Discussion of Converting a Double-Circuit AC Overhead Line to an AC/DC Hybrid Line with Regard to Audible Noise

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SUMMARY

That the large-scale integration of new renewables requires a substantial increase in transmission capacity seems to be an undoubted fact today. As new rights-of-way for transmission lines are increasingly difficult to obtain, alternatives are discussed to increase transmission capacity within the existing rights-of-way. One possibility to do so is the conversion of existing AC lines to DC. In the past, already for the very same reason of limiting the land use, overhead transmission lines have been built as multi-circuit lines on the same structure in many countries. Especially in densely populated areas such as Central Europe, bundling of circuits is inevitable although it results in higher construction costs. In such situations, changing one AC circuit to DC will result in transmission lines with AC/DC hybrid towers.

As, to the authors’ knowledge, practically no operational experience with such hybrid lines exists to date, such schemes have to be assessed rigorously before any realisation. Especially with the close proximity of AC- and DC-circuits, many potential problems can be identified. Among them is the change in surface gradients, which may lead to different kinds of corona activity: The AC circuit induces an AC ripple in the surface gradients of the DC conductors, while the DC circuit induces a DC bias in the surface gradients of the AC conductors.

According to the literature on corona and the resulting audible noise (AN) of such hybrid overhead transmission lines, calculation of the AN can be performed with the methods developed for pure DC and AC transmission lines. But disagreement remains on whether the DC-offset in surface gradients of the AC-conductors should be accounted for within these calculations or not. In this paper, these calculation methods are applied to a possible scheme of converting a 400 kV AC double circuit line to a hybrid line by replacing one AC by a ±500 kV DC circuit. After assessing the considerable increase of the thermal rating, different tower configurations are considered and the resulting electric surface gradients and AN are compared with those from the original 400 kV AC double circuit line. As to AN, the best configuration out of those considered is the horizontal arrangement of the AC-circuit on the lower cross-arms, while the DC-circuit is placed above, also in horizontal arrangement. As a further advantage, this geometry also provides the greatest shielding of the environment from ion currents originating from DC-corona. However, with this arrangement, the coupling between the two circuits is greatest, with largest DC-currents in the AC-system and vice versa.

KEYWORDS

Corona, noise-audible, HVDC, line-hybrid

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1 INTRODUCTION

For so-called hybrid corridors such as the Pacific Intertie [1], where AC and DC transmission line share the same transmission corridor, a lot of operational experience is at hand today. But as to hybrid lines with AC and DC transmission sharing the same tower, sometimes also referred to as hybrid towers [2], practically no operational experience exists to date. Due to the close proximity of the AC- and DC-circuits in a hybrid tower, the mutual influence of AC and DC lines tends to be considerable larger than in a hybrid corridor. Therefore, such schemes have to be assessed rigorously before any realisation. The mutual influence between AC and DC lines involves:

- Capacitive coupling (electric fields), resulting in displacement currents from AC to DC and in a change of the surface gradients on the conductors, at least in the case where corona is absent, see Figure 1.
- Magnetic coupling, resulting in AC currents induced from AC in the DC circuit.
- The ion current originating from DC pole corona is collected partly by the AC phases; thus a DC-current is evoked in the AC circuit.

![Figure 1: Coupling of the DC-System on the AC-system (left) and vice versa (right) with regard to the surface gradients on the conductors.](image)

This coupling of the AC and DC circuits in a hybrid line has different technical consequences, such as:

- In steady state operation the induction of AC currents into the DC circuit leads to converter transformer saturation [3]. One possible mitigation option is transposing the AC or DC lines [3]. The same problem of transformer saturation would occur with DC currents in the AC circuit (e.g. by collecting the DC corona current).
- Overvoltages in a DC line alone are smaller than for the DC circuit in hybrid environment; here the transposition of the AC phases is a possibility to mitigate the problem as well [4].
- The impact of the different conditions of DC and AC operation on insulator performance, such as the enhanced role of pollution in the case of DC, is well established. However, hardly anything is known about the requirements on insulators in a hybrid environment [5].

In addition to these technical problems occurring in the context of hybrid lines, environmental impacts have to be addressed as well. Typically, the existing investigations are based on the quite well studied environmental problems of pure AC and DC transmission lines, such as radio interference (RI), audible noise (AN), electric and magnetic fields on the ground and, in the case of DC, ion currents. All but the magnetic fields are linked to corona on the conductors.

