PRELOCATING AND PINPOINTING FAULTS ON UNDERGROUND MEDIUM VOLTAGE CABLES: REVIEW OF HYDRO-QUEBEC'S EXPERIENCE

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ABSTRACT

This paper presents a review of the experience with the SimLoc fault location method developed by Hydro-Québec and deployed in 2011 on the utility's underground distribution system. The SimLoc method helps prelocate faults on de-energized medium-voltage cables for lines up to several kilometres long. This paper also presents the development of the new CoLoc tool that is designed to pinpoint a cable fault location.

KEYWORDS

Fault location, medium voltage, cable, prelocating, pinpointing, thumper, underground, manhole

INTRODUCTION

In January 2009, Hydro-Québec Distribution gradually rolled out a new cable fault location system named **SimLoc** (for **Simulation and Location**) [1]. This system was developed at Hydro-Québec's research institute, IREQ. The goal was to reduce average fault location time and the training workers required to perform the task. The challenge was to locate faults on long lines with many branch lines. The purpose was also to reduce the number of pulses (generated by the thumper) on the cable.

The SimLoc method (Figure 1) consists of simulating thumps at regular distances along the line, measuring an actual thump on the line, comparing the simulations with the measurement and identifying the best match, which corresponds to a unique point on the line and indicates the location of the fault.

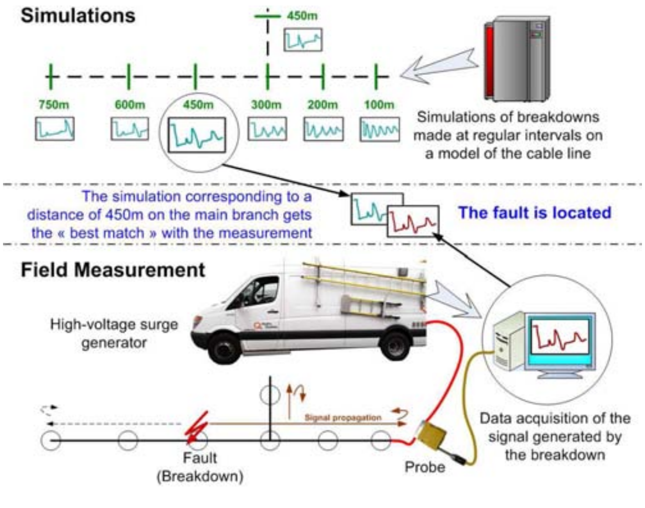

Figure 1 - Diagram of the method

On Hydro-Québec's underground system, almost all the cables run through buried conduits between two manholes. When there is a fault on a run, the latter must be removed and entirely replaced. A fairly low level of precision is thus sufficient for locating a fault: it is enough to know that the fault is located between two manholes that may be several dozen metres or a few hundred metres apart.

SimLoc has now been used for more than five years and its fault location success rate ranges from 50% to 85%, depending on the line configurations. The 15% to 50% unsuccessful locations are related to specific conditions or configurations that will be explained in this paper. Lines with a high rate of success will be referred to as "normal lines" and lines with a low rate of success as "complex lines."

SimLoc should be considered more as a fault prelocating tool rather than a pinpointing tool [2] [3]. Prelocating consists in determining as precisely as possible the location of, or distance to, a fault from a measurement point at the end of the line. To increase the efficiency of its fault location system, Hydro-Québec decided in February 2011 to mandate its research institute to develop a new tool to help locate faults that could not easily be located by SimLoc and to help confirm the location of a fault. The name of this pinpointing tool is **CoLoc** (for **Confirmation of Location**).

TOPOLOGY OF UNDERGROUND DISTRIBUTION LINES

Hydro-Québec Distribution has over 4,000 underground distribution lines with 12,000 km of 12-kV and 25-kV medium-voltage underground cables. More than 200 lines are over 10 km long and most have branch lines. The system is almost entirely comprised of duct banks containing bare concentric neutral cables with 28-kV XLPE or TR-XLPE insulation. The province of Quebec is separated into six service areas in terms of distribution line groupings (Figure 2).

