21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

A2-104

CIGRE 2016

NEW VIBRO-ACOUSTIC TAP-CHANGER DIAGNOSTIC METHOD: FIRST RESULTS AND PRACTICAL EXPERIENCE

M. FOATA, R. BEAUCHEMIN
Reinhausen Canada Inc.
Canada

K. VIERECK, A. SAVELIEV, H. HOCHMUTH
Maschinenfabrik Reinhausen GmbH
Germany

SUMMARY

The fundamental principle of an OLTC operation is the mechanical switching of contacts in vacuum or oil. In the process of an OLTC operation, the acoustic noise and the vibration pattern will reveal most of the mechanical or electrical events during the switching. Considerable information concerning the OLTC operation can then be extracted from the vibro-acoustic pattern. This contribution introduces a novel method for analysis, visualization and interpretation of the vibro-acoustic measurements on OLTCs.

In a first part, the main features of this new method will be briefly described, more specifically the measurement methodology, the signature processing through Wavelet Transform and the pattern recognition techniques. A unique benefit of these features is to allow for a detailed verification of the diverter switch on the very first measurement. By factoring in the tap-changer manufacturer's knowledge of the design and switching sequence, predefined timing tolerances of all events can be applied to determine the normal/abnormal operation of the diverter switch. Since a simple measurement shows the full performance, no trending or statistical comparisons are necessary before a diagnostic can be made. In addition to the deviation in timing, an anomaly in the system can also be recognized by the appearance or absence of expected acoustic events.

In a second part, this paper will present laboratory results of an extensive ageing simulation test. It will be shown that the wear cumulated on all the different components over a high number of operations will clearly and consistently be reflected by deviations in the timing sequence. Low temperature effects will also be discussed and it will be shown that the methodology allows for a diagnostic over a wide temperature range, typically representative of the normal operating temperatures of a transformer.

Finally, a case example from the field will be used to illustrate the built in capabilities of the new algorithm, i.e. the integrated OEM knowledge of the switching sequence and allowable timing deviations, which allow for an immediate diagnostic even from the very first measurement.

KEYWORDS

On-load tap-changer – OLTC – Vibration – Acoustic – Diagnostic – Transformer

m.foata@ca.reinhausen.com

1. INTRODUCTION

The fundamental principle of an OLTC operation is the mechanical switching of contacts in vacuum or oil. In the process of an OLTC operation, the acoustic noise and the vibration pattern will reveal most of the mechanical or electrical events during the switching. Considerable information concerning the OLTC operation can then be extracted from the vibro-acoustic pattern.

The diagnostic potential of the vibro-acoustic method was first demonstrated on OLTCs by reference [1], and confirmed later by several other investigators - recent references include [2-6]. While very different data processing approaches, measurement sensors and interpretation strategies were experimented, two common conclusions can be drawn from all these investigations:

1- The full potential of the vibro-acoustic diagnostic can only be achieved by a rather in-depth understanding of the operating principle of each specific OLTC type.
2- Degradation and anomalies will show on both the amplitudes and timing of the acoustic events, however timing will not be affected by the sensor type, mounting and location so deviations are naturally easier to interpret than for amplitudes.

This paper presents a novel interpretation algorithm in which the detailed timing sequence of the OLTC switching is extracted from the vibro-acoustic measurement and compared with built-in criteria based on the OEM's knowledge of the normal and abnormal conditions. In that process, the capabilities of the approach for the detection of normal wear cumulated over a large number of operations will be demonstrated for the application of maintenance planning. Finally the limitations arising from the extraneous effect of very low operating temperatures will be briefly discussed and a field case example will illustrate the capability of this new algorithm to produce a diagnostic with a single measurement.

2. MEASUREMENT OF THE VIBROACOUSTIC SIGNAL

2.1 Vibration sensor

The vibration signal of the OLTC can be measured with commercially available broadband acceleration sensors. The analog bandwidth of the measurement is limited to about 100 kHz. The measurement at higher frequencies does not seem to be meaningful: the sound in oil becomes beam shaped because of the short wavelength (about 15 mm at 100 kHz). The measurement can be undesirably sensitive to the sensor position.

