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Medium Voltage Underground Fault Localization using CelloC System

Abstract: - This paper addresses a medium voltage (MV) underground fault localization system (UFLS), which is capable to accurately pinpoint the location of a fault occurred on an underground cable. The localization process is performed on an offline faulty cable. The paper discusses the concept and the design of version v2b of UFLS CelloC, developed by a research team of Research Center of Hydro-Québec (CRHQ), and the results of the tests performed in laboratory or carried out on Hydro-Quebec's MV network.

Keywords: Underground Cable Network, Fault Localization, Travelling Waves, Breakdown

I. INTRODUCTION

After a fault occurs on an underground distribution feeder, linesmen crews are deployed to reconfigure the network and resupply customers affected by the outage. Then, the part of the faulty line is taken into work authorization for localizing the fault and replacing the damaged splice or cable segment. The first step is a short duration HIPOT test to determine the faulty phase. The cable on each phase might hold the prescribed voltage showing a healthy phase, might not hold any voltage, showing a conductive fault, or might hold up to a certain voltage when a breakdown or flashover occurs. This last scenario is favorable to fault localization by traveling waves method.

Looking for less invasive localization methods, the CRHQ has developed a few years ago a UFSL SIMLOC, and now is developing a novel UFLS CelloC.

SIMLOC [1] system performs the fault localization process in two steps:

- Using a geographic information system (GIS) of the network, thumping is simulated at regular distances (about every 20m) along all laterals/branches of the line (SIM module).
- In the field, the response to three thumps on the underground distribution line is recorded (LOC module).

Simulated and line test responses are compared using signal-processing techniques. The simulation having the best correlation with the test thumps pinpoints the fault on the line.

The novel UFLS CelloC system, based on traveling waves method, targets an accurate timestamping of breakdown transients detected at extremities of the underground distribution feeder. Combined with the network architecture data, fault position, either on the mainline/feeder or on a lateral can be located.

The localization process, with both UFLS is performed on offline underground faulty feeders/cables.

II. UFLS CELLOC CONCEPTION

A. *UFLS CelloC Architecture and Design*

UFLS CelloC has known so far three versions: v1, v2a and v2b. First two were presented in [2][3] and the last one is presented in this paper.

UFSL CelloC Architecture

The UFLS concept v2b (see Fig. 1) consists in:

- DC voltage generator (MV).
- Detection units (DU) composed of:
  - i. Current and voltage commercial sensors, or proprietary sensors.
  - ii. Intelligent Electronic Device (IED) including:
    1. Acquisition and processing card.
    2. Signal conditioning card.
    3. Cellular communication interface.
    4. External antennas.

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5. Rechargeable battery.

iii. Debugging software that communicate with the IED.

- Server-like Backend with fault localization application and grid/network database.
- Tablet with web interface Frontend displaying the fault location on a geographical map.

