UNDERGROUND DISTRIBUTION NETWORK MONITORING SO MUCH EASIER

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ABSTRACT

Thanks to the implementation of the smart grid concept, the distribution network has seen a significant advancement in monitoring and control. The underground network monitoring, which was significantly lagging the overhead network monitoring, has seen a critical technology evolution. It includes cable chambers/manholes, vaults with transformers and load break switches, pad mount equipment, medium voltage cables and accessories that are not currently monitored. Among past hurdles related to underground distribution, one can mention the limited options of available monitoring and communication technologies, namely the fibre optic based networks. Until recently, wireless communication was not reliable enough in underground environments and data transmission was a challenge. Innovative designs in manhole covers and new developments in communication technologies overcome this problem making the underground monitoring so much easier.

In the modern smart grid, continuous monitoring and situational awareness will play an important role due to the need to integrate higher percentages of renewables (such as wind and solar), energy storage, and also plug-in hybrid electric vehicles (PHEV). Real time monitoring will help mitigate some of the challenges related to underground distribution, determine baseline load profiles, enhance visibility at distributed generation (DG) connection points, improve grid power quality, reliability and flexibility, etc.

This paper introduces and discusses the second generation of an underground sensing and monitoring system and presents the results and the conclusions of the tests performed by IREQ (Hydro-Quebec).

INTRODUCTION

Thanks to the implementation of the smart grid concept, the distribution network has seen a significant advancement in monitoring and control of the underground network. The underground system includes cable chambers/manholes, vaults with transformers and load break switches, pad mount equipment, medium voltage cables and accessories, etc.

Among the past hurdles related to underground distribution, one can mention the limited options of available monitoring and communication technologies, namely the fibre optic based networks. Until recently, wireless communication was not reliable enough in underground environments and data transmission was a challenge. Innovative designs in manhole covers and new developments in communication technologies overcome this problem.

Currently, no real time or on-line monitoring is being deployed in vaults or cable chambers with the exception of a few utilities.

Manufacturers of monitoring systems have proposed different solutions more or less integrated with the monitored equipment. Most of them only measure the current and the e-field.

Recently, a second generation of underground sensing and monitoring system (USMS) with improved performance is capable to also measure the voltage and some environmental parameters such as: temperature, humidity, gas presence, water level, etc.

Several advanced distribution automation (ADA)/smart grid applications such as power quality monitoring, fault location, demand response, micro grid operation, Volt/Var control, overhead and underground monitoring, power theft, etc. require voltage, current and environmental measurements [1][2].

This paper discusses the status of the underground monitoring technology in the smart grid era and introduces the second generation of an underground sensing and monitoring system (USMS), including sensors and intelligent electronic devices (IEDs), and presents the results and the conclusions of the evaluation tests performed by IREQ.

UNDERGROUND SMART GRID MONITORING

The underground smart grid monitoring systems include voltage and current sensors, IEDs/monitors and communication interfaces.

Underground sensors

Old and new sensor technologies such as Rogowski coils and deadbreak basic insulating plug voltage sensors (IPVS) and test point voltage sensors (TPVS) are now available and can be used in conjunction with the USMS for underground measurements.

Voltage sensors

a) b)

Figure 1. a) TPVS; b) IPVS

The TPVS 15/25/28 kV is an insulating cap that is installed in contact with the capacitive test point of the insulating plug (see Figure 1a).

The IPVS 15/25/28 kV is a combination of a voltage sensor embedded in the deadbreak insulating plug with an insulating cap (see Figure 1b).

Both sensor types were submitted to testing to evaluate their accuracy and linearity at fundamental frequency.

Current sensors

Figure 2. Harness with Rogowski current sensors and temperature sensors

The flexible Rogowski coil current sensor is the transducer by choice because of its technical benefits and ease of installation.

The Rogowski current sensors were also submitted for measurement accuracy and linearity evaluation.

Combined voltage and current sensors

a) b) c)

Figure 3. a) QX sensored Plug in deadbreak; b) QX sensored termination; c) CVS Plug in deadbreak

A particular sensor design is the combined current and voltage sensor (see Figure 3).