An integrated Electronic Piezoelectric Accelerometer (IEPE) interface is used for the connection of the acceleration sensor to the signal acquisition device. IEPE provides higher signal quality: more resistance against EMI and less influence from the cable length.

2.2 Placement of the sensor

The best position for the acceleration sensor would be the head cover of OLTC, but this is rarely possible when the transformer is energized. A good alternative position is the side of the transformer tank close to the OLTC. This position could even be more favorable if the tap selector or pre-selector are the aim of the measurement. In the choice of sensor location, it is also important to consider possible acoustic disturbances like running motors, from oil pumps, fans etc.

There are several possibilities to fix the sensor on the transformer:

- Magnetic adapter
- Glued adapter
- Screw or female screw adapter

A screw can usually be used on the OLTC head cover. Because good acoustic coupling is desired, the best results can be achieved using the screw adapter. The second best solution is the glued adapter, if a screw is not available in the desired position. The disadvantages are slightly affected acoustic coupling and longer installation time due to the necessary surface preparation for the glue. The magnetic adapter provide poor acoustic coupling and produces strong resonances in the region of several kHz, which are disadvantageous for the data processing.

2.3 Data acquisition system

A transient recorder, armed with acquisition cards and signal conditioning modules, is used for data acquisition and data processing. Reduction of the signal spectrum by the use of analog filters in combination with a sample rate of 1 MS/s provides good anti aliasing properties. The device can accommodate four such measurement channels simultaneously.

Additional channels with lower sampling rates are used for the input of the current clamp signal.

3. DATA PREPROCESSING

3.1 Time frequency analysis

The standard approach used in the vibro-acoustic measurement of OLTC's is analysis of envelopes [1]. However, useful information about frequency content of the signal will be lost. This information can be gained by time frequency decomposition. The vibration signal is represented in both time- and frequency domains simultaneously. All expected and unexpected acoustic events as well as possible errors in the positioning of the acceleration sensor become "visible".

Collisions of metal parts in oil produce acoustic signals (or vibration signals) like step functions. This signal theoretically comprises all frequencies. However, the continuous spectrum is disturbed due to the own mechanical resonances of the colliding parts and due to propagation in a highly inhomogeneous medium (oil, metal and plastic parts of the OLTC). The quality of the mounting of the acceleration sensor and the frequency response of the sensor itself are further factors influencing the spectrum. In all cases the signal remains broadband and does not contain any narrow band signals.

The simultaneous representation in time- and frequency domain is produced using continuous wavelet transformation (CWT). The characteristics of CWT filter bank are chosen taking into account the signal properties discussed above.

A higher resolution in the time domain is achieved when higher frequencies are involved in the analysis. Non-ideal frequency response of acceleration sensors in the high frequency range is not a big disadvantage, actually it can become a clear advantage when the detection of timing is of interest such as for this model. Hence, the use of broad band measurement rather to narrow band is appropriate.

The length of the transfer function is a compromise between the quality of the filter bank and the speed of calculation. The expected best-case signal to noise ratio (SNR) of the signal is about 70 dB. The developed filter bank provides a SNR of about 100 dB and does not reduce the SNR of the input signal.

3.2 Interpretation of time frequency diagrams

A typical result of a vibro-acoustic OLTC measurement is shown in Figure 1. The horizontal axis represents time and the vertical axis represents frequency. The signal level is shown as color. It can be recognized, that the signal/noise ratio is about 70 dB. Operation of the tap selector and the diverter switch (DS) can be clearly indentified.

Figure 1 shows the measurement on an energized transformer. Further sounds, like transformer humming, arcing on the pre-selector and also 50 Hz disturbances can be recognized readily.