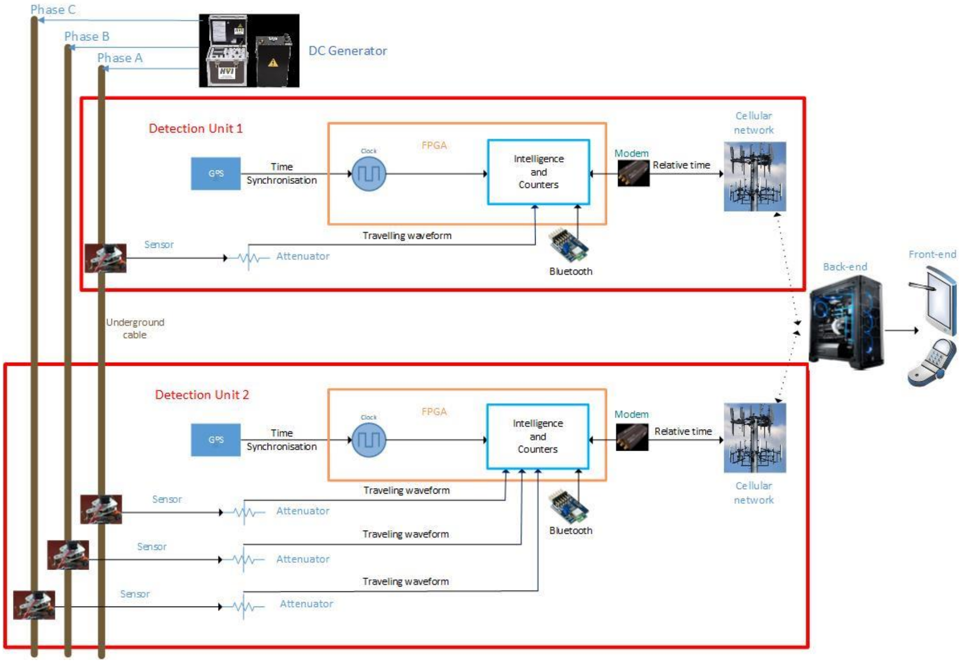


Fig. 1. UFSL CelloC v2b block diagram

Detection Unit Design

To enable the breakdown detection there must be two detection units connected to extremities of the faulty underground network. More detection units can be added if the network include multiple laterals/branches.

a) Sensors Design

A first proprietary sensor was developed initially to improve responsiveness and lower the fabrication cost. It is integrated inside a clamp that can be placed over the semiconductor of an underground cable. When a fault occurs, the sensing element can acquire the travelling wave through the semiconductor and send the signal over a coaxial cable through some tens of meters to the IED for breakdown detection and processing. A second improved version of the proprietary sensor was developed to integrate the wiring and the components inside an isolated shell (see Fig. 2).

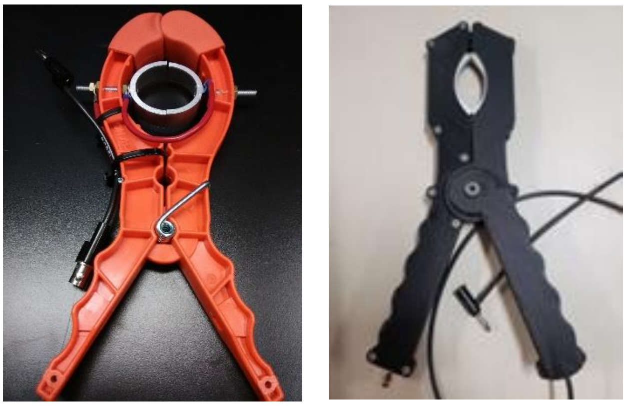

a) b)

Fig. 2 Proprietary sensors: a) version 1and b) version 2

b) IED Design

The IED is an assembly of the following several electronic circuit boards and modules that are placed inside a weatherproof enclosure (see Fig. 3).

Fig. 3 IED v2b enclosure

Acquisition and processing card

The main purpose of this intelligent circuit board is to perform fast digital acquisition and signal processing. The acquisition and processing card used is the same as in IED v2a. All the improvements have been done on the software side in relation to the FPGA and the embedded processor.

An FPGA core is used to generate a robust internal clock (100-400MHz) which is synchronized to an external atomic clock. Another core allows the detection of the rising front of the breakdown wave and the accumulation in a buffer of the detection time related to the internal clock. This core is parallelized six times to permit multiples phases acquisition in real time. The three first channels are used to detect phases A, B and C using proprietary sensors. The three last channels are used similarly for commercial actives sensors that need to be supplied.

An embedded processor allows the processing of all signals acquired by the FPGA and the interpretation of data to determine the exact time when the actual breakdown wavefront arrived at the DU location. All relevant data is forwarded through an Ethernet link to the cellular communication interface.

A Bluetooth circuit board is integrated to the processing card and provides the communication bridge between the FPGA and the debugging software on the tablet.

Signal conditioning card

The signal conditioning board is composed of several power supplies, an over discharge battery protection, a timing circuit, signal conditioners and interconnection with the acquisition/processing card.

A new revision of the board has allowed the following improvements over v2a:

- Better control over the conditioning delay.
- Detection of breakdown negative wavefront.
- Onboard integration of the timing circuit.
- Additional debugging features.

Cellular communication interface

Network communication over the cellular network is used to connect the embedded processor inside the IED to the distant DUs server.

The modem used in v2a was replaced by a newer model, which is smaller and have a lower electrical consumption. The SIM card and wiring are the same as before.

