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Field Experience with on-line Bushing Diagnostic to improve Transformer Reliability

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SUMMARY

Bushing failures are responsible for a significant number of transformer major failures and, with the aging of the transformer population, the situation is not likely to improve in the future. Off-line measurements of the capacitance and power/dissipation factor, as well as dissolved-gas analysis (DGA) of the oil have been used for several years but their performance is limited because these techniques involve power system outages.

Hydro-Québec therefore decided to test on-line diagnostic techniques for bushings based on measurements of the leakage current captured by means of a sensor connected on the bushing tap. This paper compares the different diagnostic methods, namely the ‘sum current’ method (including inter-phase calculations) and the ‘relative measurement’ method using equipment connected in parallel on the same phase. The different types of sensor technologies are also discussed.

The field experience acquired during the project clearly shows that the ‘relative measurement’ method is less prone to external interference and can be implemented for periodic measurement using portable test equipment. It was also demonstrated that standardization of sensors and test leads is important to ensure consistency between subsequent measurements. Periodic testing, complemented with monitoring of equipment showing reliability problems, is expected to be the most optimized implementation approach to improve the reliability of a large transformer population. Future developments should concentrate on sensors using wireless or similar technologies to reduce monitoring implementation costs.

KEYWORDS

Transformer, Bushing, Reliability, On-line Diagnostic, Capacitance, Power Factor

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INTRODUCTION

Transformer accessories are responsible for a significant portion of transformer outages. Bushing reliability is generally very good and much better than on-load tap changers [1] but failure of a bushing will generally have a larger impact and total failure costs because of the risk of fire (Figure 1) and projection of porcelain, causing personnel security issues and potential failure of neighboring equipment.

Conventional off-line measurements show a limited ability to prevent failures and efforts have been invested to prevent major transformer failures using on-line diagnostics. Hydro-Québec has therefore investigated various diagnostic techniques using sensors on the bushing tap to measure the capacitive leakage current and evaluate the capacitance and power/dissipation factor, in service.

Since 2001, on-line measurements have been performed on six step-up transformers rated 13.8/735 kV and nine transmission transformers 735/230 kV using different sensor technologies and measurement systems. The objectives of the project were to develop expertise on the different measurement methods and make relevant recommendations for future implementation. This paper compares the different methods and sensor technologies based on the field experience acquired during the project and presents the implementation approach selected for the Hydro-Québec network.

Figure 1 : Consequence of a bushing failure (735-kV transformer).

MEASUREMENT METHODS

There are two recognized methods to perform on-line diagnostics of bushings based on measurement of the bushing tap current, namely the ‘sum current’ method and the ‘relative measurement’ method.

The ‘sum current’ method [2] is based on the principle that, in a three-phase system, if the system voltages are perfectly balanced and the bushings identical, the vector sum of the bushing insulation currents will be zero. In practice, bushings are never identical and system voltages are never perfectly balanced, and these factors need to be addressed for data interpretation. When one of the bushings deteriorates, its capacitance and/or power factor will change and, correspondingly, the sum current will deviate. A variant of this method is to use the amplitudes and phase shifts of the fundamental component of the bushing tap currents on different phases and calculate parameters that would be sensitive to capacitance and power/dissipation factor of the bushings. Again, these parameters will be influenced by inter-phase voltage unbalances.

The second, the ‘relative measurement’, method uses two or more bushings connected on the same electrical phase and calculates the ratio of the amplitudes and the tangent of the phase angle between the fundamental components of the bushing insulation currents. The tangent of the phase angle (the relative tanδ) is sensitive to any change in the power/dissipation factor of one of the bushings, and the ratio of amplitudes is sensitive to change in the capacitance of one of the bushings. If relative measurements are performed using three items of equipment in parallel, then the faulted bushing can be identified. The inter-phase voltage asymmetry will not influence the interpretation, since the applied voltage is essentially the same for all equipment connected in parallel.

SENSOR TECHNOLOGIES

The main purpose of bushing tap sensors is to provide a reliable external diagnostic signal to the measurement equipment and to limit the tap voltage to a safe level to protect test personnel and the bushing itself.

There are two main types of commercially available sensors for bushing monitoring applications, depending on the type of impedance used to limit the open-circuit tap voltage: capacitive-type and resistive-type sensors.

