An Improved Vibration Analysis Algorithm as a Diagnostic Tool for Detecting Mechanical Anomalies on Power Circuit Breakers

Michel Landry, *Senior Member, IEEE*, François Léonard, Champlain Landry, Réal Beauchemin,
Olivier Turcotte, and Fouad Brikci

***Abstract*—This paper deals with the successful application of vibration analysis for circuit-breaker (CB) diagnostic testing with the aim of detecting mechanical anomalies in CB drive mechanisms and other moving parts in the interrupting chamber. An improved dynamic time warping algorithm was developed. Several case studies of defective mechanical components of $\mathbf{SF_6}$ power CBs equipped with hydraulic or spring-loaded drive mechanisms are presented. It is foreseen that vibration analysis can be used as a diagnostic tool for all CBs whenever mechanical anomalies are suspected.**

***Index Terms*—Circuit breakers (CBs), data acquisition, dynamic time warping (DTW), mechanical anomalies, vibration measurement.**

I. INTRODUCTION

THE SECOND CIGRE inquiry [1] on high-voltage circuit breakers (CBs) reported that 44% of major failures and 39% of minor failures are of mechanical origin. Today, these data still correspond to the daily tasks of high-voltage (HV) substation maintenance crews. Several developments related to vibration measurements [2]–[9] were accomplished. Online monitoring [3] of vibration patterns during breaker operations was even envisaged. This paper presents vibration analysis on power CBs as a result of an improvement of the well-known dynamic time warping (DTW) algorithm for the analysis of the vibration pattern.

This paper first describes the technical features of a suitable data-acquisition system with the capability to detect a wide variety of mechanical anomalies. Typical accelerometer specifications are also given with an emphasis on their attachment to specific CB components.

Second, the paper focuses on a vibration signal-analysis software program for evaluating defect severity and planning further maintenance actions. It is based on an improved DTW algorithm consisting of many features that were implemented and tested in order to enhance the diagnosis of CB conditions.

During the completion of the research project, some defects were simulated in a test laboratory while others were investigated following major CB failures that occurred in HV substations: driving rod thread stripping, low oil level in the closing oil-damper, defects in the transmission shaft, excessive contact travel, etc. The third part of this paper reports three of the aforementioned case studies. For each case, typical vibration signals are illustrated and amplitude and time deviation graphs are plotted as a result of the vibration analysis. Furthermore, for some CB types, by positioning accelerometers for detecting mechanical anomalies on drive mechanisms, it is shown that mechanical defects in the interrupting-chamber components can also be detected.

II. MEASURING SYSTEM

A. Data-Acquisition System

Measurements reported in Section IV were performed with a high-performance data-acquisition system that is easily available today, thanks to unceasing technology development. The main features of this system were: a sampling frequency of $\geq$ 150 kilosamples/s; a resolution of 16 bits; a required number of inputs for the analyzed breaker; simultaneous recordings of vibration signals and breaker contact travel or breaker contact position for thorough vibration analysis; and ideally, the data-acquisition system trigger should be the current circulating through the opening or closing coil for accurate synchronization of all the vibration signals.

It should be acknowledged that other data-acquisition units with a lower performance rating could be used depending on the breaker anomalies to be detected.

B. Accelerometers

A large variety of accelerometers is commercially available. For accurate vibration measurements on power CBs, accelerometer performance should be selected based on the maximum vibration burst that can be expected for the breaker drive mechanism. An example of suitable performance parameters includes: sensitivity of 1 to 10 mV/g ($g = 9.81$ m/s^2); measuring range of ± 1000 g; an upper frequency limit of 20–50 kHz; a resonant frequency of $\geq$70 kHz; and nonlinearity of $\leq$1%.

To complete the measuring kit, signal conditioners are required for powering accelerometers and conditioning their output signals before reaching data-acquisition inputs. Whenever possible, accelerometers should be screwed directly on at

Manuscript received March 14, 2007; revised November 2, 2007. Current version published September 24, 2008. Paper no. TPWRD-00140-2007.

M. Landry, F. Léonard, C. Landry, and R. Beauchemin are with Hydro-Québec's Research Institute, Varennes, QC J3X 1S1, Canada (e-mail: landry.michel@ireq.ca).

O. Turcotte is with Hydro-Québec TransÉnergie, Montréal, QC H2L 4M8 Canada (e-mail: Turcotte.Olivier@hydro.qc.ca).

F. Brikci is with Zensol Automation Inc., St-Laurent, QC H4R 2E9 Canada (e-mail: zensol@zensol.com).

Digital Object Identifier 10.1109/TPWRD.2008.2002846

the measuring point or on a specially designed bracket that is itself adequately attached to the measuring point. Otherwise, they can be glued in place. Magnetic bases should be avoided since they reduce the frequency bandwidth of the recorded vibration pattern.

III. DTW ALGORITHM

A. Introduction to the DTW Algorithm

Since the 1970s, the DTW algorithm has been used for voice recognition [10]–[12] by applying dynamic programming techniques. It is currently used in several applications, such as the mathematical treatment of ultrasonic images [13], signature verification [14], and curve interpretation and diagnostic techniques for industrial processes [15].

The primary function of the classical DTW algorithm is to estimate the time deviation of the same transient phenomenon that occurs in two given signals. Originally, the aim was to compare two spoken words to determine whether they are identical. To do so, the DTW algorithm deals with the variation of the frequency content as determined by Fourier transforms. The basic idea is to recognize a given word even though it is spoken at different speeds. For voice recognition, the time deviation between two recordings is not useful and can be perceived as distorted information. Conversely, time deviations are of paramount importance for assessing the mechanical condition of CBs.

Though suitable for voice recognition, the classical DTW has major shortcomings when compared to vibration signals. For instance, when a word is spoken, there is no mute interval, whereas vibration signals of breaker operations have at least one time interval for which there is no new mechanical event, signals approach the noise level, and signals do not exhibit any time deviation while amplitude deviations are significant. For tools used to assess CB mechanical conditions, the classical DTW algorithm must clearly be improved.

