Reporting on the Last 6 years of Field Inspections Using LineCore for the Non-Destructive Evaluation of Overhead Conductors

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I. SUMMARY

Hydro-Québec operates one of the largest electric grids in the world with almost 35000 km of high-voltage lines. Several overhead lines (mostly ACSR) were built hundred years ago and may suffer from galvanic corrosion. About 10 years ago, Hydro-Québec begins working on an eddy current non-destructive testing device to assess corrosion of ACSR and other conductors, the LineCore. The sensor works almost like a transformer, but the coupling between the primary and the secondary depends on the state of corrosion of the ACSR. Even if ACSR construction is complex (X aluminum strands and Y steel strands) and contacts between aluminum strands and/or contacts between steel strands can create screening currents, Hydro-Québec model allows to assess the condition of the galvanic protection (zinc coating). Further analysis can also show aluminum and steel losses. The LineCore also works on energized line.

The LineCore can measure corrosion on many ACSR construction but needs adapted deployment devices depending on lines configuration. To get maximum flexibility, Hydro-Québec several deployment devices has been such as LineScout, LineRanger, LineDrone and Motorized LineCore. The LineScout can cross obstacles and travel long distance. The LineRanger can only cross spacers but is much easier to use. The LineDrone allows installation from the ground instead of from the transmission towers. The Motorized LineCore is a complete solution, i.e., the LineCore already has its own motorisation system. However, it must be installed on each span and can be used only on 120 to 345 kV lines.

Between 2014 and 2020, Hydro-Québec performed 50 LineCore inspections (most of them in 2019-2020) using the most efficient deployment devices for the line configuration. This represents a total of 200 km mainly on the oldest overhead lines (more than 80 years old with only 2 layers of aluminum) and on lines in harsh environment. A particular LineCore inspection shows localized corrosion close to the middle of a span, a feature that was not identified using destructive evaluation where sampling is taken on a few meters of conductors located close to transmission towers. Another inspection clearly reveals the replacement of a conductor compared to the other conductors of the span showing again the capability of the LineCore.

A recent review of the collected inspection data revealed that 50 % (of 200 km of aged lines) are healthy, 30 % shows partial zinc losses, 15 % presents severe zinc losses and 5 % shows possible aluminum losses. These results where in fact encouraging about the state of these aging lines, and very useful in prioritizing the few areas that required further investigation, or in justifying conductor replacement programs for the more affected areas.

KEYWORDS

LineCore, ACSR, Corrosion, High-Voltage Lines, LineScout, LineRanger, LineDrone, Hydro-Québec, Aging, Zinc

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II. INTRODUCTION

Hydro-Québec operates the largest electric grid in North America with more than 500 substations and almost 35000 km of high-voltage lines [1] where several lines on Hydro-Québec grid are more than 80 years old or cross large rivers and major roads. The category of conductors mainly used on Hydro-Québec overhead lines are Aluminum Conductor Steel Reinforced (ACSR). When those conductors ages or must sustain harsh environments, the galvanic protection against corrosion (zinc coating on core strands) gradually thins until it disappears, and aluminum strands start to corrode. The LineCore is Hydro-Québec solution to assess the thickness of the zinc coating especially sensitive between 0 to 50 µm. LineCore inspections' raw data are interpreted using an abacus which defines five levels of corrosion. Global corrosion indexes are also proposed to facilitate interpretation of the inspection results.

In this paper, we present Hydro-Québec LineCore deployment devices such as LineScout, LineRover and LineDrone which provides flexible solutions depending on the particularity of the span inspected. Subsequently, LineCore operating principles are explained. We discuss how we assess the effect of screening current created by aluminum layers. Finally, we summarize the inspections performed by Hydro-Québec between 2014-2020. We also discuss interesting results on few inspection cases.

