Determination of Current Required to De-ice Transmission Line Conductors

Pascal Prud'Homme, Marc-Olivier Roux, Hydro-Québec TransÉnergie,
Pierre Guilbault, Paul-Antoine Séguin, Hydro-Québec Research Institute,
Éric Hounkpatin, Hydro-Québec Équipement
2 Complexe Desjardins, 10th floor East tower, Montréal, Québec, H5B 1H7, Prudhomme.pascal@hydro.qc.ca

Abstract— **Hydro-Québec TransÉnergie conducted laboratory tests at Hydro-Québec Research Institute (IREQ) Mechanical Laboratory to determine the current magnitude required to de-ice different transmission line conductors. Two campaigns were realised to quantify de-icing current required to melt different amount of ice accretion on conductors, ground wires and optical fibre ground wires for different climatic conditions. From those campaigns a mathematical model was developed by IREQ to calculate the required de-icing current for different conductors. This model was included in a numerical tool developed by TransÉnergie. The paper shows results obtained with this program for typical case studies. Finally, an outdoor test was performed, at the laboratory substation, on an 80 meters 735-kV 4 conductors bundle span to ensure the efficiency of the method. The interesting results obtain with this last test will also be reported in this paper.**

I. Nomenclature

De-icing current, transmission line conductors, laboratory testing.

II. Introduction

IN 1998, a major ice storm occurred over a five-day period along the St. Lawrence River near Montréal. During this event, the ice accumulation reached a thickness of up to 75 mm at ground level. Transmission system, towers and lines, collapsed due to excess weight of ice, causing a prolonged interruption to customers.[1] Following this exceptional event, Hydro-Québec TransÉnergie examined methods that could whether be "mechanical" or "Joule effect" type to secure its network in case of excessive ice loading. It quickly appeared that de-icing conductors with the resistive losses due to a high current (Joule effect) flowing in conductors was the most cost efficient method to be deployed as a network type solution. Laboratory tests have been required to quantify the current needed to melt various amount of ice accretion on conductors or ground wires submitted to different meteorological conditions. The results were critical to validate the effectiveness of "Joule effect" solutions such as load transfer, reduced voltage short circuit or dc-current injection before those methods could be used in system operation. This paper resume laboratory testing results conducted at Hydro-Québec Research Institute (IREQ) to validate the current magnitude required to de-ice different conductors in various climatic conditions. With these tests, Hydro-Québec TransÉnergie is now equipped with tools and knowledge to properly plan Joule effect de-icing project and operation strategies.

III. Joule effect de-icing principle

Resistive losses generated by a high current flowing in a conductor (Joule effect) are dissipated as a thermal power that melts ice accretion on conductors. A perfect cylindrical layer of ice as shown on Fig. 1a, is used to simplify the mathematical modeling of Joule effect de-icing principle. The ice temperature throughout the de-icing process depends of the temperature differential between conductor surface and ambient air. At first, this calorific energy will make the conductor and inner ice surface temperature rise to 0 °C. Once this temperature is reached, the thermal power will be transfer almost entirely to the ice still in contact with the conductor for melting. The conductor then seems to make its way to the surface of the ice as it melts. In fact, the conductor keeps is spatial emplacement as the ice goes down due to earth attraction (Fig. 1b). After some time, the conductor reaches the upper surface of the ice. Some energy will then be lost to ambient air. At that time, losses to ambient air are greater what slows down the melting process. Finally, the accumulated ice falls from the conductor when gravity becomes greater then retention forces as shown at Fig 1c.