The capacitive-type design inserts a capacitor between the bushing tap and the grounded bushing flange which reduces the output voltage to a safe level. For instance, a 735-kV bushing (424 kV phase to neutral) having C1 capacitance equal to 500 pF equipped with a 2.8-µF capacitive-type sensor will produce an output voltage of 76 V at rated system voltage. The resistive-type design uses a resistor of similar impedance value (about 1 kΩ). For both types of sensor, a varistor is connected in parallel with the sensor impedance to provide a second line of defence against transient overvoltages in the event of occurrence of switching or lightning impulses.

There is also a technology that uses a miniature current transformer to measure the current flowing in the grounding pin shorted to the local ground (i.e. bushing flange), but it is not commercially available because it has a more complex design without clear benefit for this application.

Measurements using these three types of sensor are presented in this paper.

IMPLEMENTATION APPROACHES

Hydro-Québec’s current maintenance practice on bushings is to perform off-line capacitance and power/dissipation factor measurements periodically (at 10 kV) during transformer inspections every 6 to 8 years. In service, infrared and visual inspections of oil levels and leaks are generally made at least on a yearly basis. Even if dissolved-gas analysis (DGA) of the oil may be more sensitive and predictive than capacitance and power factor measurements for some bushing failure modes, DGA is not performed at regular intervals except on certain bushing types. In fact, since bushing DGA is not always easy to do (access, oil level, gas blanket, etc.), Hydro-Québec has conducted experiments with a view to installing accessories to make bushing sampling easier. Nevertheless, it still takes an outage to perform the sampling, which is a signification limitation on this diagnostic technique.

The on-line diagnostic approach has the advantage of evaluating the insulation at full voltage and at service temperature, which is impossible for 10-kV measurements. Moreover, since the measurement is done while the transformer in service, the interval for the tests can be reduced (without impacting the network operation) which could improve the performance of this diagnostic technique for problems with a short gestation period.

There are two different ways of implementing on-line PF measurements. The first is to install sensors on the bushing tap and make a connection to a junction box accessible at the transformer base. A switch in the junction box is used to ground the signal following the measurement. With a portable instrument, the measurement can be performed by maintenance personnel at any interval and test results can be put in a database. The second way is to install the same sensors and connect them to a data acquisition system to continuously monitor a group of bushings. Table 1 compares both options.

Table 1 : Comparison of periodic testing with continuous monitoring.

Parameters	**Periodic testing using portable instrument**	**Continuous monitoring**
Costs	Economical	More costly
Installation	Very easy	More difficult, especially if permanent cabling needed between transformers
Ability to detect problems with a short gestation period	Less than monitoring Periodicity limited by maintenance personnel availability	Good ability using continuous measurements
Measurements	Personnel required for performing the measurements (long test leads to install, test equipment to be connected, etc.)	Automatic measurements
Access in case of transformer problem	Need to approach the transformer	No access needed

In order to adequately balance the costs and the performance of this diagnostic technique, one intermediate approach may be to install sensors and junction boxes to implement the periodic testing option on a large scale, and add the continuous monitoring option on bushings that show problems during periodic measurements or for some types of bushing that are known to have a reliability problem.

This intermediate implementation approach seems to be the most optimized for Hydro-Québec considering the number of bushings installed on its power transformers and reactors (more than 6000 bushings rated 69 kV and over, of which about 10% are rated 735 kV).

It should be observed that periodic testing using a portable instrument requires that the measured diagnostic parameters, sensitive to capacitance and the power/dissipation factor, not be influenced by external parameters at a level that would require averaging or statistical analysis of the data. A comparison of the different measurement techniques in terms of stability and sensitivity is presented below.

FIELD EXPERIENCE

Measurements on GSU transformers

The first field installation was at La Grande generating substation in Northern Québec. Sensors were installed on the HV bushings of two banks of single-phase step-up transformers rated 13.8/735 kV connected in parallel on the HV side (T1 and T2). The sensors were previously designed at IREQ using a miniature current transformer to measure the switching transients in 735-kV substations [3]. This current transformer has the benefit of insulating the local flange ground from the measurement system ground and increases the frequency bandwidth of the measurement, which were key requirements for the switching-transient recording project. In addition to measuring the bushing tap currents, the signals from the closest voltage transformers were also acquired, adding further data for analysis.