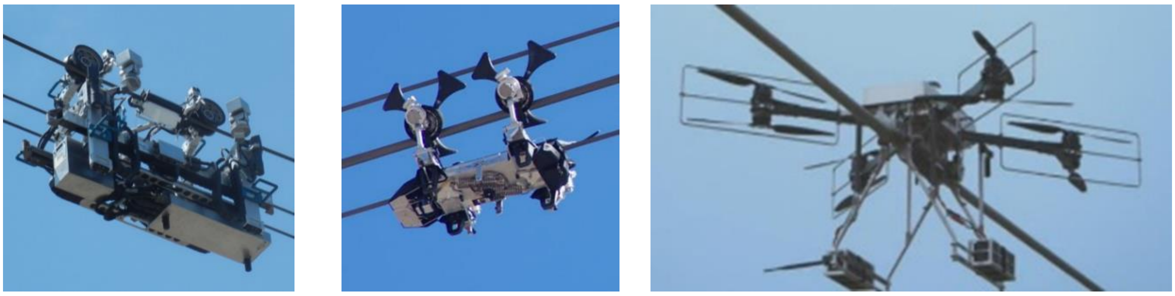
III. LINECORE DEPLOYMENT DEVICES

Figure 1: LineCore standalone

The LineCore device comes in two versions: (i) the LineCore standalone which can be mounted on Hydro-Québec's or other providers' deployment devices and (ii) a motorized LineCore which can be directly installed on high-voltage lines for inspections. Figure 1 shows the LineCore standalone. The 3 first lines of Table 1 give context of deployment, advantages, and disadvantages of Hydro-Québec deployment devices for the LineCore standalone. For example, the LineScout can cross obstacles along the way and travel long distance. The LineRanger is easier to use than the LineScout and can roll on bundled configuration. The LineDrone flies directly onto the line, so that a small crew is needed for its deployment, unlike other means that require the transmission tower to be climbed by line crew members. Figure 2 shows LineCore standalone deployment devices. The Motorised LineCore is equipped with a build-in deployment device. The Motorized LineCore is simple of use, mostly used on 169 kV and below lines, that features short and low hanging spans. It needs to be re-installed at every span. Figure 3 shows Motorized LineCore with its most important components and an example of its installation on high-voltage lines.

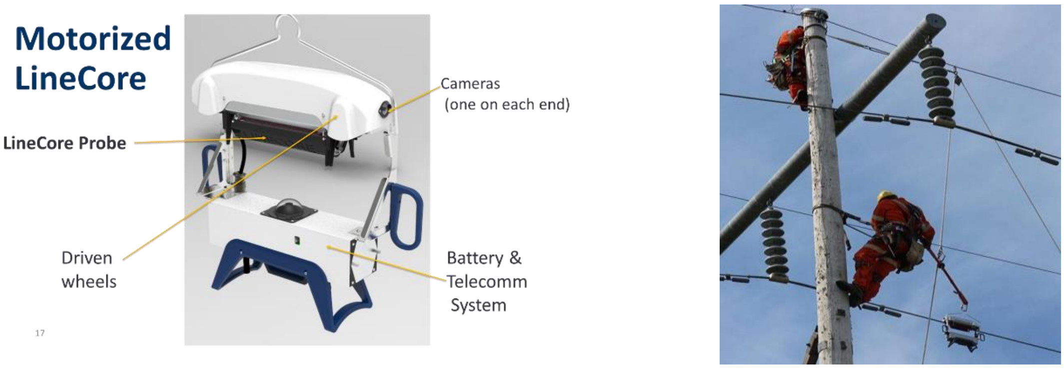
Table 1: A list of LineCore deployment devices including the context of deployment, advantages, disadvantages, and pictures of them

Deployment devices	Context of deployment	Advantages	Disadvantages	Figure
LineScout	Mono-conductor, multi-spans, obstacles along the way	Long distances, long autonomy. Safe over rivers or road crossings	Heavy and greater complexity to operate	2a
LineRanger	Bundles of conductors with spacers	Simple of use	Limited to the two (2) lower conductors	2b
LineDrone	Single span measurements	Small crew, very quick turnaround	Limited areas where flight is allowed	2c
Motorized LineCore	Mostly lower voltage, short and low hanging spans	Simple of use	Need of installing LineCore at every span.	3a



