VERIFICATION OF LV UNDERGROUND CABLE INSULATION BY AIR INJECTION

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ABSTRACT

This paper presents the development of a new method for verifying the mechanical integrity of the insulation of low-voltage cables in order to ensure a quality installation and prevent potential arcing faults. The approach consists in injecting compressed air into the cable core and to observe the subsequent pressure variations. The diagnosis of insulation failure (leak) is based on the reduction rate of the pressure of the air stored in the cable once the injection has been stopped. Conclusive results were demonstrated during a comprehensive laboratory validation program as well as on the distribution network. Prototypes developed based on this method were successfully tested on Hydro-Québec's underground distribution network.

INTRODUCTION

The development of an arcing fault on low-voltage (LV) cables in an underground duct is likely to have harmful consequences. Gases generated by the degradation of materials near the fault (pyrolysis of insulating materials and/or electrolysis) may create violent explosions. The main cause of this phenomenon on Hydro-Québec's network is likely insulation failure (latent fault) which dates back to when the cables were installed.

Conventional protection systems (e.g. fuses, circuit breakers) are not capable of eliminating this type of fault, which is often intermittent. It develops quite randomly and may occur over a long period of time (even hours). Furthermore, dielectric tests are not effective for detecting insulation failure in a dry environment.

Several studies were conducted in the past on this phenomenon [1, 2]. In 2003, CEA Technology carried out a research program in view of developing a solution to quickly interrupt arcing faults [3]. Several universities and utilities, including Hydro-Québec, took part in the program. However, the study concluded that there is no effective way of preventing arcing faults at an affordable cost using an electrically-based approach.

A certain number of faults of this type occurred on Hydro-Québec's low-voltage distribution system as well as at other electrical utilities with the same type of installation. Though their frequency is very low, the consequences can be serious for public safety and for the installations.

An example of an explosion in an underground vault with the manhole being ejected is shown in Figure 1.

Figure 1. Explosion in an underground vault

To deal with the situation, Hydro-Québec decided to develop a new method and device for verifying the mechanical integrity of the insulation of the low-voltage cables installed in ducts by pulling.

The cables used in Hydro-Québec's low-voltage underground distribution network (240/120 V and 600/347 V) are made up of a core formed of aluminum or copper strands, and an insulating sheath made of cross-linked polyethylene (Fig. 2). The cable/neutral assembly, consisting of two or three single-phase cables (2 AWG to 1000 kcmil) with a copper neutral, is installed in the form of a twisted bundle in a PVC duct.

METHOD

The new method for verifying the insulation of LV cables consists in injecting compressed air into the cable core and of observing the changes in pressure after the injection is stopped. The detection of insulation failure (leak) is based on the reduction of the pressure of the air contained in the cable.

Each cable can be verified separately or, for multi-phase electrical cables, the conductors in a bundle can be looped. There is an advantage to connecting several cables in a loop since this simplifies the acquisition and transmission of the pressure measured at the ends. In addition, this approach considerably shortens the testing time compared to separately verifying each cable.

Numerous tests were conducted in the laboratory to develop a method based on this principle that is capable of meeting the performance requirements related to its implementation on Hydro-Québec's distribution network.

Several variants were assessed regarding the optimal way of injecting air into the cable and the effectiveness of diagnosing a small leak. The tests were conducted with different types of calibrated faults that were simulated by perforating the layer of electrical insulation up to the cable core (Fig. 2).

Laboratory tests	Fault						
	No fault	Peak	0.5 mm hole	1 mm hole	1.5 mm hole	2 mm hole	6-12 mm cut
Total - type of fault	57	51	21	68	15	20	37
Total - tests	269						

Figure 2. Tests with simulated faults

The method that was subsequently retained is characterized by optimal diagnostic duration and reliability, as well as by its ability to automate the verification process. It consists of the three phases presented in Figure 3.

