Compact HVDC ±320 kV lines proposed for the Nelson River Bipole 3:

Consideration of the dimensions of the shield conductors, and initial review of the overall corona and field effects

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Compiled for:
Mr DA Woodford, CEO of the Electranix Corporation of Winnipeg, Canada

EXECUTIVE SUMMARY COMPACT AND CONVENTIONAL STRUCTURES:

The results of an initial study of the corona and field effects produced by the proposed compact ±320 kV HVDC line carrying two symmetrical monopolar circuits are presented. The results are compared with those produced by the conventional bipolar configuration being proposed for Bipole 3. The effects of unbalanced supply voltages on the corona performance of the compact line are quantified. How the optimum diameter of the shield conductor is determined is explained. It is concluded that the compact line offers acceptable corona performance from both engineering and environmental considerations, and also better performance than predicted for Bipole 3. It is pointed out that the contingent question of the susceptibility of the compact design to anomalous flashovers is still unresolved; however, it is speculated that reducing the ion generation may help

to mitigate this problem. Other aspects, such as those related to the lightning, switching and pollution withstand levels, have not been evaluated at this stage.

CONTENTS

1. INTRODUCTION

In January 2014 the author was requested by Mr DA Woodford, CEO of Electranix Corporation, to investigate the sizing and position, from a corona and electric field effects point of view, of the two underhanging shield conductors on the compact ±320 kV HVDC structure shown in Figure 1. It is understood that this structure is being considered for possible implementation in the Nelson River Bipole 3 Expansion Programme, so as to lessen the environmental impact of the scheme [1,2].

Also included in this report are the results of initial comparisons between the corona and field parameters of the likely conventional ±500 kV tower, proposed for use in Bipole 3, and the ±320 kV compact structure. (See Figures 1 and 2.)

2. TECHNICAL PARAMETERS, APPROACH AND METHODOLOGY

The author was requested to estimate and quantify the following parameters at ±320 kV for the compact tower geometry (Figure 1) and each of two pole conductor bundles, namely, 1x4.475 cm and 2x3.038 cm, with a spacing of 40-45 cm:

- Variation of the conductor surface gradients on the pole and shield conductors as a function of the diameter of the shield conductor.
- Audible noise lateral profiles at midspan.
- Audible noise and electric field levels at the 30 m lateral midspan positions, where the tower centre line is the reference position.
- Electric field lateral profile, with and without space charge, at midspan.

The author will also offer some comment on the limits of audible noise and electric fields for consideration by Electranix. The author also decided to include a comparison between the radio interference characteristics of the compact and conventional structures.

The predictions have been done means of the EPRI TLW 3.0 Programme. The key results are given mainly in the form of graphs in the body of the report, and relevant raw data in the appendices.

The elements of the compact ±320 kV compact structure are shown in Figure 1, as already noted. The conventional ±500 kV structure, which is understood to be the preferred option for Bipole 3, is shown in Figure 2.

It has been assumed that operation of the system as two ungrounded VSC-fed, balanced monopoles will imply that ideally the pole-to-ground voltages will be equal in magnitude, but opposite in polarity [3,4,5]. This means that the pole-to-pole voltage used in the studies was 640 kV, with the two pole voltages being +320 kV and -320 kV with respect to earth and the neutral point of the source. As the author understands the possible influence of unbalanced pole-to-ground resistive loading, the pole-to-pole voltage will still be 640 kV, but with the so called common mode voltages being higher on one pole than on the other; their sum will still be 640 kV [1,2]. The author has, for the purposes of these studies, assumed voltage unbalance levels of 0 to 25 %.

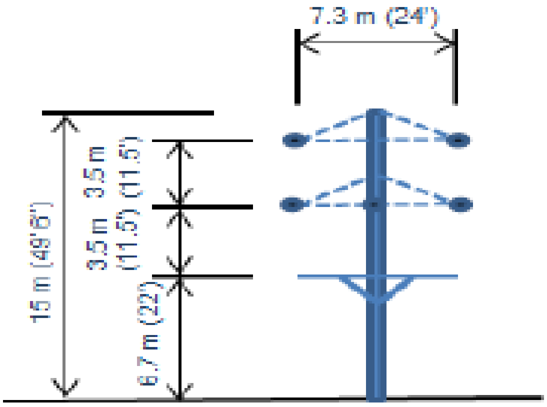

Figure 1: Dimensions of the proposed compact HVDC structure [1,2]

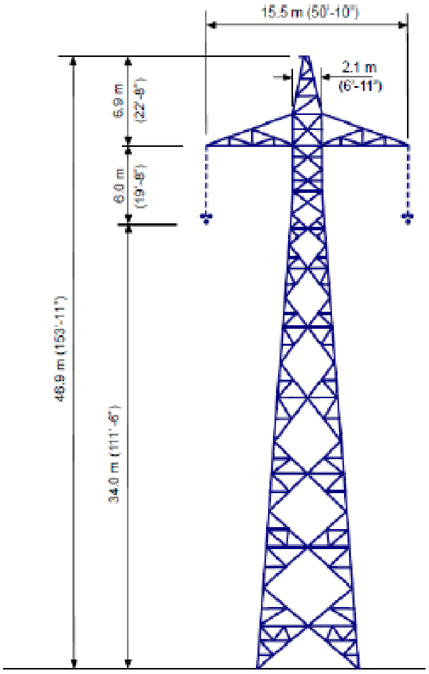

Figure 2: Dimensions of the tower being proposed for the Nelson River Bipole 3 [1]

3. RESULTS AND ANALYSIS

The results of the studies are summarised below.

COMPACT STRUCTURE: conductor surface gradients (Shield and pole conductors)

All the studies done in this report assume and use “phasing” which requires the same polarity voltages to be applied on the same side of the tower. This minimises the conductor surface gradient on the pole conductor bundle. (See Table 1) It is also shown that the above form of phasing does not minimise the surface gradients on the shield conductors; this may be done by applying the procedures illustrated in Figure 3.

Refer to Figure 1 for the dimensions of the compact tower. The left-hand upper pole conductor is Pole 1, the left-hand lower, Pole 2, the right-hand upper, Pole 3 and the right-hand lower, Pole 4. Shield conductor 1 is on the left-hand side of the tower.

Table 1 emphasises the importance of the correct phasing of the pole voltages.

Table 1: Conductor surface gradients for different, but not necessarily realistic, phasing scenarios and possible contingencies

Mode	**Pole 1**	**Pole 2**	**Pole 3**	**Pole 4**	**Shield 1**	**Shield 2**
Phasing	**+**	**+**	**-**	**-**	**0**	**0**
Conductor surface gradient in kV/cm	**+21.6** **This is the optimum phasing**	**22.2**	**-21.6**	**+22.2**	**-12.2** **Diameter of shield conductors: 1.5 cm**	**+12.2**
Phasing	**+**	**-**	**+**	**-**	**0**	**0**
Gradient kV/cm	28.0	-31.0	28.0	-31.0	9.6	9.6
	-	**+**	**+**	**-**	**0**	**0**
Gradient kV/cm	-31.5	31.1	30.5	-31.1	-7.5	7.5
Phasing	**+**	**-**	**0**	**0**	**0**	**0**
Gradient kV/cm	31.0	-29.2	1.3	-0.1	-8.5	-8.5
Phasing	**0**	**+**	**-**	**-**	**0**	**0**
Gradient kV/cm	-24.3	34.7	-15.4	-18.6	-3.5	16.3
Phasing	+	0	0	-	0	0
Gradient kV/cm	24.8	-4.4	3.2	-26.6	-1.3	10.9

It can be clearly seen that the +-+- phasing would cause unacceptably high conductor surface gradients on the pole conductors. This would probably increase the risk of anomalous flashovers, in the opinion of the author.

