Hydro-Québec TransÉnergie Line Conductor De-Icing Techniques

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Abstract — **This paper presents Hydro-Québec TransÉnergie's experience with different Joule effect de-icing methods. Descriptions of these methods will be given as well as their field applications and limitations. Experience gained with real case studies as well as considerations for equipment, control, protection and system operation will also be addressed in this paper.**

Keywords — De-icing techniques, ice storm, transmission line conductors, load transfer, reduced or full voltage short-circuit, direct current, isolated generation, magnetic forces, contactor load transfer

I. Introduction

Hydro-Québec TransÉnergie is the owner of an a.c. transmission system having more than 800 power lines. These lines are operated at voltages ranging from 49-kV to 735-kV and total more than 32 000 km.

In 1998, an ice storm of unprecedented severity 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. Many towers collapsed on some 116 lines of different voltage levels, due to the excess weight of ice buildup on the line conductors. This caused the interruption of electric service to 40% of all Hydro-Québec customers.[1] Pole-mounted 25-kV distribution lines were more severely damaged than transmission lines as their mechanical withstand is lower. Close cooperation was set up between the transmission and distribution groups so that the load centers could be re-energized as rapidly as possible. Nevertheless, up to one month elapsed before power was restored to the last customer. Given that electricity is largely used by Hydro-Québec customers as a heating source in winter time, one can easily imagine that such an ice storm had dramatic social and economic impacts.

In addition to restoring service and rebuilding damaged lines, strengthening the power system and improving the reliability of the electrical supply in areas prone to severe ice storms became a priority.

II. Reliability Improvement Objective

In order to improve reliability of the electrical supply in areas prone to severe icing, it was concluded that maintaining a minimal network skeleton was essential. Strategic lines were identified and actions were planned to make these lines capable of better resisting exceptionally severe ice storms. The storms considered here are those having a recurrence interval of 50 years or more. This strategy will be applied on a priority basis to the main 735-kV system and, to a lesser extent, to regional systems, the objective being to maintain a link between the main generation centers and the load centers. This approach is detailed in a companion paper.[2]

To meet this objective, mechanical reinforcement of identified strategic lines was first considered. However, it was soon realized that reinforcing the strategic lines to cope with ice loads similar to those observed during the January 1998 storm would be excessively costly considering the rare occurrence of such an event.

Using a risk management approach, economic studies showed that de-icing methods combined with targeted line reinforcement was the most efficient solution to secure power supply. De-icing is a practical way to limit the mechanical stress on the towers by removing the ice accumulated on line conductors.

III. De-Icing Techniques Considered

A task force composed of representatives from the units responsible for planning, line and substation design, maintenance and operations was formed to investigate the different techniques available to efficiently de-ice transmission lines. More than 25 different methods were examined, some of them classified as "mechanical methods," others as "system methods." The mechanical methods generally apply on a short portion of line, span by span. These methods can be useful to de-ice a very short line or line segment, for example a river or road crossing, as they avoid the possible consequences of ice falling down. System methods, on the other hand, can generally be applied to the entire line length. According to the task force, Joule effect de-icing techniques (where ice melting is the consequence of heat transferred from the conductor to the ice) were the most promising solutions to get rid of ice buildup on line conductors. The task force analyzed and produced a ranking of the different Joule effect de-icing methods based on aspects such as cost, reliability, R&D risks, implementation time, complexity, and impact on customers. Each criterion was weighted according to its relative importance.

Table 1 shows the result of the voting process. For some cases, only one method can be applied besides line reinforcement, which can be applied to any line but is the most costly solution. Each method has its application range and limitations depending upon:

- line length and configuration;
- the load being fed;
- voltage and source impedance;
- system configuration at the considered location.

Each of these methods will be discussed, particularly the ones that have been already applied and those considered for the near future.