Phase 1 – Filling. During an initial part of the filling phase, the compressed air is injected through one end of the loop (pressure p_1). The injected air penetrates between the core's strands and makes its way inside the cable. The resistance in opposition to the air flow is characterized by a time constant *cT*, defined as the duration needed for the pressure p_2 to begin to rise at the other end of the cable. This duration increases with the length of the cable and compaction of the strands, and decreases with the size of the conductor. The time constant thus characterizes the pneumatic impedance specific to each cable.

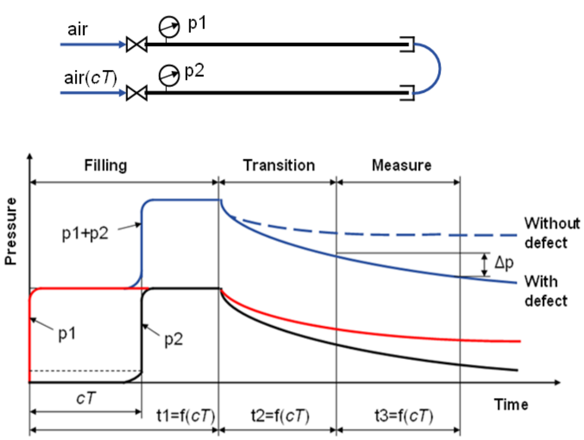

Figure 3. Principle of the chosen method

From this moment, during the second filling period, the compressed air is injected simultaneously through both ends, for a duration that is a function of the time constant of the cable. This phase, of a duration t_1, ends with the closing of the filling valves at both ends.

Phase 2 - Transition. The filling phase is followed by a transition phase of duration t_2, which is also a function of *cT*. During this phase, the pressure stabilizes in the cable.

Phase 3 - Diagnosis. Lastly, a diagnostic period of duration t_3 completes the verification of cable insulation tightness. The "leak" or "tightness" diagnosis is based on the drop Δp of the sum of the two pressures $p_1 + p_2$ during the period of time t_3. Such a diagnosis is more reliable and faster due to the variation in the sum of pressures which is more pronounced than the variation in pressure p_1 or p_2 alone. After a diagnosis is obtained, the test is completed and the cable is depressurized.

The laboratory test was used to determine the optimal values for the main parameters of the method, i.e.: i) the duration of the three characteristic phases of the test t_1, t_2 and t_3, ii) the air injection pressure p and, iii) the leak/tightness diagnostic criterion, defined by the drop in pressure Δp during the period t_3.

Parameters i) Optimized experimentally, the duration of each of the three test periods is expressed as a function of the time constant as follows: t_1=1,5 *cT*, t_2=1 *cT*, t_3=1 *cT*. In this manner, the total duration of the test is adapted to the pneumatic impedance of a specific cable, the time constant of which is measured automatically.

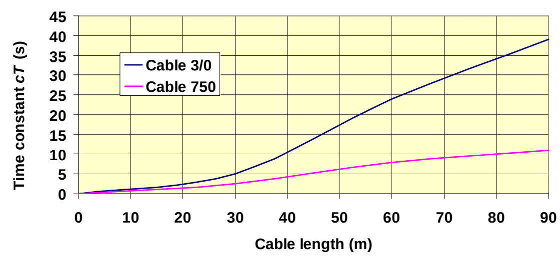

Figure 4. Time constant vs. length for 3/0 AWG and 750 kcmil cables

For instance, Figure 4 shows the change in the time constant as a function of the length of the 3/0 AWG and 750 kcmil cables. For a given length, the time constant of the small-diameter 3/0 AWG cable is considerably greater than the time constant of the large-diameter 750 kcmil cable. As a result, the test duration for these two cables shall be proportionate to the time constants.