B. Mathematical Equation of the Classical DTW

Let define the following vibration signals in the time-frequency domain:

$$\mathbf{A} = \{\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_n, \ldots \mathbf{a}_N\}$$

and

$$\mathbf{B} = \{\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_m, \ldots \mathbf{b}_M\} \tag{1}$$

where $\mathbf{a}_n$ and $\mathbf{b}_m$ are vectors containing spectral slices of the corresponding signature with n and m as time indices. The N and M values correspond to the size of vectors $\mathbf{A}$ and $\mathbf{B}$, with $N \approx M$. The time deviation function or dynamic warp function can be written as follows:

$$m = w(n). \tag{2}$$

This function will link vibration signatures $\mathbf{A}$ and $\mathbf{B}$ in such a way in order to minimize the following distance or time gap:

$$D(\mathbf{A}, \mathbf{B}) = \frac{1}{N} \sum_{n=1}^{N} d\left(\mathbf{a}_n, \mathbf{b}_{m=w(n)}\right) \tag{3}$$

where $d(\mathbf{a}_n, \mathbf{b}_m)$ corresponds to the distance of one local spectral slice. This distance can be calculated by three different formulas:

1) Euler

$$d(\mathbf{a}_n, \mathbf{b}_m) = \sqrt{\sum_{i=1}^{N} (a_{ni} - b_{mi})^2}. \tag{4}$$

2) Euler to the power of two

$$d(\mathbf{a}_n, \mathbf{b}_m) = \sum_{i=1}^{N} (a_{ni} - b_{mi})^2. \tag{5}$$

3) Sum of absolute values

$$d(\mathbf{a}_n, \mathbf{b}_m) = \sum_{i=1}^{N} |(a_{ni} - b_{mi})| \tag{6}$$

where i is the frequency index, and N is the number of frequency bands.

An analysis of several vibration signatures reveals that the Euler formula (4) yields the best results.

The amplitude deviation $(\Delta \mathrm{A}_n)$ before and after mechanical event retiming, as shown in the graphs of Figs. 3, 6, and 8, is calculated using the following equation:

$$\Delta \mathrm{A}_n = \frac{\sum_{i=1}^{N} |a_{ni} - b_{ki}|}{N}$$
$$k = \begin{cases} n & \text{: before retiming} \\ w(n) & \text{: after retiming} \end{cases} \tag{7}$$

with a_{ni} and b_{ki} as elements of the reference frequency spectrogram and that of the signal to be analyzed.

C. Improved DTW Algorithm

The vibration analysis software is based on a comparison of a reference vibration signal and the one to be analyzed. This reference signal can be either a vibration pattern taken at CB commissioning or that of another phase of the same breaker or another CB of the same family. The diagnostic results are presented by plotting the following graphs: reference vibration signal and vibration signal to be analyzed, amplitude deviation, time deviation calculated by the DTW algorithm, and amplitude deviation after retiming the various mechanical events.

Based on the amplitude and time deviations, respectively, in decibels (dB) and milliseconds (ms), minor and major alarm levels have been set according to several test results. Normal discrepancies may exist between two vibration signals obtained from two consecutive CB operations. For instance, an amplitude deviation of 10 dB or less and a time deviation of 3 ms or less are considered to be normal while values greater than 15 dB and 5 ms should trigger major alarms and immediate maintenance action. These triggering levels were previously validated by other authors [2]–[5].

The improved algorithm comprises the following key features: signal synchronization, noise suppression using time-frequency domain filtering, signal averaging of several consecutive breaker operations, an innovative concept of time deviation penalty applied to the DTW, and assessment of amplitude and time deviations after retiming of the various mechanical events. Some details of these features will be given.

To produce a revealing vibration analysis, the first mechanical event of the reference vibration signal and the one to be analyzed must be synchronized. This synchronization is achieved by calculating the envelope of the first mechanical event (e.g., using a Hilbert transform [16]) and correlating it with a numerical series of the vibration signal. This process allows for the detection of the first vibration transient with an accuracy of ± 1 sample.

Information contained in an acoustical vibration signal is usually better discriminated when illustrated on a decibel or a power-log scale. For this latter reason, the algorithm processes a 2-D numerical filter on the log scale of the power spectrogram. Note that the resulting filter is nonlinear and does not take account the whole phase information contained in the original time signal. In fact, when two recordings of the same vibration event are compared, due to small timing jitters between mechanical events contained in the vibration signal, the amplitudes show far better repeatability than the phases.

The reference signal and the one to be analyzed are derived from the average in the frequency domain of several consecutive opening or closing operations, an innovative feature that enables diagnostic reliability and accuracy.

To circumvent some inherent limits of the classical DTW [17], [18], a time-deviation-penalty parameter was implemented in the improved algorithm, thus creating a robust DTW algorithm focusing on the main mechanical events. It prevents the time warp function (time deviation) from being solved when the vibration amplitude or energy is low. All results presented in Section IV were obtained with this improved DTW algorithm. For illustrating the effect of this feature, Fig. 1 shows the time deviation $(\Delta \mathrm{t})$ for case study No. 1 of Section IV with the improved algorithm [Fig. 1(a)] and the classical DTW [Fig. 1(b)]. Fig. 1(b) clearly shows that the classical DTW does not converge. As a result, an unacceptable false indication of a time deviation of -31.6 ms would be given.

Finally, an assessment of the amplitude and time deviations after retiming the various mechanical events is helpful for deducing whether the anomaly might be related to breaker synchronization.

D. User-Interface Inputs/Outputs

To facilitate the vibration analysis, the user interface includes a certain number of useful functions:

- selection of the vibration analysis time interval;
- selection of the number of frequency bands and fast Fourier transform (FFT) in a given time interval;
- frequency spectrograms (time-frequency diagrams) depicting relevant frequencies of the vibration pattern and allowing the frequency level that generates the maximum deviation to be identified.

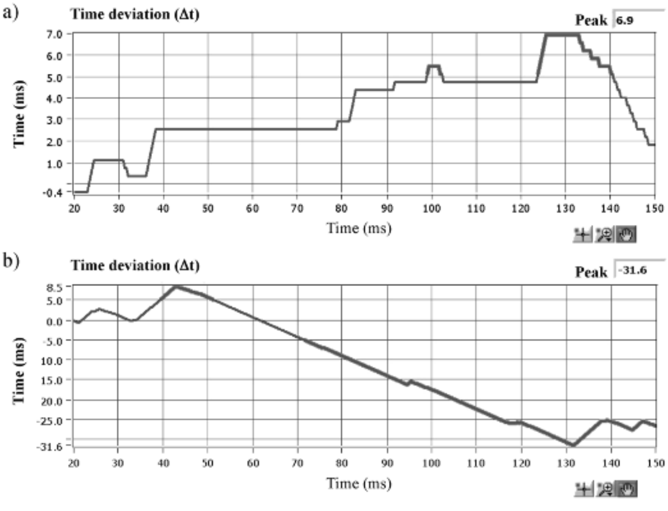


Fig. 1. Calculation of the time deviation for Case study No. 1 (Section IV). (a) Convergence of the improved DTW. (b) Divergence of the classical DTW.