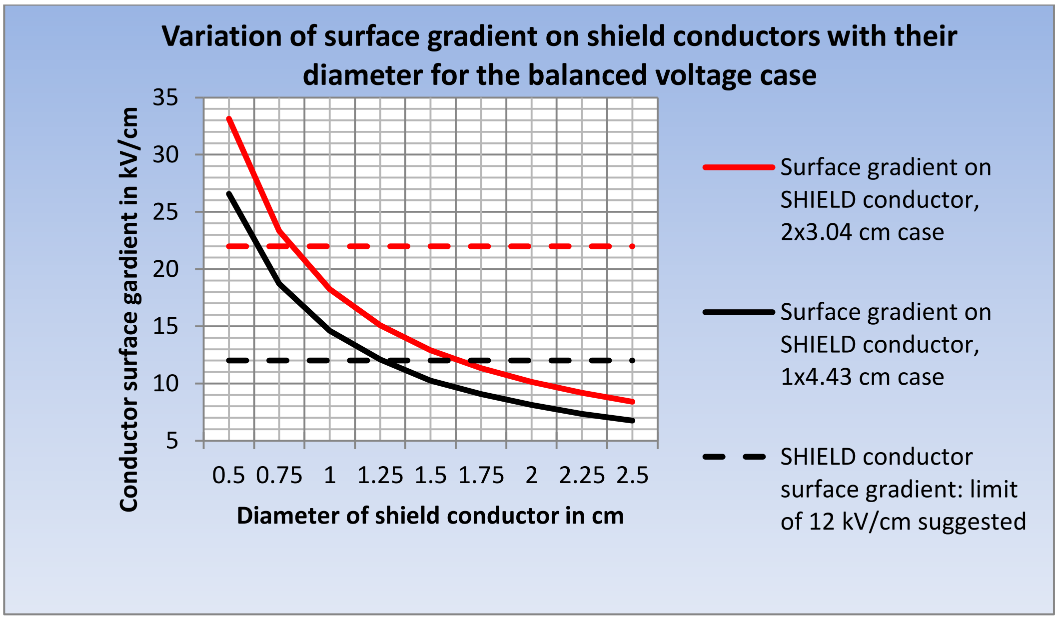

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Figure 3: Surface gradients on the shield conductors, for two different conductor bundle sizes

The data in figure 3 suggests that the diameter of the shield conductor should be at least 1.5 cm; this is to limit the gradient to about 12 kV/cm, and is a value derived from the author's experience on the Cahora Bassa scheme [3].

Figure 3 also demonstrates that the larger the effective coupling area of the pole conductor bundle, the higher will be the surface gradient on the shield conductor. This helps to improve one's insight into coupling mechanisms on a dc line.

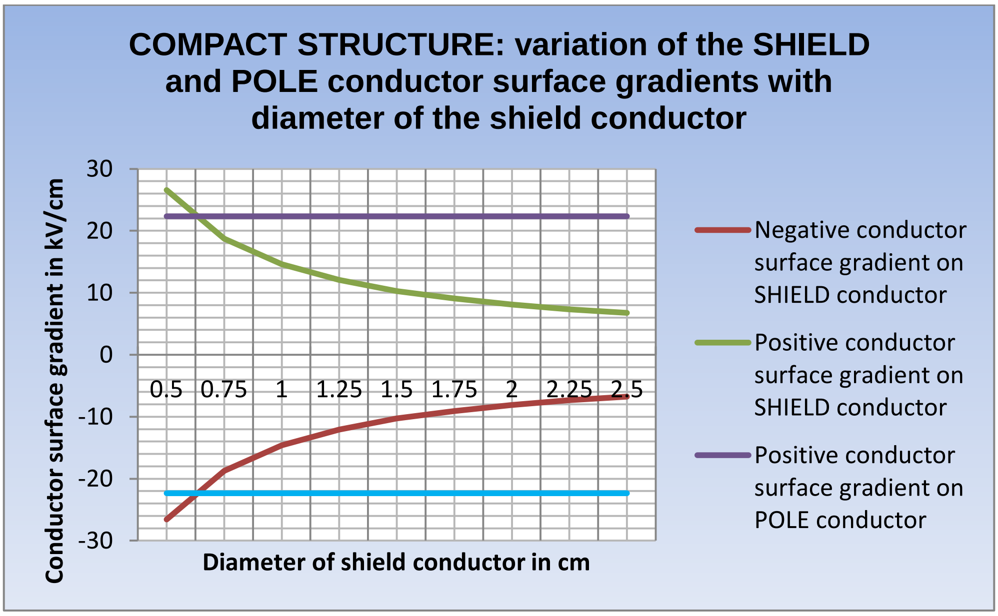


Figure 4: Same as Figure 3, but shows more detail

In Figure 4, the point is made that the surface gradient on the pole conductors is insensitive to changes in the diameter of the shield conductor. This is not the case when voltage unbalance is present, as can be deduced from Figure 5.

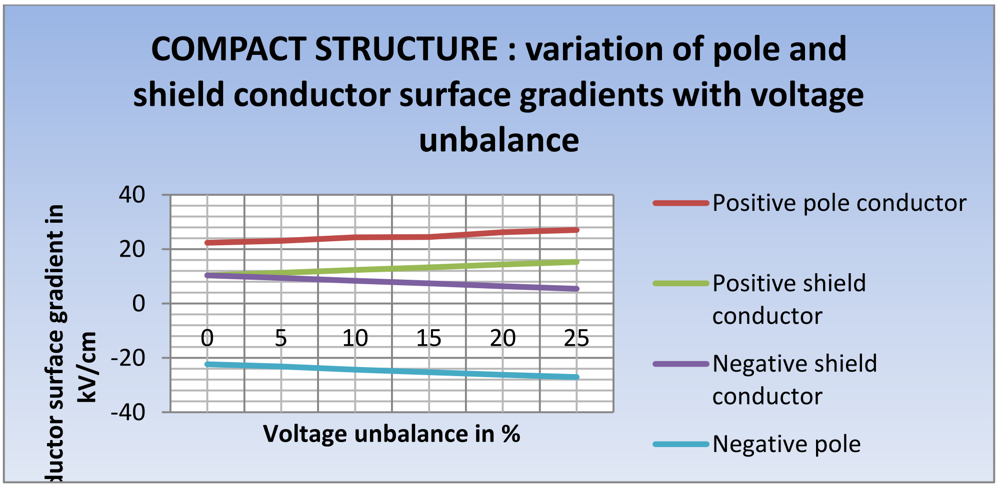


Figure 5: Influence of voltage unbalance on shield and pole conductor surface gradients

COMPACT AND CONVENTIONAL STRUCTURES: Audible Noise

Audible noise levels are expressed here in terms of Ldn which is essentially a 24-hour weighted average sound pressure level [6,7,8]. The weighting refers not only to the well-known frequency or A weighting, but also weighting which depends on the time of day. What this means is that between 21h00 and 07h00, 10 dB is automatically added to the averaged noise levels measured during this period. The result is that the 24-hour weighted level is higher than it would have been without weighting. Thus, to meet a given limit of noise from a dc power line in this case, it would be necessary for the designer to **reduce** the noise by an amount equal at least to the difference between the average weighted and unweighted levels. The unweighted level is often referred to as the equivalent A-weighted level or Laq..

Leq quantifies the energy in a sound pressure signal; mathematically, it is given by the average value in a time period T of the sum of the squares of the sound pressures.

The measure of power line noise is nowadays more and more being expressed in terms of Ldn. This metric lends itself to the measurement of DC line noise, because positive polarity DC audible noise is highest in fair-weather, and drops in rain conditions, unlike audible noise from AC lines, which increases in foul-weather. This makes the application of the Ldn concept and limits more straight-forward and less ambiguous for the designer to meet than in the case of AC. Another important point is that Ldn is widely used in international and national noise regulations.

