

De-icing EHV Overhead Transmission Lines by Short-circuit Currents

1.0 Introduction

The 1998 ice storm caused severe damage to Hydro-Québec's power transmission system. Most of the damage on overhead transmission lines was due to ice accumulation on conductors, causing towers to collapse (Figure 1).



Figure 1: Damage to overhead line by ice accumulation in 1998

De-icing methods using techniques such as conductor heating or mechanical de-icing using a roller are possible for overhead lines ranging from 25 to 245 kV. However, such methods cannot be easily applied to lines with twin or quad conductors at rated voltages of 315 & 735 kV respectively. To protect these lines against damage following future ice storms, a new de-icing method based on the circulation of short-circuit current (I_{SC}) at the rated voltage of lines was tested at IREQ [1].

2.0 Theoretical Background

2.1 Electrodynamic forces involved with twin bundles

Forces on bundle conductor spacers under fault conditions are discussed in [1,2]. The parameters to be considered in the calculation (Figure 2) of the electromagnetic forces are:

- d : distance between the two conductors;
- I : current circulating in the conductors, which is equal and in the same direction.

Under such conditions, the magnetic field intensity [3] at either wire caused by the other is equal to $I/2\pi d$. The attraction force per meter length is directly proportional to the current squared and inversely proportional to the distance between the conductors.

For a twin bundle at 315 kV, Table 1 gives the attraction forces on each conductor generated by the first crest of asymmetrical short-circuit currents. An asymmetrical factor of 2.7 for the first crest of I_{SC} is assumed to produce a maximum attraction force that is proportional to the current squared. To produce such full asymmetry, a making angle of zero degree is thus necessary.

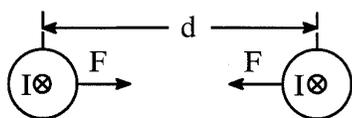


Figure 2: Twin bundle with conductors separated by a distance d

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Abstract

This paper presents a new method for de-icing EHV bundled conductor transmission lines following severe ice storms. The method involves circulating short-circuit current (I_{SC}) at the rated voltage of the transmission lines and the subsequent action of electromagnetic forces that allow conductors to knock against each other to de-ice. Tests were performed on a sample overhead transmission lines with twin (315 kV) and quad (735 kV) bundles installed in the switchyard at IREQ's high-power laboratory. Impacts on power system stability and power quality are also discussed and relevant conclusions are drawn for application of the new method on Hydro-Québec's power transmission system.

Sommaire

Cet article présente les résultats d'essais d'une nouvelle méthode de déglacage de lignes de transport à très haute tension suite à de sévères tempêtes de verglas. Cette méthode repose sur la circulation d'un courant de court-circuit, de faible amplitude et de courte durée, à la tension nominale de la ligne de transport, et de l'action de forces électromagnétiques provoquant l'entrechoquement des conducteurs et la chute de la glace. Des essais ont été effectués sur une portée réduite de faisceaux à 2 conducteurs (315 kV) et à 4 conducteurs (735 kV) installés dans l'aire d'essai extérieure du laboratoire Grande puissance de l'IREQ. Les impacts sur la stabilité du réseau et la qualité de l'onde sont aussi étudiés afin de conclure sur les possibilités d'application de cette nouvelle méthode sur le réseau de transport d'Hydro-Québec.

2.2 Electromagnetic forces involved with quad bundles

For a quad bundle at 735 kV, similar electromagnetic forces are generated except that the short-circuit current is divided into the 4 conductors. Figure 3 depicts a simplified representation of the different components (F_1 , F_2 and F_3) of the attraction force on the conductors of a quad bundle with each conductor separated by a distance d . The resulting attraction force (F_R) on each conductor is the vectorial sum of these three forces. Table 2 gives the attraction forces on each conductor generated by the first crest of asymmetrical short-circuit currents for a quad bundle with a distance of 46 cm between each conductor.