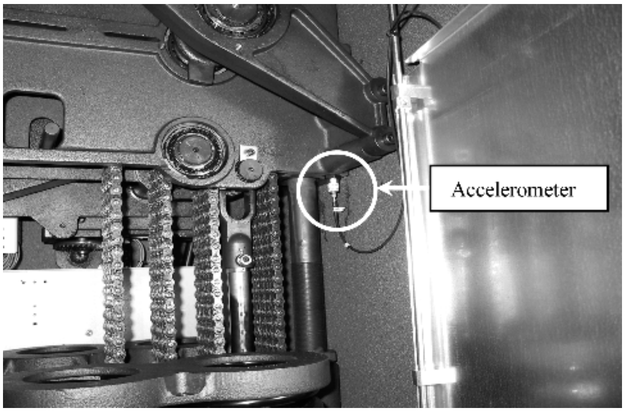


Fig. 2. Accelerometer attached to the frame of the spring-loaded drive mechanism.

IV. Test Results

Three case studies of the detection of mechanical anomalies are presented in the following section.

A. Case Study No. 1

Vibration analysis allowed the detection of a severe mechanical anomaly on a 230-kV SF_6 CB equipped with three spring-loaded drive mechanisms, one per phase. The breaker has completed 210 operations.

Fig. 2 shows the accelerometer's position inside the breaker mechanism housing. Fig. 3 shows typical graphs produced by the analysis software. The top left-hand-side graph depicts the reference signal comprised of three consecutive closing operations (F5, F6, and F7) of the phase-B operating mechanism which exhibits a normal vibration pattern.

The bottom left-hand-side graph contains the phase C vibration signal (F6 and F7) to be analyzed and compared to the reference one (Phase B). As a result of the vibration analysis, on the right-hand side, Fig. 3 contains three graphs:

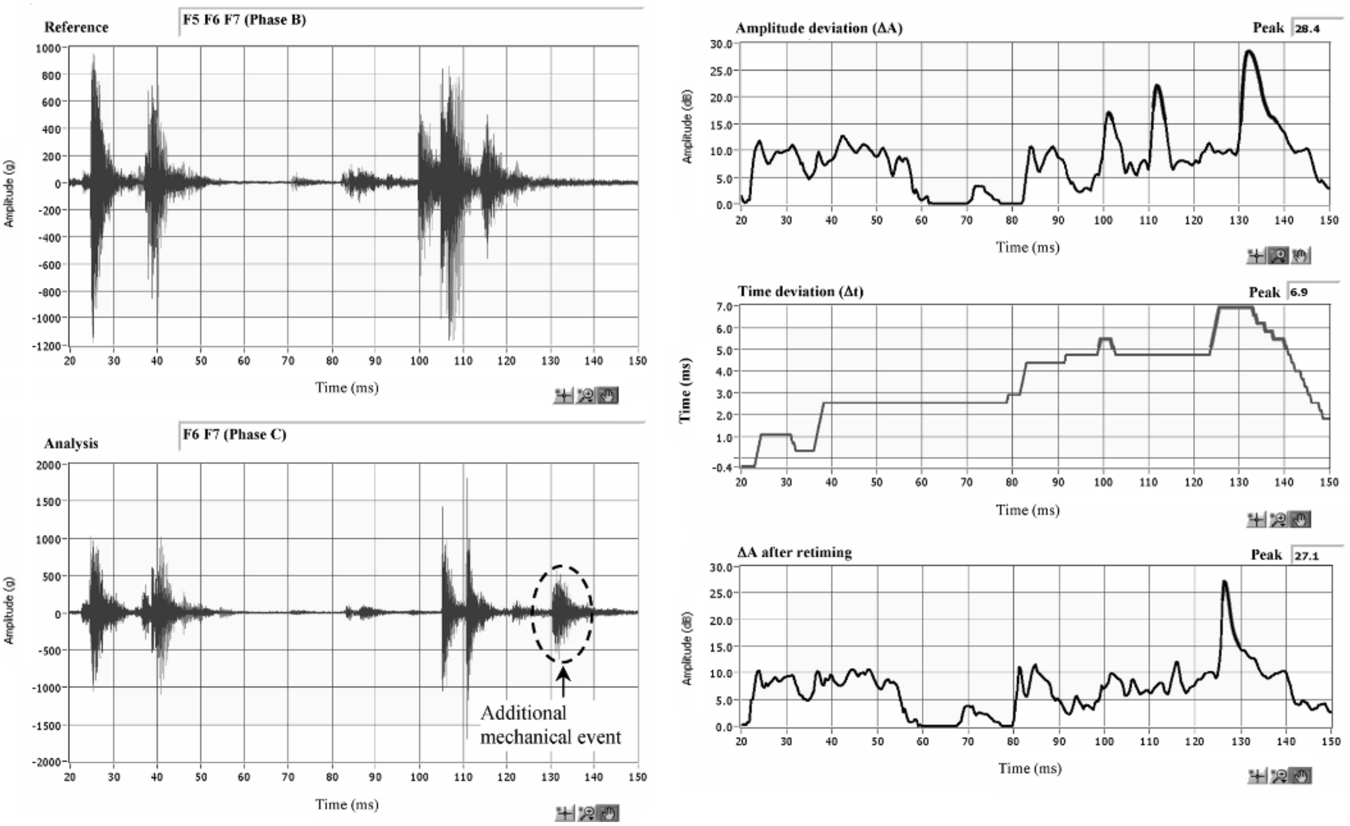


Fig. 3. Graphs of the vibration analysis on a 230-kV SF_6 CB equipped with spring-loaded drive mechanisms (Case study No. 1).