(a) (b) (c)

Figure 2: LineCore standalone deployment devices **(a)** LineScout **(b)** LineRanger **(c)** LineDrone



(a) (b)

Figure 3: The motorized LineCore **(a)** a brief description of its components **(b)** installation on lines

IV. LINECORE OPERATING PRINCIPLES

The LineCore is an inductive sensor operating like a transformer. The primary coil is a solenoid excited with a high frequency alternating current. The secondary is an encircling coil located in the center of the solenoid and the section of conductor inserted in the solenoid makes the core of the transformer. Unlike an electric transformer, the operating frequency is selected to induce current close to the surface of individual strands. These currents, better known as eddy current, undergo the well know skin effect: at high frequency, the induced current is constrained to the surface of the strand [2,3]. The frequency injected in the solenoid is chosen so the skin effect in a galvanized strand is confined to the zinc layer. For a brand new ACSR, say a 54x7, the LineCore response will be the sum of the contribution of 54 aluminum and 7 zinc coated strands. The zinc acts like a screen by hiding the presence of the steel strands. As the zinc coating thins with time by galvanic corrosion, the eddy currents will penetrate to the steel strands and the LineCore response will display an important shift of the signal (both in phase and amplitude) by the ferromagnetic nature of steel. The coil design and the characteristics of the test parameters were chosen to get an optimum response for zinc coating in the range of 0 to 50 microns.

Screening Currents

The main difficulty in applying the LineCore technology is the presence of unwanted induced currents circulating between strands. A conductor is a multilayered construction with strands alternatively winded in opposite direction. Several contact points are present between strands on the same layer, or from layer to layer, which allow induced currents to jump from strand to strand. Induced currents can thus cross at contact points and circulate along the outside circumference of the conductor, or follow an irregular pattern using interlayer contact bridges. The effect of these “screening currents” is to damp the magnitude of the flux flowing inside the conductor and thus hiding the presence of the galvanized-steel reinforced core. The presence of strong screening currents is a sign of good inter-strand contact and thus the absence of corrosion inside the ACSR. As the contact points between strands start to oxidize, screening currents will drop in intensity, and the sensing flux will reach the steel core. The LineCore analysis software uses a mathematical model to compute the response caused by screening currents and their presence confirms the absence of galvanic corrosion.

Data Analysis

As previously stated, the LineCore response is the combined effect of the aluminum and the galvanized strands. The signal is analysed to extract valuable information on the condition of the aluminum strands and of the steel strands' zinc coating, even in presence of screening currents. The most probable degradation scenario starts with water ingress that attacks inter-strand contact points. From the LineCore analysis model, this means that screening currents will decay and the LineCore will sense an average zinc coating in the nominal range from approximately 30 to 60 microns thick. Once rainwater reached the galvanized core, galvanic corrosion will attack the zinc coating starting with the outer circumference of the core. At this point, the signal will begin its journey through the corrosion bands. The signal will progressively demonstrate excursion in the corrosion band region as the galvanic corrosion keep stripping more zinc.

Mathematical analysis, supported by laboratory measurement, shows that the response to loss of zinc is more pronounced in the range between 0 to 20 microns. Thus, zinc corrosion regions have been subdivided in three states: possible loss (10-20μm), partial loss (5-10 μm) and severe loss (0-5 μm). The zinc thickness reported is an average on all steel strands and is indicative of the degradation of the galvanic protection. The next step in the corrosion degradation is the loss of aluminum cross sectional area. The last corrosion band illustrates the locus for aluminum loss. At this point in degradation, the conductor is losing its ability to transport power and its remaining lifetime has drastically been shortened.