Figure 2 – Province of Quebec's service areas for the underground distribution lines

The Réseaux autonomes and the Nord-Est service areas have less than 500 km of underground cables. Montreal represents 40% of the medium-voltage underground distribution lines. It is apart from the other service areas because of the age of the cables (the oldest are 50 years old) and their heterogeneity with 1/0, 3/0, 4/0, 350 MCM, 500 MCM and 750 MCM copper and aluminum cables (mainly XLPE but with some remaining PILC cables). The Laurentides, Montmorency and Richelieu service areas are more homogeneous with primarily 500 MCM and 750 MCM XLPE copper and aluminum cables.

This article focuses on the two main service areas, which are Montreal and Montmorency (the latter including Quebec City and representing 20% of the provincial lines). To better understand the SimLoc results, the typical normal and complex lines for each service area will first be identified.

A typical normal line in the Montreal service area (Figure 3) is about 2 to 3 km long, has 20 to 25 joints and 1 to 2 branches.

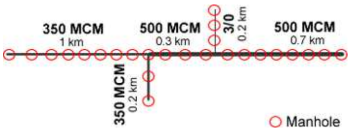

Figure 3 – Schematic of a typical “normal line” in the Montreal service area

A typical complex line in the Montreal service area (Figure 4) is about 4 km long, has 30 to 40 joints and 2 to 8 branches.

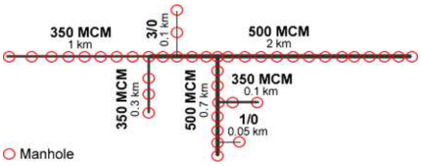

Figure 4 – Schematic of a typical “complex line” in the Montreal service area

A typical normal line in the Montmorency service area (Figure 5) is a straight line 6 to 8 km long with 30 to 50 joints.

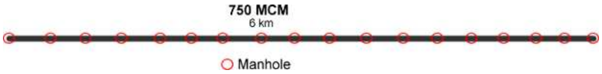

Figure 5 – Schematic of a typical “normal line” in the Montmorency service area

A typical complex line in the Montmorency service area (Figure 6) is 6 to 13 km long, has 30 to 50 joints and 2 to 8 branches.

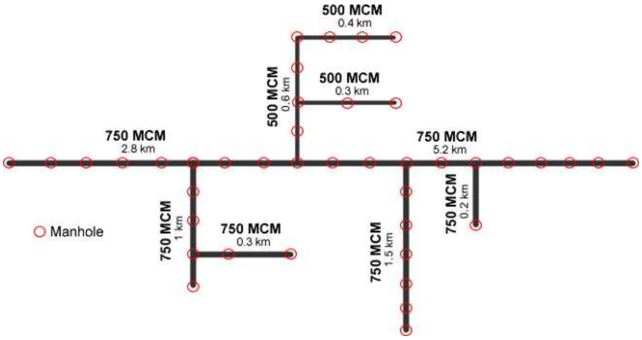

Figure 6 – Schematic of a typical “complex line” in the Montmorency service area

SIMLOC REVIEW AND STATISTICS

Based on the available data from November 2011 to the end of March 2015 (Figure 7), SimLoc has been used 77 times out of 234 (33%). Other fault location methods were preferred in 157 cases (67%). In many cases the fault location was visible and did not need advanced tools to find it. In other cases, other fault location methods were used. There were times when the SimLoc support team could not initiate the necessary simulations of the fault location (such as when the support team is off duty on weekends or when the simulation computer is down).

The overall success rate for SimLoc appears to be 52%. The definition of success is when SimLoc predicts the fault location with a precision of less than two manholes. In the log system files, 63 out of the 119 phases on which SimLoc was used to locate a fault were successful (52%) (Figure 8). The successful fault location cases are distributed as follows: 50% for Montreal (57 phases) and 100% for Montmorency (6 phases).