Another point to note is that the annual statistical spread of the values of Leq, typically the 24-hour values, depend on the climate in a given area. Techniques have been developed for deriving the resultant value of Ldn from a large number of Leq values [9].

The above text helps to explain why the author has concentrated on the Ldn metric for expressing noise, from DC lines in particular.

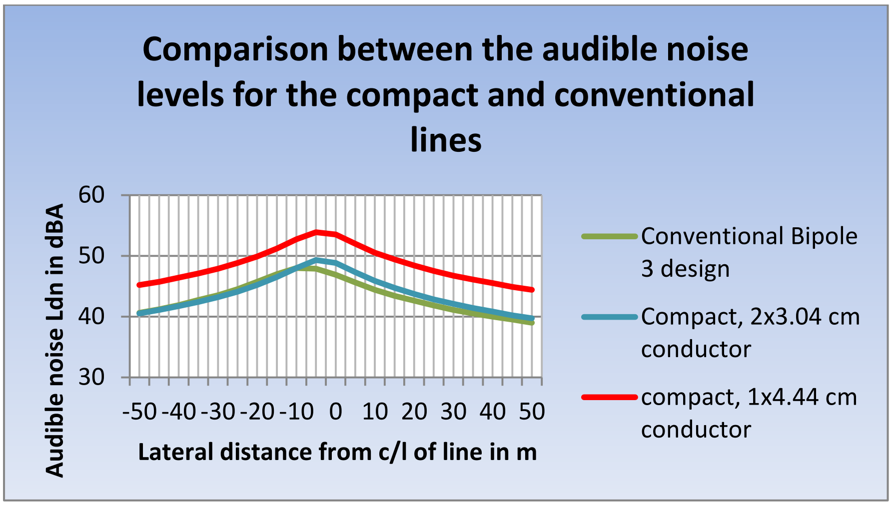


Figure 6: Audible noise, expressed in Ldn, from the compact and conventional DC lines

If a limit of Ldn = 50 dBA at the edge of the right of way were to be applied to the data in Figure 6, it can be seen that the two lower curves comply easily. The curve for the single conductor bundle compact line (where the left-hand portion is generated by positive corona) just complies. It can be deduced that the compact design does not constitute an audible noise problem under conditions of balanced supply voltage. The data in Figure 7 (for the one conductor bundle) shows, however, that a sustained positive voltage unbalance of a few percent, will cause the 50 dBA limit to be exceeded.

Audible noise will to some extent be a constraining factor in the application of the compact design, if voltage unbalance does indeed occur. (Note that the conventional design does of course not experience voltage unbalance.)

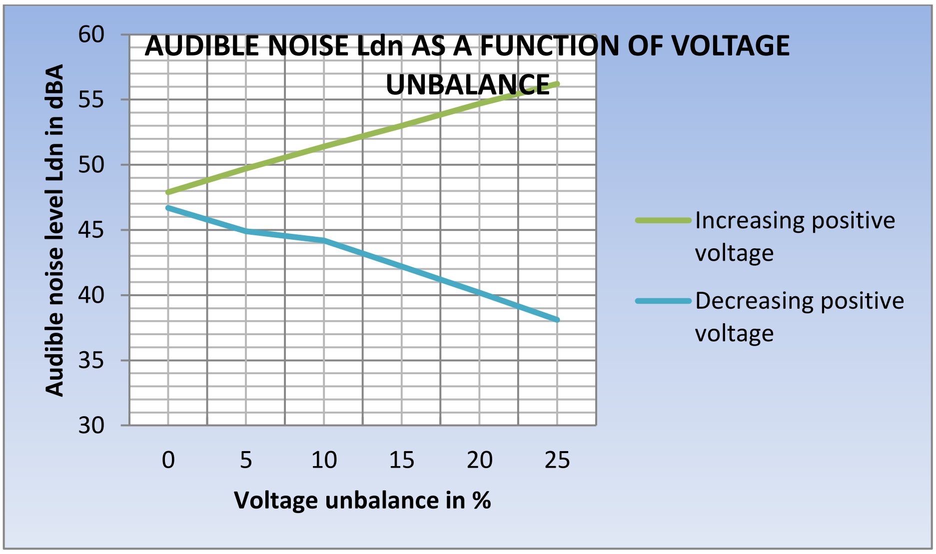
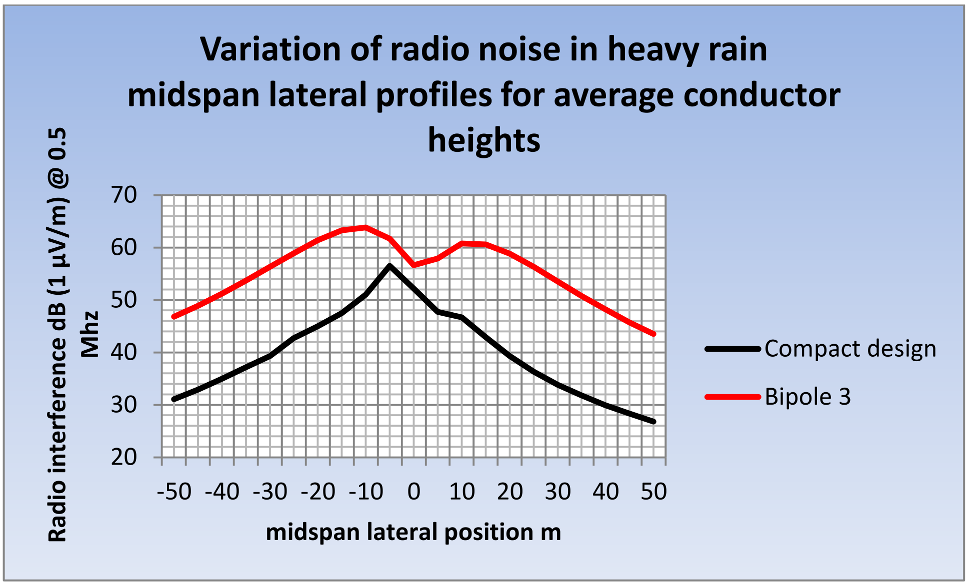


Figure 7: Variation of the audible noise levels at the ±30 m positions, with voltage unbalance

3.3 COMPACT AND CONVENTIONAL STRUCTURES: Radio interference



<u>**Figure 8: radio interference profiles in heavy rain conditions**</u>

The comparison between the radio noise profiles for the compact HVDC and the Bipole 3 designs shows (Figure 8) that the compact line out-performs the conventional design by a considerable margin. If power line carrier were to be used, the noise performance of the compact line, being superior to that of the conventional design, would make the power line carrier system easier to engineer.

3.4 COMPACT AND CONVENTIONAL STRUCTURES: Electric Fields

The author has been informed that the main concern as regards electric fields is the question of the degree to which such fields can be perceived by persons, become annoying or become dangerous. These aspects have been studied for both the compact line and the conventional tower designs. Unlike the case for audible noise, the important limit to be complied with is the maximum field, and not just the field at the edge of the right of way.

The response of humans to electric fields varies, **on average**, as shown in the Table 2 below.