Advantages of LineCore

The main objective with the LineCore is to assess the condition of the galvanic protection and report spans with acute degradation of the zinc coating. Inspection campaigns were planned to validate LineCore analysis and included visual inspection with on-board robotic cameras. Supplementary magnetic flux leakage inspections and conductor sampling operations can be undertaken to further confirm the diagnosis. A correlation was made between LineCore Data and other source of information, and it demonstrated that the analysis mathematical model can also be used to detect other conditions than zinc loss. An informed analysis of LineCore data can then proceed with the following evaluations of a span:

- Identify total loss of zinc and general condition of the galvanic protection
- Corrosion of aluminum strands with/without zinc loss
- Damage to the ACSR outer layer
- Steel core corrosion

Energized Line

Robotic delivery systems and the LineCore has the capability to be deployed on energized lines. Laboratory works and field inspection proved that there is no drawback in applying these solutions to an energized line. Current load of up to 200A has no effect on the LineCore response. With higher currents, in the range of 400-1000A, the steel core is slightly magnetized by the load current, and this translates into a small incremental change in the permeability that is sensed by the LineCore. There are two scenarios with high current load: (1) when the galvanization is in good condition, the LineCore does not sense the presence of steel strands and the magnetic effect is unnoticed. (2) when the galvanization is degraded, the signal of permeability variations has a characteristic direction that is in quadrature with the zinc loss signal. The two effects, permeability variation and zinc loss, are easily separated during analysis because the data is plotted on an overlay where the grid shows the direction of permeability variation.

V. SUMMARY OF INSPECTION DATA FROM 2014 TO 2020

Selection of the most critical lines for inspection

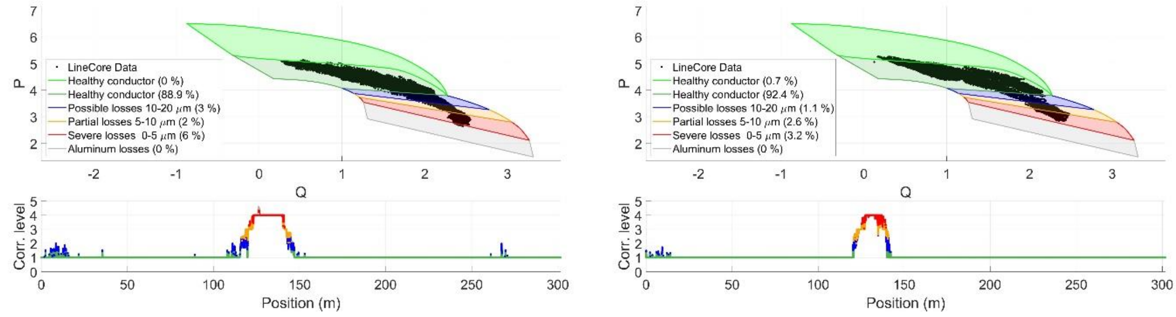
Since Hydro-Québec has the largest grid in north America, a total of 34000 km of high-voltage lines, inspection sites must be prioritized, and specific lines must be slotted in a multi-year schedule. For inspections performed between 2014-2020 (a total of 50 LineCore inspections), a selection of 200 km of high-voltage lines has been made in terms of age (lines over 80 years old), harsh environment (river crossing, industrial zones, highways) and previous visual inspections (aluminum corrosion, broken strand). Figure 4 shows a histogram of all the inspected length of cables along their commissioning year. It shows that more than 60 % of the inspections were made on lines being over 80 years old, lines having a higher probability of showing corrosion. The conductor types installed on those old lines are mostly Partridge, Hawk and Lark, all made of 7 steel wires and comprising only 2 aluminum layers which tends to be more susceptible to corrosion. The remaining inspections were mostly made on river crossing high-voltage lines which are inspected every 10 years. Few results of inspection are presented in the next section.