TABLE 1
RANKING OF SECURING METHODS

DESCRIPTION	APPLICATION	CRITERIA / WEIGHT									
		R&D cost	R&D risks	Implantation cost	Maintenance cost	Operating cost	Realization time	Reliability	Complexity	Impact on customers	TOTAL / 5
		5 %	14 %	16 %	9 %	10 %	12 %	15 %	10 %	9 %	
Load transfer (Joule effect)	49 to 315 kV lines	5	5	5	5	4	5	3	4	3	**4.32**
Direct current (Joule effect)	Bundle conductor lines	5	5	2	4	4	3	4	4	4.5	**3.80**
Reduced or full voltage short-circuit (Joule effect)	49 à 315 kV lines	5	5	3.5	4	3	3	4	3	4	**3.79**
High magnitude short-circuit (Magnetic forces)	Bundle conductor lines	3	3	4	5	4	4	3	3	3	**3.56**
Mechanical reinforcement	Any line	5	5	0	3	5	2	4	5	5	**3.51**
Contactor load transfer (Joule effect)	Bundle conductor lines	0	2.5	3.5	2.5	4.5	0	3	4.5	3	**2.76**

IV. JOULE EFFECT DE-ICING OBJECTIVES

Experiments were conducted at the IREQ laboratories, and the results were used to develop a software program to estimate the level of current required to melt ice on conductors of different sizes. The test methodology and software characteristics are presented in a companion paper.[3]

The following criteria have been adopted to define the levels of current required:

- De-icing duration not exceeding 1 hour based on 10 mm ice thickness, -5°C ambient temperature, and 20 km/h transverse wind speed;
- De-icing current not exceeding the thermal capacity of the line conductors based on an ambient temperature of 0°C and 2.2 km/h transverse wind speed;
- For lines with sections having different conductor sizes, de-icing current shall not exceed the thermal capacity of the smallest conductor.

Considering typical conductor sizes used on TransÉnergie lines, de-icing currents range between 1 000 and 1 500 amperes rms representing approximately 75% of the thermal capacity. Tests conducted at IREQ laboratories also determined the current required to prevent ice buildup on the conductors. As a general guideline, it was determined that ice buildup can be avoided if current in the conductors is about 80% of the de-icing current and is applied before the freezing rain begins.

V. LOAD TRANSFER DE-ICING METHOD

This method requires no additional equipment on the system. It involves modifying the system configuration in order to increase the current flowing in the lines to be de-iced. This has to be realized considering operating restrictions. An example of de-icing with the load transfer method is to remove one circuit of a double-circuit line feeding a substation. If the load fed by the substation is high enough and depending on the ambient conditions (temperature and wind speed), the current in the remaining circuit will melt the ice accumulated on the line conductors.

The scope of application depends on the system configuration, the power load available, the ambient conditions and the line configuration (conductor size, numbers of conductors per phase). Considering the power load only, the risk of unsuccessful de-icing is fairly high since customer load demand—which determines the current flow—is difficult to control. On the TransÉnergie system, the average power consumption at a steady temperature of 0°C varies typically from 55 to 70% of the winter peak load over a 24-hour period. Moreover, the possibility of load losses caused by the ice storm reduces the periods in a day where de-icing is practicable. Simulations on a scale model also showed that after more than 2 hours in de-icing mode at the very minimum required current, the process can be unsuccessful even when applied for a much longer period of time. On the other hand, the minimum current required for de-icing may exceed the equipment overload capability, especially under severe climatic conditions. Thus the power load available and the climatic conditions in the area where de-icing is performed must be in correlation to determine the efficiency of the load transfer method given the equipments rating.

On the Hydro-Québec TransÉnergie system, about 120 circuits of the 800 transmission lines (49-kV and above) potentially lend themselves to de-icing by the load transfer method. Considering the number of lines and the various parameters to take into account, a software named StraDeg was developed to help operating people in their decision process by suggesting optimized de-icing strategy to adopt. The method is mostly applied on single-conductor lines, as bundled conductors generally require too large currents. Moreover, this method is not suitable at 735-kV because of the level of current required (up to 7 200 Amps per phase) and possible impact on system stability.

VI. REDUCED OR FULL VOLTAGE SHORT-CIRCUIT METHOD[4]

This method consists in applying a three-phase short-circuit at one end of a line and a three-phase voltage source at the other end. The voltage must be high enough to generate the necessary current.