The measurement system was developed in-house using 16-bit digitizers. The bushing tap currents were acquired simultaneously every 15 min at a sampling frequency of 10 kHz for 0.5 s. The raw data was transmitted via modem to a central processing unit at the Montreal office once a day. The CPU computed the fundamental frequency vectors (amplitude and phase angle) from the sampled signals to calculate the capacitance and power factor. Higher-frequency interference was eliminated by signal processing (Fourier Transformation) [4].

Figure 2 shows one week of measurements of the system voltage, the bushing tap current and the calculated capacitance for T2 phase B. As expected, the amplitude of the bushing tap current fluctuation is larger than the capacitance variation (2.5% versus 0.2%) because the change in loading conditions will influence the voltage but not the capacitance.

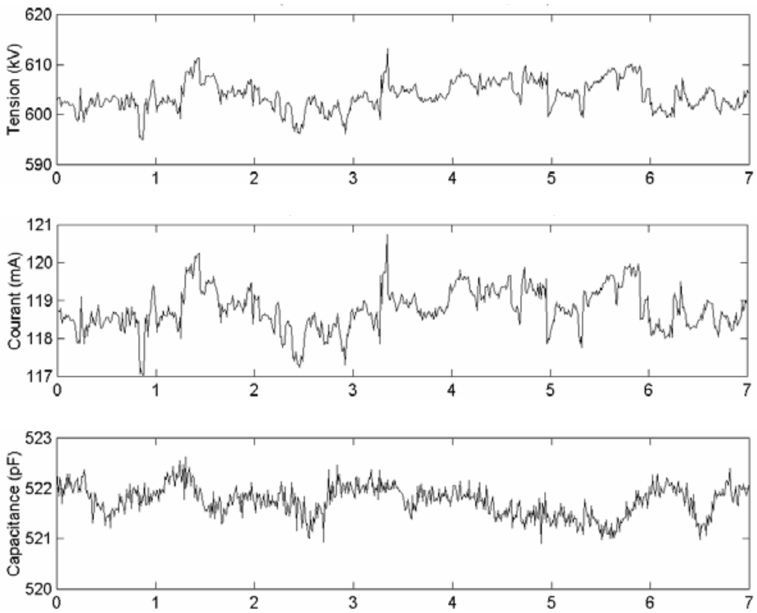


Figure 2 : Peak voltage, bushing tap current and calculated capacitance measured during one week.

Figure 3 illustrates the sum-current amplitude for the bushings of T1. The average amplitude of the bushing tap current is 118 mA. The average sum-current amplitude over one year is 1.7 mA representing 1.4% of the average bushing tap current. The fluctuation of the sum-current amplitude is in the order of ±0.6 mA (±0.5% of the average bushing-tap current). The reason why the sum-current amplitude is not zero in this case is mainly because the miniature current transformer of the sensor introduces a different phase shift for each sensor at power system frequency. This phase shift appeared to remain constant over time. The fluctuations of the sum-current amplitude were due to the system voltage unbalance and possibly to small variations of the capacitance and power factor of the bushings at rated conditions (temperature and voltage dependencies). Analysis of the inter-phase parameters is necessary to help discriminate the system influence from the insulation problems and eventually identify a faulty bushing.

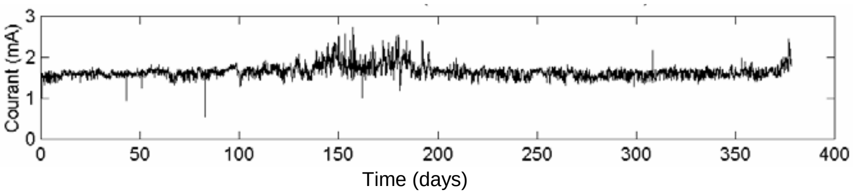


Figure 3 : Amplitude of the sum-current vector.

In order to compare the sensitivity of the inter-phase calculation and the 'relative measurement' to detect small variations of the capacitance and the power factor, an analysis of relevant parameters was performed. Representative examples of calculated parameters over a 90-day period are shown in Figure 4.

The results indicate the following:

- The fluctuations of the parameter related to capacitance (amplitude) are in the range of ±0.5% for inter-phase calculation, and ±0.15% when comparing bushings on the same phase.

- The fluctuations of the parameter related to the power factor (or tanδ) are in the range of ±0.5% for inter-phase calculation, and ±0.1% when comparing bushings on the same phase.