Figure 4: Percentage of inspections performed between 2014-2020 versus the year of commissioning of the high voltage lines

Some examples of LineCore inspections

In this section, we focus on two LineCore inspections: (i) one showing localized corrosion of Duck conductors (54 aluminum wires and 7 steel wires) and (ii) one showing corrosion of the galvanic protection of river crossing conductors (42 aluminum wires and 19 steel wires) as well as a replacement of a conductor on one phase. Figure 5 shows LineCore data (clouds of black dots) of Duck conductors in the abacus for two different phases. The legend shows that around 90 % of the conductors are healthy, i.e., 90 % of LineCore data falls within the green zone. The 10 % remaining shows possible to severe losses. When looking at the chart, one can see that the corrosion is localized between 120 m to 150 m for the two conductors on different phases. Moreover, there is no visual sign betraying the presence of corrosion and this demonstrate LineCore's ability at revealing hidden internal corrosion.

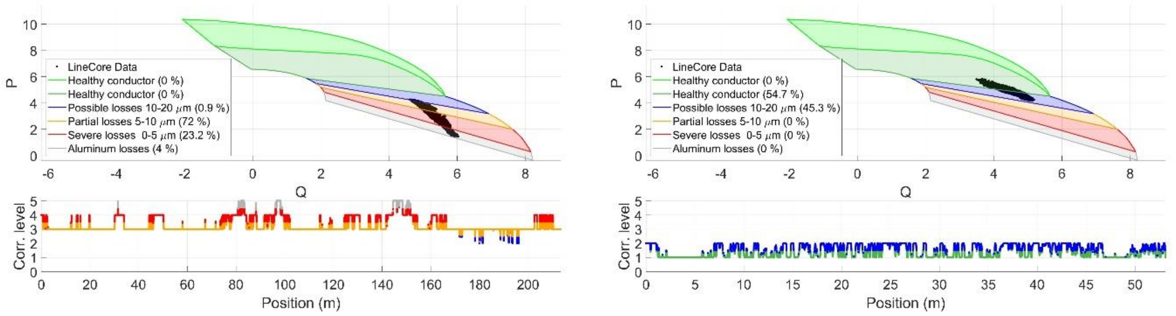
The cause of corrosion is not identified yet, but the most probable hypothesis is a stream of water coming from a close hydroelectric dam, but other tests using a magnetic probe will be carried out. Many situations can produce a localized degradation of the galvanic protection such as (i) highway crossing, (ii) span located downwind of an industrial complex and (ii) damage to the outside aluminum layer. Interestingly, one can also note that taking out a sample near one of the transmission towers, which is a more classical methods of assessing the conductors' condition, would have miss the decaying mid-span condition.



(a) (b)

Figure 5: LineCore data plotted in the abacus (top figure) showing the state of corrosion of Duck conductors versus the position (bottom figure). The legend indicates the percentage of Duck conductors in five states of corrosion (actually six states but both green states indicate a healthy conductor). **(a)** LineCore measurement on phase A and **(b)** LineCore measurement on phase B

Figure 6 shows LineCore data of ACSRs containing 42 aluminums wires and 19 steel wires which crosses St-Laurent River. In Figure 6a, one can see that the data mostly fall within partial to severe losses (corr. level of 3 and 4 with 10 µm to 0 µm of zinc remaining) of galvanic protection. The drop of signal in the last band (aluminium losses) means that aluminum strands corrosion may have begun and that remaining service life of this conductor is short. Figure 6b shows LineCore data for a conductor that has already been replaced on the same span. The results indicates that the conductor is healthier since there is at least 10 µm of zinc coating on average along the conductor. There are many other cases where the LineCore reveals an “undocumented replacement” of a conductor.