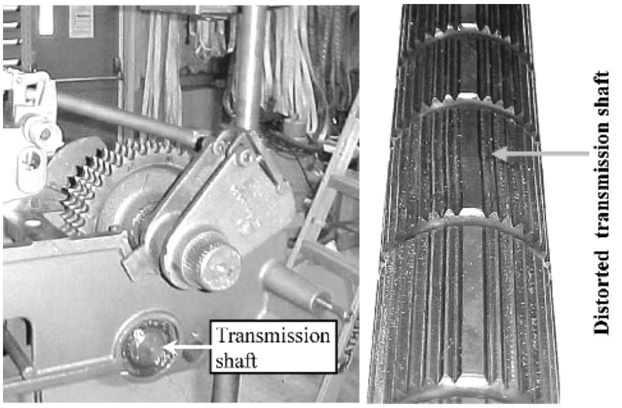


Fig. 4. Distorted transmission shaft of the spring-loaded drive mechanism.

1) amplitude deviation with a peak value of 28.4 dB which triggers an alarm (i.e., >15 dB);
2) time deviation with a peak value of 6.9 ms, also over the alarm threshold of 5 ms;
3) amplitude deviation after retiming with a similar peak (i.e., 27.1 dB) than that before retiming, which confirms that the suspected anomaly is not just a matter of synchronization.

It must be pointed out that this high amplitude deviation of 28 dB is the result of an additional mechanical event at 130 ms.

The maintenance crew discovered a very severe mechanical anomaly consisting of a distorted transmission shaft in the operating mechanism (Fig. 4).

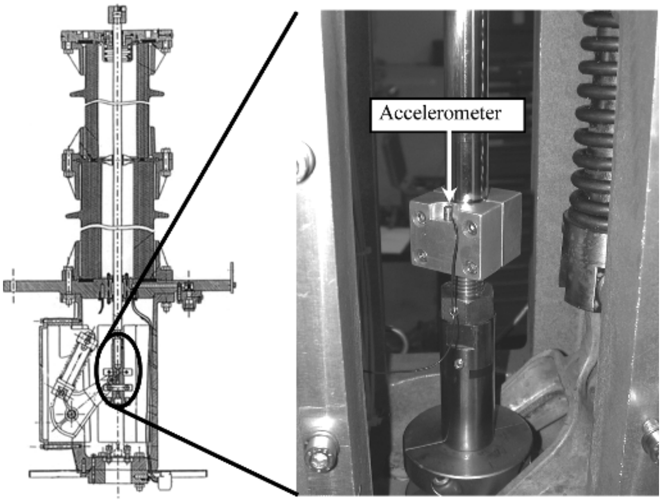


Fig. 5. Accelerometer screwed on a specially designed bracket attached to the operating rod of a hydraulic drive mechanism.

B. Case Study No. 2

The second case study deals with a mechanical anomaly in the interrupting chamber of a hydraulic drive mechanism of a 315-kV SF_6 CB with two breaks per phase (A1, A2, B1, B2, C1, and C2) and having completed 4000 operations.

The accelerometer has been screwed on a specially designed bracket attached to the operating rod (Fig. 5).

The observed dispersion (in gray scale, Fig. 6) of the vibration measurements in the time domain demonstrates the necessity of

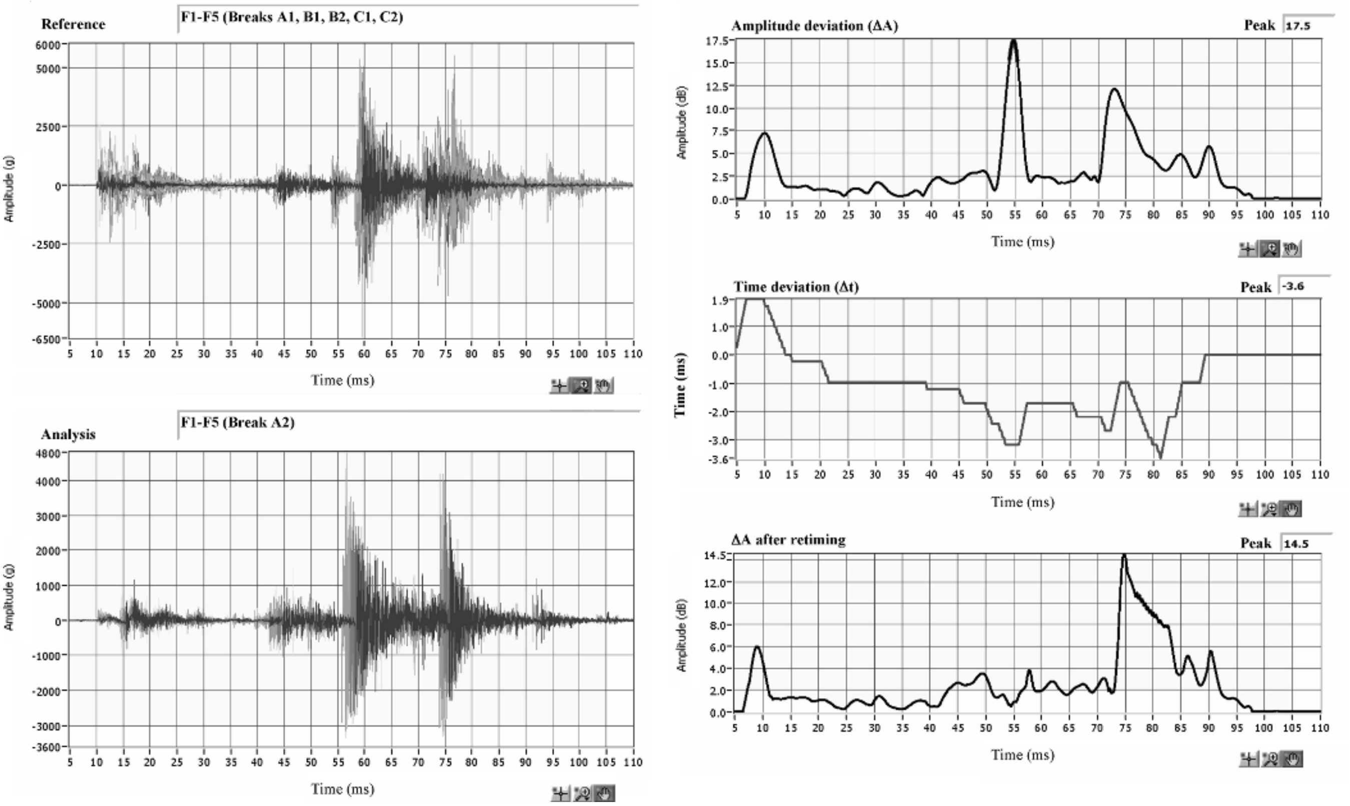


Fig. 6. Graphs of the vibration analysis on break A2 of a 315-kV 6-break SF_6 CB equipped with a hydraulic drive mechanism (Case study no. 2).