<u>**Table 2: Subjective assessments of the electrostatic and space charge – enhanced electric fields [7,8,9,10]**</u>

Typical Voltage kV	Electric Field kV/m	Result	Reaction
+400	+22	Very slight sensation on scalp.	Aware of field
+500	+27	Hair stimulation, slight feeling on ears and hair.	Moderate nuisance
+600	+32	Strong tingling sensation on scalp.	Disturbing nuisance
+750	+40	Sensation on face and legs.	Very disturbing to painful

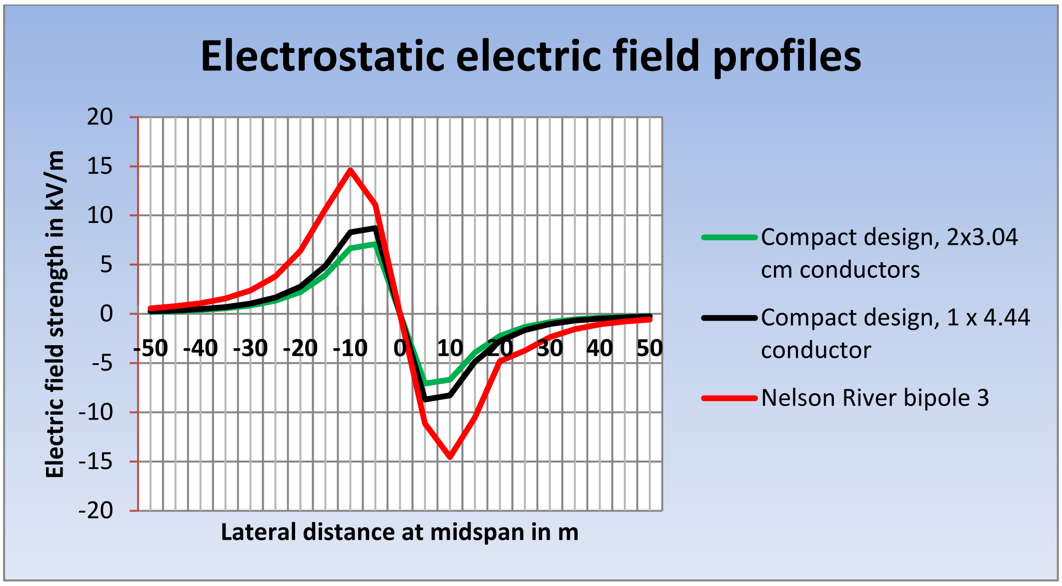


Figure 9: Electrostatic field profiles for the basic compact and conventional line designs at the midspan positions, with the conductor heights 4.7 and 8.80 m

According to the criteria given in Table 2, the above fields would not be perceptible.
The electric field limit of 25 kV/m, in the electrostatic case, would be possible to meet without difficulty.

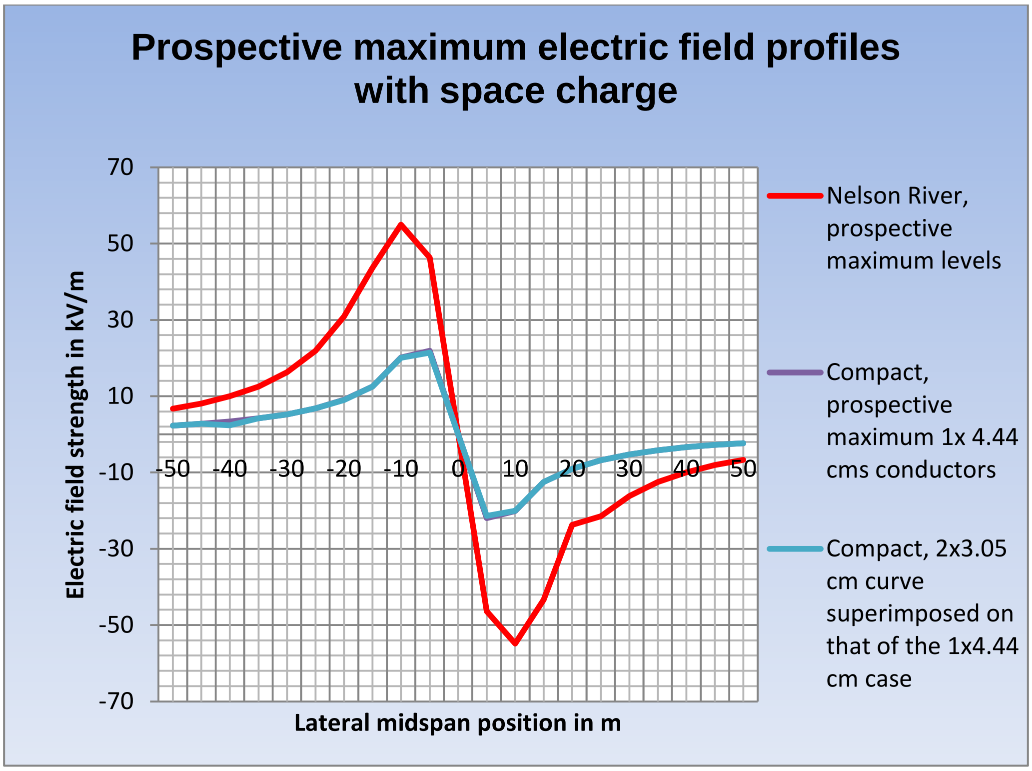
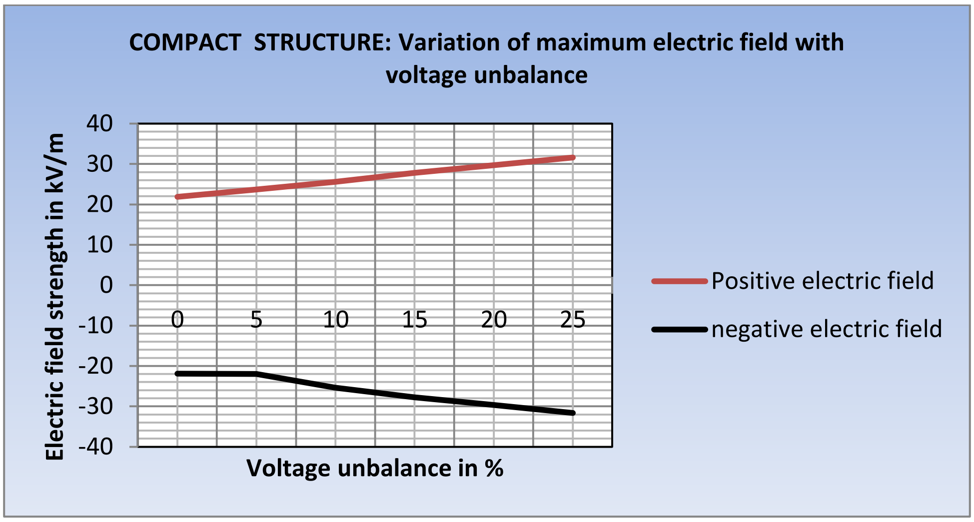
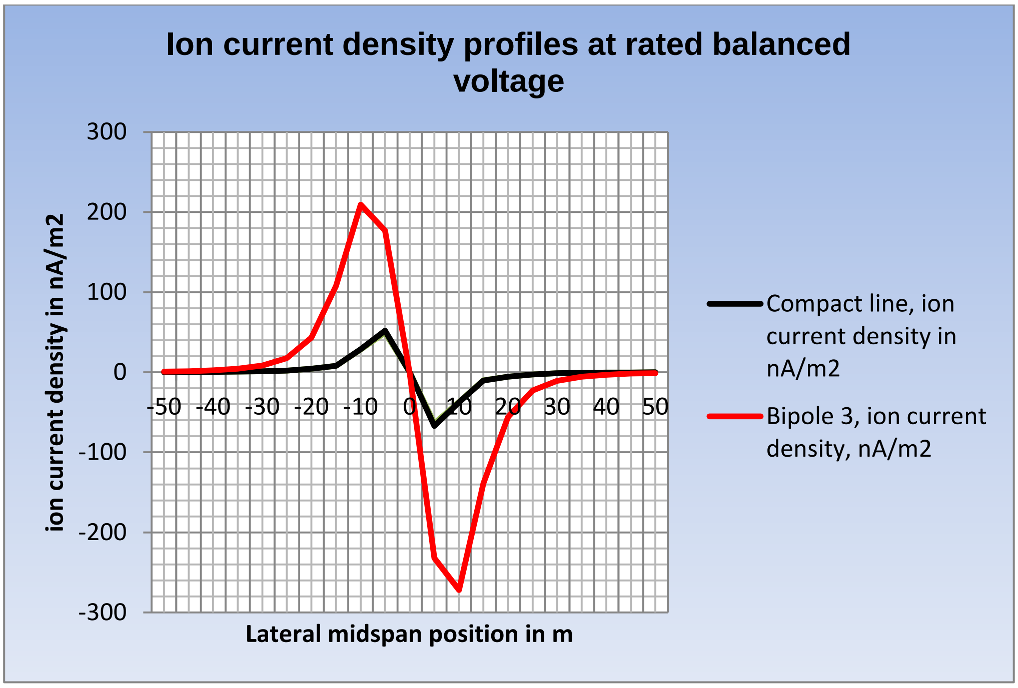