(a) (b)

Figure 6: LineCore data plotted in the abacus (top figure) showing the state of corrosion of river crossing conductors versus the position (bottom figure). The legend indicates the percentage of duck conductors in five states of corrosion (actually six states but both green states indicate a healthy conductor). **(a)** LineCore measurement on phase A and **(b)** LineCore measurement on phase B

Definition of global corrosion index

As previously discussed, the abacus gives the percentage of conductors in five states of corrosion defined as **1)** Healthy conductor, **2)** Possible losses 10-20 µm (of galvanic protection), **3)** Partial losses 5-10 µm, **4)** Severe losses 0-5 µm and **5)** Aluminum losses. Using these five states of corrosion, we propose a definition for a global corrosion index which gives an overview of the state of corrosion for a given span, featuring a single number $\boldsymbol{I_g^c}$ between 1 and 5. With this definition, an index of 1 means a healthy conductor while an index of 5 means a highly corroded conductor. The index is defined by the following equation (1):

$$I_g^c = ceil\{1 \times (\%\,Healthy) + 2 \times (\%\,Possible) + 3 \times (\%\,Partial) + 4 \times (\%\,Severe) + 5 \times (\%\,Aluminum)\}$$

We also proposed a second index $\boldsymbol{I_w^c}$ to give the worst corrosion state of the span. For example, the conductor in Figure 5b will have $I_g^c = 2$ and $I_w^c = 4$. The conductor in Figure 6a will have $I_g^c = 4$ and $I_w^c = 5$. Indeed, we encountered lines where $I_g^c = 1$ and $I_w^c = 1$ which are not showed in this paper. In the end, with these two-corrosion index, it is easy to spot critical lines or spans and take action if necessary.

Mapping degradation of Hydro-Québec high-voltage lines

As said previously, Hydro-Québec has been monitoring the state of corrosion of its 34000 km of high-voltage lines for over 6 years. A recent review of the collected inspection data (mostly on lines over 80 years old or in harsh environment) revealed that 50 % (of 200 km of aged lines) are healthy, 30 % shows partial zinc losses, 15 % presents severe zinc losses and 5 % of possible aluminum losses. These results where in fact encouraging about the state of these aging lines, and very useful in prioritizing the few areas that required further investigation, or in justifying conductor replacement programs for the more affected areas. That review allows Hydro-Québec to begin mapping its high-voltage lines degradation using the indexes defines above in a decision support tool.

This decision support tool, see Figure 7, allows to regroup and exploit all the data of five categories which includes (i) equipment (ii) environment (iii) maintenances history (iv) visual inspections and (v) LineCore inspections. The equipment data includes the kind of conductor, transmission towers, historic of transit current or line fault tripping which can help identify premature degradation. The environment can cause degradation in various ways such as chemical aggression (industry, road, saltwater body) and climatic aggression (wind, ice, thunder, fire). Visual inspections give a general view of the conductor, but the LineCore data give the internal state of corrosion of conductors which is highly valuable.

The decision support tool also includes models (in development) that evaluate the level of degradation of Hydro-Québec lines and predict their remaining lifespan. In the end, the decision support tool help to justify scientifically and economically investment strategy in renewal and maintenance of assets. The decisional needs are divided over three-time horizons:

1. Strategical planning (0-50 years),
2. Grid project planning (0-15 years),
3. Planning of maintenances and inspections (0-3 years).