TABLE I
SUMMARY OF THE VIBRATION ANALYSIS ON THE 315-kV SF_6 SIX-BREAK CB EQUIPPED WITH A HYDRAULIC DRIVE MECHANISM

Break identification	Amplitude deviation (ΔA) (dB)	Time deviation (Δt) (ms)
A1	13.1	**-5.3**
A2	**17.5**	-3.6
B1	11.3	**-7.5**
B2	8.2	4.0
C1	**17.6**	**10.0**
C2	11.3	2.0

averaging these signals in the frequency domain before further processing. This dispersion is usual, not exceptional, for a vibroacoustic measurement of a sequence of mechanical events taking place during the operation of a CB.

The vibration analysis was performed by comparing a given break (A2) to all of the other breaks. As shown in the left-hand-side graphs in Fig. 6, five closing operations (F1–F5) for break A2 are compared to 25 other vibration signals (i.e., five operations for each of the five other breaks (A1, B1, B2, C1, and C2). This analysis was similarly completed for all breaks in an attempt to identify mechanical anomalies.

Table I summarizes the amplitude and time deviation for all of the breaks. Amplitude deviations for breaks A2 and C1 are higher than the alarm threshold of 15 dB (i.e., 17.5 and 17.6 dB, respectively), while the corresponding time deviations are −3.6 and 10 ms. Time deviations on breaks A1 (−5.3 ms) and B1 (−7.5 ms) were not investigated.

Fig. 7. Loosening of the auxiliary closing contact of the 315-kV 6-break SF_6 CB equipped with a hydraulic drive mechanism.

An inspection of interrupting chambers A2 and C1 revealed that the auxiliary closing contact started to unscrew (Fig. 7). No other anomalies have been detected on these breaks and all other breaks of the breaker. Consequently, these amplitude deviations of 17.5 and 17.6 dB are not due to natural differences between breaks.

C. Case Study No. 3

The third case study involves a low oil level in a closing oil damper of a spring-loaded drive mechanism on a 120-kV SF_6 CB. A laboratory test setup was designed for simulating the variation of the oil level in the closing oil damper, which can take the form of missing oil volume.

In our simulation test setup, the total oil volume (i.e., ≈125 ml) was reduced from 5 to 25 ml. This simulation is of particular

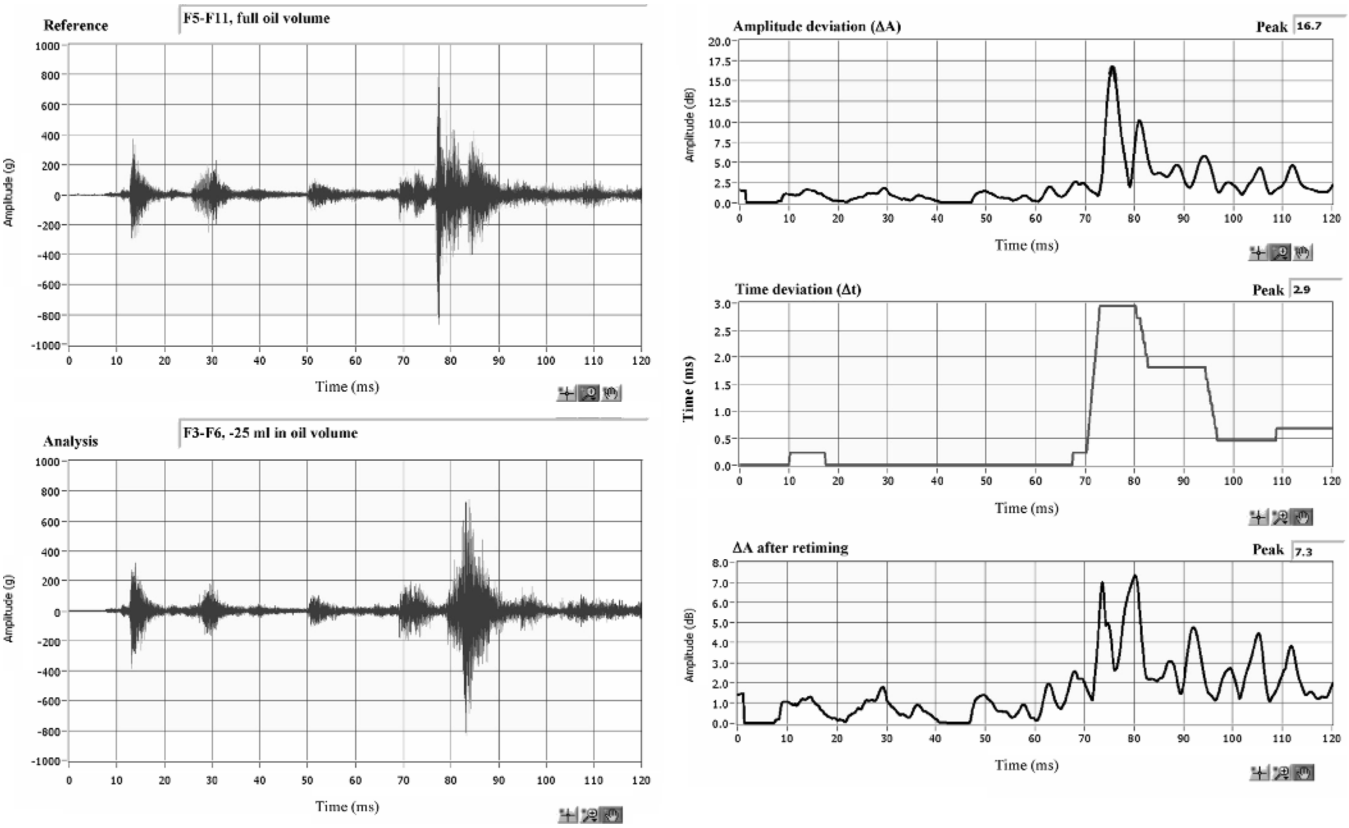


Fig. 8. Graphs of the vibration analysis for an oil volume reduction of 25 ml in the closing oil damper (Case study No. 3).

interest since the maintenance crew already reported oil leaks of closing oil dampers in some CBs.