External Antennas

A first compact magnetic GNSS external antenna must be connected to the timing circuit present on the signal conditioning card. This will allow the IEDs placed in different locations to be GNSS synchronized.

A second compact cellular antenna must be connected to the cellular modem to allow the communication between an IED and the DUs server.

According to the particularity of DUs installation, outdoor or indoor (inside a substation, vault, manhole or padmount cabinet), different antennas and connection cables can be used.

Battery

The same rechargeable 12V/12Ah LiFePO4 (LFP) battery supplies the detection unit's internal components. A fully charged battery can supply the system for more than two days.

c) Debugging Software Design

A debugging software can be used to connect to each DU locally. A Bluetooth link is used by the software to communicate with the internal IED. The debugging software has multiple functions:

- Configure internal IED's parameters.
- Run IED's self-tests.
- Debug problems occurring with the IED.
- Operate the IED when the cellular network is not available.

B. Fault Localization Computing and Graphic User Interface (GUI)

There are three software processes involved in underground fault localization with CelloC system:

- The DUs server, which handles all DUs communications and the computation of faults localization.
- The Backend, which serves the frontend and does all the sessions management.
- The Frontend which allows the user to interact with the whole system.

DUs Server and Fault Localization Computing

The DUs server receives messages from all DUs using a simple in-house TCP protocol. Upon a message reception, the server will reply with an acknowledge or an error, if the message is invalid or the data caused a processing error. All messages are stored in a database prior to processing. On a fault message reception, the DUs server will attempt to compute a localization of the fault. If only one fault message has been received within the same minute, it won't succeed. When two messages have been received from two different DUs, a fault localization is computed and stored in database so the Backend can access it.

Backend

The backend is a REST API server that manages the detection sessions. It will:

- Prepare the information required by the localization process like:
  i. Information about faulty feeder/line including:
    - Lengths of segments and subsegments composing the feeder/line.
    - Type of underground cables.
  ii. Equipment associated to a DU such as:
    - Type of sensors.
    - Sensor cable length.
  iii. Traveling wave velocity.
- Save this information into the database so the DUs server can retrieve it.
- Compute an accurate position of the fault using dedicated algorithms.
- Associate the fault breakdown signal detection to the right subsegment position.

GUI Frontend

The Frontend software interface allows control of the Backend, visualization of circuit mapping fault and sensor communication status.

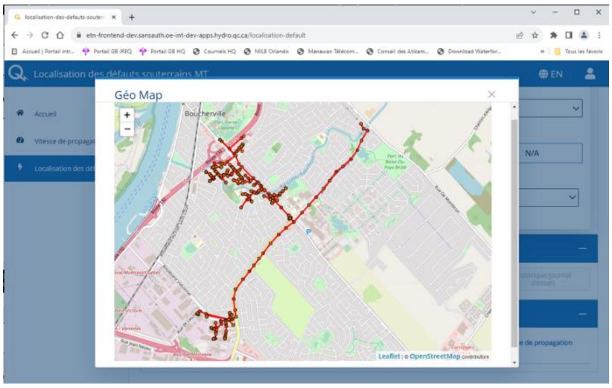
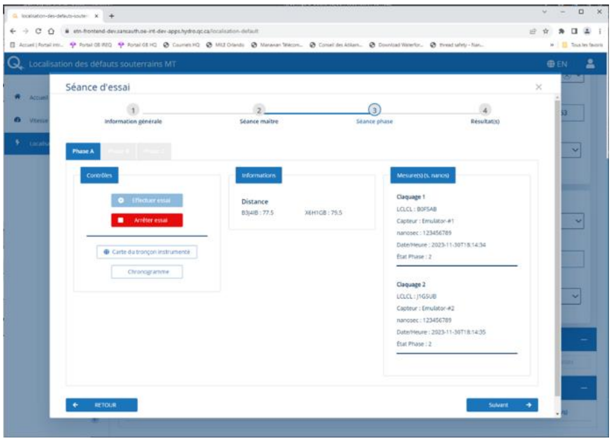


Fig. 4 Feeder/line section of the setup used for underground fault localization

The user must first choose a feeder and download its topology (<1 min). Once downloaded, the user specifies at what locations the DUs are connected. From this step, the visualization of the circuit mapping is possible (see Fig. 4).

