Condition Analysis and Assessment of On Load Tap Changer Acoustic Monitoring Principles and Techniques

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Abstract

On Load Tap Changers (OLTC) are one of the main causes of failures in High Voltage transformers, leading to unplanned outages and interruption in supply. This has sparked an investigation into the use of non-intrusive acoustic monitoring equipment to capture the audible waveforms created as an OLTC switches between taps. Digital signal processing techniques are then used to analyse this data to determine the health of the OLTC.

This paper details the process involved in the collection of the switching waveforms using the acoustic monitoring equipment, followed by the subsequent development and testing of time and frequency domain analysis techniques. The analysis techniques have been used on data collected from 42 OLTCs comprising of 9 different makes. A summary of the results generated from the application of the analysis techniques in two OLTC case studies are included in this paper. Based on the initial results achieved, this paper concludes that the time and frequency domain diagnostic tools developed are able to successfully show the development of deterioration of an individual OLTC with respect to specific parts such as the drive mechanism and tap contacts.

1.Introduction

A typical power distribution network contains a large number of transformers that are fitted with On Load Tap Changers (OLTC) for the purpose of voltage regulation. Due to their large number of moving parts, OLTCs are also one of the main causes of failure in High Voltage transformers, leading to unplanned outages and interruption of supply [1] [2]. At present, the only way to determine whether maintenance is required on an OLTC is to perform an oil sample test or take the transformer out of service to allow for the opening of the OLTC to perform an inspection. This process can take several hours and result in added stress and reduced reliability of the network or in some cases, customers going without power until the transformer is put back in service.

A desired solution would be to implement a non-intrusive method of diagnosing the health of an OLTC, making it only necessary to take a transformer out of service when maintenance is *actually* required [2][4]. Ergon Energy has proposed to use acoustic monitoring to capture the audible signal made by an OLTC as it switches taps [5]. This signal can then be analysed in digital form in the time and frequency domains to determine the health of the OLTC. In this paper an explanation of the time and frequency techniques and the results achieved in their application in two case studies, is presented.

2.OLTC Switching Sequence

In oil-type OLTCs there are two types of switching principles used, the diverter which consists of an arcing switch and a tap selector, and the selector which consists of an arcing tap switch [1]. Diverter type OLTCs change taps in two steps: “First, the next tap is pre-selected by the tap selector at no load (Figure 1 a – c). Then the arcing switch transfers the load current from the tap in operation to the pre-selected tap” [1] (Figure 1 d – g). The tap selector is operated directly by the OLTC drive mechanism, whereas the arcing switch is operated by a stored energy spring.

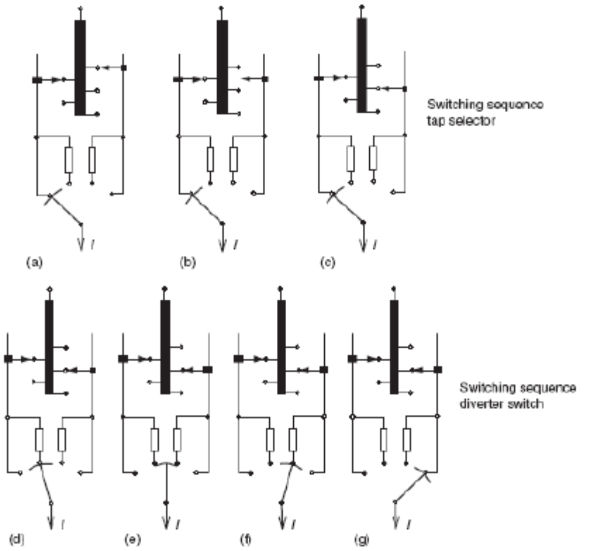


Figure 1 - Switching of a Diverter Type OLTC [1]

Alternatively, the Selector type OLTCs carry out the tap change in only one step [1]. As the main contact leaves the tap, the load current passes through the impedance of the switching contact as the switch continues to turn (Figure 2 a – c). At the point where the first switching contact breaks away from the starting tap, the main contact connects to the new tap and the entire load current again passes through only the main contact (Figure 2 d – e).