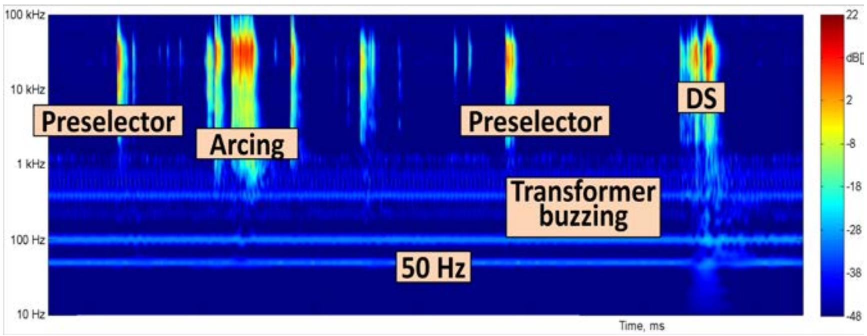

Figure 1:Time frequency representation of an OLTC operation on a transformer in service

4. ANALYSIS OF THE DIVERTER SWITCH

4.1 Preparation of data

The signal structure of the diverter switch operation is more complicated (see Figure 2 at the top). Because the original signal has a broadband nature and the vibration reaches the sensor in different ways, the main information of the signal is contained in its envelope [1].

Characterization of the high-speed operation sequence of the diverter switch needs temporal resolution of less than 1 ms. As the analysis of low frequency components cannot supply sufficient temporal resolution, the evaluation of the signal is appropriate only for the higher frequency range. In practice, the power component of the signal in the frequency range higher than some kHz is used to produce an envelope. To improve the signal to noise ratio of the resulting curve, selective filtering of the signal could be applied. An example of an envelope curve is shown in Figure 2 (green curve at the bottom). A smoothening filter is then applied on the green envelop to yield a cleaner signature as shown by the blue curve.

Generally, the sound of the release of the diverter switch, which starts at rest, is much less intensive than the sound at the end of the switching when the mechanism is stopped from full speed. The amplitude of the vibration signal during the switch over of the diverter switch can spread over a few orders of magnitude. For this reason, the signal level is represented on a logarithmic scale (in dB). The algorithm calculates the threshold value for the background noise (red line) and identifies significant peaks by means of multi resolution analysis (read crosses).

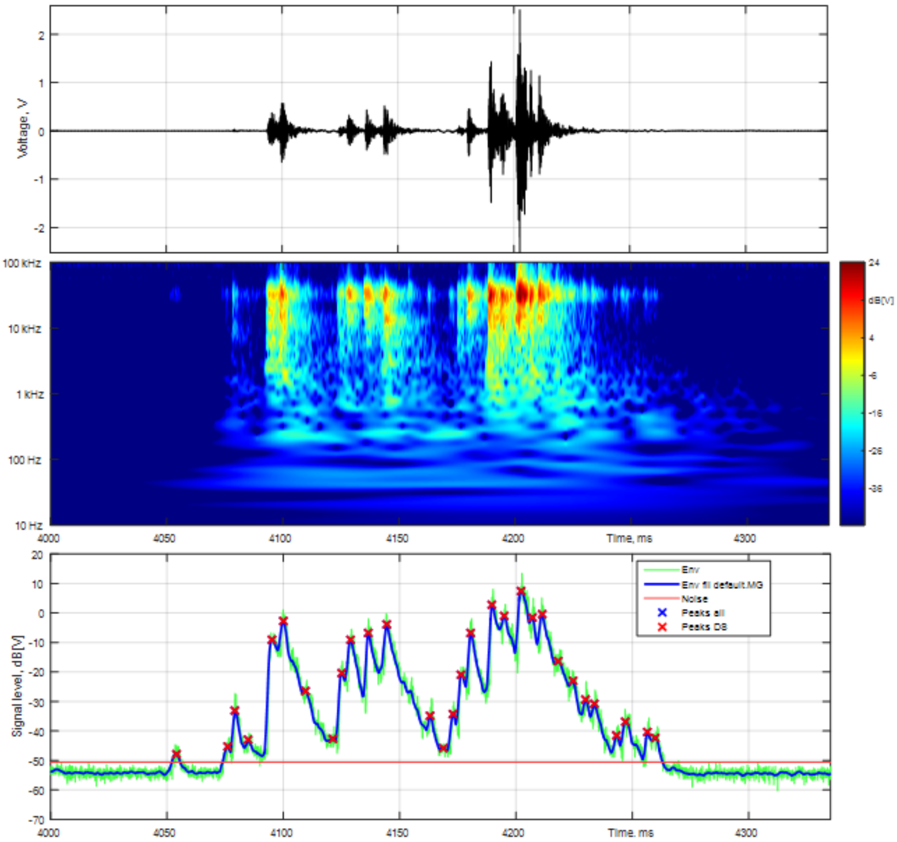

Figure 2: Raw signal of the acceleration sensor (at the top),
time frequency diagram (in the middle) and
resulting envelope (at the bottom) for a diverter switch operation