The fault localization process can begin by creating a session, selecting a phase of the faulty feeder to which DUs are connected and finally by starting the fault localization or the acquisition session (see Fig. 5). Once engaged, the circuit under test must be slowly exited by the HIPOT tension while the system is waiting for the fault breakdown frontwave signal. Every time the DUs detect a fault breakdown, the Frontend will display the time stamped measurements and the computed fault localization, if the localization was possible. This procedure can be repeated.



Distance
B3J4IB : 77.5
X6H1GB : 79.5

Claquage 1
LCLCL : B0F5AB
Capteur : Emulator-#1
nanosec : 123456789
Date/Heure : 2023-11-30T18:14:34
État Phase : 2

Claquage 2
LCLCL : J1G5UB
Capteur : Emulator-#2
nanosec : 123456789
Date/Heure : 2023-11-30T18:14:35
État Phase : 2

Fig. 5 Starting an underground fault localization session

Fault map plotting will present the exact estimation of fault localization with a lighting icon and will highlight the subsegment in which it occurs.

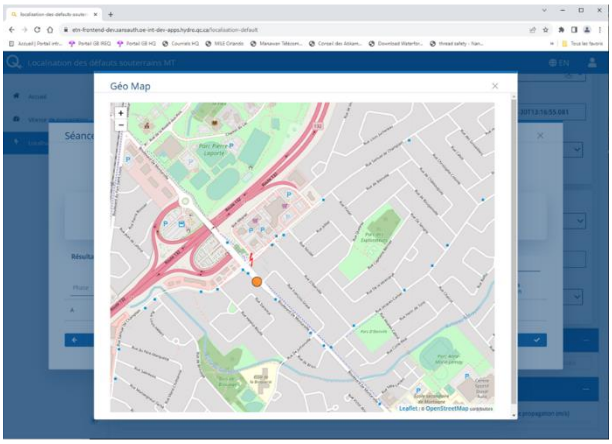


Fig. 6 Example of a fault localization expressed as a subsegment

If this localization is close to a non-instrumented lateral/branch, a pop-up dialog will advise the user that the fault breakdown signal may origin from that lateral/branch.

Once all the fault localizations are done, the user closes the opened session, and can review them, then display them on a map for better visualization.

The graphic presentation of the localization is expressed as a subsegment (interval between two manholes or a manhole and a vault) (see Fig. 6).

III. FAULT LOCALIZATION

Laboratory and field tests were performed to validate the UFSL functioning and evaluate its localization accuracy.

A. *Laboratory Tests*

Two different setups were used for fault localization laboratory tests, one was composed of a straight cable feeder [2] and the second one, besides the main feeder, also included an additional lateral/branch, which is shown in Fig. 7. The straight feeder has a length of 1000m and the lateral/branch joints it at 600m, respectively 400m from extremities. The spark gap was installed on the lateral/branch at 50m far from the joint. Two detection units were connected at the extremities of the main feeder, DU1 at 650m from the spark gap, and DU2 at 450m. A third one, DU3 was connected at the extremity of the lateral/branch at 100m far from the spark gap.

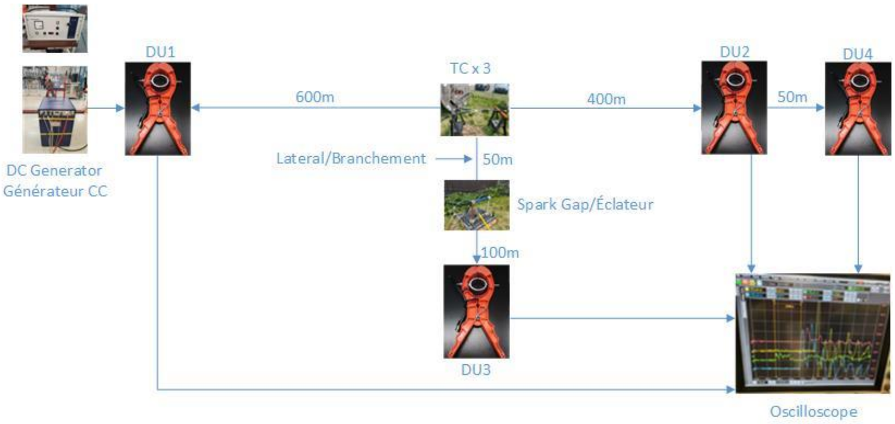


Fig. 7 Laboratory setup for MV fault localization using UFSL CelloC

The laboratory tests included:

- Tests with faults generated with spark gaps.
- Tests with faults simulated with a signal generator.

