NEW 735 kV SEMI-URBAN LINE WITH HIGH MECHANICAL RELIABILITY

by

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SUMMARY

This article presents the design of the new 735 kV high mechanical reliability line Hertel/Point Saint-Césaire. The supports are the strongest ever used in the province of Québec, apart from the large river crossing towers.

The line has been optimized for conditions found in outlying areas and in agricultural zones. The emphasis has been placed on the innovative or original aspects of the design, notably in the choice of geometry, conductor optimization, special testing for prediction of plastic elongation, tower-foundation interaction, live maintenance and reduction of radio interference. The design also bears innovations in the field of foundations and construction methods.

KEYWORDS


1. INTRODUCTION

An exceptional icestorm in 1998 had damaged or destroyed more than 2000 wooden portals and some 620 steel towers, from 49 kV to 735 kV, in the Montreal region. Several recent articles, among which [1, 2, 3, 4] give an account of this storm. Despite the exceptional character of this event, the standard requirements for line design have been upgraded and new high-reliability strategic links have been added, amongst which the 735 kV Hertel/Montérégie/Des-Cantons line, in order to improve the reliability of the network. This line was carried out in two stages, with two different families of towers.

2. FIRST SECTION: DES-CANTONS / MONTÉRÉGIE/ POINT ST-CÉSAIRE

In 1998, immediately after the icestorm, Hydro Québec constructed the first section of the 735 kV line, from the Des Cantons substation up to a point situated near the village of St-Césaire (Point St-Césaire) in order to secure the Montreal South Shore, severely affected by the storm. This first section runs across a generally wooded area located far from urban centers. It touches two climatic zones characterized by maximum predicted radial icing thickness of 45 and 55 mm. The design used for this
section was one of the standard designs for 735 kV lines, with classic four-leg lattice towers and standard ACSR Bersfort conductors. These components were originally optimized for zones of 45 mm of icing. An new suspension tower was designed and the average span reduced in order to adapt the line to icing loads found in the 55 mm zone. The strategy chosen for the design of this section was made the object of a technical article in 2000 [1].

3. SECOND SECTION: POINT ST-CÉSAIRE / HERTEL

Although the standard family of towers quite adequately suited the climatic and environmental conditions within the first section, it was not optimal for the second section between Point-St-Césaire and the Hertel substation.

This 44 km section runs through an outlying area in which cultivated land, highways and villages are found. In addition, the major part of this territory is situated in a severe 65 mm climatic zone. Standard towers with large square bases are poorly suited to agricultural zones because of the considerable amount of soil area they take up. Moreover, the standard Bersfort conductor was not optimized to sustain such high loads. Its use would have led to very short spans and high structures, creating an undesirable visual impact from roads and residences. A new solution had therefore to be studied.

The solution decided upon was a single-circuit line on lattice portals with some tubular portals inserted in sensitive zones. The conductors are in bundles of four. A new special aluminium-alloy reinforced conductor (AACSR) of the same diameter as the Bersfort has been designed. The justifications for these choices are given in the paragraphs which follow.

4. CLIMATIC LOADS AND SECURITY REQUIREMENTS

This line is classified as ‘strategic’ for the utility company and must therefore offer very high reliability. It was designed to withstand climatic loads for which the return period is at least 150 years, in a zone particularly exposed to icing, which may reach 65 mm in radial thickness. It conforms to all requirements of IEC 60826 specification [5], including unequal accretion of ice on adjacent spans, as well as scenarios of broken phases with bare or loaded cables depending upon the type of tower. Table 1 gives the details on climatic loadings.

Finally, all major road crossings are protected by anti-cascading strain towers resisting broken phases under maximum ice accretion. This line counts among the most resistant ever constructed in the province of Quebec.

5. GEOMETRY

The geometry selected for this line ensues from a comparative detailed study of five families of towers with different geometries (See Figure 1). The technical, economic, esthetic and environmental aspects have been evaluated for each one. The choice finally came down to a portal-type geometry (Family 2 in the figure).

This geometry minimizes the tower height, improves the line’s general visual aspect and reduces land encroachment. This latter aspect was a determining factor in the acceptance of the project. The portal reduces wasted cultivable space by 20 to 40% with respect to the four-legged standard tower. These

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gains in agricultural area take into account the effective distances necessary to skirt around the towers as well as the towers’ orientation relative to the direction of land cultivation. Finally, portal geometry lends itself well to the combined use of tubular and lattice structures. To minimize costs, tubular towers are used only in zones where the visual environment is the determining factor. Lattice towers, less costly, are used everywhere else, notably on agricultural land. The transition between the two designs remains visually harmonious.