Figure 3 displays on top the electrical references (breaking and making pattern) produced by the internal contact system of another type of diverter switch. This diagram illustrates the exact mapping of electrical contact events into the acoustic signature during a diverter switch operation. The diagram was recorded on a test stand in the factory, because on a transformer in operation it is not possible to log the contact events of a diverter switch. From this process, it is typically possible to identify between 10 and 20 relevant mechanical and electrical events on the acoustic signature, these are then used as a reference for pattern recognition.

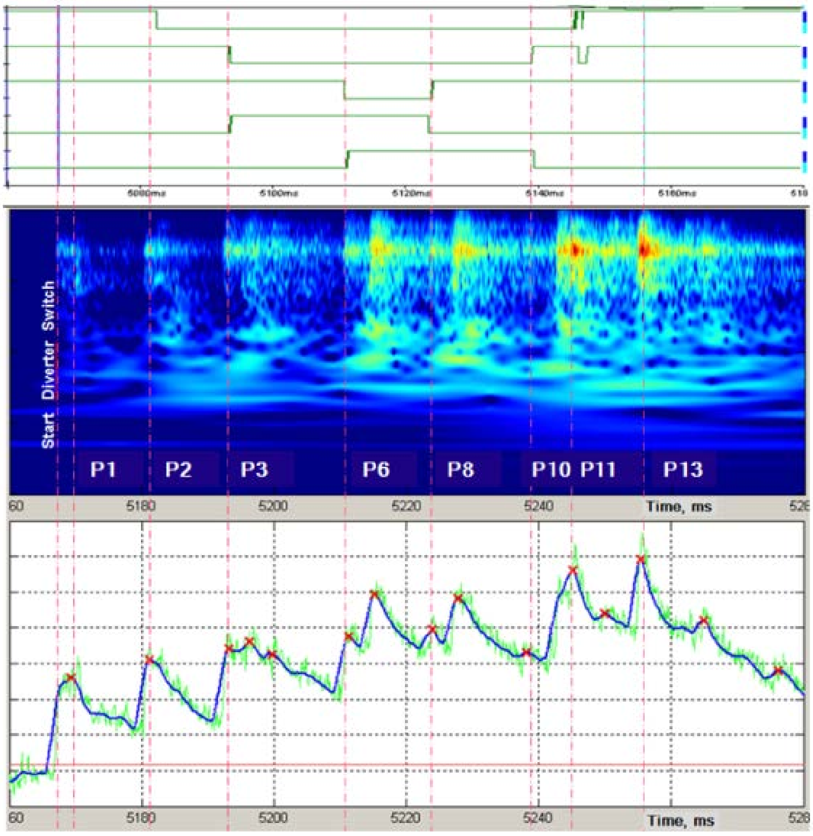

Figure 3: Electrical reference of the contacts breaking and making (at the top), time frequency diagram (in the middle) and resulting envelope (at the bottom) for a diverter switch operation

4.2 Recognition of switching events

The peaks on the envelope of the sound signal are acoustic events and each of them corresponds to a mechanical event in the OLTC. The maxima of the sound signals are the acoustic events and they are in a certain relation to the mechanical events in the OLTC. This relation can be determined through knowledge of the OLTC construction, supported by special OLTC tests. The acoustic events do not directly represent the electrical events like opening and closing of contacts, but these events are often in a certain relation to each other. For example, the opening of a contact does not directly produce any sound. However, the sound can be produced by actuation mechanisms. Not all mechanical or electrical events are represented by acoustic events. Loud sounds could cover softer ones.