Tests with faults generated with spark plugs

Some of tests were performed using the setup presented in Fig. 7. The breakdowns were generated at voltages from a few kV to 15kV. Traveling waves, that propagates in both directions along the lateral/branch and then along the main feeder, were detected and time stamped by DUs. The difference between the time tags and the distance between the DUs was used to compute the fault location.

When the fault occurs on a branch that is not equipped with a DU sensor, the localization will point at the junction between this branch and the main feeder, leading the maintenance crew to the right branch. Then, depending on the length of this branch, a precise localization using thumping can be performed or a new breakdown test can be performed with an additional sensor placed at the end of this branch.

The error for the laboratory tests with spark gaps was in the range of a few meters.

Tests with faults simulated with a signal generator

The signal generator was used to:

- Verify the GPS synchronization of DUs clocks.
- Evaluate the minimum breakdown amplitude detectable by the DUs.
- Validate the communication between the DUs and the Backend.

B. *Field Tests*

Several localization field tests have been performed and two of them are discussed in the next two subsections.

Localization of fault on feeder DTR XXX

The single line diagram of the DTR XXX feeder is shown in Fig. 8.

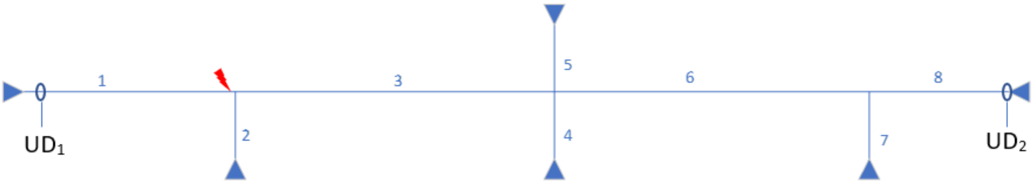


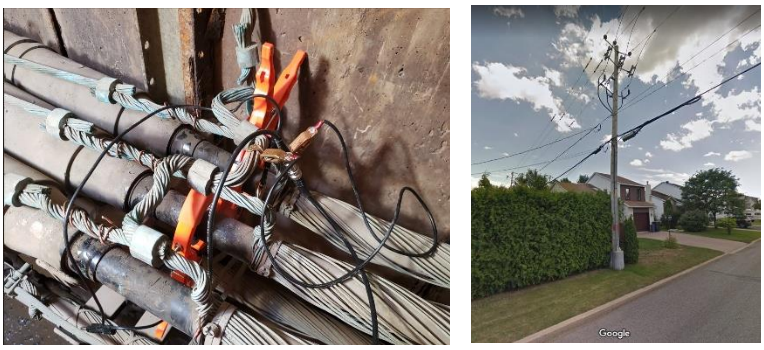
Fig. 8 Single line diagram of underground feeder DTR XXX

Lengths of component cable segments are available in TABLE I. The segments are composed of subsegments (interval between two adjacent joints) whose number, for each segment, is specified in the same table.

Table 1. Feeder DTR XXX segments' lengths

Segments	1	2	3	4	5	6	7	8
Length [m]	4774	102	3812	151	54	2289	100	278
Subsegments	18	1	13	2	1	9	2	1

Usually, sensors are installed at the extremities of an off-line feeder. In this case, the access to substation was exceptionally prohibited for safety reason. For this reason, one sensor was placed inside the first manhole following the substation as presented in Fig. 9a and the second one on the aerial outlet of the cable at the connection with the overhead segment of the line DTR XXX (see Fig. 9b).



a) b)

Fig. 9 Single line diagram of underground feeder DTR XXX

The results of several tests are presented in TABLE II. The time stamps (in second) associated with UD1 and UD2, are presented as T1 and T2, respectively. The distance (in meters) from the fault location to the UD1 and UD2, are indicated as L1 and L2, respectively. The propagation velocity Vp is expressed in m/s.