<table>
<thead>
<tr>
<th>FAMILY 1</th>
<th>FAMILY 2</th>
<th>FAMILY 3</th>
<th>FAMILY 4</th>
<th>FAMILY 5</th>
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<tbody>
<tr>
<td>TOWER</td>
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</tbody>
</table>

Figure 1: Comparative Study of Geometries

6. CONDUCTORS AND GROUND WIRES

Optimisation and Selection

As has been mentioned previously, the standard conductor presented an insufficient mechanical capacity (UTS) to be optimal. The relaxation in tension required to sustain the loads leads to excessive sags. Although several replacement solutions have been put forward, certain important restrictions have limited the acceptable alternatives, notably:

- keeping the same diameter of conductor in order to use standard accessories;
- limiting the increase of DC resistance to 10%
- limiting conductor tension under maximum ice to 200 kN, in order to use 300 kN insulators.

The conductor finally decided upon, called BerA4, is of the same diameter as the standard Bersfort conductor, but reinforced by using aluminium alloy A4 (57.5% IACS, 250 MPa) rather than standard aluminum A1 (61% IACS, 170 MPa). Table II shows the comparative characteristics of the two conductors:

- The alloy substitution increases the DC resistance of the new conductor by only 6%, while increasing UTS by 39%.
- Sag is reduced by 8.7 m for the average span which permits a corresponding diminution in tower height.

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The longitudinal load on the suspension arising from the unequal ice accretion is reduced by 25% with the new conductor, while the maximum tension of the conductor under maximum icing conditions is increased by 39%.

The combined effect of these variations of forces at the attachment points and the diminution in height of the towers affect the overturning moments in the following way:

- tangent suspensions: a 20% reduction in transverse moments and a 40% reduction in longitudinal moments;
- angle suspensions: a 2% increase in transverse moments and a 40% reduction in longitudinal moments;
- anchor angles: a 10% decrease in both directions

Overall, the new conductor lowers the height of the towers, which is beneficial to the visual aspect of the line and reduces the cost of towers and foundations.

### Table II: Conductor Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Standard Conductor</th>
<th>New Conductor</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>Bersfort</td>
<td>Ber-A4</td>
<td>-6%</td>
</tr>
<tr>
<td>Equiv A1 Area</td>
<td>mm²</td>
<td>686</td>
<td>647</td>
</tr>
<tr>
<td>Components Stranding</td>
<td>A1/S1A</td>
<td>A4/S1A</td>
<td></td>
</tr>
<tr>
<td>O. Diameter</td>
<td>mm</td>
<td>35.6</td>
<td>35.6</td>
</tr>
<tr>
<td>Envelope Area</td>
<td>mm²</td>
<td>686.5</td>
<td>686.5</td>
</tr>
<tr>
<td>Envelope Material</td>
<td>A1</td>
<td>A4</td>
<td>--</td>
</tr>
<tr>
<td>Steel Area</td>
<td>mm²</td>
<td>60.6</td>
<td>60.6</td>
</tr>
<tr>
<td>UTS*</td>
<td>kN</td>
<td>180.1</td>
<td>249.8</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>Ω/km</td>
<td>0.0422</td>
<td>0.0448</td>
</tr>
</tbody>
</table>

**380 m span with 65 mm of ice (1 conductor)**

- Sag: m 29.2 20.5 -30%
- Tension: kN 135.1 187.4 +39%
- IEC ice shedding (70% / 28% gₑ): kN 23.8 17.8 -25%

*Note: UTS= Ultimate Tensile Strength*

The 23 mm diameter optical ground-wire (OPGW) and the 16 mm standard steel ground-wire were chosen in order to withstand a 70 mm thick ice load. These robust cables are sagged in order to match the conductor sag under daily conditions, allowing a minimum vertical distance of 3.5 m between the bare conductors and the ground wires loaded with 70% of the maximum ice load.

**Additional Plastic Elongation**

Even if very few of the lines had to be resagged after the 1998 icestorm despite a systematic verification in the field, the storm demonstrated that important accretions of ice could persist for several days on the cables and could cover many spans. If the storm is a large one and the accumulation approaches the maximum design conditions, the conductors are tautened for several consecutive days at values that could easily exceed 50% of their ultimate resistance (UTS). The plastic elongation can therefore exceed the predicted values and diminish the ground clearances.