The accelerometer was positioned at the same location as the one shown in Fig. 2.

Table II shows amplitude and time deviations as a function of the oil volume reduction in the closing oil damper. It indicates that this anomaly is detected by excessive amplitude deviation rather than time deviation that remains below the threshold level of 5 ms. When the oil volume is lowered, the amplitude deviation increases up to a peak value of around 17 dB (i.e., from -19 to -25 ml). Based on these results, it may be concluded that a red alarm (i.e., >15 dB) is triggered from an oil-volume reduction of 16 ml. Fig. 8 contains graphs of the vibration analysis for an oil volume reduction of 25 ml (-25, Table II). The reference signal (i.e., full oil volume) comprises seven consecutive measurements that are averaged in the time-frequency domain for the analysis. Meanwhile, four vibration measurements for an oil-volume reduction of 25 ml are considered and compared to the reference one. The amplitude deviation reaches a peak of 16.7 dB, which exceeds the threshold level of 15 dB.

After retiming the various mechanical events (ΔA after retiming), the amplitude deviation is lower (i.e., 7.3 dB), thus confirming that low oil volume in the closing damper is mainly affecting the timing of the mechanical events.

D. Correlation With the Breaker Contact Position

For a thorough analysis, it becomes crucial to correlate the vibration signal with the breaker contact position. Fig. 9 shows an example where the vibration signature of a spring-loaded operating mechanism is plotted in conjunction with the contact position for closing [Fig. 9(a)] and opening [Fig. 9(b)] operations.

TABLE II
AMPLITUDE AND TIME DEVIATIONS AS A FUNCTION OF THE OIL VOLUME REDUCTION IN THE CLOSING OIL DAMPER

Oil volume reduction (ml)	Amplitude deviation (ΔA) (ms)	Time deviation (Δt) (ms)
0 (Start and End)	7.4	1.3
-5	4.1	0.5
-10	12.7	1.5
-13	13.4	1.7
-16	**15.3**	2.0
-19	**17.2**	2.5
-22	**16.9**	3.0
-25	**16.7**	2.9

The occurrence of the various vibration bursts can be studied in relation to the breaker contact position. In fact, for a given breaker type, the detailed breaker kinematics of the moving parts can be studied in terms of maximum acceleration values.

For closing and opening operations of an SF_6 CB with a hydraulic drive mechanism, Table III gives the event chronology during contact motion that was derived from the geometry of the interrupting chamber and breaker contact travel.

High-speed images of the operating rod motion along with the recordings of the contact travel and vibration signals may ease correlating the vibration signature with the breaker mechanical events. Fig. 10 shows the result of such analyses over which three curves are superimposed:

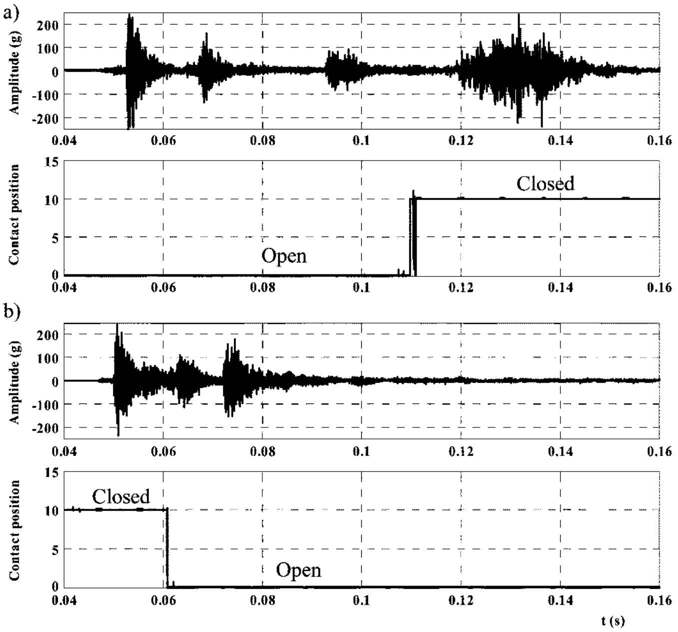


Fig. 9. Vibration analysis complement by correlating the vibration signature of a spring-loaded operating mechanism and contact position. (a) Closing operation. (b) Opening operation.

TABLE III
TYPICAL CHRONOLOGY OF MECHANICAL EVENTS DURING CONTACT MOTION OF AN SF_6 CB

Events	Position of the moving part (mm)	Chronology	
		Closing operation (ms)	Opening operation (ms)
Open breaker	200	0	31
Fixed arcing contact close to the inner walls of the nozzle	77	30	13.5
Arcing contact touch or part	46	36	10
Main contact touch or part	22	41	6.5
Closed breaker	0	47	0

- the coil signal and the breaker-contact position plotted in linear scale (right-end-side Y-axis) for which the amplitude values are not identified since only the time transitions are relevant;
- the envelope of the vibration signal traced in logarithmic scale (left-end-side Y-axis).

Calculating the envelope of the vibration signal implies taking the absolute values of the vibration signal and tracing the curve joining the peak values. Tracking discrepancies in the maximum acceleration value for the various mechanical events might provide a better diagnosis of the breaker condition.

For the arcing contact touch or part, no specific acceleration variation is visible. One possible explanation could be a misaligned fixed arcing contact, thus already exerting a significant force on the inner walls of the nozzle before the final arcing contacts touch.

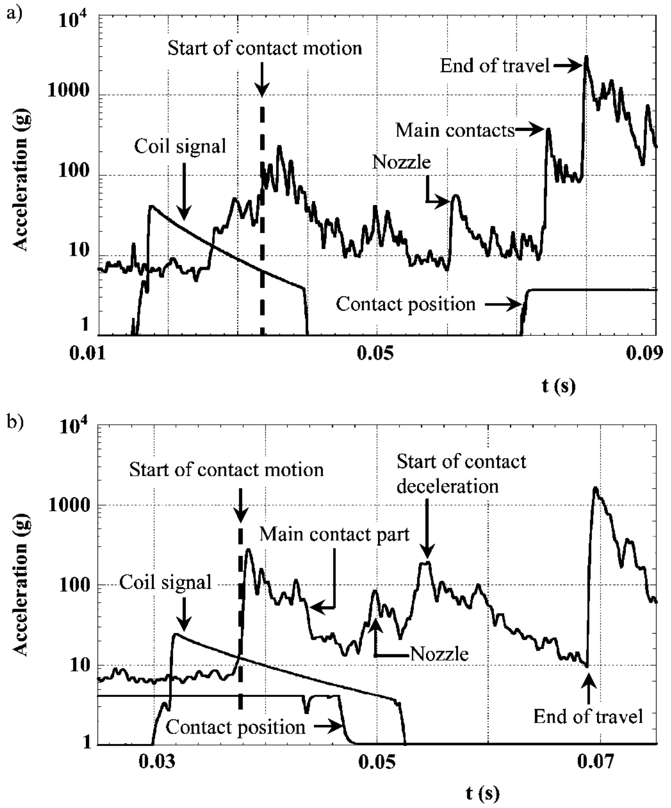


Fig. 10. Vibration analysis by correlating the vibration signature of a hydraulic operating mechanism and contact position. (a) Closing operation. (b) Opening operation.