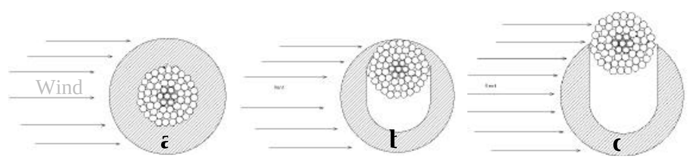


Fig. 1. Joule effect de-icing principle

IV. Laboratory tests to determine the current required to de-ice different conductors [3,4]

A. Tests objectives

Two laboratory testing campaigns where realized at IREQ Mechanical Laboratory to validate and confirm the effectiveness of Joule effect de-icing concept. The current required to melt different amount of ice buildup for different conductors submitted to various climatic conditions was the key result of these campaigns. The first campaign was held from September 1998 to January 1999 and the second was realized between December 2001 and January 2002. Both of these campaigns had distinct goals and the second tended to answer interrogations raised after the first campaign. These laboratory tests objectives were:

1998-1999 tests objectives

1- Determine de-icing current and duration to melt different ice accumulation on different conductors considering various climatic conditions (temperature and wind velocity);
2- Determine current required to prevent ice buildup on conductors;
3- Observe the impact of the ice geometry on the de-icing duration;
4- Quantify the heat transfer coefficient of ice;
5- Develop a mathematical model to predict de-icing current and duration as well as ice buildup prevention current applicable to any conductor size.

2001-2002 tests objectives

1- Demonstrate the repetitiveness of de-icing duration for three identical tests (same current, temperature, wind velocity and ice accumulation);
2- Validate the numerical de-icing model for high wind velocity;
3- Test effectiveness of de-icing on optical fibre ground wire (OPGW) and impact on optical transmission;
4- Evaluate the heating of OPGW without ice;
5- Evaluate the local overheating of steel ground wire and OPGW having strands sectioned.

B. Testing environment and specifications

These tests were conducted in a climatic room inside the Mechanical Laboratory at IREQ. The test environment was a climatic chamber in which the ambient temperature could be controlled. Also, blowers where mounted to simulate the wind effect on de-icing duration for different wind velocity. The tested conductors where coated with a uniform cylindrical layer of ice with radial thickness varying between 10 to 50 millimeters and about 1 to 1.5 meter long. Finally, an alternative current source was adjusted to generate the desired efficient de-icing current. The Fig. 2 presents one de-icing sample with ice near falling point.

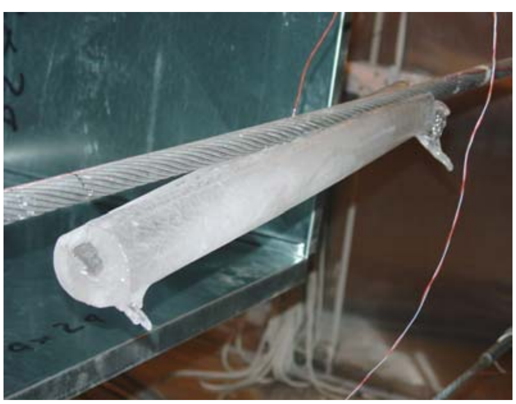


Fig. 2. De-icing sample with ice near falling point

To have a representative sample of test to judge the effectiveness of de-icing, many conductors, steel ground wires (GW) and optical ground wires (OPGW) were submitted to various test conditions. The Table 1 presents a summary of the test conditions combination investigated.

TABLE 1
SUMMARY OF DE-ICING CONDITIONS TESTED ON DIFFERENT CONDUCTORS, GROUND WIRE AND OPTICAL FIBRE GROUND WIRE

Conductor	Diameter (mm)	Ice Thickness (mm)	Wind velocity (km/h)	Ambient temperature (°C)	Current (A rms)
Bersimis 1 360 MCM ACSR	35	10, 20, 50	10, 30	-1, -5	1 320, 1 850
Condor 795 MCM ACSR	28	10, 20	10, 30	-1, -5, -10	970, 1 350
GW ½ in.	13	10, 20, 50	10, 30	-1, -5	120, 170
Bersfort 1 354 MCM ACSR	36	20	60	-2, -5	1 900
OPGW	23	20	30, 60	-2, -5	920
GW 7/16 in.	11	20	60	-2, -5	170
OPGW	17	20	30, 60	-2, -5	600