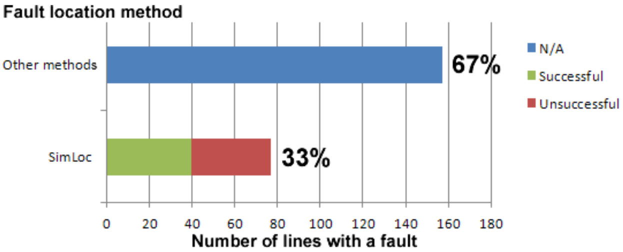

Figure 7 – Number of faulty lines vs Fault location methods, from November 2011 to March 2015

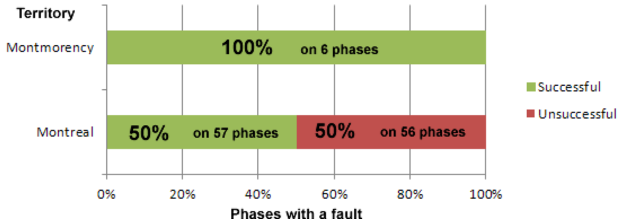

Figure 8 – Success rate percentage with SimLoc, from November 2011 to March 2015

Only the data for 2015 was logged into the system for Montmorency. The information is incomplete for this service area and accounts for the low number of cable phases with a fault location. After a brief survey of the workers in the field, it appears that the statistics for Montmorency should be closer to an 85% success rate. The 15% of unsuccessful fault locations mainly occurred on complex lines because of their many branches. In situations like these, when the fault is very far from the generator (where the SimLoc system is installed), the measured signal of the breakdown is weak and is difficult to match with the simulations. A solution would be to move the generator to an opposite point on the line and to simulate signals from that point as well. However, this is not always possible because of manhole access restrictions or lack of time.

In Montreal, the statistics seem weaker than expected. This can be explained by the fact that the proportion of complex lines is higher in Montreal than in Montmorency. It can also be explained by the fact that SimLoc is less commonly used in Montreal than in Montmorency. Workers have fewer opportunities to develop their skills with the system. Even when SimLoc predicts the fault location, a value can be added to this prediction by analyzing the displayed measured signal. In such a case, the worker's experience comes into play.

FAULT LOCATION USING THE RESONANCE METHOD (COLOC)

CoLoc is a new method for pinpointing faults on an underground cable with a voltage impulse that causes a breakdown. When all other methods fail to confirm the location of the fault, Hydro-Québec workers very often use an electromagnetic impulse detector (Figure 9). This instrument has to be placed directly onto the cable and the workers need to go inside the manhole, which is not always possible because of environmental conditions (water, snow) or because access is not allowed. At Hydro-Québec, workers are not allowed to go inside a manhole when a thermal hot spot or partial discharges were previously detected on a component.

Figure 9 – Electromagnetic impulse detector

The CoLoc tool based on the new proposed method will be placed near the cable (up to three metres away, and possibly farther if the sensor is sensitive enough), but workers will not need to go inside the manhole. Workers will be provided with two indications:

1. The distance from the impulse source to the fault;
2. An indication if the user has just gone past the fault or not while walking along the line (in most but not all cases).

The location by resonance tool measures the magnetic field caused by the impulse source current (thumper discharge) and analyzes it. Before the location of the fault, the magnetic field contains two components in its signal (Figure 10):

A. Fault reflections at higher frequency (from the source to the fault, then back to the source and so on);

B. An oscillation at lower frequency caused by the capacitor of the source and the total inductance of the line (resonance).

In theory, and starting from the impulse voltage source, the resonance oscillation disappears right after the fault location.