Taking into account that single-conductor lines have an impedance of about 0.5 Ω/km, that the de-icing current required for most single-conductor lines (49-kV and above) is between 1 000 and 1 500 A, and that the voltage drop caused by the short circuit at the remote end, the voltage source needed is approximately 1 kVrms phase-to-phase per line kilometer. So for short lines the source requires a lower voltage than the nominal operating voltage. For long lines the voltage source required may be as high as the nominal line voltage. In general, reduced voltage is adequate to generate the required de-icing current for lines having a nominal voltage up to 230-kV. For 315-kV lines, full voltage source may be required because of the line length or because the line has more than one conductor per phase. This method will be applied on more than 50 lines on the transmission system. It will not be applied to 735-kV lines, since these lines have four conductors per phase and, being an average of twice as long as the 315-kV lines, would need too much power from the system.

a. Operating aspects

The typical installation for a 120/25-kV substation reduced voltage short-circuit application is shown in Fig. 1 where a 25-kV feeder serves as the voltage source to de-ice the 120-kV incoming lines.

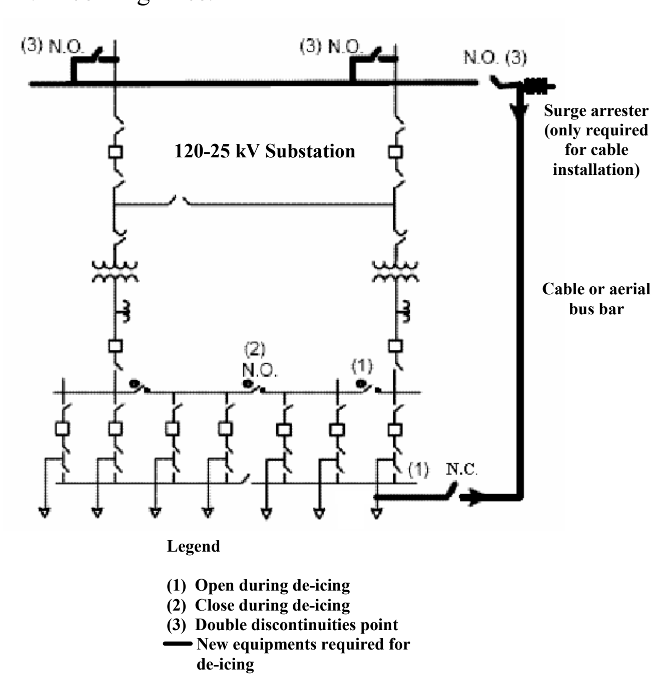

Fig. 1. Typical installation for reduced voltage short-circuit de-icing

In this figure, the 25-kV feeder connects the high-voltage lines to the "de-icing" transformer. The 25-kV switch on the source side of the cable is operated normally closed (better cable reliability). The 25-kV switch at the remote end of the cable and the 120-kV switches connected to the 120-kV lines are operated normally open. In this configuration, there are two break points between the 120-kV and 25-kV systems.

During the de-icing period, circuit breakers will be opened at both ends to isolate the line to be de-iced. The short-circuit switch at the remote end will be closed to produce the three-phase short-circuit. On the source side, the transformer used as the voltage source will be isolated from other feeders on the secondary side and dedicated to the high-voltage lines to be de-iced (one at the time). The substation load will be fed in radial mode by the remaining transformer (switches 1 and 2 respectively open and closed). For a multi-tapped line, all line breakers must be opened. If a tap has to be de-iced, it must be equipped with a short-circuit switch, and the breakers at all the other ends must be opened. There is no constraint against de-icing a line segment that has already been de-iced because the line current is always less than the thermal capability (de-icing current adjusted between 75 and 100% of thermal capability).

b. Equipment considerations

This de-icing method requires some new equipment. On the short-circuited side, switch (normally open) have to be installed on each of the lines to be de-iced in order to produce the three-phase fault. On the source side, switches and an aerial busbar or cable (and a surge arrester if a cable is installed) are required to make the connection between the voltage source and the lines to be de-iced.