In the Table 1, when two de-icing current were tested, the currents corresponded respectively to 70% or 100 % of the thermal capacity of the conductor. When only one de-icing current was tested, the current corresponded to 100% of the thermal capacity of the conductor. The thermal capacity of a conductor is defined as the maximal current acceptable to avoid an excessive overheating of the conductor. It is determined with assumption of a ambient temperature of 0 °C and cross wind velocity of 2.2 km/h. The maximal temperature considered acceptable for ACSR conductor and steel ground wire is respectively 95 °C and 125 °C. These temperature guarantees that those conductor won't have deterioration of their electrical or mechanical properties. For the particular case of optical ground wire, a maximal temperature of 85 °C is considered. This temperature was given by the manufacturer who guarantees that no damaged to fibre or miss operating of optical transmission would be encountered. As a planning criterion for de-icing solutions, it is considered that the maximal de-icing current in a line won't exceed the thermal capacity of the conductor having the smallest diameter (smallest thermal capacity) for lines constituted of sections with different conductors caliber.

Another part of these tests was to determine the current required to prevent ice accumulation on conductors. This was achieved by installing sprinklers above the tested conductors and simulating a definite precipitation rate. Two conductors were installed in the climatic room. One was used as witness to determine the precipitation rate (no current flow in the conductor) and the second one was used to determine the ice accumulation prevention current. The test conditions are summarized in the following Table 2:

TABLE 2
SUMMARY OF ICING PREVENTION CONDITIONS TESTED

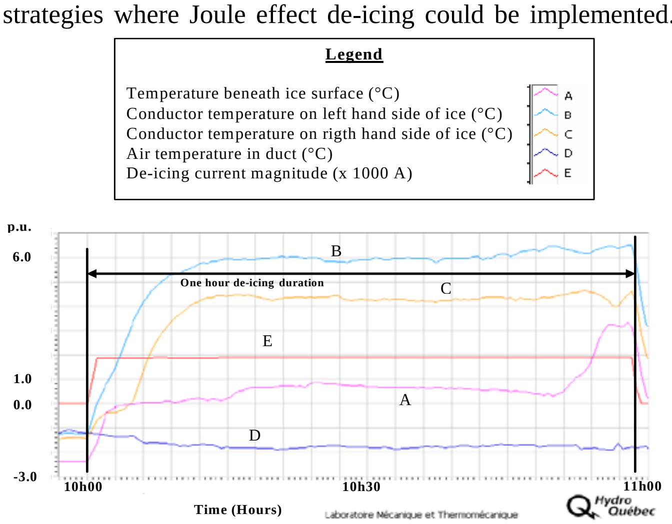
Conductor	Wind velocity (km/h)	Precipitation rate (mm/hour)	Ambient temperature (°C)	Icing prevention current (A rms)
Bersimis 1 360 MCM ACSR	0, 10, 30	5	-5	[560, 1 470]
Condor 795 MCM ACSR	0, 10, 30	5, 10	-5	[390, 1 080]
GW ½ in.	0, 10, 30	5, 10	-5	[60, 130]

The icing prevention currents range given at Table 2 were determined experimentally and they permit to prevent ice buildup for all climatic conditions given in this same table.

Finally, some tests were made to characterize the overheating of GW and OPGW when they have strands broken. The test methodology was to measure the ground wire temperature for a current flow susceptible to raise the temperature near its thermal limit before and after some strands were sectioned. The temperature measurement was made by thermograph. These tests were realized on steel GW 7/16 in. and OPGW 22.9 mm.

C. Testing results

For the test conditions detailed in Table 1, the de-icing duration was measured for a given applied current. As an example, on Fig. 3, we see that it took almost 1 hour for the 20 mm diameter thick ice layer to fall off the ACSR conductor "Bersfort" 1 354 MCM submitted to a 1 900 A de-icing current considering air temperature of -2 °C and a 60 km/h wind velocity. Based on this type of result, it rapidly became clear that Joule effect de-icing was a very efficient method to limit the ice loading on transmission lines. This being said, the network system planning department began to identify the de-icing methods (load transfer, reduced voltage short-circuit, direct current injection, etc.), locations and operation strategies where Joule effect de-icing could be implemented.



This process is presented in companion papers [6,7,8] presented at this conference.