Figure 10: Comparisons between the space charge enhanced fields (10 % probability of occurrence)

From Figure 10, it appears that the ground level fields produced by the compact line would just be perceptible to the average person. Conversely, the maximum fields generated by the conventional design will be “very disturbing” to “painful”. This could be an important point in favour of the use of the compact structure.



<u>Figure 11: Maximum ground level electric field in ROW, for the compact design, with voltage unbalance the variable</u>



<u>Figure 12: Ion current density profiles for the two tower configurations, for rated voltage</u>

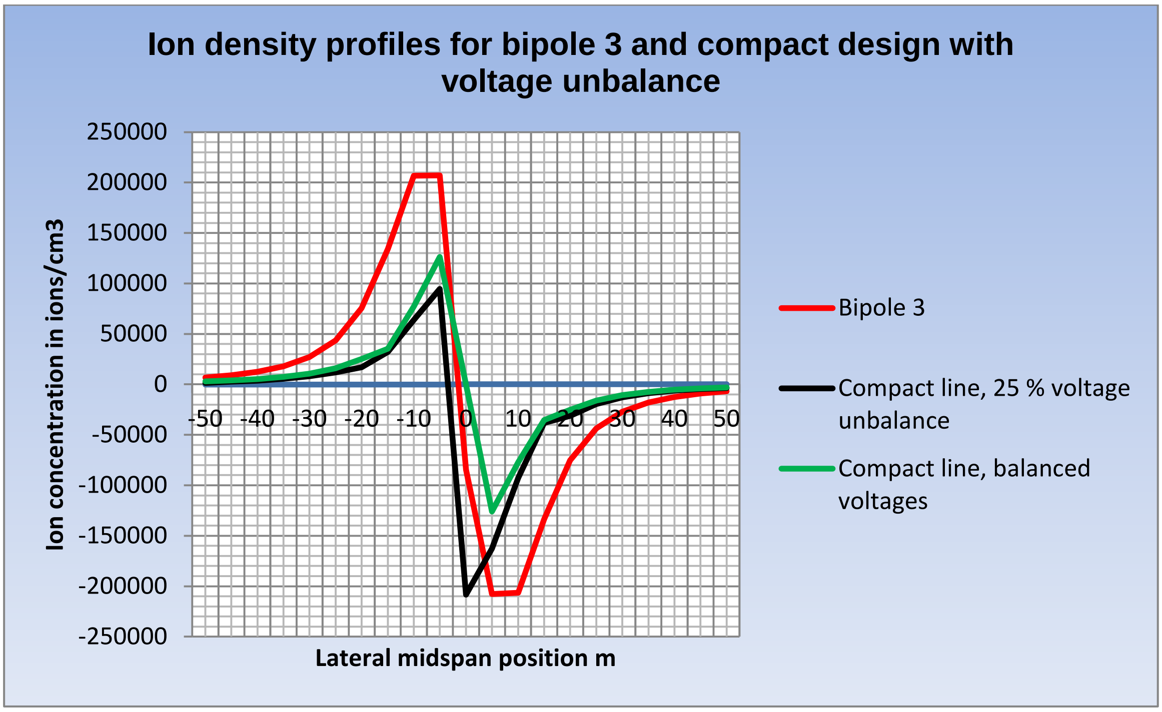


Figure 13 Ion concentrations for 25% unbalance, for the compact and (balanced) conventional lines

The results contained in Figures 12 and 13 show, or suggest that, the ion concentrations under the positive and negative poles of the compact will be quasi–balanced.

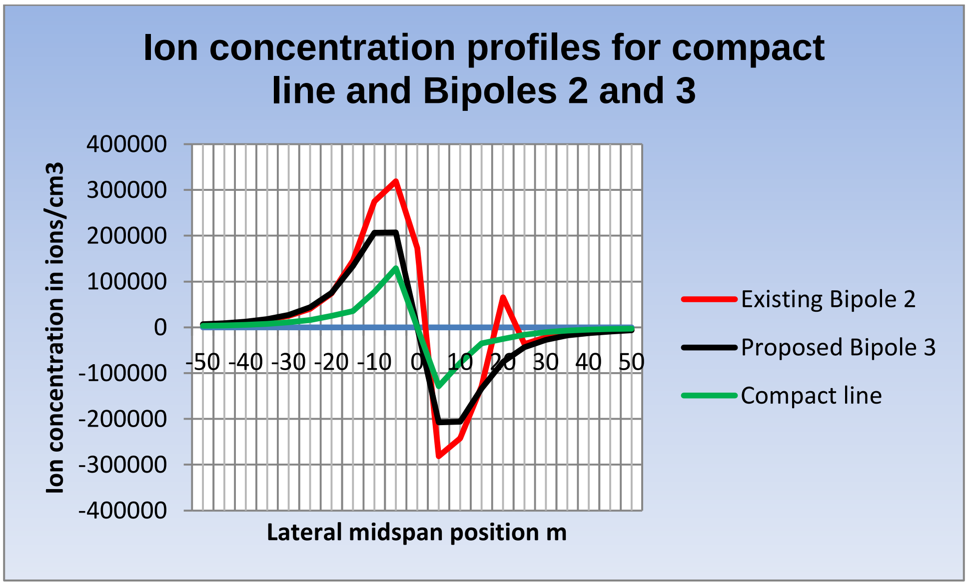


Figure 14: maximum ion concentrations which have a 1% probability of being exceeded in a cold North American climate

It is observed in Figure 13 that the peak ion concentrations near the conventional structure for Bipole 3 are about twice those applicable to the compact designs. Figure 14 shows the profile for the existing Bipole 2 line geometry; it is clear that the peak ion concentrations under these lines, in transverse wind conditions, are substantially higher than the values predicted for Bipole 3. The high ion concentration provides a clue about where to look for factors which could contribute to the high incidence of anomalous line faults.

The author has looked into this aspect and has found that the ratio of the pole-to-pole spacing to the minimum conductor height is unusually high in the case of the original Nelson River lines; this fact combined with the high conductor surface gradient on the these lines, could provide a fruitful and useful direction for further investigation.

As regards the compact design, the author’s assessment at this stage is that such lines will not suffer from anomalous negative polarity flashovers.

4. CONCLUDING REMARKS

What has this preliminary study revealed about the viability of a heavily compacted ±320 kV HVDC line from corona and field effect points of view?

Can such a line be engineered to be compatible with the environment, and yet withstand some elements the environment?

To what extent will the compact design be affected by the yet unexplained factors which cause anomalous flashovers of the Nelson River HVDC lines?