Even new OLTC's do not have identical sound patterns because of natural construction tolerances. Differences can even be observed between switch over in even or odd directions. However, it should be not seen as a problem, as long as the switching time sequence is in the permitted tolerance range. The algorithm allows the identification of important events and save their characteristics as a reference. The measurement results of the examined OLTC are compared to the references. The result of such a procedure is shown in Figure 4. Such representation identifies differences to the reference curves. For referenced OLTCs, the positions of recognized peaks can be compared with its allowable tolerances.

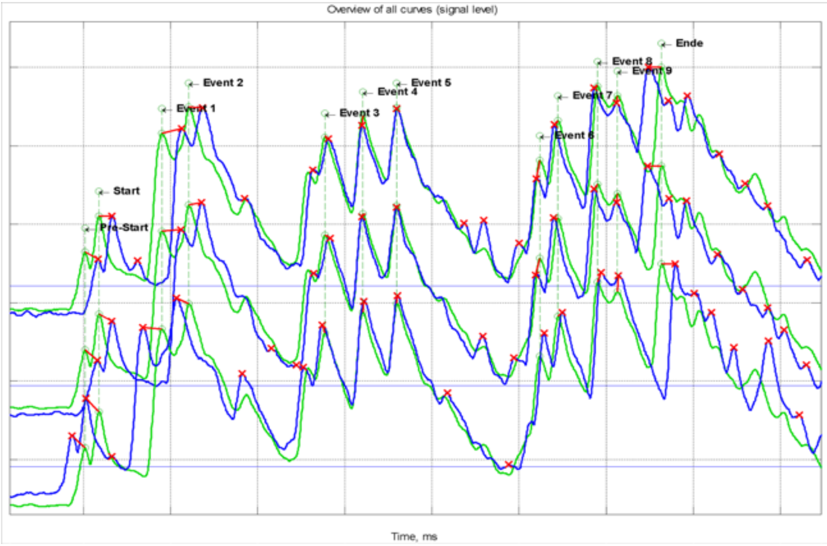

Figure 4: Matching of envelopes (blue curves) to a reference (green curve)

4.3 Effects of low temperature

For practical use in the substation environment the ambient temperature has a strong influence on the acoustical signal quality in the case that the transformer is not energized. If the transformer is in operation, the oil temperature of the diverter switch and also in the selector compartment can affect the quality of the measurement. Figure 5 shows the evolution of the acoustic signatures and gives an impression about the signal quality over a wide temperature range. Down to -10°C oil temperature, no correction of the pattern recognition is deemed necessary because of the remapping capabilities of the algorithm. Below -15°C, the measurement is also possible but for the evaluation of acoustic events a temperature matched reference data set is required. Accordingly, all measurements must have an oil temperature stamp for a more accurate interpretation of the deviations.

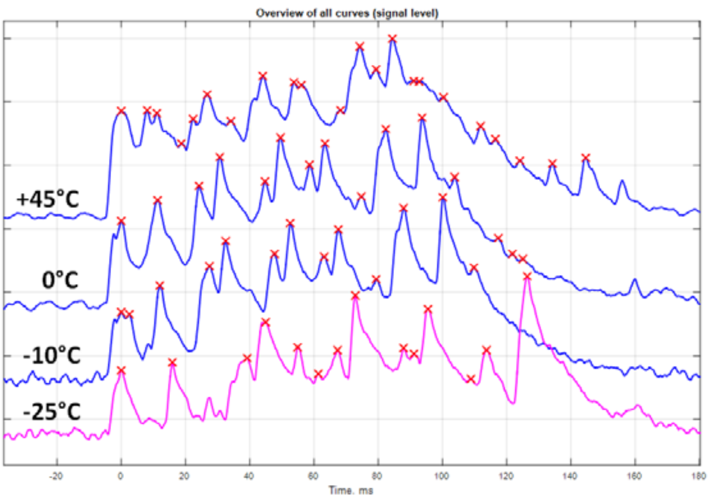

Figure 5: Influence of oil temperature on diverter switch runtime

5. SWITCHING SEQUENCE AND AGEING OF AN OLTC

An OLTC comprises different contacts, which switch different currents and voltages. Arcing on the switching contacts leads to contact wear. Especially in the oil-type OLTC's, the contact wear is significantly high and can reach several mm during normal operation. Therefore changes in the switching sequence in the order of several ms caused by wear could be expected. Additionally, the oil becomes polluted due to thermal cracking and solid products due to arcing on the contacts resulting in increased friction in the system. Figure 6 shows the evolution of acoustic signatures for an oil type OLTC during a 200,000 operations current switching test.