Fig. 3. De-icing test on conductor Bersfort 1354 MCM ACSR

Using existing literature [2,9,10,11,12,13] and tests results, IREQ researchers developed a mathematical model to estimate the de-icing duration depending on the current magnitude in the conductor and for given temperatures and wind velocities. The general energetic balance equation (1) of this model is the following:

$$E_c + E_{cg} + E_{fg} = (RI^2 + P_s - P_r - P_c)\cdot t \quad (1)$$

where
- E_c Required energy to heat the conductor (J/m)
- E_{cg} Required energy to heat the ice (J/m)
- E_{fg} Required energy to melt ice (J/m)
- R Conductor resistance (Ω/m)
- I Current in the conductor (A)
- P_r Radiation losses (W/m)
- P_c Convection losses (W/m)
- Ps Power delivered by the sun (W/m)
- t Current application duration (seconds)

In this equation (1), the term RI^2 represents the "Joule effect" losses which are generated by the current flow in the conductor.

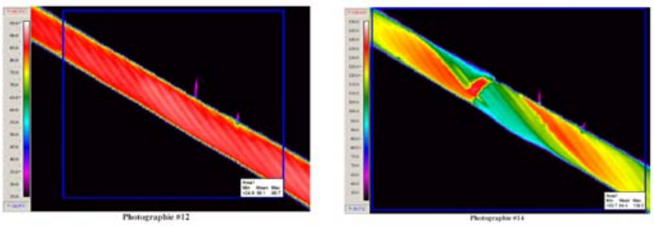
As for de-icing, a model was also developed to determine the ice accumulation prevention current based on tests results as described at Table 2. The energetic balance equation to prevent ice formation (2) on conductors is:

$$P_e = (Q_C + Q_R)_{atT_C = 0°C} + P\cdot\rho_e\cdot S_C\cdot L_f \quad (2)$$

where:
- P_e Joule effect power available (W/m) = RI^2, R being calculated at 0 °C
- Q_c Convection heat losses for a conductor temperature maintained at 0 °C (W/m)
- Q_r Radiation heat losses for a conductor temperature maintained at 0 °C (W/m)
- P Freezing rain precipitation rate (mm/hour).
- S_c Efficient capture surface (m^2/m) = Incident surface * capture efficiency
- L_f Ice fusion energy (335 kJ/kg)
- ρ_e Water density (1 000 kg/m^3)

In the 2001-2002 tests, a de-icing repetitiveness test was performed. This test consisted of de-icing 3 times a 1 354 MCM ACSR conductor submitted each time to identical tests conditions. Test conditions where 20 mm thick ice layer with ambient temperature of -2 °C, wind velocity equal to 60 km/h and de-icing current equal to 1 900 A. De-icing duration obtained for this repetitiveness test where 54, 57, and 62 minutes.

It is planned to de-ice some ground wire or optical fibre ground wire. For this, some tests were made to characterize the overheating of GW and OPGW when they have strands sectioned. GW and OPGW are exposed to lightning which may cause damaged to strands on the extern layers. With this test, we demonstrated that careful maintenance should be made before de-icing ground wire because the local overheating of a ground wire having some strands broke could damage seriously the wire itself or the optical fibre it contains. Fig. 4 shows a test result for a OPGW 22.9 mm carrying a current of 920 A when ambient temperature is 0 °C and wind velocity is 2.2 km/h. On left hand side, we see that the intact conductor has a temperature of 91 °C while from right hand side, we see that the temperature of the hottest point is 140 °C when the OPGW has 7 out of 23 strands sectioned.



T_{max} = 91 °C T_{max} = 140 °C

Fig. 4. Thermograph of OPGW without and with strands sectioned

D. Observations and conclusion

From the laboratory test realized between 1998 and 1999, basic and crucial knowledge was acquired by Hydro-Québec TransÉnergie. Based on test results, de-icing duration and ice buildup prevention models were developed as a tool to plan de-icing intervention. It has also been validated experimentally that heat transfer coefficient proposed by literature could be used in these models. Finally, it was demonstrated that freezing rain precipitation rate had minor influence on icing prevention current magnitude.