Parameter ii) The air injection pressure results from a compromise between the test duration and the tightness of the test system, as well as the integrity of the cable insulation. Taking these constraints into account, the optimal injection pressure was established at about 75 psi (~517 kPa). Figure 5 presents a sample test duration for a 90-m-long 750 kcmil cable as function of the air injection pressure and type of insulation fault. The figure shows that a decrease in the pressure of the injected air causes the test time to be extended. However, this increase remains rather moderate since, for the case shown in Figure 5, the reduction in injection pressure from 100 to 50 psi extends the test duration by a factor of about 1.25.

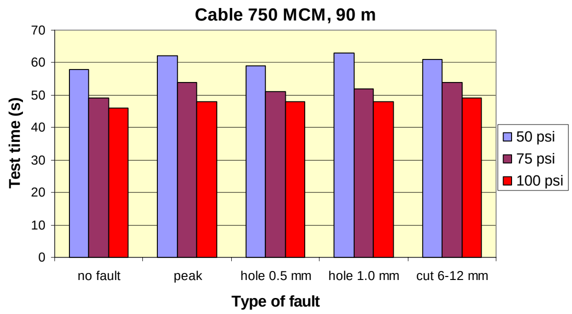

Figure 5. Air pressure vs. test duration

Parameter iii) Figure 6 presents the diagnostic results for a group of cables tested in the laboratory. Each point represents the decrease Δp in the sum of the pressures at the cable ends during the time interval t_3. The blue dots represent the cables without any defects, while the red dots correspond to the cables with different types of insulation punctures. A clear division can be observed between the two groups of points. All the dark-blue dots are found below the pressure drop equal to 2 psi, while the red dots are above this level. The red dots closest to this level correspond to the small puncture created with a needle-point where the diameter is less than 0.5 mm.

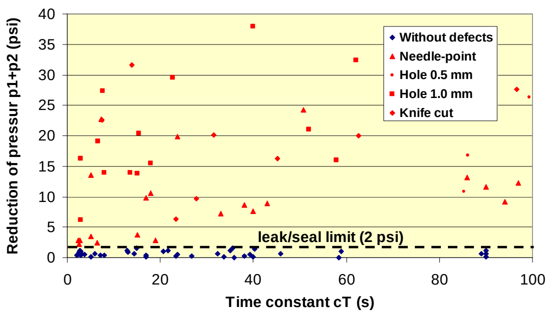

Figure 6. Diagnostic criterion

This observation led to the determination of a leak/tightness diagnostic criterion, i.e. if the drop Δp of the sum of the pressures at the ends $p_1 + p_2$, measured over the time period $t_3 = 1\ cT$, is greater than 2.5 psi (~0,172 kPa), cable insulation failure is diagnosed. Otherwise, the cable is considered to be in good condition for service.
An exaggerated value of the time constant cT, measured during a test, constitutes an additional leakage diagnosis criterion. Based on the experience that was acquired, if the time constant exceeds 180 s, this means that either the cable is seriously damaged or there is a major leak at the pneumatic connections that have been incorrectly installed. In case of doubt, it is recommended that the seal of all the air connections be checked and the test to be done again.
In summary, the complete validation program revealed the following performances for the method that was developed:

- The method is effective for detecting holes less than 1.0 mm in diameter on cables over 200 m in length.
- The diagnostic duration ranges from about one minute to a few minutes, mainly depending on cable size and length. It is automatically adjusted based on the pneumatic impedance of the test cable in order to minimize the test time.
- The test in the environmental chamber showed that the diagnosis is not affected by ambient air temperature and/or humidity conditions.
- The dielectric properties of the cable insulation are not altered by an air injection pressure of 75 psi (~517).

PROTOTYPE

Based on the method that was presented, a cable insulation verification prototype (VIC) was developed in the form of a stand-alone, fully automated mobile test unit, the design of which is shown in Figure 7.