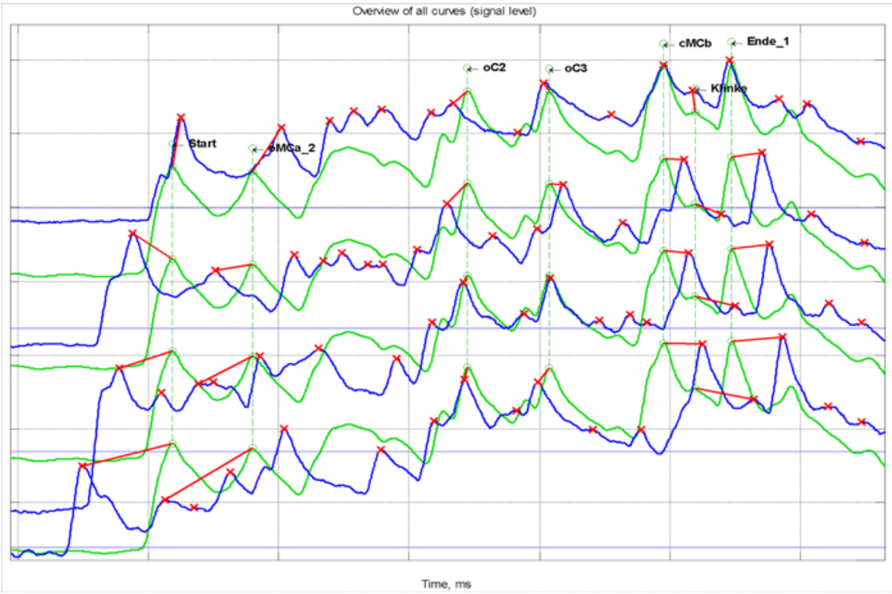

Figure 6: Test curves (blue) and the reference curve (green) for an oil type OLTC. From top to bottom, evolution of the acoustic signature with increasing number of operations.

The acoustic events observed in Figure 6 are assigned to mechanical events in the OLTC, and shown in Figure 7 together with electrical events. Each point on the graphs is an average value for several measurements. The evaluation shows significant changes in the timing sequence after the beginning of load switching operations caused by initial contamination of the oil. Further operation leads to steady changes of switching times because of the continuous wearing of the contacts. The tested OLTC is constructed in such a way, that no arcing occurs on the main contacts (MC). So, the time between the start of mechanical operation and the opening of the MC (oMC) as well as from the closing of the MC (cMC) on the other side until the end of the movement, changes at the beginning (break in period) and remains rather constant after (Figure 7a). The OLTC becomes slower (Figure 7b, oMCa-cMCb). Strong correlation between electrical measurements and acoustic events can be observed (Figure 7b, 7c). Because of different individual loads and consequently different wear of different contacts, the time difference between two events can also be shorter with the aging of switch (Figure 7c, oC2-oC3).

It should be mentioned that different transformer load conditions together with the loading due to circulating currents, result in different wear patterns, depending on the relation between these two parameters.