For the same I_{SC} , the attraction force on each conductor is two times smaller than that on a twin bundle. For instance, for $I_{SC} = 10$ kA rms, the attraction forces on each conductor are 88.9 and 42.6 N/m, respectively, for twin bundles (Table 1) and quad bundles (Table 2). These

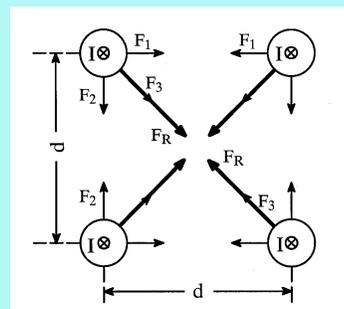


Figure 3: Attraction force on conductors of a quad bundle with conductors separated by a distance d

Table 1: Attraction force per meter length on each conductor of the twin bundle (d = 41 cm)

I_{SC} in the bundle (kA rms)	I_{SC} in each conductor (kA rms)	I_{SC} 1st-crest in each conductor (kA peak)	Attraction force (N/m)
6	3	8.1	32.0
8	4	10.8	56.9
10	5	13.5	88.9
12	6	16.2	128.0
15	7.5	20.3	201.0

Table 2: Attraction force per meter length on each conductor of the quad bundle (d = 46 cm)

I_{SC} in the bundle (kA rms)	I_{SC} in each conductor (kA rms)	I_{SC} 1st-crest in each conductor (kA peak)	Attraction force (N/m)
8	2.0	5.4	26.9
10	2.5	6.8	42.6
12	3.0	8.1	60.5
15	3.8	10.1	94.0
20	5.0	13.5	168.0

values already indicate that it will be possible to de-ice a twin bundle with a smaller short-circuit current.

2.3 Key parameter for de-icing using short-circuit currents

For de-icing conductors with a relatively small current, synchronized reclosing must be used in order to excite the natural oscillation of the conductors.

For BERSFORT conductors (diameter = 35.1 mm, $w = 21.4$ N/m), Figure 4 depicts the variation of the oscillation period as a function of the conductor spacer span and ice thickness r_I and conductor tension F_T . For a spacer span of 55 m, typical for 735-kV lines, the oscillation period is approximately 1 s.

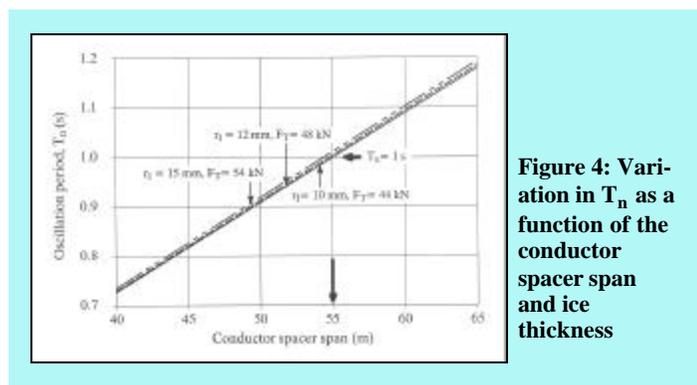


Figure 4: Variation in T_n as a function of the conductor spacer span and ice thickness

3.0 Power Tests On Twin And Quad Bundles

3.1 Test setup

Twin and quad bundle spans, 91 m in length, were mounted in the outdoor switchyard of IREQ's high-power laboratory. A load cell was connected in series with the bundle in order to adjust the conductor tension equivalent to that applied on a typical 400-m span between towers on EHV transmission lines.

A novel ice formation method was used. First, a thin and transparent plastic tubing of appropriate diameter was slid over each conductor. The diameter of this tubing is such that the required equivalent radial ice thickness (13-19 mm) is obtained on each conductor. Second, after re-tensioning the conductors, the tube was filled with water. Once it was completely frozen (i.e. a huge "Mr. Freeze"), the plastic tubing could be easily cut and removed. This process allows highly adherent ice to be formed on the conductors. Using this method, asymmetrical ice is produced around the conductors (see the insert, Figure 5), thus simulating actual conditions.

3.2 Test program

The test program was conducted on twin and quad bundles with the objective to find the smallest I_{SC} amplitude and duration required to de-ice the conductors. In order to reduce I_{SC} , it appeared very early in the test program that synchronized reclosing should be used in order to excite the natural oscillation of the conductors (Section 2.3), and then increase the knocking forces.

3.3 Test results

3.3.1 Twin bundle for 315-kV lines

For the twin bundle used, eight tests were completed with the outdoor temperature range from -3°C to -21°C . Due to space restrictions, only 3 test series are given in Table 3; a full set of results is available in [1].

The present de-icing principle is based on appropriate conductor dynamic motion that will cause the conductors to knock against each other and break the ice (Figure 5). During the test program on a twin bundle, I_{SC} values between 8 and 12 kA were applied with short-circuit durations up to 20 cycles. In addition, since the natural oscillation of conductors depends on the distance between conductor spacers (d_S), various distances (57, 62 and 42 m) between conductor spacers were also tested with the objective of validating a reclosing sequence that will provide maximum de-icing of the total 400-m span between the towers of EHV lines with the following typical distances between conductor spacers: 46, 59, 67, 62, 53, 59 and 47 m.