V. CONCLUSION

This paper presented an improved DTW algorithm for detecting mechanical anomalies in breaker drive mechanisms and internal parts of the interrupting chambers of power CBs. The three case studies presented here confirm that the vibration analysis can be used as a diagnostic tool for all CBs whenever mechanical anomalies are suspected. It is anticipated that a large variety of mechanical anomalies can be detected, such as defects in transmission shafts, loosening of internal parts in breaker interrupting chambers, low oil levels in closing and opening oil dampers, contact overtravel, driving rod thread stripping, etc.

Vibration analysis is based on a comparison of a reference signal to the one to be analyzed. The reference signal could be recorded at CB commissioning or may be composed of signals of other phases of the same breaker or another breaker of the same family. The excellent performance of the new algorithm is due to the implementation of many analysis parameters, such as noise suppression and filtering, analyzed vibration signals resulting from the average in the time-frequency domain of several consecutive measurements, DTW focusing on the main mechanical events (i.e., where the vibration energy is significant).

When performing vibration analysis, it should be emphasized that the correlation of the vibration signal with the breaker contact position is crucial for improving diagnosis of the breaker condition. In fact, breaker contact travel and vibration signals should be recorded simultaneously.

Moreover, the maintenance crew is provided with relevant criteria for selecting the operating mechanisms or interrupting chambers that should be inspected and refurbished. In fact, the diagnostic tool can be used to track CB mechanical conditions in order to better determine when maintenance tasks are required. It is expected that a reduction in maintenance costs can be achieved by dismantling the defective interrupting chambers prior to a costly major failure while keeping the healthy ones in service.

ACKNOWLEDGMENT

The authors would like to thank all of Hydro-Québec TransÉnergie's personnel for their contributions to the vibration measurement program. They would also like to thank M. Soarès for his contribution to the measurement test setup at various substations.

REFERENCES

[1] CIGRE Working Group 13.06, "Final report of the second international enquiry on high voltage circuit breaker failures and defects in service," CIGRÉ Rep. No. 83, 1994.

[2] M. Runde, B. Skyberg, and M. Öhlén, "Vibration analysis for periodic diagnostic testing of circuit breakers," presented at the High Voltage Engineering Symp., London, U.K., Aug. 22–27, 1999.

[3] H. K. Hoidalen and M. Runde, "Continuous monitoring of circuit breakers using vibration analysis," *IEEE Trans. Power Del.*, vol. 20, no. 4, pp. 2458–2465, Oct. 2005.

[4] M. Runde, G. E. Ottesen, B. Skyberg, and M. Öhlén, "Vibration analysis for diagnostic testing of circuit breakers," *IEEE Trans. Power Del.*, vol. 11, no. 4, pp. 1816–1823, Oct. 1996.

[5] M. Runde, T. Aurud, L. E. Lundgaard, G. E. Ottensen, and K. Faugstad, "Acoustic diagnosis of high voltage circuit breakers," *IEEE Trans. Power Del.*, vol. 7, no. 3, pp. 1306–1315, Jul. 1992.

[6] A. A. Polycarpou, A. Soom, V. Swarnakar, R. A. Valtin, R. S. Acharya, V. Demjanenko, M. Soumekh, D. M. Benenson, and J. W. Porter, "Event timing and shape analysis of vibration bursts from power circuit breakers," *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 848–857, Apr. 1996.

[7] V. Demjanenko, H. Naidu, A. Antur, M. K. Tangri, R. A. Valtin, D. P. Hess, S. Y. Park, M. Soumekh, A. Soom, D. M. Benenson, and S. E. Wright, "A noninvasive diagnostic instrument for power circuit breakers," *IEEE Trans. Power Del.*, vol. 7, no. 2, pp. 656–663, Apr. 1992.

[8] M. L. Lai, S. Y. Park, C. C. Lin, H. Naidu, A. Soom, A. M. Reinborn, Y. H. Lee, T. T. Song, V. Demjanenko, D. M. Benenson, and S. E. Wright, "Mechanical failure detection of circuit breakers," *IEEE Trans. Power Del.*, vol. 3, no. 4, pp. 1724–1731, Oct. 1988.

[9] P. R. Voumard, "A simple approach to condition monitoring of circuit breakers," CIGRÉ 1994 Sess. Paper 13–203.

[10] H. Sakoe and S. Shiba, "A dynamic programming approach to continuous speech recognition," presented at the Int. Congr. Acoust., Budapest, Hungary, 1971, Paper 20C-13.

[11] F. Itakura, "Minimum prediction residual principle applied to speech recognition," *IEEE Trans. Acoust., Speech, Signal Process.*, vol. ASSP-23, no. 1, pp. 67–72, Feb. 1975.

[12] H. Sakoe and S. Shiba, "Dynamic programming algorithm optimization for spoken word recognition," *IEEE Trans. Acoust., Speech, Signal Process.*, vol. ASSP-26, no. 1, pp. 43–49, Feb. 1978.

[13] A. R. Brenner, K. ECK, G. Engelhard, and T. G. Noll, "Phase aberration correction using dynamic time warping," in *Proc. IEEE Ultrasonics Symp.*, 1995, vol. 2, pp. 1361–1365.

[14] R. Martens and L. Claesen, "Dynamic programming optimisation for on-line signature verification," in *Proc. IEEE 4th Conf. Document Analysis Recognition*, 1997, vol. 2, pp. 653–656.

[15] S. B. Dolins and J. D. Reese, "A curve interpretation and diagnostic technique for industrial processes," *IEEE Trans. Ind. Appl.*, vol. 28, no. 1, pt. 1, pp. 261–267, Jan./Feb. 1992.