This type of medium-term creep elongation under such large traction is not normally evaluated. Typically, the plastic elongation is deduced from two calculated values: the short-term plastic elongation, read on the 1-hour curve for the traction under maximum icing, and the long-term creep elongation, read on the 10 year creep curve for the traction under bare conditions. In heavy icing zones, it is generally the first value which is the determining one. This approach therefore boils down to considering that the maximum accumulation is of short duration (near 1 hour) and limited to a restricted number of spans.

The chosen A4 alloy (6101-T83) for the ACSR conductor is already less sensitive to plastic elongation than the A1 aluminum (1351-H19) of the original ACSR conductor. It should therefore offer a better performance on this aspect. In order to validate this assumption, special medium-term creep tests have been carried out on 3 samples of the new ACSR cable. An additional goal was to evaluate whether the already available creep curves at low traction could be used to predict the medium-term elongation under strong traction.

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Cable samples underwent the normal stages of loading for the standard stress-strain test, then were kept for 200 hours at 70% UTS with continuous recording of displacements. The results of these tests are summarized below:

- The additional plastic elongation due to the steady load of 70% UTS for 4 days (100 hours), is in the order of 0.06%, causing a permanent increase in sag of 0.8 m in the average bare span.

- Graphed logarithmically, the displacements as a function of time present a slope quite comparable to the slopes obtained from classic creep tests carried out on lesser tractions, in the order of 35% UTS. The standard curves already available may therefore be used to estimate the elongation, assuming certain theoretical hypotheses. It will take, however, several other tests on different cables before coming to a general conclusion.

Finally, the ground clearances were not increased for this project, given that a safety margin in the order of 1.2 m had already been included in the current norms, and that the value of 0.8 m is very conservative. However, controls were tightened during the sagging operations and the most critical spans were verified to ensure that this additional clearance was systematically kept.

7. HARDWARE

The dead-end insulator assemblies are composed of four strings of 300 kN insulators per phase, while the tangent tower suspension assemblies have double strings. All the assemblies were designed for live line maintenance. In order to allow the replacement of one or two insulators, at any time, the lines each include 2 or even 3 additional insulators to ensure sufficient safety during normal maintenance work. Electrical tests in a high-voltage laboratory were carried out to validate these criteria.

In addition, radio interference trials permitted to validate the shape of the accessories and confirmed the need to install arcing rings to limit the maximum admissible level. Radio interference values were measured with respect to two specifications:
- NEMA 107-1987 (1500 µV under 465 kV and a frequency of 1.0 MHz)
- and IEC 694 (2500 µV under 465 kV and a frequency of 0.5 MHz).

The tests demonstrated that the NEMA specification is stricter than the IEC. Nevertheless, the two criteria have been respected for this line built in outlying areas.

8. TOWERS

The lattice portal family, named FV, is limited to three types of towers: a suspension alignment (FVA), a 0°- 20° suspension angle (FVG), and a strain angle 0°- 55° also used as an anti-cascading tower (FVJ). This family is completed by a tubular alignment. The alignments are presented in Figure 2.

The line includes, in total, 121 towers, 88 of which are alignment towers, 7 suspension angles, 22 strain angles and 4 tubular towers. The average design span of 380 m results principally from practical constraints related to tower spotting. The utilization limits were determined as a function of real project characteristics in order to optimize costs.

Towers are extremely robust and heavy, their average mass varying from 40T for alignment types to nearly 100T for anchor types. These are the most robust line structures ever used in Quebec and the strongest to have been tested in North America. The steel angles used for the main members at the base of the masts are L 203 x 22 for the alignment towers. Anchor towers use double LL 250 x 28 angles produced in Belgium, placed one inside the other in order to simplify detailing and soften the visual effect of the lattice base. The tower characteristics are shown in Table III.
A particularity of these structures results from the exceptionally great stiffness of the frames and the possible stress distribution problems resulting from it. The junction between each mast and the beam, which acts like a global rigid connection, causes a stress distribution which is sensitive to the relative movements and differential rigidity of the masts. The complete structure-foundation interaction was therefore investigated in order to evaluate the influence of these differential movements and the unequal heights of the masts on the internal stresses in the structure.

![Suspension towers – lattice and tubular](image)

First, the foundations were completely modelized, including the soil and the metallic grillage. Then the foundations were replaced by equivalent elastic supports of variable stiffness, more rigid in compression than in tension. These studies permitted to quantify the typical load increases in the members, which in fact varied between 5 and 10%. Appropriate overload factors were subsequently applied on members according to their function (main, transverse and longitudinal diagonals) and the loading cases to get the final dimensioning.