How does the corona performance of the compact line compare with that of conventional HVDC bipolar lines?

These are just a few of the questions which this study has looked into; it is felt that some progress has been made in providing answers to them.

The author contends that the studies have clearly revealed the following findings:

The surface gradients on the pole and shield conductors can be kept economically to values low enough to prevent the generation of excessive space charge.

The author speculates that voltage unbalance may occur, but that its extent is still unknown.

In the event of unbalance occurring, special attention may have to be given to the suppression of abnormal corona; however, this is seen as “doable”, an aspect that, can be engineered “not to be a problem”.

Compared with conventional ±500 kV HVDC lines, the compact design gives better corona performance. This is an encouraging finding, especially in relation to the much lower ion generation by the compact line design.

The lower conductor surface gradients and reduced ion generation suggest that anomalous flashovers on the compact lines should not be a problem.

The radio interference studies done on the compact and conventional designs show that the former design meets acceptable limits of noise.

Overall, the corona and field effect assessments show that the compact design (as given in Figure 1) is viable from a corona and field effects point of view, provided the voltage unbalance can be kept to below 25 %.

5. REFERENCES

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2. DM Larruskain et al, VSC-HVDC configurations for converting AC distribution lines into DC lines. Electrical Power and Energy Systems 54 (2014) pp 589-597.
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4. MMC Merlin et al, A new multi-level VSC converter with DC fault blocking capability. IET International Conference on AC/DC transmission, 2010.
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7. HVDC Transmission Line reference Book, EPRI TR 102764, September, 1993.
8. Transmission line reference book: HVDC to ±600 kV. EPRI Project RP 104, 1977.
9. EPRI AC Transmission line handbook: 200 kV and above, third edition, 2005.
10. Bipole 3 DC EMF Brochure, Manitoba Hydro, October 2009.

6. APPENDICES

APPENDIX A1: Example of the data output sheet generated by the TLW programme

COMPACT STRUCTURES:

Limited example of the printout as it relates to the calculation of the conductor surface gradient in a particular case.

```
 Results of AC/DCLINE program CORONA (EPRI/HVTRC  7-93) for:

---------------------------------------------------------

    SURFACE GRADIENTS at AVERAGE LINE HEIGHT

    CORONA LOSS

    AUDIBLE NOISE


Configuration file name: C:\TLW30\ACDCLINE\DATA\ACCASE1

Date:  3/ 7/2014   Time: 13: 3



 CASE1 compact dc with single conductor


*************************************************************************

*                       BUNDLE  INFORMATION                        *

*************************************************************************

|   |   |  VOLTAGE  |  CURRENT  | # |  BUNDLE COORDINATES  |    |

|BNDL|CIRC|VOLTAGE|ANGLE|  LOAD |ANGLE| OF |    X   |   Y  |  SAG | PH  |

|  # |  # | (kV)  |(DEG)|  (A)  |(DEG)|COND|   (m)  |   (m) |  (m) |     |

*************************************************************************

|  1 |  1 |  320.0|   0.|  1000.|   0.|  1 |   -3.65|  11.70|   .00|  +  | POSITIVE POLE

|  2 |  1 |  320.0|   0.|  1000.|   0.|  1 |   -3.65|   8.00|   .00|  +  | POSITIVE POLE

|  3 |  1 | -320.0|   0.|  1000.|   0.|  1 |    3.65|  11.70|   .00|  -    NEGATIVE POLE

|  4 |  1 | -320.0|   0.|  1000.|   0.|  1 |    3.65|   8.00|   .00|  -    NEGATIVE POLE |

|  5 |  1 |    .     0|   0.|     0.|   0.|  1 |   -3.65|   4.70|   .00| GND | SHIELD CONDUCTOR

|  6 |  1 |         .0|   0.|     0.|   0.|  1 |    3.65|   4.70|   .00| GND | SHIELD CONDUCTOR

*************************************************************************

 *            MINIMUM GROUND CLEARANCE = 4.70  meter              *

 *            SOIL RESISTIVITY                    = 100 ohm meter         *

*             ALTITUDE  ABOVE SEA LEVEL       = 0 meter
```

```
*************************************************************************


****************************************************************************
*            SUBCONDUCTOR INFORMATION - REGULAR BUNDLES            *
****************************************************************************
|BNDL |  CONDUCTOR | DIAMETER | SPACING | DC RESIST | AC RESIST |  AC REACT |
|  #  |    NAME    |   (cm)   |   (cm)  | (ohm/km)  | (ohm/km)  | (ohm/km)  |
****************************************************************************
|  1  |unnamed     |    4.440 |    .000
   2  |unnamed     |    4.440 |    .000 |
   3  |unnamed     |    4.440 |    .000 |
|  4  |unnamed     |    4.440 |    .000 |
|  5  |unnamed     |    1.500 |    .000 |
|  6  |unnamed     |    1.500 |   . 000 |
****************************************************************************
     Results of AC/DCLINE program CORONA (EPRI/HVTRC  7-93) for:
    ------------------------------------------------------------
         SURFACE GRADIENTS at AVERAGE LINE HEIGHT
         CORONA LOSS
         AUDIBLE NOISE

    Configuration file name: C:\TLW30\ACDCLINE\DATA\ACCASE1
    Date:  3/ 7/2014   Time: 13: 3



 CASE1 compact dc with single conductor

*************************************************************************
*                    BUNDLE  INFORMATION                    *
*************************************************************************
|    |    |  VOLTAGE   |  CURRENT   | #  |  BUNDLE COORDINATES  |     |
|BNDL|CIRC|VOLTAGE|ANGLE|  LOAD |ANGLE| OF |    X   |   Y   |  SAG | PH  |
|  # |  # | (kV)  |(DEG)|  (A)  |(DEG)|COND|   (m)  |   (m) |  (m) |     |
*************************************************************************
```

```
|  1 |  1 |  320.0|   0.|  1000.|   0.|  1 |   -3.65|  11.70|   .00|  +  |
|  2 |  1 |  320.0|   0.|  1000.|   0.|  1 |   -3.65|   8.00|   .00|  +  |
|  3 |  1 | -320.0|   0.|  1000.|   0.|  1 |    3.65|  11.70|   .00|  -  |
|  4 |  1 | -320.0|   0.|  1000.|   0.|  1 |    3.65|   8.00|   .00|  -  |
|  5 |  1 |     .0|   0.|     0.|   0.|  1 |   -3.65|   4.70|   .00| GND |
|  6 |  1 |     .0|   0.|     0.|   0.|  1 |    3.65|   4.70|   .00| GND |
*************************************************************************
*          MINIMUM GROUND CLEARANCE =     4.70  meter          *
*          POWER SYSTEM FREQUENCY   =    60.    Hz             *
*          SOIL RESISTIVITY         =   100.    ohm meter      *
*************************************************************************


****************************************************************************
*           SUBCONDUCTOR INFORMATION - REGULAR BUNDLES            *
****************************************************************************
|BNDL | CONDUCTOR | DIAMETER | SPACING | DC RESIST | AC RESIST |  AC REACT |
|  #  |    NAME   |   (cm)   |   (cm)  | (ohm/km)  | (ohm/km)  | (ohm/km)  |
****************************************************************************
|  1  |DRAKE      |    4.440 |    .000 |     .0720 |     .0730 |     .2480 |
|  2  |DRAKE      |    4.440 |    .000 |     .0720 |     .0730 |     .2480 |
|  3  |DRAKE      |    4.440 |    .000 |     .0720 |     .0730 |     .2480 |
|  4  |DRAKE      |    4.440 |    .000 |     .0720 |     .0730 |     .2480 |
|  5  |DRAKE      |    1.500 |    .000 |     .0720 |     .0730 |     .2480 |
|  6  |DRAKE      |    1.500 |    .000 |     .0720 |     .0730 |     .2480 |
****************************************************************************
```

```
 *                              *
        * MAXIMUM SURFACE GRADIENT (kV/cm) *
        *                              *
        ************************************

BNDL  Type       DC     PEAK(+)  PEAK(-)
  ------ ---------  ------   -------  -------
     1      DC       22.34    22.34    22.34
     2      DC       22.88    22.88    22.88
     3      DC      -22.34   -22.34   -22.34
     4      DC      -22.88   -22.88   -22.88
     5 Ground Wire  -10.35   -10.35   -10.35
     6 Ground Wire   10.35    10.35    10.35
```