The largest corona activities (corona current and loss) occur in foul weather condition in both cases of AC- and DC-transmission [6]. Thus, the ion currents under DC-lines are largest
during foul weather. Nevertheless, as the corona-discharge type is different in fair and foul weather, RI and AN are reduced from fair to foul weather in the case of DC [6]. The contrary to DC is evident with AC, where these AN-relevant corona-discharges are more present in foul weather than in fair weather. Therefore, changing from fair to foul weather, AC AN is increased and DC AN decreased.

The negative pole can be neglected in the case of bipolar lines [6] (if the absolute values of the surface gradients are comparable on both poles), because of the following reasons:

- It is well known that the broadband AN is produced mainly by strong, impulsive corona-discharges occurring on the positive DC pole [6] (the same is valid for AC, where these discharges occur in the positive half-wave [7]).

- The cause of the strong DC corona in fair weather is pollution on the conductors due to airborne particles and, prevailing, insects [8]. Both are collected much more in the case of DC as they are, if charged, continuously attracted to the corresponding pole. Interestingly, due to triboelectricity, insects are more often charged negatively and, therefore, attracted to the positive pole [8]. Thus, corona activity during fair weather also depends on the season, with largest AN levels during summer fair weather [8].

Because of this role of airborne particles and insects, the difference in AN between fair and foul is not so considerable in the case of DC (according to EPRI about 6 dB [8]), whereas the difference of AC AN levels is usually so large that fair weather AC levels are negligible. Further it has to be respected that noises of the same level are “[…, in general, more objectionable in fair weather than in foul weather […]” [6]. Therefore, fair weather AN must meet stronger limits than foul weather AN; in [6] the difference in suggested limits is about 10 dB.

As to such environmental impacts of hybrid lines, literature is scant. Especially on the topic of experimentally underpinned methods of AN calculation, only a scarce amount of literature exists, [1], [2] and [9], to the knowledge of the authors. The common result is that the corona activities of pure AC and DC lines are not changed fundamentally when combined in a hybrid line. Therefore, the known calculation procedures for determining the AN levels for AC and DC lines can be used for hybrid lines, even though [9] advocates the necessity for some slight modification in assessing the relevant surface gradients of the AC conductors.

In the work presented here, a conversion of a 400 kV double circuit AC overhead line to a ±500 kV DC/400 kV AC hybrid line is investigated. The conversion is discussed for two typical conductor bundles and one tower geometry in the original double circuit line. The conversion is assumed to be without reducing or adding conductors, but by replacing the three phases of the AC circuit with one bipole. Thus a modification of the towers would be needed for such conversions.

In section 2 of this paper, the implication on (thermally limited) transmission capability through this conversion is investigated. Then the calculation procedures of AN are discussed (section 3) and applied to the examples under investigation (section 4).

2 THERMAL RATINGS OF THE INVESTIGATED EXAMPLES

2.1 Investigated Conductor Bundles

The two investigated bundles of the original AC double-circuit line are a two conductor bundle 2 x AAAC 600 and a four conductor bundle 4 x ACSR 265/35. As mentioned above, the conversions of one of the AC-circuits to DC considered here consist of a rearrangement of all conductors from the three phases to form the DC bipole. This results in the bundles depicted in Figure 2.
Figure 2: The bundles of the considered transmission lines.

Noticeably, the diameter of the six-conductor bundle is unusually small. But so is the diameter of the subconductors, by which smaller fields are reached with the shown bundle geometry. As the calculation method for determining the AN from the DC circuit does not directly depend on the bundle diameter, this somewhat unconventional bundle diameter (of the already unconventional bundle) is considered. Further, in contrast to AC, the surge impedance has no relevance for the DC transmission capability; thus there is also no need to decrease the surge impedance by increasing the bundle diameter from that point of view. However, the calculated difference in AN between these small and usual bundle diameters is not substantial.

2.2 Calculation Method

In the steady-state case of interest here, heating and cooling of the conductor are in equilibrium. Given the conductor temperature, the corresponding current is

\[
I = \left( \frac{P_{rad} + P_{conv} - P_{sol}}{R_T} \right)^{0.5},
\]

with \( P_{rad} \) as the heat loss by radiation of the conductor, \( P_{conv} \) as the convection heat loss, \( P_{sol} \) as the solar heat gain by the conductor, \( R_T \) the electric resistance of the conductor at temperature \( T \). All these components dependent either on the conductors or the atmospheric conditions or both.