For $d_S = 57$ m, test series no. 1 indicates that 30% of the conductors

Figure 5: De-icing a twin bundle using 10 kA and an appropriate reclosing sequence



Table 3: Test results on a twin bundle used for 315-kV overhead lines

Test Series	I _{SC}		Test Sequence	T(°C)	Ice	
	I _{SC} (kA rms)	I _{SC} (1st crest) (kA peak)			Equivalent radial ice thickness (mm)	De-icing* (%)
Conductor spacer span (d_S) = 57 m						
1**	10.3	28.3	C-12 cycles-O	-21	16	5
	10.2	28.0	C-20 cycles-O			30
	10.1	27.7	C-20 cycles-O			42
	12.2	33.3	C-20 cycles-O			54
Conductor spacer span (d_S) = 42 m						
6**	10.2	27.9	C-18 cycles-O-0.9s - C-12 cycles-O	-16	16	< 1
	10.2	27.8	C-18 cycles-O-0.7s - C-12 cycles-O			39
	10.2	27.8	C-12 cycles-O			55
Conductor spacer span (d_S) = 62 m						
7**	10.2	28.0	2 x [(C-10 cycles-O) - 0.9s]	-15	16	18
	10.2	28.0	3 x [(C-10 cycles-O) - 0.9s]			70

Notes

* Within a given test series, the percentage of conductor de-icing is cumulative.

** Due to space restrictions, only 3 test series are given here; a full set of results is available in [1].

Table 4: Test results on a quad bundle used for 735-kV overhead lines (Conductor spacer span = 55 m)

Test Series	I _{SC}		Test sequence	T (°C)	Ice	
	I _{SC} (kA rms)	I _{SC} (1st crest) (kA peak)			Equivalent radial ice thickness (mm)	De-icing* (%)
1	20.1	54.7	C-12 cycles-O	-4	19	10
	20.1	54.8	C-12 cycles-O			26
2	15.5	42	C-6 cycles-O	-4	14 / 9	No de-icing
	15.5	42	2 x [(C-6 cycles-O) - 1s]	-4	-	6
	15.5	42	3 x [(C-6 cycles-O) - 1s]	-4	-	21
	15.1	41	3 x [(C-6 cycles-O) - 1s]	-3	-	42
3	10.1	28	3 x [(C-6 cycles-O) - 1s]	-2	13.4	No de-icing
	10.1	28	4 x [(C-6 cycles-O) - 1s]	-2	13.4	No de-icing
	10.1	28	4 x [(C-6 cycles-O) - 1.1s]	-2	-	No de-icing
4	12	32	4 x [(C-6 cycles-O) - 1.1s]	-2	-	Not measured
	12	32	4 x [(C-6 cycles-O) - 1.1s]	-2	-	70

were de-iced with a single application of 10 kA during 20 cycles (C-20 cycles-O).

For d_S = 42 m, test series no. 6 revealed that the time delay of 0.9 s, effective for the previous spacer distance of 57 m, had to be changed to 0.7 s. In fact, 55% de-icing was obtained at 10 kA with the following reclosing sequence: C-18 cycles-O-0.7s-C-12 cycles-O. This result confirms the graph of Figure 4, which gives an oscillation period of approximately 0.7 s for d_S = 42 m.

For d_S = 62 m, test series no. 7 demonstrated that the time delay of 0.9 s was totally suitable. In fact, approximately 70% conductor de-icing was obtained with this reclosing sequence: 2 x (C-10 cycles-O-0.9 s) plus 3 x (C-10 cycles-O-0.9s).

3.3.2 Quad bundle for 735-kV lines

Four test series were completed (Table 4) with the outdoor temperature range from -2°C to -4°C. I_{SC} values between 10 and 20 kA rms were applied with short-circuit durations up to 12 cycles. The distance between conductor spacer was fixed at 55 m.

As can be observed from test series no. 1, after two single attempts (C-12 cycles-O) at 20 kA, only 26% of the conductors were de-iced. Therefore, the reclosing sequences were tested for the subsequent test series. Test series no. 3 revealed that an I_{SC} of 10 kA does not produce sufficient electromagnetic forces for conductor de-icing. With I_{SC} = 15 kA (test series no. 2), about 20% of the conductors were de-iced after each reclosing sequence of 3 x (C-6 cycles-O-1s). Finally, for test series no.