The QX 24 kV is a combined sensor (capacitive divider for voltage and Rogowski coil for current) integrated into a deadbreak T body and a cold shrink silicone termination.

The CVS 24 kV is a combined current and voltage sensor (capacitive divider for voltage and Rogowski coil for current) integrated into a separable 24kV deadbreak (T) connector. Both active and passive versions are available.

The accuracy class of these combined sensors is 0.5 for the voltage sensor and 1 for the current sensor.

Underground IED

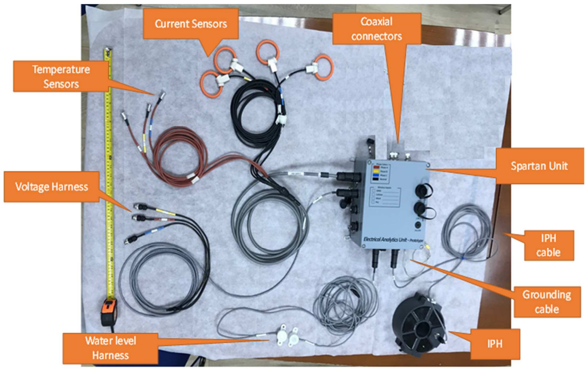


Figure 4. USMS including EAU, sensors, IPH

The first generation of USMS was tested by IREQ and the results helped improve the design and performance of the second generation of USMS (see Figure 4) [4]. Design improvements consist of:

- Unique, more compact electrical analytic unit (EAU), consolidating previously separated modules for current inputs, environmental inputs, power regulator and sensor analytics unit.
- Smaller size inductive power harvester (IPH) capable of operating at lower load currents with overcurrent and overvoltage protection unit.
- Additional communication protocols (DNP3) and functionalities related to ADA/smart grid applications including power quality monitoring, faulted circuit indicator (FCI) and power flow direction detection.
- Compatibility with low power sensors (LPS).
- 16 current channels, 12 voltage channels
- Calibration and tuning software interface and over the air upgrades.
- Multiple power supply options.

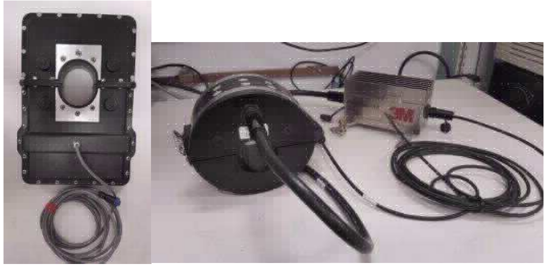
Electrical analytics unit

Figure 5. EAU – Top and side views

The EAU (see Figure 5) is a powerful universal controller that can monitor electrical and environmental parameters [3]. This second generation of EAU accommodates 16 current sensing channels, 12 voltage sensing channels, 3 digital channels for environmental monitoring such as a Gas Sensing Unit. The monitored data collected by the sensors is aggregated, filtered, time-synchronized, time stamped, GPS located, analysed, encrypted and communicated to the wireless communication gateway(WCG) located in the manhole cover. Approximately 3.5W of power are required by the EAU during data transmission.

Inductive power harvester module

The function of the IPH is to harness power from medium voltage power cables. This function is fulfilled by the magnetic core assembly (MCA) which is installed around a cable. The second generation IPH is capable to supply 12V at 45A load current. In addition to a more efficient MCA there also is an overcurrent and overvoltage protection unit (see Figure 6b). The MCA supplies power to the power regulator module (PRM) located in the EAU. In the event of power loss, a supercapacitor located in the EAU as well is capable to provide power for a period of up to 2 hours (with radio communication duty cycle adjustments).



a) b)

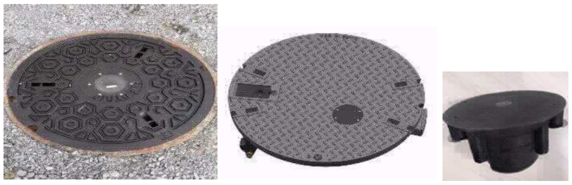
Figure 6. Inductive power harvester: a) First generation; b) Second generation