Many methods to approximate these contributions can be found in literature. Three of the most common ones are [10], [11] and [12]. The calculation results shown here are based on IEC’s Technical Report [12], whereas some parameters and the determination of the AC-resistance are taken from [13]. The environmental parameters are from [12] (Appendix A). The maximum conductor temperature is assumed to be \( T_{max} = 80^\circ C \).

2.3 Transmission Capabilities

Together with the voltages of the transmission circuits, the resulting thermal ratings are shown in Table 1.

<table>
<thead>
<tr>
<th>subconductors</th>
<th>400 kV AC</th>
<th>±500 kV DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAAC 600</td>
<td>1.94 GVA</td>
<td>4.31 GW</td>
</tr>
<tr>
<td>ACSR 265/35</td>
<td>2.51 GVA</td>
<td>5.47 GW</td>
</tr>
</tbody>
</table>

Table 1: Thermally limited transmission capability of the different transmission circuits (conductor bundles depicted in Figure 2) under consideration.
Therefore, the transmission capability by converting one 400 kV AC circuit to ±500 kV DC is increased by the factor 2.2 for the circuit and 1.6 for the whole line, which is, as expected, quite significant.

3 CALCULATION OF AUDIBLE NOISE LEVELS

3.1 Formulas to Predict AN

Operational Experience with Hybrid Corridors
Due to the comparatively large line separation, measurements on a real hybrid corridor [1] reveal no interactive effects between AC and DC circuits for most of the environmental impact quantities. However, RI from the AC line is increased, when the positive peak gradients of the AC conductors is increased (i.e. by increasing the voltage of the negative pole or decreasing the voltage of the positive pole) and vice versa. In [1], no such effect is reported in the case of AN, but in [9] and [2], however, where the environmental impacts named above on hybrid tower line-models in the laboratory and outdoors were investigated.

Effect of DC Bias on AC AN
As in the case of RI in [1], it is observed that the negative pole increases and the positive pole decreases the activity of the corona-type on the AC conductors responsible for RI and AN [9]. Further, it is claimed that DC ions (and their enhancement of surface gradients on the AC-conductors) have negligible effect on the AC corona activity. This is why Chartier et al. [9] conclude that AN from hybrid lines may be determined by the formulas known for pure DC and AC transmission lines. However, in the case of AN from the AC conductors, the usage of the positive peak value (the sum of the AC-peak and the DC bias) of the surface gradient in the calculation formula is advocated, while the effect of ions on the surface gradients and AN are supposed to be neglected [9].

Other findings from a conductor bundle energized with an AC voltage with a DC bias are reported from EPRI [2]. Even though an increase of the positive bias on the AC conductors resulted in an increase of AN in the experiments, this increase is smaller than expected with the positive peak value argumentation of [9]. Also in contradiction to [9], AN even increases if the negative bias on the AC conductors is increased [2]. The reason for the weak dependence of AN on positive DC bias is supposed to lie in the effect of the ions, as they might reduce the positive DC bias actually present in the surface gradient of the AC-conductors [2]: With a positive DC bias, AC conductors are expected to produce more positive ions, which shield the conductor and reduce the DC bias. Therefore, it is concluded that AN from hybrid lines may be determined with the formula of pure DC and AC lines without considering the DC bias on the AC conductors [2]. As the findings of [2] are quite convincing, the DC bias in the AC surface gradients is neglected in the following.

Effect of AC Ripple on DC AN
As to the DC AN from the hybrid line, both references [2] and [9] conclude that the influence of the AC ripple on the surface gradients of the DC conductors is negligible.

Tonal Emission at Mains Frequency
Despite the broadband AN, a further component not commented in the literature discussed above, namely tonal emission, could also be of importance. According to the mechanism of the tonal component from AC lines [14], the presence of DC-ions in an AC-field could evoke tonal emissions at mains frequency. However, the only investigation on such emissions from hybrid lines reveals only a small increase of this tonal component [15]. As its level is considerably below that of the usual tonal component from the AC line at twice the mains frequency, it seems to be negligible, even though the experiments were performed on a model line, where as DC circuit only a positive monopole was investigated [15].
**AC Formulas**
The formulas used in this paper to calculate the AC AN are those from EPRI [16]. According to [16], the exceedance levels $L_5$ (exceeded during 5% of the time) in [dB(A)] per phase are calculated by

$$L_5 = 20\log_{10}(n) + 44\log_{10}(d) + 67.9 - \frac{665}{E} + 22.9(n-1)\frac{d}{D} - 10\log_{10}(R) - 0.02R ,$$

with

- $n$ number of subconductors per bundle
- $d$ diameter of the conductors [cm]
- $E$ average-maximum bundle gradient: arithmetic mean of the maximum gradients of the individual subconductors [kV/100/cm]
- $D$ bundle diameter [cm]
- $R$ radial distance from the phase to the point of observation [m].