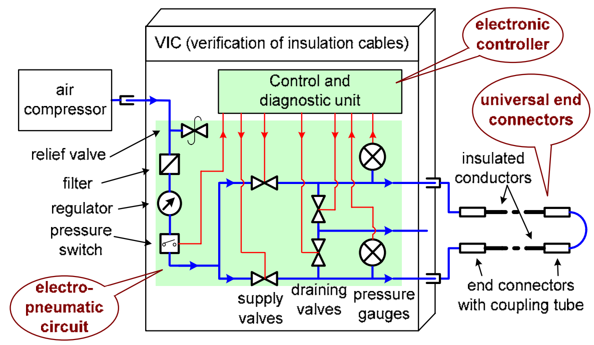

Figure 7. VIC design

There are three main parts:

- An electro-pneumatic system used to inject the compressed air into the cable core.
- An electronic controller with software that makes up the system's intelligence; and
- End connectors and pneumatic hoses to connect the verification device to the cables.

Special emphasis was placed on the development of the end connectors, which must ensure a tight connection for a reliable diagnosis and solid anchoring of the cable to prevent his ejection by the pressure of the injected air.
The end connector is made of reinforced rubber and has a conical shape on the inside and a cylindrical shape on the outside (Fig. 8).

Figure 8. Universal end connector

A clamp with a smooth strip on the inside that does not damage the rubber provides a reliable end connector/cable connection. As a result of its unique geometry, the end connector can accommodate the entire range of cables (from 8 to 32 mm in diameter) used on Hydro-Québec's distribution network.

The verification system components were placed in a case so that the device would be easy to use, compact and transportable (Fig. 9). The system is powered by a rechargeable battery installed inside the device. However, the compressed air must be supplied from an outside source, such as a compressor. The diagnosis is fully automated, with a single result displayed, "tight" or "leak". The device does not require the input of any parameter of the test cable.

Figure 9. VIC prototype

The 50 or so tests conducted with the VIC on Hydro-Québec's underground distribution network confirmed the performances of the device that were demonstrated during the laboratory tests. The total duration of a test on the distribution network, including the installation of the end connectors, is about 20 minutes.

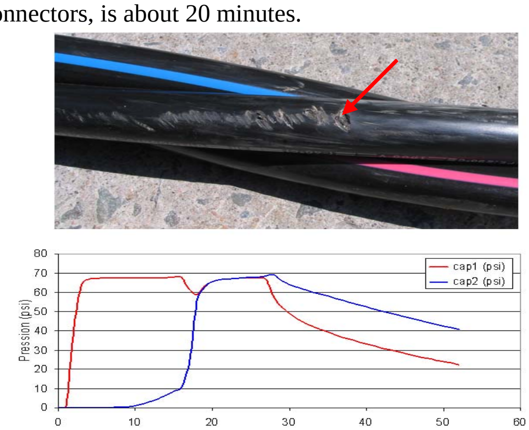

Figure 10. Cable fault diagnosed with the VIC device

An example of a fault on an in-service cable, diagnosed as defective with the VIC device, is shown in Figure 10.

The cable was most likely damaged during installation. After the cable was removed from the duct, a perforation was in fact found a dozen metres from the cable end. The leak was fairly sizeable (see the graph), though without the cable core being exposed.

It should be mentioned that the dielectric tests conducted on the above cable prior to its removal were not able to detect the fault.

CONCLUSION

The VIC system used to verify the integrity of the insulation in low-voltage underground cables is an efficient tool capable of ensuring that a cable's electrical insulation is not damaged either during manufacture, transport or installation in the duct. Its use, with automated diagnostics, ensures quality control of the installation of LV cables to prevent arcing faults, thus improving the safety of the public and workers, while ensuring better service continuity.

Following the conclusive results of the test conducted on its underground distribution network, Hydro-Québec decided to implement the technology in 2012.

Even if this technology was developed for cables installed in a duct, we believe that it would be applicable for buried cables as well as for cables different than those used on Hydro-Québec's underground distribution network. However, the developed equipment would require modifications in order to achieve the desired fail/pass outcome operation mode.

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