Communication

The second generation USMS has a new wireless communication gateway (WCG), which supports:

- 900 MHz mesh network
- Cellular LTE/3G/2G
- Power line communication (PLC) (future development)
- Fibre optic(future development)

The WCG houses a dual band antenna (700MHz-2.4GHZ) and a GPS module. The WCG can be integrated with different manhole cover types from different manufacturers (see Figure 7).



a) b) c)

Figure 7. Manhole cover: a) First generation; b) Second generation; c) Antenna second generation.

• USMS EVALUATION

The tests, which were performed in IREQ’s laboratories at its facility in Varennes, QC, Canada, included:

1) Voltage and current measurement accuracy and linearity of the second generation of USMS.
2) Efficiency of the IPH supplying the USMS.
3) USMS compliance with IEEE 495 [5].

Measurement accuracy and linearity

The measurement accuracy and linearity tests for voltage and current were performed twice, once before and once after the IEEE 495 test. The reason was to discriminate if high magnitudes short-time currents would affect the integrity of the USMS and its measurement accuracy and linearity.

Evaluation performed before IEEE 495 test

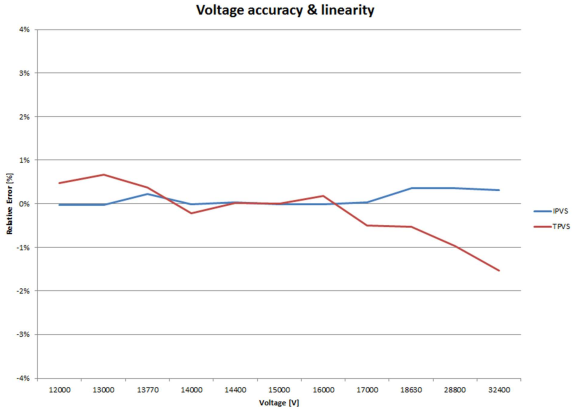


Figure 8. Voltage magnitude response (% relative error)/60Hz, 12kV-32.4kV, before IEEE495 test

The plots shown in Figure *8* reflect the rms voltage measurement accuracy and linearity of the monitoring chain USMS composed of:

- EAU
- TPVS
- IPVS

The plots of the relative error are quite linear and the relative error was lower than ±1% for a range from 12kV to 28.8kV. At 32.4kV, the relative error of the TPVS reached -1.54%. The IPVS reading accuracy for the full tested range is lower than 0.35%.

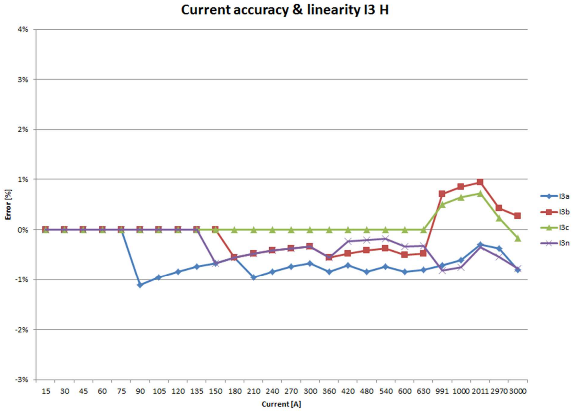


Figure 9. Current magnitude response (% error)/60Hz, 15-3000A, before IEEE495 test

The current error for measurements from 15 to 630A was calculated using magnitudes of the current output of a Fluke calibrator and the Rogowski coils readings. To calculate the relative error over a range from 991 to 3000A, the readings from the Rogowski coils were compared to those from HIOKI CT-flex sensor.

The plots shown in Figure 9 illustrate the rms load current measurement accuracy of the device under test (DUT). The error and relative error magnitude of the Rogowski coils (3 phases + neutral) for the range from 15 to 630A and from 991 to 3000A, respectively, was lower than ±1%.