Table 5: Identification of simulated lines

Line #	Substations Source/ End of line	Length (km)	3-ph faults I_{SC} (kA rms)	1-ph faults I_{SC} (kA rms)
315-kV lines				
3066	Hertel/Viger	15.4	15.0	11.8
3071	Duvernay/Notre-Dame	16.6	16.6	16.7
735-kV lines				
7036	Hertel/Boucherville	23.9	10.7	10.4
7010	Lévis/Laurentides	26.9	11.7	10.7

4, a de-icing effectiveness of 70% was obtained by applying 4 x (C-6 cycles-O-1.1 s) repeated 2 times.

4.0 Impact On The Power System

Numerical simulations were performed on a model of Hydro-Québec's power system in order to assess the impact of a short-circuit on typical system with 315 and 735 kV lines. The lines chosen were those with at least a 10-kA symmetrical short-circuit current for an end-of-line fault. Table 5 lists the short-circuits subjected to the analysis and gives their length along with the short-circuit current for three-phase and single-phase end-of-line faults.

The system was simulated and the short-circuit levels calculated while taking into account all lines in service and the generating facilities with a load level equivalent to 70% of the 2001 peak load. The load level corresponds to the load forecast for an ambient temperature of -5°C , the temperature expected during an ice storm. Adjustments were made to the system's shunt-compensation conditions so that the voltage at the substation at the beginning of the line of the circuit to be de-iced is equal to 1 p.u. The aim of the study was to evaluate the effects of short-circuits on system stability, on the voltage levels at the customer's installations, and on frequency. IREQ's stability program was used to simulate the short-circuits and evaluate the different phenomena. Models for dynamic and static system components were extracted from stability limit studies of Hydro-Quebec's power system for winter conditions. All simulations were performed for a 10-s time frame.

4.1 Stability

Two operating sequences were applied during the short-circuit simulation: a single closing operation C-tsc-O where the duration tsc of the short-circuit was 6 to 24 cycles, and a sequence of four closing operations, C-tsc-O-1.1s - C-tsc-O-1.1s - C-tsc-O-1.1s - C-tsc-O, where the duration tsc of the short-circuit was 6 or 12 cycles. The simulations on the four studied lines showed that system stability is compromised during a sequence of four closing operations on a 3-ph short-circuit at the end of a 735-kV line. In fact, the sequence of four closing operations

Table 6: Number of customers affected by short-circuits

Voltage Drop (V_D)	735-kV lines		315-kV lines	
	3-ph short-circuits	1-ph short-circuits	3-ph short-circuits	1-ph short-circuits
$V_D < 10\%$	5%	8%	15%	37%
$10\% < V_D < 20\%$	13%	35%	29%	61%
$V_D > 20\%$	82%	57%	56%	2%

applied to circuit 7036 caused a voltage instability after the fourth closing operation. The same sequence applied to circuit 7010 did not result in any system instability, but the analysis of the voltage graphs showed that the stability limits had almost been attained and that some instability could be expected if the system was evenly slightly in degraded or high-load mode.

4.2 Voltage drops

System faults cause a voltage drop which can affect industrial customers. In fact, the protection systems of industrial customers which are sensitive to disturbances may react on a voltage drop and disconnect some or all of a customer's electrical installations. In addition to affecting the customer's production, an overly large loss of load results in an increase in voltage on the network which can lose control and cause successive tripping. Based on past experiences, a voltage drop lower than 10% at the HV side of customer's busbar could result in an acceptable level of disturbance in relation to a situation where action must be taken to prevent towers of the line from collapsing.

The voltage drop was evaluated when short-circuits are applied at the end of the four lines being studied. The assessment was done at the connection points of 60 industrial customers in different parts of the system. Table 6 gives an overview of disturbances at the customers' installations in terms of voltage drop and number of customers affected.

Voltage drops for three-phase faults are unacceptable, at the end of both 735-kV and 315-kV lines, due to the large number of industrial customers who would be affected. Voltage drops for 1-ph faults at the end of 735-kV lines are also unacceptable. Even if 1-ph short-circuits at the end of 315-kV lines produce less substantial voltage drops, the number of customers affected by voltage drops $>10\%$ is considerable.

4.3 Frequency variations

A 3-ph short-circuit current lasting 12 or 24 cycles at the end of a 735-kV line causes a frequency variation of $+0.40/-0.20$ or $+0.60/-0.30$ Hz, respectively. The frequency variation attains $+0.90/-0.45$ Hz during a sequence involving four closing operations on a 3-ph fault. Single-phase short-circuits at the end of 735-kV lines as well as 315-kV 1-ph and 3-ph short-circuits produce frequency variations typically under $+0.30/-0.15$ Hz. Such frequency variations are acceptable and their effect can be easily countered through the application of preventive measures.