APPENDIX A2: RAW DATA FOR THE COMPACT LINE STUDIES

Diameter of the shield conductor (Case 1: 1x4.44 cm pole conductor bundle)

Diameter of SHIELD WIRE (cm)	Conductor surface gradient on SHIELD WIRE kV/cm, E5	Conductor surface gradient on SHIELD WIRE kV/cm, E6	Conductor surface gradient on Pos POLE kV/cm	Conductor surface gradient on Neg POLE, kV/cm
0.50	-26.58	+26.58	+22.32	-22.32
0.75	-18.71	+18.71	+22.33	-22.33
1.00	-14.62	+14.62	+22.33	-22.33
1.25	-12.08	+12.08	+22.33	-22.33
1.50	-10.25	+10.25	+22.34	-22.34
1.75	-9.08	+9.08	+22.34	-22.34
2.00	-8.12	+8.12	+22.34	-22.34
2.25	-7.35	+7.35	+22.35	-22.35
2.50	-6.75	+6.75	+22.35	-22.35

CASE 2: 2x3.038 cm

Diameter of SHIELD WIRE (cm)	Conductor surface gradient on SHIELD WIRE kV/cm	Conductor surface gradient on SHIELD WIRE kV/cm	Conductor surface gradient on Pos POLE kV/cm	Conductor surface gradient on Neg POLE, kV/cm
0.50	-31.34	+31.34	+21.56	-21.56
0.75	-22.07	+22.07	+21.57	-21.57
1.00	-17.24	+17.24	+21.57	-21.57
1.25	-15.34	+15.34	+22.33	-22.33
1.50	-12.90	+12.90	+22.21	-22.21
1.75	-11.11	+11.11	+22.34	-22.34
2.00	-10.13	+10.13	+22.34	-22.34
2.25	-9.18	+9.18	+22.35	-22.35
2.50	-8.41	+8.41	+22.35	-22.35

AUDIBLE NOISE

Audible noise case 1: 1x4.43 cm; lateral profile at midspan

Lateral Distance m	L50 FAIR dBA	L5 RAIN dBA	L50 RAIN dBA	Leq (24) dBA	Ldn dBA
-50	38.9	32.9	32.9	38.9	45.2
-45	39.5	33.5	33.5	39.5	45.7
-40	40.1	34.1	34.1	40.1	46.4
-35	40.9	34.8	34.8	40.8	47.1
-30	41.7	35.6	35.6	41.6	47.9
-25	42.6	36.5	36.5	42.5	48.8
-20	43.6	37.6	37.6	43.6	49.9
-15	44.9	38.9	38.9	44.9	51.2
-10	46.4	40.2	40.2	46.2	52.7
-5	47.7	41.7	41.7	47.7	53.9
0	47.2	41.2	41.2	47.2	53.5
5	45,7	39.7	39.7	45.7	52.0
10	44.3	38.3	38.3	44.3	50.5
15	43.1	37.1	37.1	43.1	49.4
20	42.5	36.1	36.1	42.1	48.4
25	41.3	35.2	35.2	41.2	47.5
30	40.5	34.5	34.5	0.5	46.7
35	39.8	33.8	33.8	39.8	46.1
40	39.2	33.2	33.2	39.2	45.5
45	38.7	32.7	32.7	38.7	44.9
50	38.2	32.2	32.2	38.1	44.4

Audible noise case 2: 2x3.04 cm; lateral profile at midspan

Lateral Distance m	L50 FAIR dBA	L5 RAIN dBA	L50 RAIN dBA	Leq (24) dBA	Ldn dBA
-50	34.3	28.3	28.3	34.2	40.5

-45	34.8	28.8	28.8	34.8	41.1
-40	35.5	29.5	29.5	35.4	41.7
-35	36.2	30.2	30.2	36.1	42.4
-30	37.0	31.0	31.0	36.9	43.2
-25	37.9	31.9	31.9	37.9	44.1
-20	39.0	33.0	33.0	38.9	45.2
-15	40.3	34.3	34.3	40.2	46.5
-10	41.8	35.8	35.8	41.8	48.0
-5	43.1	37.1	37.1	43.0	49.3
0	42.6	36.6	36.6	42.6	48.8
5	41.1	35.1	35.1	41.0	47.3
10	39.7	33.7	33.7	39.6	45.9
15	38.5	32.5	32.5	38.4	44.7
20	37.5	31.5	31.5	37.4	43.7
25	36.6	30.6	30.6	36.6	42.8
30	35.8	29.8	29.8	35.8	42.1
35	35.2	29.2	29.2	35.1	41.4
40	34.7	28.6	28.6	34.5	40.8
45	34.0	28.0	28.0	34.0	40.2
50	33.5	27.5	27.5	33.5	39.7

Nelson River bipole 3: audible noise

Lateral Distance m	L50 FAIR dBA	L5 RAIN dBA	L50 RAIN dBA	Leq (24) dBA	Ldn dBA
-50	34.4	28.4	28.4	34.3	40.6
-45	35.0	29.0	29.0	35.0	41.2
-40	35.7	29.7	29.7	35.6	41.9
-35	36.4	30.4	30.4	36.4	42.7
-30	37.3	31.3	31.3	37.3	43.5
-25	38.3	32.3	32.3	38.3	44.5
-20	39.5	33.5	33.5	39.5	45.7
-15	40.8	34.8	34.8	40.7	47.0

-10	41.8	35.7	35.7	41.8	48.0
-5	41.7	35.7	35.7	41.7	47.9
0	0	34.6	34.6	46.9	46.9
5	39.4	33.4	33.4	39.3	45.6
10	38.2	32.2	32.2	38.2	44.4
15	37.2	31.2	31.2	37.2	43.4
20	36.4	30.4	30.4	36.3	42.6
25	35.6	29.6	29.6	35.6	41.8
30	34.9	28.9	28.9	34.9	41.1
35	34.3	28.3	28.3	34.8	40.5
40	33.8	27.8	27.8	33.7	40.0
45	33.2	27.2	27.2	33.2	39.5
50	32.8	26.8	26.8	32.7	39.0

ELELCTRIC FIELD STUDIES

1x4.44 cm conductor, balanced voltage

Lateral Distance m	**DC ELECTROSTATIC FIELD Em kV/m**	**MAXIMUM FAIR WEATHER FIELD WITH SPACE CHARGE kV/m**	**ELECTRIC FIELD L50 IN RAIN kV/m**	**Ion current density nA/m2**	**Ion density Ions/cm^3**
/-50	0.21	2.32	1.5	0.1	2984
-45	0.28	2.78	1.8	0.2	3947
-40	0.39	3.37	2.2	0.3	5335
-35	0.55	4.17	2.8	0.6	7436
-30	0.84	5.23	3.6	1.0	10676
-25	1.33	6.80	4.7	2.0	16122
-20	2.23	9.04	6.5	4.2	25270
-15	3.93	12.49	9.3	8.1	35135
-10	6.68	20.13	15.0	28.7	77585
-5	7.08	21.93	16.3	52.0	128802
0	0	0.03	0	0	0
5	-7.08	-21.93	-16.3	-67	-128802