![Figure 2 – Suspension towers – lattice and tubular](image)

<table>
<thead>
<tr>
<th>Tower</th>
<th>Function</th>
<th>Cond height (m)</th>
<th>Max WNSP (m)</th>
<th>Max WGSP (m)</th>
<th>Mass (T)</th>
<th>Max corner angle</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVA</td>
<td>0° to 1,5°, long span 0°</td>
<td>28 to 36</td>
<td>400</td>
<td>420</td>
<td>35 to 42</td>
<td>L 203 X 22</td>
<td>Max Weight-spans Max Wind-spans and Max height vary with angle</td>
</tr>
<tr>
<td>FVG</td>
<td>Susp. angle 0° to 20°</td>
<td>28 to 36</td>
<td>380</td>
<td>390</td>
<td>54 to 64</td>
<td>L 250 x 26</td>
<td></td>
</tr>
<tr>
<td>FVJ</td>
<td>Strain angle 0° to 55°</td>
<td>28 to 36</td>
<td>400</td>
<td>420</td>
<td>85 to 106</td>
<td>LL 250 x 28</td>
<td></td>
</tr>
</tbody>
</table>

Note: WNSP = wind-span  WGSP = weight-span

The two suspension towers were tested with loads exceeding their design limits, without failing. The anchor tower was tested up to its limits, in order to be able to reuse the tower for the project. Given the overload and resistance factors applied on the members, an approximate reserve of 20% was confirmed for the suspension towers.

9. FOUNDATIONS

Two categories of soil are generally found along the line. The first is made up of a thin layer of silty clay, 0.3 to 2.0 m deep, over medium to dense till. This type of soil is encountered at about 60% of the sites. The second typical configuration consists of thick silty clay. The depth of the bedrock is less than 3 m in the first quarter of the line, then reaches almost 20 m over the rest of the line with several
short passages at less than 4 m. The average depth is around 10 m. The quality of the rock varies from poor to average in the first three meters, to become good to excellent afterwards.

The common practice for portal foundations through overburden is to use a single large caisson topped with a concrete head where the structure stubs are anchored. These foundations perform very well but are very costly. Therefore, a special effort has been carried out to adapt more closely the foundation concept to the types of soil, to optimize costs, and especially reduce construction delays. Consequently, the following types of foundations have been the object of an in-depth techno-economic study: standard large caissons of great diameter with or without excavation, individual pipe piles anchored to rock for each leg, concrete and metallic rock foundations, shallow separate grillages foundations in overburden, metallic grillages joining the two masts, single grillage per mast (2 per tower), double grillages per mast (4 per tower).

For earth foundations, structural analyses have demonstrated that deformations become excessive with the single large grillage. Moreover, the adjustment of the longitudinal spacing between the foundation stubs on a single grillage was complicated to provide with universal pieces, in order to fit the tapered mast for different heights. Finally, the double grillages per mast showed themselves to be the best performing and easiest to install.

Figures 3 and 4 show these double grillages for a suspension tower. Their dimensions of 3.0 m x 9.5 m to 3.9 m in depth are controlled by uplift. The design criteria have been chosen conservative enough to limit vertical displacements and ensure good verticality in the poles in the longitudinal axis of the line. Such a solution had never been used before.

In zones of soft deep clay, the large diameter caisson with concrete head has been retained. It can be installed rapidly without being emptied. In medium-depth clay deposits over bedrock, the foundation made of 4 pipe piles of small diameter (per mast) has been retained. These piles are anchored in the rock and resist all the bending stresses, shear, tension and compression. The design of the caissons and pipe piles was carried out based upon the in-site results of pressiometric tests.

In summary, there are four types of foundations in the project: earth grillages, concrete foundations anchored to the rock, standard large caissons with concrete heads and independent pipe piles for each vertical leg of the masts.

10. CONCLUSIONS

The Hertel/Point St-Césaire section was completed at the end of 2003, slightly in advance of the original deadline. The tower geometry was generally well-received by the public although construction beside a major highway was made the object of several criticisms. As for integration into the rural milieu, it has been a success.
The designers felt some anxiety about the construction of the line, notably as concerned the adjustment of the rigid structures on their foundations. The contractors demonstrated their ingenuity in positioning the foundations by means of very rigid jigs and by adopting an appropriate sequence for the erection of the structures.

This line with a high mechanical reliability, well adapted to its environment and designed to facilitate maintenance, now contributes to the reinforcement of the main 735 kV network.

REFERENCES


[5] IEC Publication 826