Based on these measurements, it appears in this particular example that the sensitivity to detect minor variations in the capacitance and power factor based solely on the raw data is roughly five times better when the comparison is made using bushings connected in parallel on the same phase instead of inter-phase analysis. It is planned to perform a similar experiment in a transmission substation to verify whether this comparison is transposable.

Since power factor and capacitance variations in the order of 0.5% and 1% respectively can be significant for detecting faults, the results indicate that the comparison with a bushing on the same phase can be used to implement periodic testing using a portable instrument because it does not call for averaging or statistical analysis of the data over a long period to remove external influence.

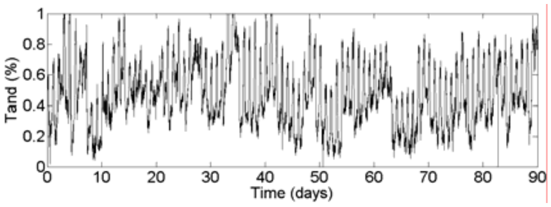
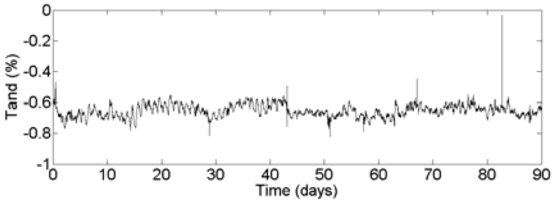
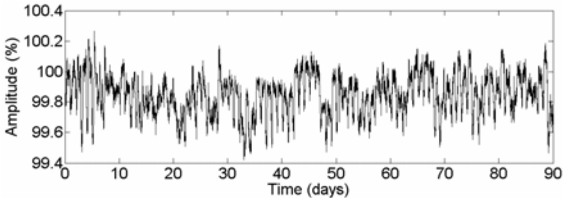
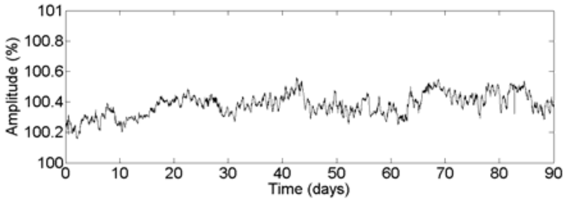
Inter-phase calculations (phases A and B of T1)	Bushings on the same phase calculations (phase A of T1 and T2)
$\tan\delta(\%) = \tan(\angle I_{aT1} - \angle I_{bT1} - 120) * 100$  	$\tan\delta(\%) = \tan(\angle I_{aT1} - \angle I_{aT2}) * 100$ 
$\text{Amplitude}(\%) = \frac{\lvert I_{aT1} \rvert}{\lvert I_{bT1} \rvert} \times 100$  	$\text{Amplitude}(\%) = \frac{\lvert I_{aT1} \rvert}{\lvert I_{aT2} \rvert} \times 100$ 

Figure 4 : Comparison of the inter-phase and bushings on the same phase parameters calculated for a 90-day period (left and right graphs are on the same range for tanδ and amplitude scales to emphasize the differences).

Measurements on 735/230 kV transmission transformers

The second installation was done at Nicolet substation on three banks of single-phase autotransformers rated 370 MVA (735/230 kV) connected in parallel (T2, T3 and T4). This substation is part of the HVDC multi-terminal transmission system for energy exchange between Québec and New England.

At first, capacitive-type sensors were installed on the 735-kV bushings of T3 and T4 (6 sensors). The 735-kV bushings of T2 and all the 230-kV bushings were instrumented with resistive-type sensors (12 sensors).

The measurements were performed periodically using two commercially available instruments. An important issue when making simultaneous measurements on different equipment is the ground potential difference. The instrument should provide galvanic insulation of signal inputs to ensure the ground potential difference does not influence the measurement [5]. With this requirement fulfilled, both measuring systems gave identical results.

Relative capacitance and power factor measurements were performed between each pair of bushings of transformers T2, T3 and T4. Since three transformers are in parallel at this substation, three different pairs of bushings in parallel can be tested: T3-T2, T4-T3 and T4-T2. Two measurements are independent, the third is redundant but it is good practice to do the third test to confirm the quality of the measurements. For example, Table 2 demonstrates the validity of the measurements by comparing the calculated and measured values of T4-T3, the calculation being made using the measurements on T3-T2 and T4-T2.

Table 2: Calculated and measured values for pair T4-T3.