From the repetitiveness tests realized in 2001 and 2002, we can conclude that even in controlled and constant environment, de-icing duration can vary by more then 15%. This observation will bring us to be more careful when using a de-icing method on the network. Also, this test program confirms a suspected limitation of the de-icing model that has precision lacks for high wind velocity (over 50 km/h). Finally, it has been proven that de-icing GW and OPGW could be successful as long as they don't have broken strands.

V. System Planning Use of Laboratory Test Results

A. Planning Joule effect de-icing method

Different de-icing method can be used on Hydro-Québec TransÉnergie network. Among them, there is load transfer, low voltage short-circuits, nominal voltage short-circuits, load flow forced with local production and direct current. The explanations of functioning principles are exposed in a companion paper.[6] The choice to use one method among these is guided by the network characteristics near planned intervention and the line to be de-iced characteristics. More important, the choice of a method will be influenced by the required de-icing current and main considerations for this choice are:

1- Conductor resistance;
2- Presence of bundle conductor or not;
3- Line length;
4- De-icing climatic conditions to face.

With laboratory test conducted at IREQ, particularly models issued from these tests, TransÉnergie developed an in-house program to quickly evaluate de-icing current for all conductors used on its network and susceptible to be de-iced.

B. In-house program

Some minor adjustments where made to de-icing and freezing rain prevention models delivered by IREQ to be integrated in an "In-house" program. This program built with a convivial user interface permit quick evaluation of de-icing duration depending on current and climatic conditions. Conductor, ground wire and optical ground wire data base are linked to the program to optimize the use of the program. Main user screen of this program and options are shown in Fig. 5.

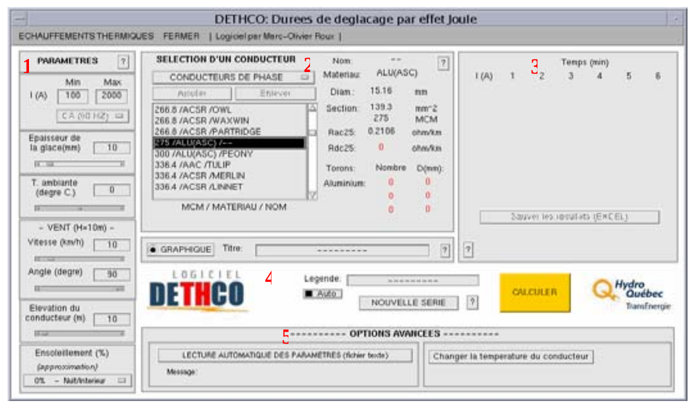


Fig. 5. De-icing program main screen

1- Simulation parameters: De-icing current (A a.c. or d.c.), Ice thickness (mm); Ambient temperature (°C); Wind velocity (km/h); Incident wind angle (°); Conductor height (m); Solar power gain (%).
2- Conductor selection and characteristics;
3- De-icing duration table output;
4- Graphical output options;
5- Advanced options: Batch simulation option and conductor temperature definition;

Fig. 6 shows an example of graphical output generated by this program.

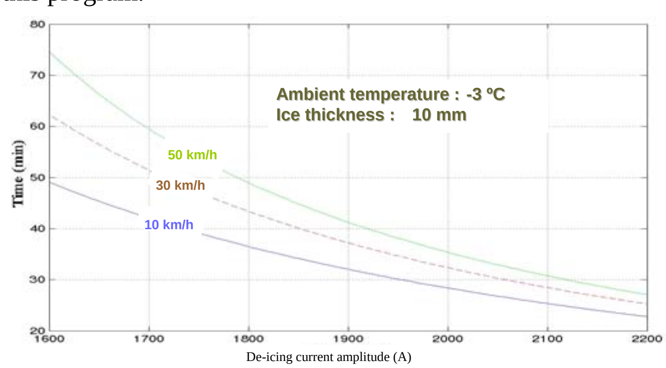


Fig. 6. De-icing duration example for Bersfort 1354 MCM ACSR conductor

This tool proved to be very helpful to this day to plan load transfer de-icing operation strategies that have been issued for

Hydro-Québec TransÉnergie network.

