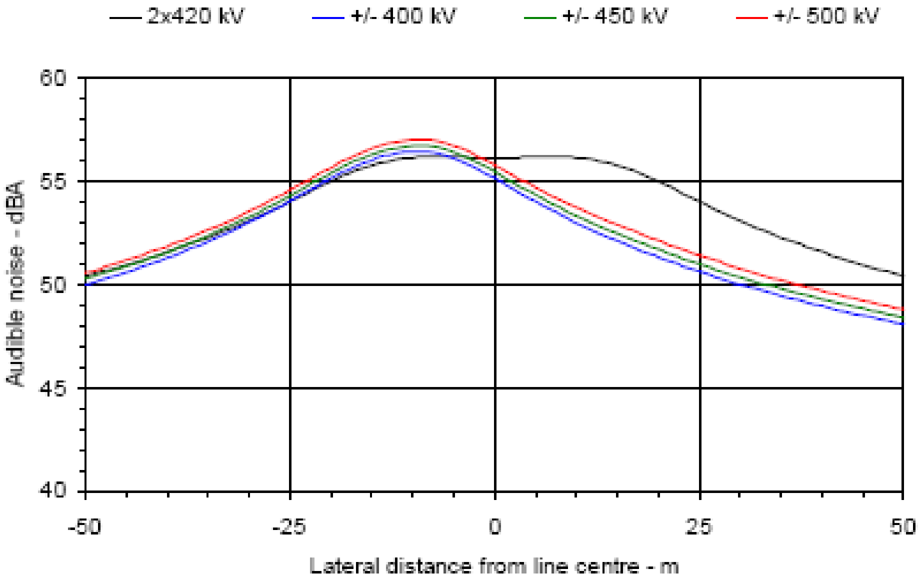


Figure 10-1. Audible noise level in rain for AC double-circuit and hybrid line configuration A.

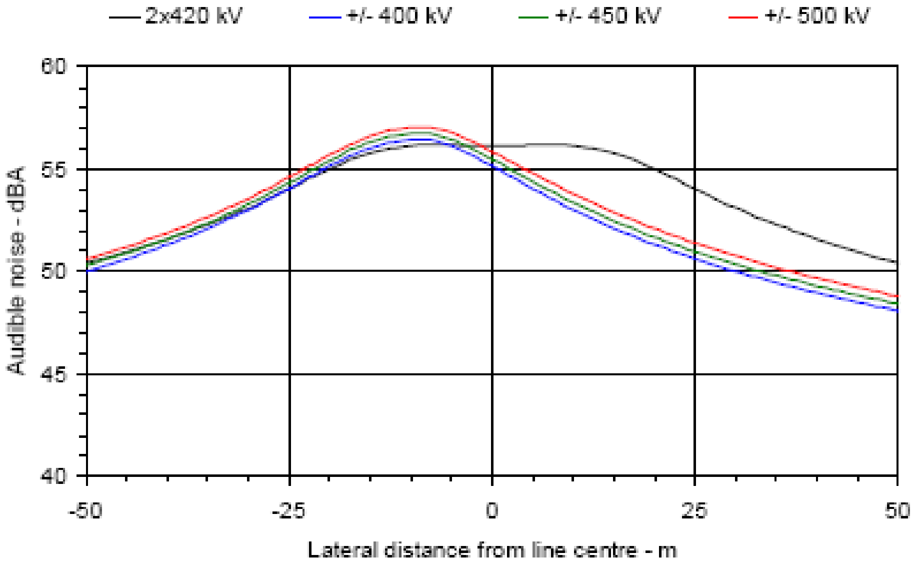


Figure 10-2. Audible noise level in rain for AC double-circuit and hybrid line configuration B.