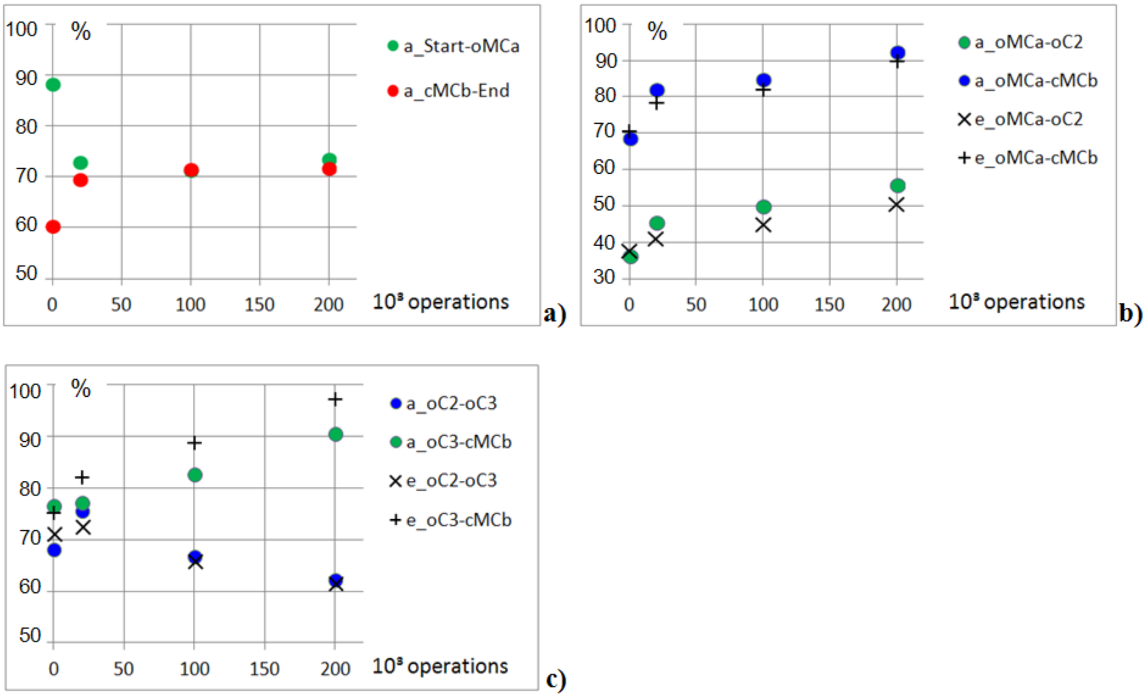

Figure 7: Evaluation of time durations between acoustic events (a_xx) and in comparison with electrical events (e_xx)

6. FIELD CASE EXAMPLE

Trending over time and statistical comparison on a number of similar units have been diagnostic strategies used by numerous previous investigators. These are the only available schemes when an in-depth understanding of the operating principle and detailed design criteria on a given OLTC type are not easily accessible. In addition to these ‘blackbox’ approaches, field measurements with the proposed methodology have also allowed to confirm, in real practical cases, the diagnostic capabilities of the algorithm from a first and unique measurement. This section will provide a detailed example and description of the process of this special feature.

Figure 8 shows below a typical diverter acoustic envelop (blue curve) of a vacuum resistor type tap-changer obtained from a field measurements on an energized transformer. A reference signature (green curve) from a different unit of the same type is also superimposed, this reference is built-in the algorithm and plays a key role in detecting and identifying the main switching events on the sample signature. For this particular OLTC model, up to 16 acoustic events can be related to mains steps of the switching sequence (meaningful for a diagnostic purpose). These include breaking and making of contacts (main, transition), the transfer switch operation, latches and mechanical stops.

Obvious deviations can be observed between the sample and reference curves, these are expected due to a number of factors mentioned previously such as temperature variations, sensor position, normal material and manufacturing tolerances and also possible design revisions. A robust algorithm must have the capability to handle this type of scatter; which is achieved within this proposed methodology by setting a high level of certainty in the events identification scheme. In doing so, a number of events are typically discarded from the interpretation but, considering the high redundancy, sufficient data remains available to allow for an excellent view into the complex mechanical operation sequence of the diverter switch. In this example, as indicated on the figure, a number of 6 events have been automatically identified with a high level of certainty by the algorithm. Upon these 6 events, a number of criteria based on the design and OEM’s expertise can be applied enabling a detailed verification of the diverter switching process. In a non-automatic mode, the algorithm can yield further events identification with some minimal guidance from an educated user.