The localization was quite accurate, the calculated distances L1 and L2 indicating the lateral/branch shown in Fig. 8 as segment 2. The exact location of the fault was a few meters from the junction between the main feeder and the lateral/branch.

Table 2. Fault localization for feeder DTR XXX

L total	10971	10971	10971	10971
L1	**4694,22**	**4641,40**	**4634,59**	**4504,52**
L2	**6276,78**	**6329,60**	**6336,41**	**6466,48**
T1	0,332247071	0,06530817	0,478965616	0,53084764
T2	0,332256598	0,065318333	0,478975861	0,530859451
Vp	166112956,8	166112956,8	166112956,8	166112956,8

Localization of fault on feeder LAN YYY

The single line diagram of the LAN YYY feeder is shown in Fig. 10 and the component cable segments and number of subsegments can be found in TABLE III.

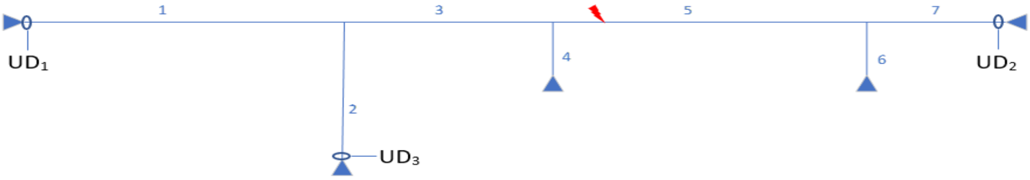


Fig. 10 Single line diagram of underground feeder DTR XXX

Table 3. Feeder LAN YYY segments lengths

Segments	1	2	3	4	5	6	7
Length [m]	1057	479	535	49	761	119	206
Subsegments	9	4	4	1	5	1	2

The sensors were installed at the extremities of the off-line feeder LAN YYY, namely in substation feeder departure cell (see Fig. 11a) and on two aerial cable outlets at the connection with overhead segments. One of them is shown in Fig. 11b.

a) b)

Fig. 11 Substation feeder cell a) and cable aerial outlet b) were UD_1 and UD_2 have been installed

The detection unit UD2 composed of an IED (grey box) and proprietary sensors, which are connected to the IED by the green cables, is shown in Fig. 12.

Fig. 12 Detection unit UD_2 (IED and green sensor cables), oscilloscope and portable computer

An oscilloscope was used to visualize the sensor signals and take snapshoots of the breakdown curves. The portable computer is used to run the Bluetooth debugging software.

Several tests were performed, and the time stamps (in second) associated with UD1 and UD2, are presented in TABLE IV as T1 and T2, respectively.

The distance (in meters) from the fault location to the UD1 and UD2, are indicated in TABLE IV as L1 and L2, respectively. The propagation velocity Vp is expressed in m/s.

Table 4. Fault localization for feeder LAN YYY

L total	2651	2651	2651	2651
L1	**2087,65**	**2092,86**	**2088,76**	**2089,10**
L2	**563,35**	**558,14**	**562,24**	**561,90**
T1	0,065195274	0,750113859	0,174844910	0,771456944
T2	0,065186360	0,750104884	0,174835983	0,771448013
Vp	171000000	171000000	171000000	171000000

The localization was very accurate, the cable subsegment containing the fault was identified using the calculated distances L1 and L2.

IV. CONCLUSIONS

The fault localization is computed by using an equation based on traveling waves theory. The known parameters are:

- Propagation velocity.
- Cable length.
- Time stamps of breakdown transients detected by DUs and sent to the DU Server.

The DUs clocks synchronization is extremely important for the localization accuracy. A difference of six nanoseconds is the equivalent of a localization error of one meter.

The sensors must allow high frequency acquisition of breakdown signal by the DUs.

Successful field localizations of underground cable faults with the UFLS CelloC requires the capability of generating breakdown transients with a DC generator or VLF.

The field localization error for the performed field tests was within a few tens of meters.

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