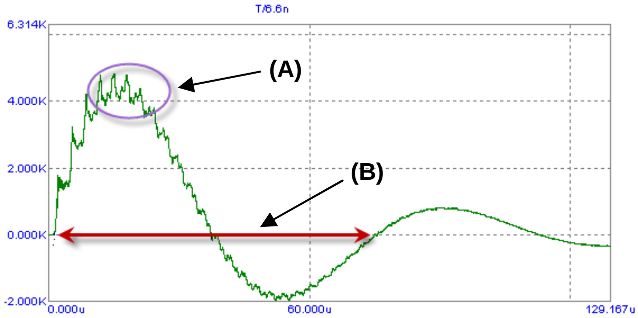

Figure 10 – Measured current (magnetic field)

The four aspects of the method are:

1. Before the fault, the resonance oscillation period always represents the distance from the source to the fault. We call this characteristic "fault location by resonance." The signal contains both the resonance oscillation (lower frequency) and the reflections of the breakdown to the generator (higher frequency).
2. After the fault, the signal only contains the reflections of the breakdown to the end of the line, which is in open circuit. Therefore, the shapes before and after the fault are different.
3. The amplitude of the measured signal is not a concern, only the shape is analyzed (i.e. the distance from the tool to the cable is not a concern as long as it can measure something).
4. Branches before or after fault location do not have any effect on the method.

The above figure (Figure 10) is a typical measurement of the magnetic field in a manhole. The calculation of the distance to the fault is based on the frequency of the oscillation:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}. \qquad [1]$$

C = capacity of the impulse voltage source
L = inductance per metre of line

Below is a schematic of a line with a branch. The impulse generator is connected at the left end and the fault (breakdown) is at the right end.

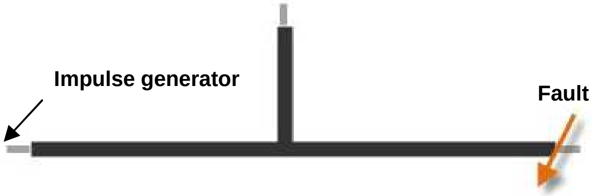

Figure 11 – Schematic of a line with a branch

If the same line is drawn in terms of wired equivalence during the breakdown, the following line is obtained (Figure 12).

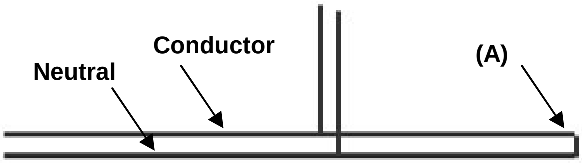

Figure 12 – Wire equivalent line during breakdown

(A): The fault acts as a short-circuit between the conductor and the neutral.

All ends except for the impulse source end and the breakdown end are viewed like open circuits during thumping. The overall electric equivalent diagram is as follows:

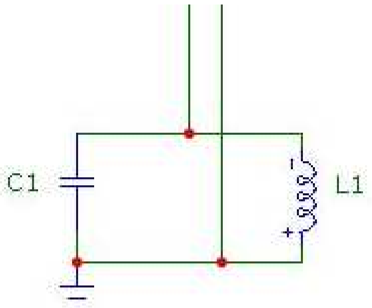

Figure 13 – Electrical equivalent circuit during breakdown.

C1: Source capacity
L1: Total line inductance

The opened branch does not add any inductance to the total inductance of the line and has no effect on the calculation method.

In the real world, the behaviour of each breakdown differs from the fault impedance, temperature, presence of water, charging time before the breakdown occurs, and several other parameters. But the case studies shown in this paper prove that the results are good enough for locating the fault.

COLOC CASE STUDIES

Research on the new location by resonance method is still in progress and the CoLoc tool is in development. The next cases describe the measurements that were made on Hydro-Québec's underground medium-voltage network to validate the method's potential. In all the following case studies, the fault location was known and measurements were made just before and after the fault.

The impulse generator that was used during the tests has a 4-µF capacitor. The generator connexion cable has an inductance of L = 475 nH/m and is 50 m long. It is important that these specifications be included in the calculations. All the following calculations are based on manual measurements on the graphs. Digital computing would give better precision.