Evaluation performed after IEEE 495 test

The chart in Figure 10 presents the relative error values corresponding to the voltage magnitude measurement test performed after the IEEE 495 test.

The results are similar to the first test. The plots show a relative error lower than ±1% for measurements from 12 kV to 28.8kV. The relative error of the reading at 32.4k with the TPVS reached -1.52%.

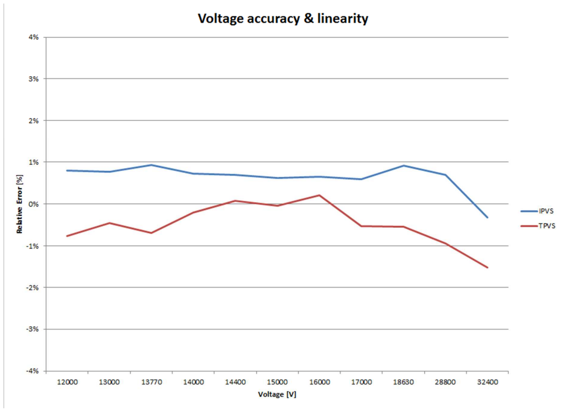


Figure 10. Voltage magnitude response (% relative error)/60Hz, 12KV-32.4kV, after IEEE495 test

The results of the second test on current magnitude accuracy and linearity measurement are illustrated in Figure 11.

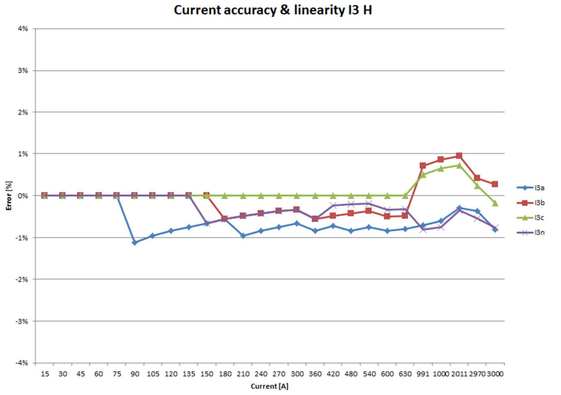


Figure 11. Current magnitude response (% error)/60Hz, 15-3000A, after IEEE495 test

A comparison between the plots shown in Figure 9 and those from Figure 11 indicates a consistent measurement performance of the Rogowski coils. Despite the fact that one of the current sensors, from the current sensor harness, has been performing much better than the other three, the current error and relative error for each sensor were within ±1%.

During the tests, the temperature sensors were measuring the laboratory temperature. The readings were consistent with each other and with the ambient temperature.

Efficiency of the Inductive Power Harvester

The laboratory test of the second generation of IPH was split between the evaluations of the minimal charging load current required to supply the USMS and of the compliance of the IPH with the standard IEEE 495/2007.

Evaluations of the minimal charging load current

The setup for this evaluation included a Fluke calibrator, which allowed step-wise increasing of the current circulating through the MCA.

Table 1: Results from minimum IPH charging load current test before and after IEEE 495 short-time test.

No	Current [A]	IPH output [V]	
		Before IEEE495	After IEEE495
1	10		3.25
2	20		6.26
3	30	8.60	8.86
4	40	10.84	11.26
5	44.3	11.98	
6	45.2		12.42
7	50		13.52
8	60	15.06	15.70
9	63	15.60	
10	70		17.88
11	74	18.00	

This test was also performed twice, once before the short-circuit test/IEEE 495 and once after. The results from both tests were similar and the results are presented in Table 1.

USMS compliance with IEEE 495 (short-time current)

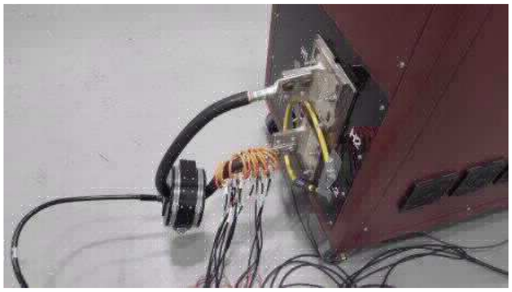


Figure 12. Phenix high current test set

The standard specified threshold (13kA) was exceeded during the test by currents of magnitudes up to 16kA. The sequence of successive short-time currents from 5kA to 16kA rms is available in Table 2.