The exceedance levels $L_{50}$ are calculated from $L_5$ according to [16] via

$$L_{50} = L_5 + \Delta A_{wc}$$

with

$$\Delta A_{wc} = 10.4 - \frac{14.2E_c}{E} + 8(n-1)d/D ,$$

$$E_c = 24.4/d^{0.24} .$$

These formulas are valid for $3 \leq n \leq 8$. The contribution of all phases are summed energy-equivalently to determine the levels of the corresponding circuit.

**DC Formulas**
The DC levels are calculated by means of the formulas from EPRI [8]. The exceedance level $L_{50}$ of the positive pole during summer fair weather is calculated by

$$L_{50} = 56.9 + 124\log_{10}(E/25) + 25\log_{10}(d/4.45) + 18\log_{10}(n/2) - 10\log_{10}(R) - 0.02R ,$$

with the same meaning of the parameters as above in (2) [8]. In [8], the difference between $L_{50}$ and $L_5$ is quantified to be

$$L_5 - L_{50} = 6 \text{ dB} .$$

**Equivalent Sound Levels**
To convert the exceedance levels to (energy) equivalent sound levels $L_{eq}$, the noise level is supposed to be a lognormal distribution [8], by which the relations

$$L_{eq} = L_{50} + 0.115 \cdot \sigma^2 ,$$

$$\sigma = (L_5 - L_{50})/1.64,$$
can be deduced [8], which is used here for calculating equivalent sound levels both for AC and DC.

4 RESULTS

As mentioned in the introduction, the most significant noise levels are reached in foul weather in the case of AC and in summer fair weather in the case of DC. This is why AC levels are identified with foul weather levels, while DC levels are identified with (summer) fair weather levels in the following. In the section 4.3 the justification of this identification is examined.

4.1 ACSR 265/35 example

The line configuration of the original double circuit AC line is depicted in Figure 3. The distance from ground corresponds to an average of the catenary sag. Based on these geometric data, the surface gradients have been calculated by means of a FEM-software. Their values are depicted in Table 2. The resulting AN levels are also depicted in Figure 3.

![Figure 3: Configuration of the original AC double circuit transmission line (left) and the corresponding AN level L_{eq} on ground during foul weather (right).](image)

The two hybrid line configurations investigated in this paper are depicted in Figure 4 (configuration 1 taken from [17]). As power flow reversal is connected with polarity reversal (in typical current source converters, CSC [18]), both situations must be assessed. In the following the configurations with reversed polarities are designated with “±rev”.

![Figure 4: The two hybrid tower geometries under consideration; configuration 1 (left, taken from [17]) and configuration 2 (right).](image)
Obviously the coupling between AC and DC is larger in configuration 2 than in configuration 1. The resulting AN levels are depicted in Figure 5 and their maxima are summarized in Table 2.

**Figure 5:** AN levels on ground of the hybrid line configuration 1 (left) and configuration 2 (right).

As mentioned above, the average-maximum bundle gradients are also listed in Table 2, i.e. the values of all three phases are given in the case of AC, while the value of the positive pole is given in the case of DC. These are the values determining the AN levels to a great extent. As the values are calculated for AC and DC separately (the other circuit is grounded when determining the surface gradients, resulting in DC gradients without AC ripple and AC gradients without DC bias), changes within one system have no effect on the other, e.g. the polarity reversal on the DC side does not change the AC levels.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>400 kV AC [kV_{rms}/cm]</th>
<th>±500 kV DC [kV/cm]</th>
<th>fair [dB(A)]</th>
<th>foul [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC double circuit</td>
<td>15.2/13.8/15.9</td>
<td>–</td>
<td>–</td>
<td>43.0</td>
</tr>
<tr>
<td>hybrid 1</td>
<td>15.8/14.2/15.7</td>
<td>22.5</td>
<td>38.9</td>
<td>41.4</td>
</tr>
<tr>
<td>hybrid 1, ±rev</td>
<td></td>
<td>23.3</td>
<td>42.5</td>
<td>“</td>
</tr>
<tr>
<td>hybrid 2</td>
<td>15.4/12.9/14.8</td>
<td>19.5</td>
<td>31.1</td>
<td>39.3</td>
</tr>
<tr>
<td>hybrid 2, ±rev</td>
<td></td>
<td>20.0</td>
<td>32.5</td>
<td>“</td>
</tr>
</tbody>
</table>

**Table 2:** Average-maximum bundle gradient (only positive pole in case of DC) and AN maxima on ground for the three configurations with the ACSR bundles.