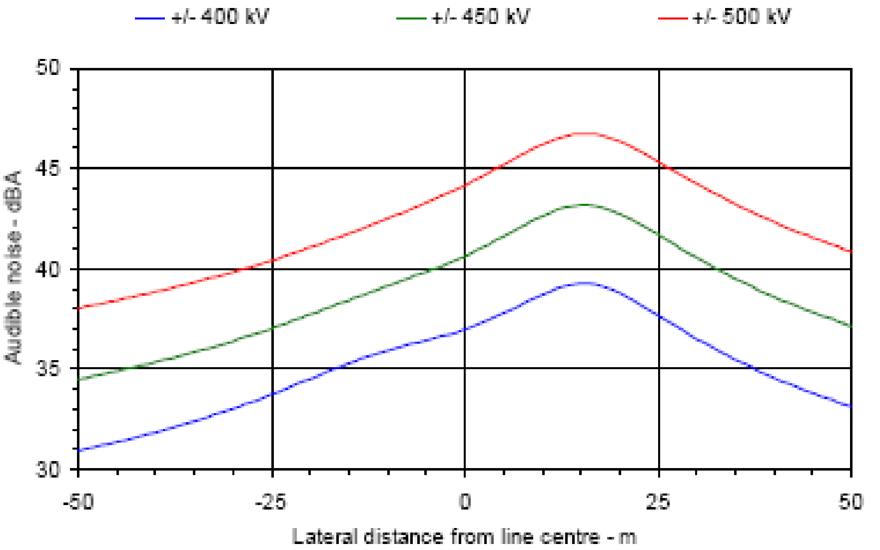


Figure 10-3. Audible noise level in fair weather for hybrid line configuration A.

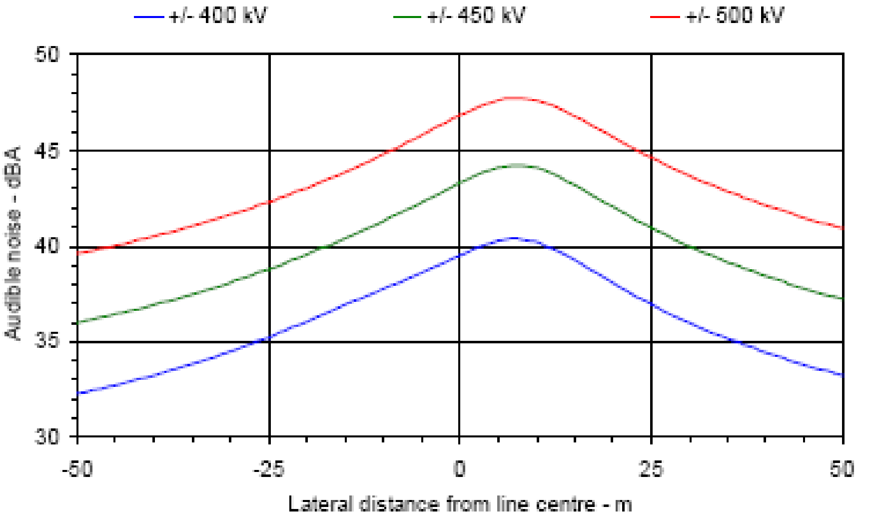


Figure 10-4. Audible noise level in fair weather for hybrid line configuration B.