The measurements were taken 1-3 metres from the cable, outside the manholes, using a custom antenna, an amplifying circuit and an oscilloscope.

Case study 1: DEL-101 line (Montreal)

This line has three branches and a total cable length of 4928 metres (Figure 14).

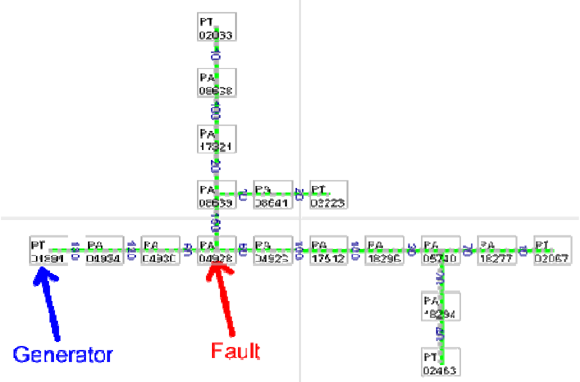

Figure 14 – Schematic of the topology of the DEL-101 line (distances between manholes are not proportional)

- Distance to the real fault: L = 175 m
- Cable type: 500 MCM
- Cable inductance: 238 nH/m

Below are samples of the measurements made on the line.

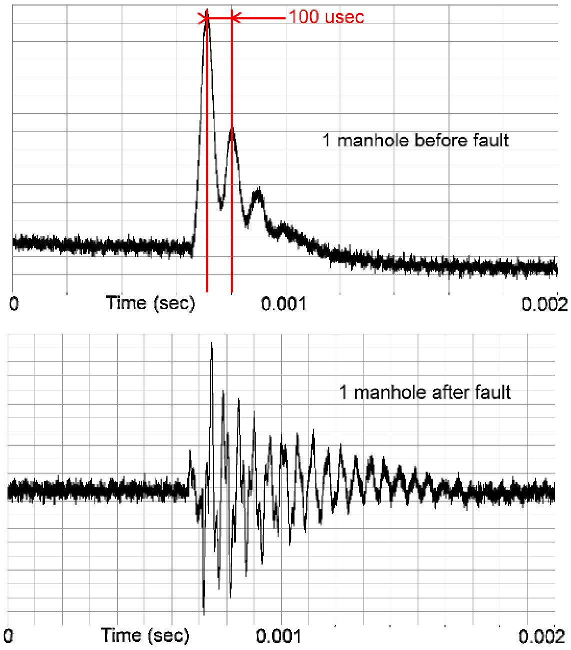

Figure 15 – DEL-101 line, one manhole before the fault and one manhole after the fault

In this case, the lack of lower frequency resonance oscillations clearly indicates that the fault was passed. The measured resonance oscillation has a period of 100 µsec. Calculations show that it corresponds to a distance of 165 m compared to the real fault distance of 175 m.

Case study 2: ATW-235 ØB line (Montreal)

This line has one 30-metre branch and a total cable length of 2,463 metres (Figure 16).

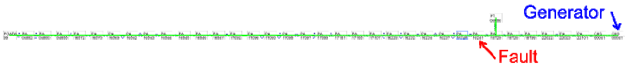

Figure 16 – Schematic of ATW-235 ØB line topology (distances between manholes are not proportional)

- Distance to the real fault: L = 380 m
- Cable type: 500 MCM
- Cable inductance: 238 nH/m