Pairs of bushings	**Calculated amplitude* (%)**	**Measured amplitude (%)**	**Variation (%)**	**Calculated relative PF** (%)**	**Measured relative PF (%)**	**Variation (%)**
735 kV - phase A	106.45	106.44	-0.01	-0.086	-0.099	-0.013
735 kV - phase B	105.29	105.33	0.04	-0.035	-0.026	0.008
735 kV - phase C	105.91	105.95	0.04	0.166	0.139	-0.028
230 kV - phase A	114.18	114.13	-0.05	0.106	0.102	-0.004
230 kV - phase B	99.15	99.31	0.16	-0.062	-0.066	-0.004
230 kV - phase C	115.03	114.97	-0.06	0.425	0.425	-0.001

*Calculated T4-T3 amplitude (%) = $\frac{|I_{T4}|/|I_{T2}|}{|I_{T3}|/|I_{T2}|} \times 100$

**Calculated T4-T3 relative PF (%) = $\left[\tan(\angle I_{T4} - \angle I_{T2}) - \tan(\angle I_{T3} - \angle I_{T2})\right] * 100$

since tanδ ≅ δ in radian (by small angle approximation)

The data were also compared with capacitance and dissipation/power factor tests at 10 kV. The agreement is generally good, although in some cases the variations between off-line and on-line results are higher than expected (0.3-0.5% for the power factor, and 5-15% for the capacitance). These variations need further investigation but a possible cause is that 10-kV measurements are usually done on different days, by different operators, using different test equipment. As mentioned earlier, the operating conditions (rated voltage and operating temperature) may also influence the measurements. For example, Table 3 shows the 10-kV and on-line measurements for T3 and T4 (735-kV bushings).

Table 3 : Comparison of 10-kV and on-line measurements.

10-kV data			**Relative measurements**			**Variation**
			Tests	**10-kV data**	**On-line**	
735-kV bushing	**C (pf)**	**PF (%)**		**Amplitude (%)** **Relative PF (%)**	**Amplitude (%)** **Relative PF (%)**	
T4A	522	0.39	T3A-T4A	112.3	106.5	-5.8
T3A	586	0.35		0.0	-0.1	-0.1
T4B	533	0.63	T3B-T4B	103.9	105.3	+1.4
T3B	554	0.39		-0.2	0.0	+0.2
T4C	530	0.34	T3C-T4C	119.6	106.1	-13.5
T3C	634	0.68		+0.3	0.0	-0.3

Figure 5 illustrates abnormal variations of the power factor and small but detectable amplitude variations which were consistent between the three phases. In October 2005, the relative power factor of the three phases was initially around 1% and increased to around 2% in November. This increase was accompanied by a decrease in the amplitude by about 1%. The decrease of the leakage current amplitude, together with the consistency of the abnormal results between the three phases, indicated that the source of variations was in the measurement system and not a developing bushing problem.

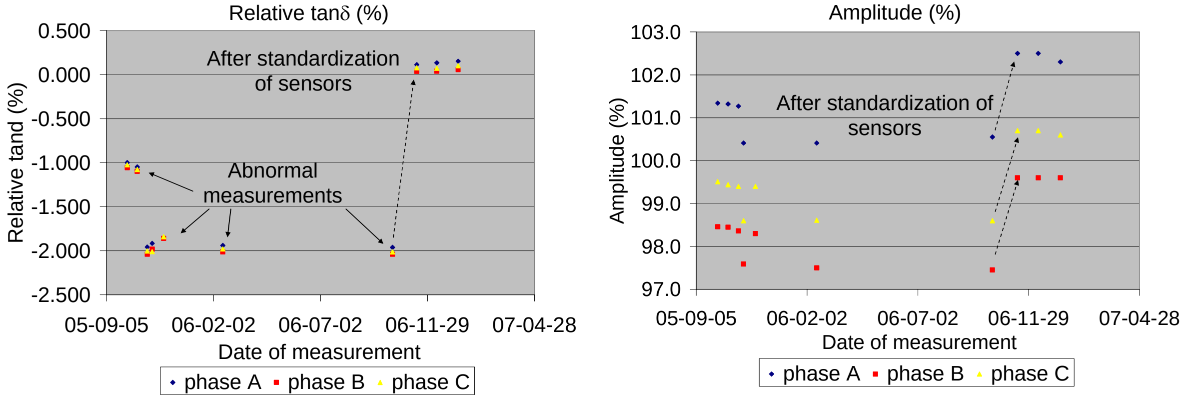


Figure 5 : Abnormal measurements and effect of standardization of sensors.