The overload capability of existing equipment carrying the de-icing current (busbars, feeder breaker, switches and transformer) must also be addressed. For instance, the feeder, usually with a capacity of 600 to 800 A, must now sustain over 1 000 A. The incoming high-voltage lines must be capable of carrying the total load fed by the substation plus the de-icing current. The system voltage regulation shall also be addressed. For example, the transformer must be capable of maintaining the secondary-side voltage at the required value throughout the de-icing period for all lines. Also the use of on-load tap changers may be required when switching from one line to another as line characteristics vary. A voltage regulator can be added in series if necessary. Finally, load flow studies are useful to determine the impact of de-icing on system voltage regulation. The reduced or full voltage short-circuit method may be jeopardized if the voltage at a given busbar is beyond its operating limits established for emergency operating mode. From the mechanical point of view, switches must be able to operate under heavy ice accumulation as anticipated on the basis of ice load maps. Appropriate tests will be conducted in laboratories to validate proper operating of switches submitted to such constraint.

c. Protection considerations

The short-circuit applied at the remote end could be either a grounded or an ungrounded three-phase fault. The grounded type of short-circuit was considered first because of the existing line ground switches at both ends. However, their current capability is generally far less than the 1 000 A required. Furthermore, to ensure that no large current flows into the substation grounding grid during de-icing periods, the grounding switches would have to be modified and connected to a common point before connecting to the grid. Because of these reasons, the ungrounded type of short-circuit has also been considered because of its technical advantages. First, the magnitude of a (sudden) single line-to-ground fault occurring along the line decreases more rapidly compared to the same case with an ungrounded three-phase short-circuit applied at the remote end. The ground potential rise at the fault location is then lower. This is more important for a fault occurring close to the short-circuited end of the line. Because the fault current seen from the source is only a little larger than the de-icing current, the line protection may have difficulty distinguishing between the two, resulting in a prolonged application of the fault. The other advantage is that ground overcurrent protections typically used on 25-kV feeders can cover 15 to 20% longer with the ungrounded type of short-circuit because 100% of the ground current returns to the source while the fault current splits between the ground path at the source side and the path at the ground switch with a grounded type of short-circuit. Therefore, the ungrounded type of short-circuit was adopted.

From the protection point of view, a new relay protects the line in "de-icing mode." The existing relay is still used in normal operating mode. Permutation from one to the other is achieved by the operator according to desired operating mode. This functioning way is less time-consuming and safer than implementing a single relay setting for both operating mode (normal and de-icing). Also, the new relay is more sensitive. Pick-up current is typically 10% higher than the de-icing current for the phase protection and around 100 A rms for ground ($3I_0$) and negative sequence currents. With these settings, it is not possible to detect a fault close to the three-phase short-circuiting switches since fault current is almost zero. Nevertheless this risk is considered acceptable. Indeed, as the de-icing process starts a long time before the ice thickness on conductors reaches the line's mechanical limit, conductor or tower collapse is not likely to happen. Also, the probability of a fault resulting from ice accumulation on insulators is also very low because the phase voltage is well below the nominal voltage at locations where the line protection cannot operate. Typical faults that are likely to happen are those resulting from the loss of a massive ice block on one phase. The swing of this conductor can reach an upper phase conductor (or ground wire) and cause a phase-to-phase (or phase-to-ground) fault. If the fault is close to the source side, the fault current will be high enough to be detected by the line protection. But if the fault is close to the shorting switch, protection will not operate and the fault will be sustained. However, an arc will appear between conductors as the "unloaded" conductor returns to its original position. Due to the low voltage difference between phases and the significant distance between conductors, the arc will extinguish. Experimentation at the IREQ laboratories on disconnect switches showed that an arc between two conductors will extinguish if the following (approximate) equation is satisfied (applicable for current magnitude greater than 100 Amps):

$$D \geq \frac{\Delta V}{2}$$

Where:

D is the distance between conductors (in meters);

ΔV is the voltage difference between conductors (in kV rms).

For instance, if we suppose the distance between two phases of a typical 120-kV line is about 4 m, the arc between the two conductors will extinguish if the phase voltage is 8 kV or less. Using the "1 kV rms per km" rule of thumb, an arc between two phases will extinguish for a fault located up to 8 km away from the short-circuit switch.

Finally, in de-icing mode, some of the control systems usually installed in substations have to be shut down to prevent any interference. These include:

- The automatic line recloser of the 25-kV source. After a fault, visual inspection is required prior to voltage restoration;
- The high-voltage line permutation control. Detection of low voltage on the line in de-icing mode may be interpreted as a line loss in permanent mode, which may initiate the permutation system;
- The power transformer automatic tap changer control. The voltage level required in de-icing mode may be totally different from the voltage in normal operating mode;
- The control system initiated after the loss of a power transformer.