11. Appendix B: Calculated lateral profiles of AC electric and magnetic fields

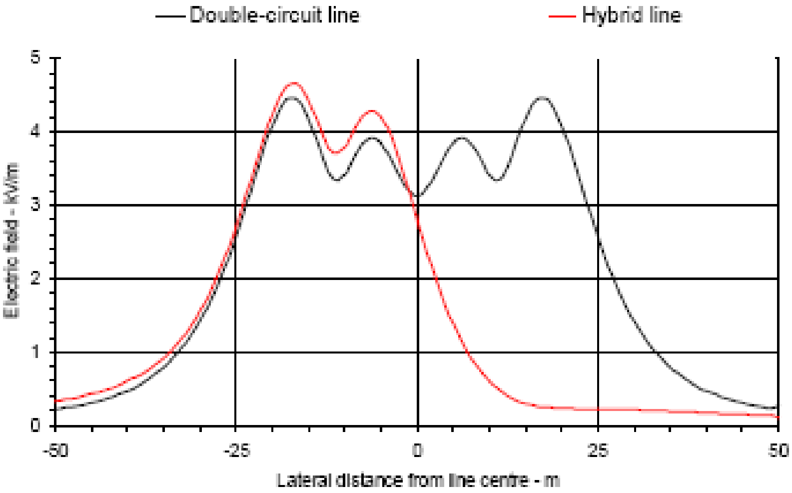


Figure 11-1. AC electric field levels for double-circuit line and hybrid line.

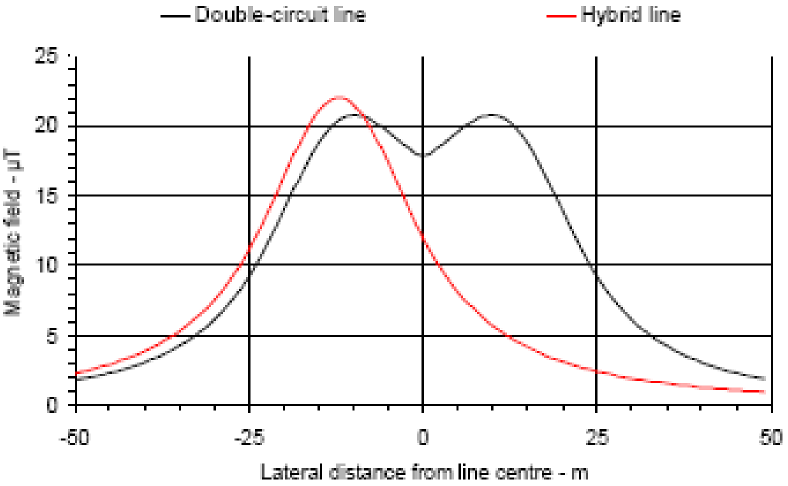


Figure 11-2. AC magnetic field levels for double-circuit line and hybrid line.

12. Appendix C: Calculated lateral profiles of DC electric field and ion current density

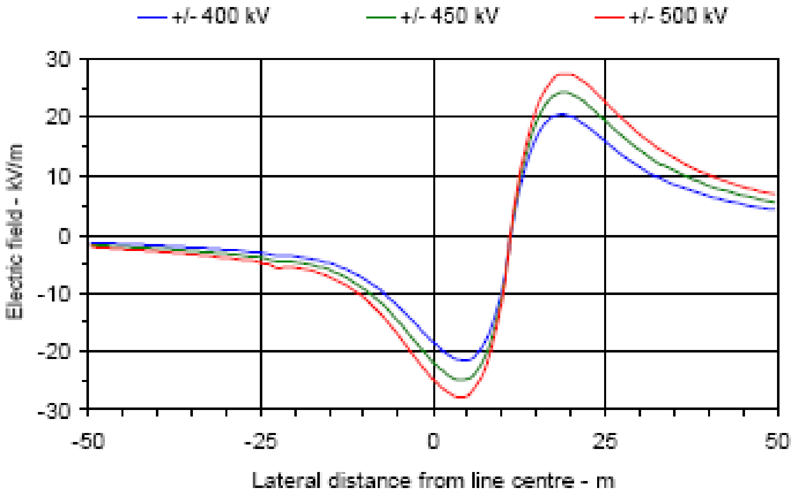


Figure 12-1. DC electric field levels for hybrid line configuration A.