C. De-icing duration evaluation uncertainties and limitations

Conservative assumption concerning the evolution of ice loading on transmission lines were taken in order to have safety factors on de-icing duration obtained with the mathematical model. Those assumptions are:

1- Ice accumulation geometry on conductors is assumed concentric and symmetric

When asymmetrical ice is formed on conductors, a thin layer of water is formed during de-icing. This permits the ice to rotate around its gravity center resulting in a diminution of de-icing duration. A conductor having high torsion rigidity, accumulate ice in an asymmetrical pattern. Due to this fact, phase conductors ice accumulation is generally asymmetrical. The assumption of concentric and symmetric ice accumulation is conservative as planning criteria.

2- Ice accumulation on conductors is assumed the same as on ground

This assumption is another conservative one because in fact, a ratio between 0.5 and 0.8 is generally applicable between ground ice accumulation and radial ice thickness on conductors.

3- Impact of incident angle of freezing rain on the transmission line

No diminution factor is applied on ice accumulation to consider the angle between precipitation and line orientation. Lines perpendicular to precipitations accumulate more ice accretion than others. For lines having an angle with precipitations, our assumption is conservative because observations show that ice accretion on lines parallel to wind is 70% of ice accretion for perpendicular lines.

4- Effect of conductor bending and vibrations

Those two phenomenons should accelerate the ice falling process. Still, the lack of documentation on these phenomenons prevents us from quantifying their positive contribution.

Despite these conservative assumptions, two factors where neglected in calculation which can increase de-icing duration:

1- Conductor temperature rise during de-icing

The temperature of the de-iced conductor will be maintained near 0 °C during de-icing. Still, it is possible that conductor temperature rise above 0 °C when conductor becomes in touch with ambient air. When this happens, less Joule energy is available to melt ice which can increase de-icing duration.

2- Conductor cooling effect when it reaches ice external surface

When conductor reaches ice external surface during melting (see Fig. 1c), the conductor becomes submitted to cooling effect caused by the wind. Here again, this effect can increase de-icing duration compared to the calculated one.

After weighting the above points, Hydro-Québec TransÉnergie considers that its approach to evaluate de-icing current and duration is globally conservative and is convinced that Joule effect de-icing method is effective. Operation experience that will be gained during years to come will be an additional entrant to refine its approach when planning de-icing projects on its network

VI. Outdoor de-icing test on a 80 meters 735-kV, 4 conductors bundle span [5]

A. Test objective

One last point needed experimental validation. Many 315-kV lines and all 735-kV lines are equipped with bundle conductors. Spacers are used to maintain the conductors at a constant distance one from the other along the span. Spacers are installed every 50 to 80 meters in a span. We could anticipate that these spacers will increase de-icing duration but we could not know if they would prevent ice from falling. To validate this point, an outdoor test was schedule on a small scale 735-kV span equipped with 2 spacers distant of 50 meters one from the other. The four de-iced conductors in this span where 1 354 MCM ACSR conductors, typical for 735-kV line.

B. Test specifications

Two outdoor de-icing tests where performed at IREQ High Power laboratory. Test number 1 was realized on March 14 2003 and test number 2 was held on 1st April 2003. The average de-icing conditions that prevailed during those two tests are described in Table 3 that follows.

TABLE 3
OUTDOOR 735-KV SPAN DE-ICING TEST CONDITIONS

Test number	Average ice thickness (mm)	Average wind velocity (km/h)	Average ambient temperature (°C)	Average current per conductor (A rms)
1	10	10	-8	1 800
2	20	5,5	-3	1 800

C. Test results and observations

For both de-icing tests described in previous section, it took a little more than an hour for the conductors to melt ice coating and be free of initial accumulation. As shown in Fig. 7, during de-icing, ice accumulation fragments itself in sections of about 1.5 to 2 meters long. Each of these sections felt off the conductor in various time during the de-icing period.