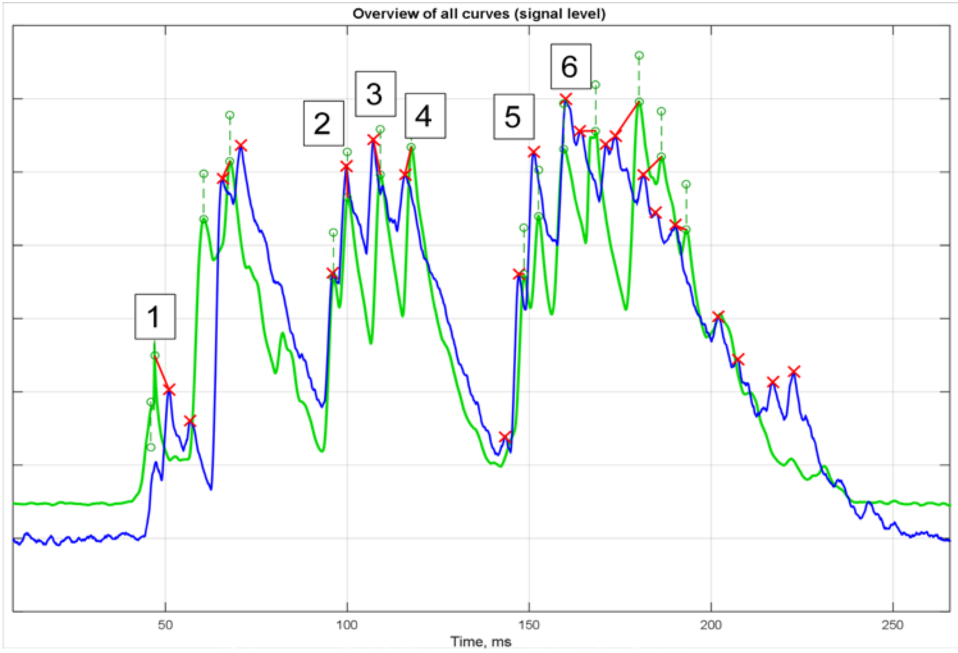

Figure 8: Field example of the analysis of a VACUTAP tap-changer diverter switch

7. CONCLUSION

The vibro-acoustic method is an easy and time-saving method for condition assessment of OLTCs and accordingly has received significant attention from different team of investigators over the last couple of decades. Previously proposed methodologies have relied heavily on 'blackbox' models such as trending or statistical schemes for the interpretation of deviation in the acoustic signatures. However, the necessary education of these blackbox models requires significant data and efforts before practical and reliable diagnostics capabilities can be achieved.

This paper has presented a novel algorithm in which the integration of the OEM's in-depth understanding of the OLTC operation and design allows to lift efficiently many of the limitations inherent to blackbox models. The most interesting feature of this new algorithm is certainly the capability to perform a detailed verification of a given OLTC unit on the very first measurement, and to provide unequalled details on the individual events in the switching sequence. In order to achieve this, the proposed methodology is optimized to detect and interpret the time sequence of events.

BIBLIOGRAPHY

[1] T. Bengtsson et al., M. Foata et al. "Acoustic Diagnosis of Tap Changers" (Paper No 12-101, CIGRÉ Session, 1996).

[2] R. Vilaithong et al. "On-Line Tap-Changer Diagnosis Based on Acoustic Technique" (Paper S3-5, Mat Post 07 - 3rd European Conference on HV and MV Substation Equipment, Lyon, 2007).

[3] D. McPhail "Condition Analysis and Assessment of On-Load Tap-Changer Acoustic Monitoring Principles and Techniques" (Proccedings of Energy 21C Conference, Melbourne, 2009).

[4] L. Allard et al., M. Foata et al. "Vibro-Acoustic Diagnostic : Contributing to an Optimized On-Load Tap Changer (OLTC) Maintenance Strategy" (Paper No A2-202, CIGRÉ Session, 2010).

[5] A. Cichon et al. "Characteristic of Acoustic Signals Generated by Operation of On-Load Tap-Changers" (Optical and Acoustical Methods in Science and Technology, Vol. 120, No 4, 2011).

[6] M. Gauvin et al. "Field Experience with Tap-Changer and Bushing Monitoring" (Paper PS1-O-9, CIGRÉ SC A2 & D1 Joint Colloquium, Kyoto, 2011).