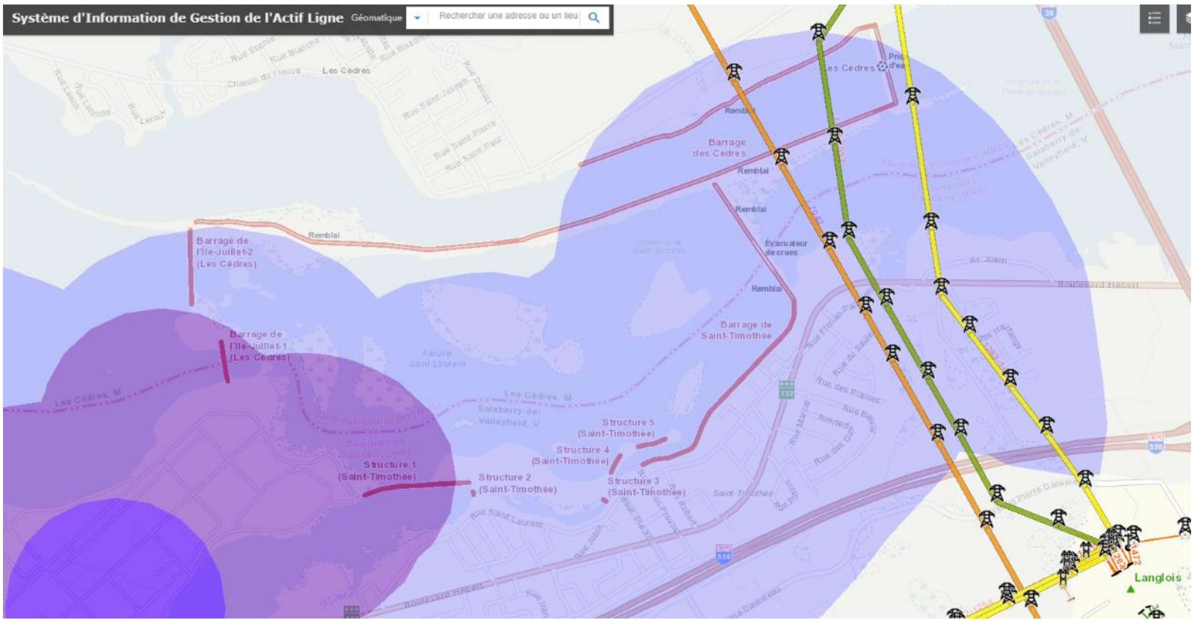


Figure 7: Example of the decision support tool showing lines in green, yellow and orange depending on the level of degradation and color zones indicating the type of environment

VI. KEY FINDINGS & CONCLUSIONS

In this paper, we have summarized the capability of the LineCore along with its deployment devices, and inspections performed with it between 2014 and 2020. The LineCore was designed to be very sensitive to the galvanic protection (zinc coating) between 0 to 50 µm. Even if the LineCore is mostly used to detect losses of the galvanic protection, further analysis allows to assess aluminum and steel losses. The aluminium layer in ACSR conductors creates screening currents hiding the steel core. However, the model built by Hydro-Québec and used to interpret LineCore data take screening currents into account. Moreover, the LineCore can be used on energized line as it is included in Hydro-Québec model.

Without deployment devices, the LineCore cannot performed any measurement. Hydro-Québec developed several deployment devices such as LineScout, LineRanger, LineDrone and Motorized LineCore. Those deployment devices offer flexibility depending on obstacles encounter, the distance to be covered, the line voltage or environment below the line.

Between 2014 to 2020, the LineCore was used over a total of 200 km of high-voltage lines on specifically chosen lines having over 80 years old (more than 60 % of inspections) or located in harsh environment. A case study shows that galvanic corrosion can be very localized, i.e., few tens of meters on hundred meters of span. A destructive testing like conductor sampling on only few meters of conductor cannot reveal that galvanic corrosion located in the middle of the span showing the capability of the LineCore. To easily interpret the data, two indexes have been proposed: (i) one indicates the global galvanic protection and (ii) one indicates the worst galvanic corrosion measured. Those indexes are included in a decision support tool which helping in strategical planning (0-50 years), grid project planning (0-15 years) and planning of maintenances and inspections (0-3 years).

Hydro-Québec's LineCore has proven its worth as a useful tool to detect corrosion in ACSR conductors. In 2021 and beyond, Hydro-Québec will perform plenty of other inspections to keep the condition of the conductors of its high-voltage lines up to date. Finally, Hydro-Québec concludes an agreement with Nucleom for the commercialization of the LineCore as well as the LineOhm (another Hydro-Québec NDT device) [4].

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