### 4.2 AAAC 600 example

The resulting average-maximum bundle gradients and the maxima of the AN on ground are summarized in Table 3.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>400 kV AC [kV_{rms}/cm]</th>
<th>±500 kV DC [kV/cm]</th>
<th>fair [dB(A)]</th>
<th>foul [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC double circuit</td>
<td>17.0/15.6/17.6</td>
<td>–</td>
<td>–</td>
<td>55.4</td>
</tr>
<tr>
<td>hybrid 1</td>
<td>17.5/16.0/17.4</td>
<td>28.1</td>
<td>49.3</td>
<td>53.6</td>
</tr>
<tr>
<td>hybrid 1, ±rev</td>
<td></td>
<td>29.0</td>
<td>52.7</td>
<td>“</td>
</tr>
<tr>
<td>hybrid 2</td>
<td>17.1/14.8/16.6</td>
<td>24.4</td>
<td>41.6</td>
<td>51.8</td>
</tr>
<tr>
<td>hybrid 2, ±rev</td>
<td></td>
<td>25.0</td>
<td>42.9</td>
<td>“</td>
</tr>
</tbody>
</table>

**Table 3:** Average-maximum bundle gradient (only positive pole in case of DC) and AN maxima on ground for the three configurations with the AAAC bundles.
4.3 Discussion

The calculation results justify the identification of DC and AC with fair and foul weather AN respectively: On the one hand, the greatest differences in the examples between AC and DC levels constitute about 10 dB. The decrease of AC AN levels from foul to fair are generally expected to be larger. On the other hand, the contribution of DC AN during foul weather can be neglected, as the expected DC foul weather levels (foul levels minus 6 dB [8]) are considerably lower than the corresponding foul weather AC levels. An exception may be configuration 1 with polarity reversal, were some contribution from the DC circuit to foul weather AN is possible.

But configurations 1 do not seem to be viable because of that very reason: DC fair weather levels come near to the corresponding foul weather levels of the original AC double circuit line, especially in the case of polarity reversal. As AN during fair weather is to be considerably lower than during foul weather to cause to same or less annoyance to local residents (reduction of about 10 dB from foul to fair [6]), the conversion from the original lines to the hybrid configurations 1 seems to result in a worsening of the situation with regard to AN. The calculated AN levels of the hybrid configurations 2, however, suggest a fulfilment of this requirement (reduction of about 10 dB). But for these configurations, non-AN-related coupling between the AC and DC circuits is increased.

Even though the corresponding national regulations are decisive, a comparison with level limits suggested in [8], i.e. (50...60) dB for AC (foul weather) and (40...50) dB for DC (fair weather) is made: Configuration 1 with the AAAC bundle exceeds these values in the case of polarity reversal, while with configuration 2, the levels are in the lower part of the given intervals. In the case of the ACSR bundle examples, configuration 2 results in levels below the given intervals for DC as well as for AC levels. As to this aspect, this configuration 1 would even allow higher DC voltages. An increase to ±600 kV, for example, would raise the surface gradients in the range of those of the corresponding configurations 1 with DC levels still within the given intervals. However, the required reduction of AN from foul to fair weather would then be violated.

5 CONCLUSIONS

1) Even though a larger coupling between the AC and DC circuits may be disadvantageous in some technical respects, intermixing the AC phases and DC poles on both sides of the tower reduces the surface gradients and the AN levels in the investigated examples. Such intermixing may also lead to further advantages, such as reduced ion currents onto the ground [9].

2) Polarity reversal may be accompanied by a remarkable change of DC AN levels.

3) In the case that polarity reversal for changing power flow direction is omitted (e.g. with future Voltage Sourced Converters (VSC) or CSC with additional switching arrangements), the advantage of choosing the pole arrangement with lower surface gradients on the positive pole is viable, resulting in lower AN levels.

4) Even though many technical aspects would have to be considered, conversion from existing AC 400 kV double circuit lines to hybrid lines seem to be a viable possibility for a considerable increase of transmission capability.

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BIBLIOGRAPHY