In general, for any situation involving system protections, operator actions will be required prior to resuming the de-icing process.

d. Ground wire de-icing

Ground wire de-icing is also possible with the "low" voltage short-circuit method. However, the preferred approach is to reinforce the ground wire and the tower top members to withstand the amount of ice accumulation forecast on the basis of geographical area. The main reasons for this approach are:

- The need to insulate the ground wire from the tower;
- The need to install spark gaps to protect insulators from direct lightning strikes;
- The effect of increasing the grounding resistance;
- The effect of induced voltage on communications systems close to the line while the ground wire carrying a high current (100 to 600 A);
- Replacing a ground wire costs only a little more than insulating the existing wire.

VII. Isolated Generation De-icing Method

This method is inspired by the load transfer de-icing method. One or more generating units are isolated on a line and their current outputs are set to de-icing current. An example is shown in Fig. 2.

One unit at Sainte-Marguerite-3 power plant is isolated to supply the de-icing current for circuits # 1615 and # 1616 between Arnaud and Hauterive substations (shown in bold). Some of the adjacent line circuit breakers (160-14, 160-21 and 160-23) at Arnaud substation are opened to isolate the power plant on # 1615 and # 1616 circuits. The line connecting Sainte-Marguerite-3 power plant to Arnaud (circuits # 3175 and # 3176) does not need to be de-iced since the tower are built to more stringent design criteria.

During de-icing of these circuits, all local loads remain normally fed. However, one industrial customer cannot be fed by circuit # 1615 during the de-icing process otherwise, line thermal capacity would be exceeded. To prevent an alimentation interruption to this client, its load alimentation is transfer to other surrounding lines.

From the protection point of view, de-icing by isolated generation is not very different from the normal operating condition, with the exception that the line current is higher. In many cases overcurrent and distance protections commonly used on these systems can also be used during the de-icing process as long as the pick-up currents or the impedance locus are coordinated with the load flow current.

Control systems like automatic line reclosers are disabled during the de-icing process.

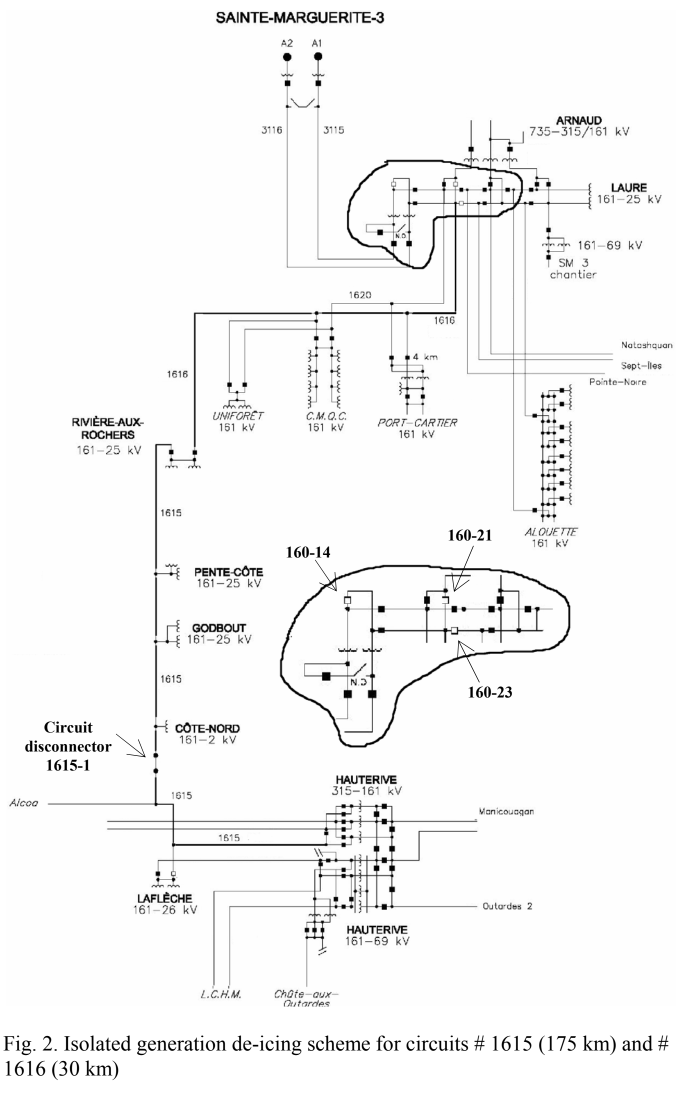

Fig. 2. Isolated generation de-icing scheme for circuits # 1615 (175 km) and # 1616 (30 km)