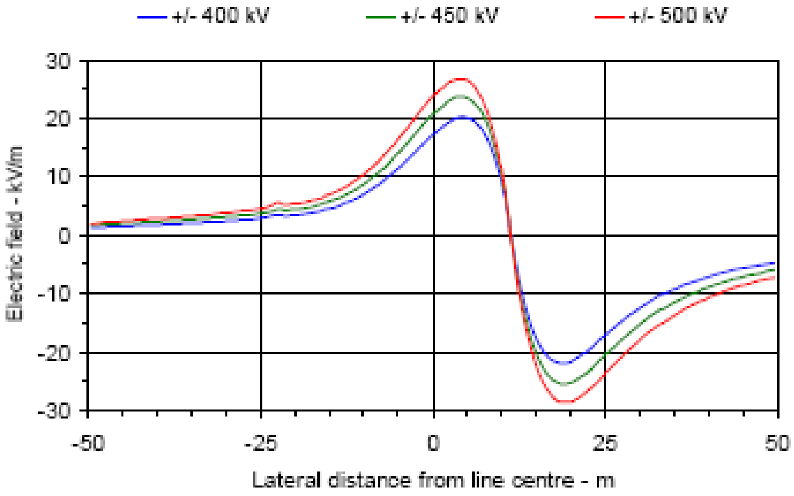


Figure 12-2. DC electric field levels for hybrid line configuration B.

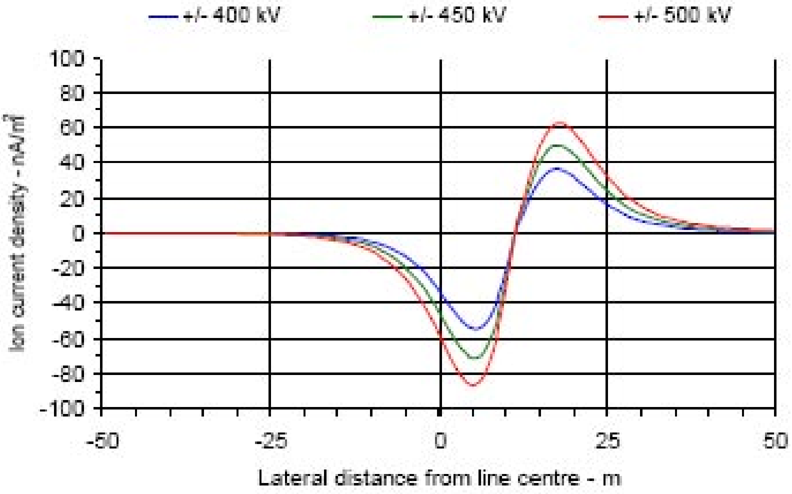


Figure 12-3. DC ion current density levels for hybrid line configuration A.

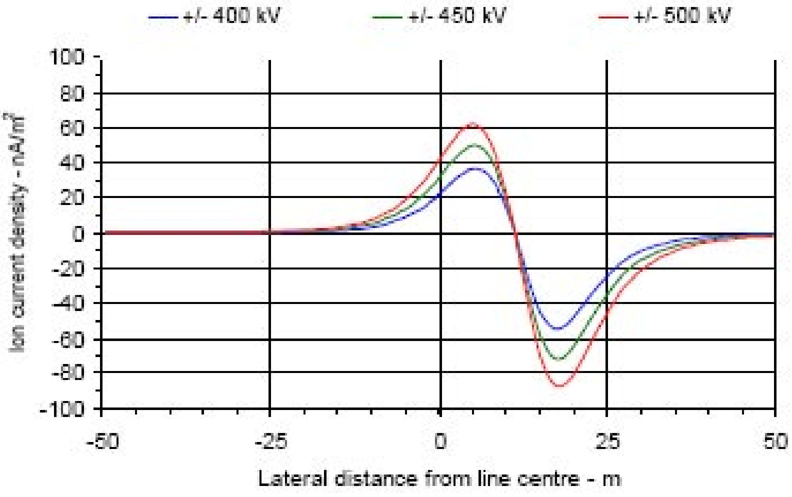


Figure 12-4. DC ion current density levels for hybrid line configuration B.