[16] F. Léonard, M. Foata, and C. Rajotte, "Vibro-acoustic signature treatment process in high-voltage electromechanical switching system," U.S. Patent 6 215 408, Apr. 19, 2001.

[17] F. Léonard, M. Foata, and J. Y. Paquin, "Vibro-acoustic signature comparison and time-warping correction with multi-scale correlation," *Mechan. Syst. Signal Process.*, vol. 14, no. 3, pp. 443–458, 2000.

[18] S. Rastrom, "Evaluation of method for high voltage circuit breaker monitoring based on an acoustic vibration technique," M.Sc. thesis, Dept. Signals, Sensors, Syst., Royal Inst. Technol., Stockholm, Sweden, May 2002, IR-SB-EX-0212.

Michel Landry (S'75–M'77–SM'90) was born in St.-Albert. QC, Canada, on August 23, 1952. He received the B.Sc.A. degree in electrical engineering from Sherbrooke University, Sherbrooke, QC, Canada, in 1975 and the M.Sc. degree in energy from INRS-Energie, Université du Québec à Montréal, Montréal, QC, Canada, in 1977.

From 1977 to 1979, he was responsible for testing electrical power apparatus for the high-power laboratory at Hydro-Québec's Research Institute (IREQ). In 1979, he joined the IREQ's Electrical Equipment Department and until 1983, participated in the development of mathematical methods and computer programs for the selection of electrical components for IREQ's synthetic platform designed to perform synthetic breaking tests according to IEC and ANSI standards. From 1983 to 1985, he was involved in a research and test program to qualify the required electrical performance of 2-MV air-blast CBs for Hydro-Québec's James Bay Power System. He also contributed to the development of a new post-arc technology applied to power CBs. He worked on research related to the design of a new SF_6 puffer breaker for low-temperature applications ($-50\,^\circ\mathrm{C}$) from 1985 to 1990.

Mr. Landry is a member of the Canadian IEC Technical Committee 17 on switchgear. He received the 1991 Méritas prize in Engineering awarded by the Ordre des Ingénieurs du Québec. He is now involved in a multitude of research projects related to breaker interrupting performance and inservice condition monitoring for which MONITEQ, an online monitoring system for high-voltage CBs, earned an R&D 100 from prestigious *R&D Magazine*. He has authored or coauthored more than 35 international publications, one of which earned a prize paper award from the IEEE Power Engineering Society in 1986. He is a registered Professional Engineer in the province of Québec.

François Léonard received the M.Sc. degree in physics from Ecole Polytechnique de Montréal, Montréal, QC, Canada, in 1981.

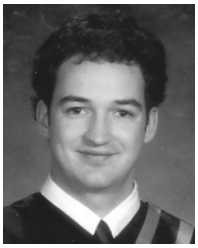
He joined a research team working on wind turbines at Hydro-Québec's Research Institute as a specialist in instrumentation and signal processing in 1981. Among other achievements, he has developed a special modal tool for estimating the low damping modes of wind turbines, the "Zmodal." From 1987 to 1989, he wrote the code for a monitoring system now used for every large hydroturbine at Hydro-Québec. From 1990 to 1995, he worked on hydro-turbine vibration diagnosis and the krigging of the data base in monitoring systems. Since then, he has worked on the vibroacoustical monitoring of electrical equipment, vibroacoustical crack detection in insulation porcelain, and partial-discharge detection and location in underground power cable networks. He wrote the signal-processing algorithm behind many of the leading-edge commercial products originating from Hydro-Québec.

Champlain Landry was born in, Arvida, QC, Canada, on November 6, 1968. He received the B.Eng. and M.Eng. degrees in mechanical engineering from McGill University, Montréal, QC, Canada, in 1992 and 1994, respectively.

From 1994 to 1999, he was a Research Engineer with the Research Center of the Centre Hospitalier de l'Université de Montreal (CHUM) and from 1999 to 2001, he was with the Montreal Clinical Research Institute (IRCM). In 2001, he joined the IREQ's Measurement and Automation Department where he specializes in the development of diagnostic systems for high-voltage equipment.

Réal Beauchemin was born in Québec, Canada, on October 14, 1956.

He is a Senior Technologist with Hydro-Québec's Research Institute with more than 25 years of experience in vibration measurements in laboratory and field applications. From 1981 to 1991, he was mainly involved in a research program on the aeolian vibration of overhead high-voltage transmission lines. He contributed to the development of a new technology applied to the measurement of conductor self-damping. Since 1993, he has participated in a multitude of research projects to improve the use of vibroacoustic measurements for the monitoring and diagnosis of mechanical anomalies on high-voltage substation equipment.



Olivier Turcotte was born in Pointe-Claire, QC, Canada, on February 18, 1981. He received the B.Eng. degree in electrical engineering from Sherbrooke University, Sherbrooke, QC, Canada, in 2003.

During the last year of his bachelor degree, he completed his specialization in Electrical Energy at the Institute of Electrical Energy Engineering (IGEE), Montréal, QC, Canada.

For his outstanding academic achievements, he received the Jean-Jacques Archambault Scholarship awarded by Hydro-Québec. Since 2004, he has been working as a registered Professional Engineer for TransÉnergie, Hydro-Québec's Transmission Division, in the Electrical Apparatus Group. He is mainly involved in the certification and maintenance of medium- and high-voltage CBs and surge arresters. He is also in charge of research-and-development projects on new diagnostic methods for high-voltage CBs.

Fouad Brikci was born in Marrakech, Morocco, on April 20, 1951. He received the M.Sc. degree in electronics, electrotechnics, and automation and the Ph.D. degree in electronics from Bordeaux University, Bordeaux, France, in 1975 and 1977, respectively.

Currently, he is the President of Zensol Automation Inc., St-Laurent, QC, Canada, one of the leading manufacturers of CB analyzers in the world. He was the first to introduce on the market the concept of TRUE computerized test equipment in the field of CB analyzers. As a former university teacher at Ecole Polytechnique Algiers and CNRS-LAAS researcher in France, he has developed experience in electronics, automation, and computer science. Most of his work has focused on the industrial application of computers. His achievements include the development of fully computerized measuring systems for quality control in CB manufacturing, laboratories, and maintenance services of electric utilities. He has specialized in CB testing since 1990.