Since these variations were associated with the pairs of bushings involving capacitive-type sensors together with resistive-type sensors, it was decided to standardize the resistive-type. As soon as this was done, measurements of the relative power factor returned to normal values (close to 0%). This power factor change was accompanied by a 2% increase in the amplitude.

The diagrams of Figure 6 help to understand the measurement problem associated with this sensor mismatch. The bushing tap currents are modeled by current sources I_1 and I_2 while the currents flowing in the measuring-instrument inputs are I_{1m} and I_{2m}. R_{lead} and R_i represent the resistance of the lead and the input impedance of the test equipment.

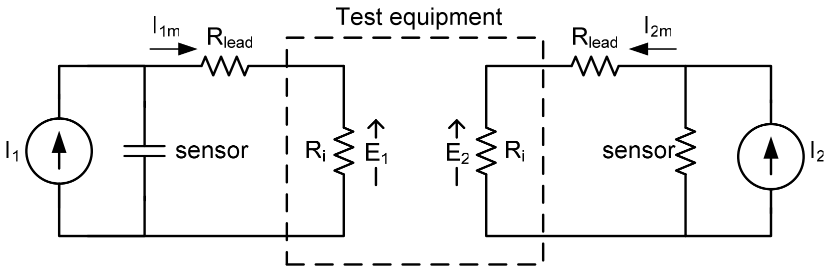


Figure 6 : Simplified circuit representing impedance of sensor, cable and instruments.

The parallel circuit formed by the sensor capacitance and the test lead resistance together with the measurement impedance creates a phase shift that will not be present for the resistive-type sensor. This will be ‘interpreted’ by the tester as a high relative bushing power factor, which is not the case in reality. In this case, the capacitance value is 2.8 µF, which represents 947 Ω (X_c) at 60 Hz. The input impedance of the instrument is about 8 Ω and the test lead resistance used initially was 1 Ω. The phase shift introduced by the parallel capacitive-resistive circuit is calculated as follows:

$$\mathrm{atan}((R_{lead}+R_i)/X_c)=\mathrm{atan}((1+8)/947)=0{,}54^{\circ}\ ;$$

which corresponds to a relative tanδ of 1%, as measured initially. The increase in the power factor from 1% to 2% can be explained by the change of test leads. The new test leads have a smaller cross section and higher resistance (about 10 Ω). The higher test lead resistance led to an increase in the phase shift (relative dissipation factor) due to interaction with the capacitive-type sensor as well as a decrease in the amplitude ratio due to interaction with the resistive-type sensor. Following the standardization of the resistive-type sensor, the power factor and the amplitude changed simultaneously by about 2%. To summarize, when using capacitive- and resistive-type sensors with 1 kΩ internal impedance, every 10 Ω increase in the test lead or measurement impedance will cause a systematic error in the power factor and amplitude of about 1%.

CONCLUSION

A comparison of methods to derive parameters related to the capacitance and power/dissipation factor from on-line measurements of the bushing tap current shows clearly that the 'relative measurement' method of bushings on the same electrical phase is more sensitive than the 'sum current' method or any inter-phase-based calculations. The stability of the parameters derived using the 'relative measurement' method on equipment connected in parallel is sufficient to allow periodic testing without the use of averaging or statistical analysis of the data, which is not the case for other methods studied.

Field experience shows that the measurement circuit resistance (test lead and input impedance of the test equipment) has a different influence on the measurement, depending on the type of sensor used. The interaction between the measurement circuit resistance and the capacitive-type sensor will influence the tanδ mainly, and the interaction of this resistance with a resistive-type sensor will influence the amplitude (capacitance). As a general recommendation, the sensor types and test leads should be standardized before implementing an on-line bushing diagnostic technique using portable test equipment.

Considering the large population of transformers at Hydro-Québec, the most interesting implementation approach will be to install the bushing-tap sensors progressively (during transformer inspections) and start the on-line diagnostic of bushings using portable test equipment. The continuous-monitoring option will be justified only for some types of bushings that are known to have reliability problems.

Future developments should concentrate on bushing-tap sensors using wireless or similar technologies in order to reduce the cost of the permanent cabling installation currently required between transformers when the monitoring option is selected.

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