Fig. 7. Outdoor de-icing test on a 80 meters 735-kV 4 conductors bundle span equipped with 2 spacers

Only small sections (about 1 meter) on each side of spacers and on all 4 conductors were still coated with ice at the end of the test. These sections were not de-iced because the spacer and its tie rods act as a heat sink and a retention element preventing ice from falling near the spacer. This phenomenon can be observed in Fig. 8.

Fig. 8. Ice retention effect of spacer and tie rods

D. Observations and conclusion

Although little amount of ice stayed attached to conductor near spacers, the span was free of almost the entire initial ice accumulation for both tests. The little amount of ice still attached to conductors after de-icing represents a small remaining loading if we consider the ice load relieve gained with de-icing. These outdoor tests proved that Joule effect de-icing was an appropriate solution to minimize ice loading on transmission line even if they are equipped with bundle conductors.

VII. Conclusion

Experimental tests have been a determinant element for Hydro-Québec TransÉnergie to gain knowledge and to master Joule effect de-icing principles applied to transmission lines. Effectiveness of this type of de-icing principle has been proved experimentally. From this observation many Joule effect de-icing methods are susceptible to be use to limit ice loading on transmission lines. The determination of de-icing current or duration becomes an influent planning criterion to choose proper de-icing method for particular application and network characteristics. Operating experience with de-icing is still to gain in real life situations and appropriate adjustments will be made to planning criteria if needed.

VIII. References

Papers from Conference Proceedings:

[1] J.-P. Gingras, S. Breault, R. Brodeur, C. Crevier, A. Déry, A. Vallée, "Stratégie de renforcement du réseau d'Hydro-Québec à la suite du verglas exceptionnel de janvier 1998 : une démarche pour sécuriser davantage l'alimentation électrique," in *CIGRÉ Session 2000 Conf.*, 37-101

[2] J. Hall., K. Hesse, I.H. Williams, P. Wilson "Ice Storm Management of Overhead Lines," CEA Workshop, Manitoba Hydro, Février 1993

Confidential intern reports:

[3] P. Guilbault, "Déglaçage des conducteurs par effet Joule – Compte-rendu d'essais #17448," IREQ Mechanical Laboratory, 7 January 2000

[4] P.-A. Séguin, Essais supplémentaires de déglaçage des conducteurs, CGA et CGFO," IREQ-53012643, IREQ Mechanical Laboratory, 3 October 2002

[5] E. Hounkpatin, "Essais de déglaçage par échauffement d'un faisceau de quatre conducteurs, avec entretoise, pour une ligne 735 kV," Rapport d'essais 53019767, IREQ High Power Laboratory, 28 May 2003

Papers Presented at this Conference:

[6] P. Prud'Homme, A. Dutil, S. Laurin, S. Lebeau, J. Benny, R. Cloutier, "Hydro-Québec TransÉnergie Line conductor De-Icing Techniques," presented at the 11th Int. Workshop on Atmospheric Icing of Structures, Montreal, Canada, June 2005.

[7] M. Granger, A. Dutil, A. Nantel, S. Laurin, " Performance aspects of Lévis substation DC de-icing project," presented at the 11th Int. Workshop on Atmospheric Icing of Structures, Montreal, Canada, June 2005.

[8] A. Déry, J.-P. Gingras, "Hydro-Québec TransÉnergie De-icing project at Lévis Substation," presented at the 11th Int. Workshop on Atmospheric Icing of Structures, Montreal, Canada, June 2005.

Books:

[9] F. Kreith, "Principles of heat transfer," 3th edition, 1976

[10] V.T. Morgan.,"The thermal Rating of Overhead-Line Conductors Part 1: The Steady state thermal Model," Electric Power Systems research, 1982

[11] J.Kestin and R.T. Wood, "the infleunce of turbulence on Mass Transfer from cylinders," ASME Trans. ser.C., J. Heat Transfer, Vol 93, 1971

[12] A.G. Davenport, "Rational for determining design wind velocities," Proc. Am. Soc. Civ. Eng.,J. Struct. Div. 86b(ST5), 1960

[13] Hubbs, "Ice Physics," 1959