Table 2. Short-time currents injected during the IEEE 495 compliance test

No	Time stamp	Current [A]	No	Time stamp	Current [A]
1	14:13	6641	11	14:13	13066
2	14:14	8091	12	14:14	13052
3	14:15	9247	13	14:15	13062
4	14:15	10000	14	14:15	14588
5	14:15	10000	15	14:15	15076
6	14:17	10944	16	14:17	15591
7	14:17	11679	17	14:17	15765
8	14:18	12265	18	14:18	15950
9	14:19	12624	19	14:19	15968
10	14:19	13046			

The short-time current waveform presented in Figure 13 was captured during the compliance test. Its crest value reached slightly over 20kA, which corresponds to 14.58kA rms (see position 14 in Table 2).

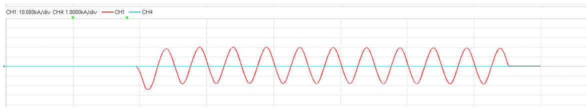


Figure 13. Short-time current waveform capture (14.58.kA rms)

The USMS and the IPH passed the test successfully.

Acknowledgments

The prototype system presently under evaluation at IREQ/HQ's facility was provided by 3M. The tests and the evaluation of the results have been performed by researchers from IREQ/HQ.

CONCLUSIONS

The smart grid relies on deployment of Advanced Distribution Automation applications also called Smart Distribution (SD) applications. As a result, the information provided by underground and overhead monitoring systems is essential to the efficient operation of these applications.

An analysis of the structure of the power distribution networks reveals that the level of ADAs and automation in general has various implementation stages throughout the system.

Better performing sensors and IEDs, in combination with new developments in communications have enabled technological advancements in underground monitoring systems, which were lagging the overhead monitoring. These systems can be implemented with minimal infrastructure modifications, are modular and can be scaled up or down depending on the specific monitoring needs.

The underground distribution network monitoring got so much easier.

The management of the smart grid has improved due to the availability of various parameters such as current, voltage, temperature, etc. provided by underground monitoring systems.

The tests performed on the first generation of USMS and the results obtained were useful and have been incorporated in the second generation.

The evaluation of the underground sensing and communicating infrastructure included laboratory tests and the results indicated good measurement accuracy, with respect to the values mentioned in the technical specifications of the DUTs.

The tests were performed at the fundamental frequency (60 Hz), for a voltage range from 12kV to 32.4kV and for a current range from 15A to 3000 A.

Also the USMS was compliant with the standard IEEE 495/2007 "IEEE Guide for Testing Faulted Circuit Indicators".

The USMS website is currently under construction. It will allow remote real time monitoring of voltage, current and environmental parameters.

More testing required and should include frequency response, advanced power quality, waveform capture capability, and faulted cable segment identification algorithms, etc.

REFERENCES

[1] F. Zavoda, 2011, "Sensors and IEDs required by Smart Distribution Applications (SDA)", *Proceedings ENERGY conference*.

[2] F. Zavoda, M. Bollen, S. Rönnberg, J. Meyer, J. Desmet, 2015, "CIGRE/CIRED/IEEE working group C4.24 – New measurement techniques in the future grid", *Proceedings CIRED conference*.

[3] F. Zavoda, C. Abbey, Y. Brissette, R. Lemire, 2013, "Universal IED for distribution smart grids", *Proceedings CIRED conference*.

[4] K. Sherwood, A. Ranade, 2018, "Improving underground system reliability through monitoring", tutorial, IEEE PES T&D conference 2018, Denver, USA

[5] IEEE Standard 495/2007, "IEEE Guide for Testing Faulted Circuit Indicators"