5.0 Conclusion

This paper presents a new method for de-icing EHV overhead lines, based on exciting the natural oscillation of conductors by the action of electromagnetic forces to knock conductors against each other and the ice to fall off. In order to reduce the amplitude and duration of the short-circuit currents as much as possible, asymmetrical I_{SC} and reclosing sequences are necessary. To produce maximum asymmetry in I_{SC} , a special relay must be used to synchronize the breaker's closing time with the system voltage, thus ensuring a making angle as close as possible to zero degrees.

Impact studies on Hydro-Quebec power's system reveal that:

- On 735-kV overhead lines and for three-phase short-circuits, network stability would be jeopardized after the fourth reclosing.
- For 3-phase faults, voltage drops are unacceptable for both 315 & 735-kV lines as too many industrial customers would be affected.
- For 1-phase faults, voltage drops are lower but the number of customers affected by a voltage drop greater than 10% remains high.
- Frequency variations are, however, acceptable.

In summary, the method proposed here could likely be used for 315 kV lines, but only during emergency conditions such as those found during severe ice storms. For 735-kV lines, the required short-circuit currents and reclosing sequences are none-the-less too detrimental to network stability and, therefore, the method would probably not be applied.

6.0 References

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- [4]. Gilbert Commonwealth, "Transmission Line Reference Book - Wind-Induced Conductor Motion", Chapter 1 (pages 11-12) by E.S. Doocy and A. Hard (reprinted from "The Vortex Wakes of Vibrating Cylinders at Low Reynolds Numbers" by G. H. Joopmann, Journal of Fluid Mechanics, 1967, Vol. 28, Part 3, pp. 501-512).

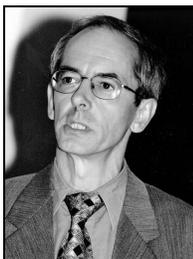
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Michel Landry, a circuit-breaker expert, is a research engineer at IREQ since 1979. During his career, he was involved in many research projects related to breaker interrupting performance and in-service condition monitoring. He has authored or co-authored more than 35 international publications, one of which earned a prize paper award from the IEEE Power Engineering Society in 1986.



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In 1972, he joined Hydro Québec as an engineer in substation design and equipment standardization. While with the Transmission Equipment Department, he was responsible for the development of the Hydro Québec Standards on HV and EHV circuit-breakers and their certification. Roger joined the Power Network Planning Department of Hydro Québec in 1990.

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Letters to the Editor/Lettres envoyées au rédacteur en chef

Become A Lake

An aging Hindu master grew tired of his apprentice complaining, and so, one morning, he sent him for some salt. When the apprentice returned, the master instructed the unhappy young man to put a handful of salt in a glass of water and then to drink it.

"How does it taste?" the master asked.

"Bitter," spit the apprentice.

The master chuckled and then asked the young man to take the same handful of salt and put it in the lake. The two walked in silence to the nearby lake, and once the apprentice swirled his handful of salt in the water, the old man said, "Now drink from the lake."

As the water dripped down the young man's chin, the master asked, "How does it taste?"

"Much fresher," remarked the apprentice.

"Do you taste the salt?" asked the master.

"No," said the young man.

At this, the master sat beside the young man who so reminded him of himself and took his hands, offering, "The pain of life is pure salt, no more, no less. The amount of pain in life remains the same, exactly the same. But the amount of bitterness we taste depends on the container we put the pain in. So when you are in pain, the only thing you can do is to enlarge your sense of things... Stop being a glass. Become a lake."

Bob McLoud
Markham, ON

Today in the Stock Market

Helium was up, feathers were down.

Paper was stationary.

Fluorescent tubing was dimmed in light trading.

Knives were up sharply.

Cow steered into a bull market.

Pencils lost a few points.

Hiking equipment was trailing.

Elevators rose, while escalators continued their slow decline.

Weights were up in heavy trading.

Light switches were off.

Mining equipment hit rock bottom.

Diapers remain unchanged.

Shipping lines stayed at an even keel.

The market for raisins dried up.

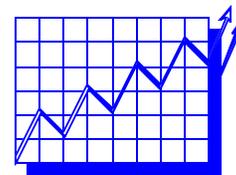
Cola fizzled.

Caterpillar stock inched up a bit.

Sun peaked at midday.

Balloon prices were inflated.

And batteries exploded in an attempt to recharge the market.



Lewis Vaughan
Montreal, QC



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