VIII. DC CURRENT DE-ICING METHOD

This method is well suited in situations requiring very large de-icing currents or for very long lines such as 735-kV lines. These lines have 4 conductors per phase and an average length of 250 km. The short-circuit method with an AC source is not suitable for this case because the power and voltage magnitude required from the source would exceed 12 000 MVA and 1 000 kV! With a DC source the de-icing current remains the same (identical RI^2 losses) but the voltage of the source is proportional to the resistive part of the line impedance only, because $I*\omega L$ is zero. For this 250-km, 735-kV line, the power of the DC source would be 285 MVA (7 200 A * .011 Ω/km * 250 km * 2 * 7 200 A). The reason for the factor 2 is that the line ends are connected to the DC positive and negative poles, and the current must make a round trip to the next substation and back. Depending on the line characteristics, more than two steps may be required to de-ice all three phases.

A DC converter installation is a very expensive project and economically difficult to justify if it is to be used only as de-icer device. So TransÉnergie has designed the converter to operate as a static var compensator under normal operating conditions. For more details on this double-function device, please refer to the companion papers [2, 5].

IX. MAGNETIC FORCE DE-ICING METHOD

This method consists in causing all the conductors in a bundle to knock against each other, which will cause the ice to fall off. The knocking effect is produced by the application of a very large current—of the same type as a short-circuit—through the conductors for a short period of time producing an attractive force between the bundled conductors. This method has been tested on a short span of a bundled line at the IREQ research laboratory. To be effective, the solution requires two consecutive short-circuit applications of 10 kA or more. Short-circuit durations are less than half a second and the time between applications is about 1 second in order to excite the natural oscillation of the conductors and then increase the knocking force. Both short-circuits are initiated at zero crossing voltage in order to produce the maximum crest current (full DC offset). Considering the amount of current required, this method only applies to short lines.

Unfortunately, this solution has not been retained for network application because of severe voltage drops on the transmission system and the possible impact on stability. More details can be found in.[6]

X. CONTACTOR LOAD TRANSFER DE-ICING METHOD

This de-icing method was developed for lines with bundled conductors. It consists of a contactor device installed in the bundle spacers to control the current flow in the bundle. In normal operating mode, the current flows in all of the conductors. In de-icing mode, the contactor forces the current through one conductor only. The process is repeated for the other conductors in the bundle until complete de-icing is achieved [7].

Major drawbacks to this solution are the R&D cost and risk, the time required to implement the device in the field, reliability issues, and the need to de-energize other lines to obtain a sufficient current in the line being de-iced (impact on stability).

This solution has been classified as a long-term potential solution and could be studied if the highest ranked solutions do not prove to meet the objectives at a reasonable cost.

XI. Conclusion

The Joule effect de-icing techniques combined with tower reinforcement appears to be the most cost effective solutions to limit mechanical loads on transmission lines subjected to severe ice storms. TransÉnergie will use different de-icing methods on its strategic lines. Among them, the load transfer method, being the cheapest way to melt ice on conductors, can be applied to about 120 transmission lines rated from 49 to 315 kV. The reduced (or full) voltage short-circuit method will also be used on many lines (more than 50) where voltage and power available at the source substation are appropriate for the line length and configuration. TransÉnergie is also planning to operate generating units in radial mode on transmission lines. The power output will be adjusted to obtain the required de-icing current. Finally, TransÉnergie will use a DC source to de-ice 315-kV and 735-kV lines with up to 4 conductors per phase. Currents of up to 7 200 A per phase are required. With a power source of about 30 times less than its AC equivalent, a DC current converter is the only practical solution to de-ice these lines. The first DC source will be installed at Lévis substation to de-ice 5 strategic lines connected to this substation. In normal operating mode, the converter will be used as a static var compensator. Another DC installation is also planned in the near future.

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