10	-6.68	-20.13	-15.0	-37.5	-77585
15	-3.93	-12.49	-9.3	-10.5	-35136
20	-2.23	-9.04	-6.5	-5.5	-25270
25	-1.33	-6.80	-4.7	-2.6	-16122
30	-0.84	-5.23	-3.6	-1.3	-10676
35	-0.55	-4.17	-2.8	-0.7	-7436
40	-0.39	-3.37	-2.2	-0.4	-5335
45	**-0.28**	**-2.78**	**-1.8**	**-0.3**	**-3947**
50	**-0.21**	**-2.32**	**-1.5**	**-0.2**	**-2984**

2x3.04 cm conductor

Lateral Distance m	DC ELECTROSTATIC FIELD Em kV/m	MAXIMUM FAIR WEATHER FIELD WITH SPACE CHARGE kV/m	ELECTRIC FIELD L50 IN RAIN kV/m	Ion current Density nA/m2	Ion density Ions/cm^3
-50	0.26	2.32	1.5	0.1	2984
-45	0.34	2.78	1.8	0.2	3947
-40	0.48	2.37	2.2	0.3	5335
-35	0.69	4.17	2.8	0.6	7436
-30	1.04	5.23	3.6	1.0	10676
-25	1.65	6.80	4.8	2.0	16122
-20	2.77	9.03	6.6	4.2	25270
-15	4.88	12.50	9.5	8.1	34941
-10	8.29	20.1	15.5	28.4	76753
-5	8.71	21.41	16.5	49.7	125035
0	0.0	-0.03	0	0	0
5	-8.71	-21.41	-16.5	-64	-125035
10	-8.29	-20.01	-15.5	-37	-76753
15	-4.88	-12.5	-9.5	-10	-34941
20	-2.77	-9.03	-6.6	-5.5	-25270
25	-1.65	-6.80	-4.8	-2.6	-16122
30	-1.04	-5.23	-3.6	-1.3	-10676

35	-0.69	-4.17	-2.8	-0.7	-7436
40	-0.48	-3.37	-2.2	-0.4	-5335
45	-0.34	-2.78	-1.8	-0.3	**-3947**
50	-0.26	-2.32	-1.5	-0.2	**--2984**

Bipole 3: Electric field and ion concentrations for a bipolar voltage of ±500 kV

Lateral Distance m	DC ELECTRO STATIC FIELD Em kV/m	MAXIMUM FAIR WEATHER FIELD WITH SPACE CHARGE kV/m	ELECTRIC FIELD L50 IN RAIN kV/m	Ion current density nA/m^2	Ion density Ions/cm^3
-50	0.57	6.73	4.2	0.8	6781
-45	0.77	8.06	5.1	1.3	9004
-40	1.08	9.98	6.4	2.3	12522
-35	1.57	12.53	8.1	4.2	17932
-30	2.38	16.31	10.7	8.2	27121
-25	3.81	21.95	14.6	17.7	43526
-20	6.39	30.92	21.0	43.1	75296
-15	10.63	43.65	30.3	107.9	133608
-10	14.6	54.93	38.6	209.1	206335
-5	11.07	46.37	32.1	176.7	207481
0	0.00	0.05	0.00	-1.2	-12
5	-11.14	-46.37	-32.2	-232.1	-207481
10	-14.56	-54.87	-38.6	-272	-206335
15	-10.52	-43.32	-30.3	-139	-133608
20	-4.82	-23.76	-21.0	-55.8	-75296
25	-3.73	-21.44	-14.6	-22.9	-43526
30	-2.36	-16.14	-10.7	-10.6	-27121
35	-1.55	-12.46	-8.1	-5.4	-17932
40	-1.07	-9.93	-6.4	-3.0	-12522
45	-0.76	-8.03	-5.1	-1.7	-9004
50	-0.57	-6.71	-4.2	-1.1	-6781

VOLTAGE UNBALANCE

Influence of the common mode voltage unbalance on the conductor surface gradients, ground level electric field and audible noise (1x4.44 cm conductor)

VOLTAGE UNBALANCE ±%	POLE VOLTAGES kV	ES1,2 kV/cm	EP kV/cm	EMAX kV/m	Ldn dBA @ 30 m (ROW)
0 (NORMAL)	+320	-10.4	+22.3	21.9	46.7
	-320	+10.3	+22.9		47.9
5	+336	-9.4	-23.1	-25.6	44.9
	-304	+11.3	-24.3		46.0
	+304	+9.4	+23.1	+23.7	48.5
	-336	-11.3	+24.3		49.7
6	+339	-11.5	+23.9	+24.1	48.8
	-301	+9.2	-21.9		50.0
	+301	-9.2	-23.9	-4.1	45.7
	-339	+11.5	+21.9		44.6
8	+347	+8.7	+24.3	-25.0	49.7
	-294	-12.0	-21.6		50.9
	+294	-8.7	-21.6	25.0	43.8
	-347	+12.0	-24.3		44.9
10	+352	-8.4	+24.27	-25.4	44.2
	+288	+12.3	21.57		
	+352	+8.4	+23.7	+25.6	51.4
	-288	-12.3	+24.5		
15	+368	+7.3	+25.3	+27.8	53.0
	-272	-13.3	-20.4		51.9
	+272	-7.4	+20.3	-27.8	42.2
	-368	+13.3	-25.3		41.1
20	+384	-14.30	+26.2	+29.7	53.5
	-256	+6.37	-19.6		54.7
	+256	-6.37	+19.6	-29.7	39.0
	-384	+14.32	-26.2		40.2

25	+400	-15.3	+27.0		55.1
	-240	+5.4	-18.9	+31.6	56.2
	+240	-5.4	+18.9		37.1
	-400	+15.3	-27.0	-31.6	38.1

Influence of the common mode voltage unbalance on the conductor surface gradients, ground level electric field and audible noise (2x3.04 cm conductors)

VOLTAGE UNBALANCE ±%	POLE VOLTAGES kV	ES1,2 kV/cm	EP kV/cm	EMAX kV/m	Ldn dBA @ 30 m (ROW)
0 (NORMAL)	+320	-10.4	+22.3	21.9	46.7
	-320	+10.3	+22.9		47.9
5	+336	-9.4	-23.1	-25.6	44.9
	-304	+11.3	-24.3		46.0
	+304	+9.4	+23.1	+23.7	48.5
	-336	-11.3	+24.3		49.7
6	+339	-11.5	+23.9	+24.1	48.8
	-301	+9.2	-21.9		50.0
	+301	-9.2	-23.9	-24.1	45.7
	-339	+11.5	+21.9		44.6
8	+347	+8.7	+24.3	-25.0	49.7
	-294	-12.0	-21.6		50.9
	+294	-8.7	-21.6	25.0	43.8
	-347	+12.0	-24.3		44.9
10	+352	-8.4	+24.2	-25.4	44.2
	+288	+12.3	+21.5		
	+352	+8.4	+23.7	+25.6	51.4
	-288	-12.3	+24.5		
15	+368	+7.3	+25.3	+27.8	53.0
	-272	-13.3	-20.4		51.9
	+272	-7.4	+20.3	-27.8	42.2

	-368	+13.3	-25.3		41.1
20	+384	-14.30	+26.2	+29.7	53.5
	-256	+6.37	-19.6		54.7
	+256	-6.37	+19.6	-29.7	39.0
	-384	+14.32	-26.2		40.2
25	+400	-15.3	+27.0		55.1
	-240	+5.4	-18.9	+31.6	56.2
	+240	-5.4	+18.9		37.1
	-400	+15.3	-27.0	-31.6	38.1