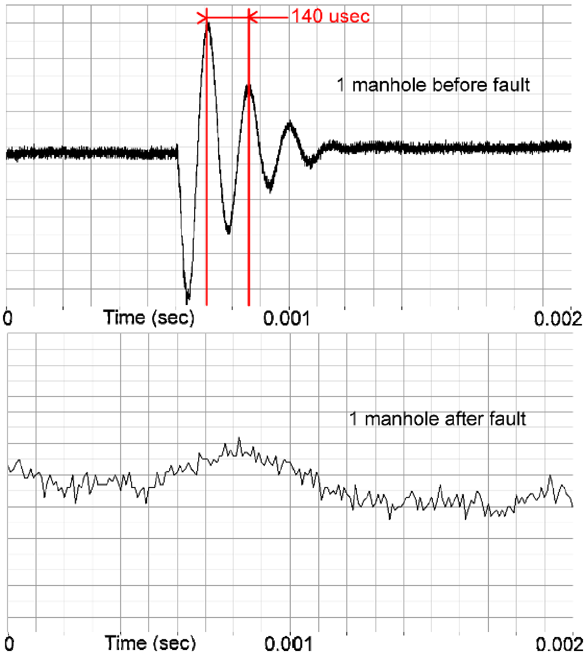

Figure 17 – ATW-235 ØB line, one manhole before the fault and one manhole after the fault

The signal after the fault location was undetectable. Only a low-intensity signal noise was recorded. The signal is clearly different before and after fault location.

The measured oscillation has a period of about 140 µsec. Based on our calculations, it corresponds to a distance of 415 m compared to the real fault distance of 380 m.

Case study 3: *ATW-235 ØC underground MV line (Montreal)*

This line has one 30-metre branch and a total cable length of 2,463 metres (Figure 18).

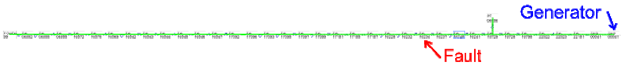

Figure 18 – Schematic of the topology of the ATW-235 ØC line (distances between manholes are not proportional)

- Distance to the real fault: L = 591 m
- Cable type: 500 MCM
- Cable inductance: 238 nH/m

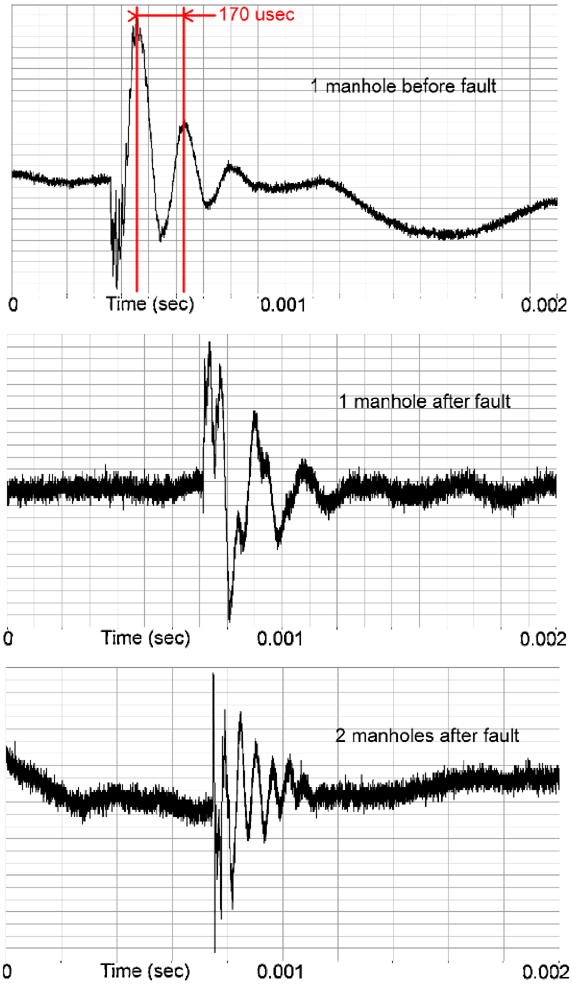

Figure 19 – ATW-235 ØC line, one manhole before the fault, one and two manholes after the fault

It is interesting to note that the signal shape starts to change at fault location but the resonance oscillation disappears only two manholes after the fault.

The measured oscillation has a period of about 170 µsec. The calculations show that it corresponds to a distance of 655 m compared to the real fault distance of 591 m.

Case study 4: *RNC-278 underground MV line (Quebec City)*

This line has no branch and a total cable length of 4,579 metres (Figure 20).

Figure 20 – Schematic of the topology of the ATW-235 ØC line (distances between manholes are not proportional)

- Distance to the real fault: L = 240 m
- Cable type: 750 MCM
- Cable inductance: 160 nH/m

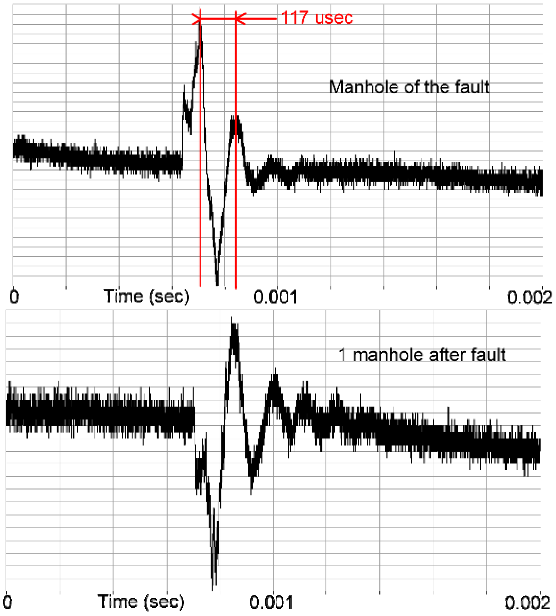

Figure 21 – RNC-278 line, manhole of the fault and one manhole after the fault

In this case, the first measurement was at fault location. The signal is slightly distorted compared to an expected signal before the fault.

The measured oscillation has a period of about 117 µsec. Calculations show that it corresponds to a distance of 390 m compared to the real fault distance of 240 m. It is a decent result on a 4.5-kilometre line. However, in this case the resonance oscillations do not clearly disappear after the fault. They tend to indicate that the fault characteristics come into play. Depending on how bolted the fault is, some signal can still remain on the rest of the line.

CONCLUSION

Hydro-Québec Distribution has implemented the SimLoc method to make fault location times shorter and more consistent, and to facilitate staff training and work planning. These objectives have been attained. The statistics for successful fault locations with this system are below expectations for the Montreal service area. It is a question of allowing workers time to gain experience and the utility to fully integrate SimLoc into its operational processes, including data logging of the fault location information. The statistics for the first three months of 2015, in both the Montreal and Montmorency service areas, tend to prove this to be the case (Figure 22).

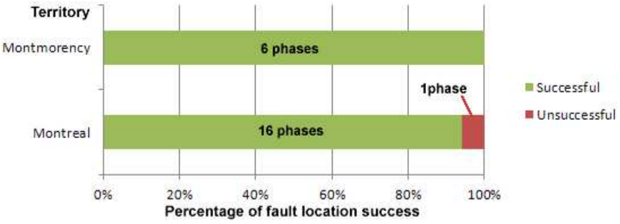

Figure 22 – Fault location success rate for the first three months of 2015

Field measurements (case studies) show that the CoLoc method seems promising. The results have proven that it works for both determining the fault distance and locating the fault. Some results are more difficult to interpret than others (Case study 4 - Figure 21). This seems to be caused by the type of fault (low or high impedance) that can significantly impact the measured signal. Also, the evaluated fault distance is directly dependent on cable inductance. If these inductances are not known, it will be interesting to see what the error range is using a default inductance value. All these aspects will have to be taken into account for the remaining development stage.

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GLOSSARY

CoLoc: confirmation of localization

IREQ: Institut de recherche d'Hydro-Québec (Hydro-Québec's research institute)

SimLoc: simulation and localization

PILC: paper-insulated lead cable

MCM: 1 MCM = 1 kcmil = 0.5067 square milimeters

XPLE: cross-linked polyethylene