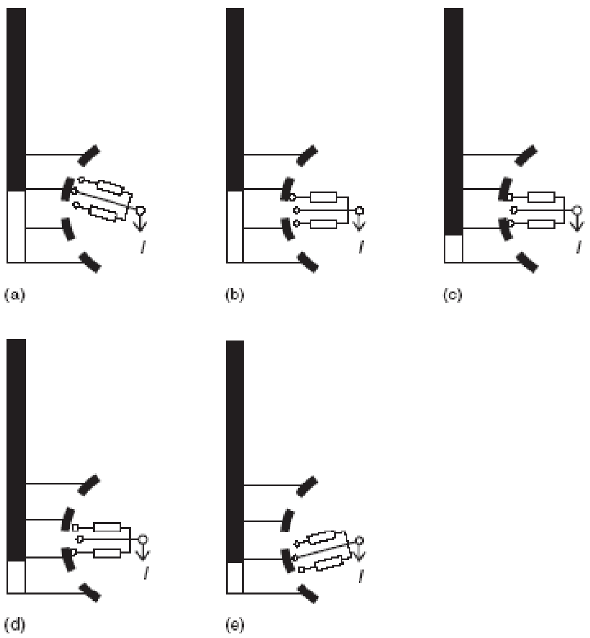


Figure 2 - Switching of a Selector type OLTC [1]

3.Acoustic Data Collection

The acoustic waveform created as an OLTC performs a tap change is captured using a commercially-available portable data acquisition system [5] [6]. The instrumentation used consists of a portable data logging device, a clip-on current coil and a piezoelectric accelerometer that attaches to the steel OLTC tanks by a magnetic clamp. The equipment is arranged as shown in Figure 3 whereby the clip-on coil is used to continually monitor the motor drive current. Upon the occurrence of a tap-change, the current coil triggers the data acquisition device to begin sampling the vibrations created by the OLTC tank at a rate of 50 000 samples per second.

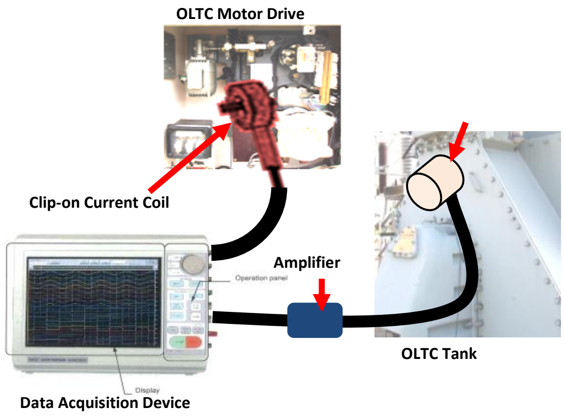


Figure 3 - Configuration of Data Acquisition System

When an OLTC is in service, the tap range that can be monitored is limited to the voltage sensitivity of the network. Generally between 2 to 4 tap changes can be made in the forward and reverse directions. Although not ideal, an OLTC is usually connected to a contact of high use when in service and therefore will show the largest amount of wear in the tap changes available for monitoring [5].

To date, the described data acquisition method has successfully been used to collect tap change data from 42 OLTCs of a variety of ages, under a variety of load conditions and of the following makes:

- ABB - UZFRT and UZFDT
- AEI - 3S21
- AGE - LSA3
- ASEA
- ATL - AT317

- ATL FULLER - F317
- EE - 145AFP
- Ferranti - ES3
- Reinhausen - CIII, DIII, MIII, VIII and HIII.

4.Waveform Analysis Techniques

In order to develop effective means of OLTC diagnosis, analysis tools have been developed using Fourier, Wigner-Ville and Wavelet analysis ideologies. Three such methods, the *Quantitative Curve, Wigner-Ville Spectrum* and *Denoised Waveform Analysis* are discussed in what follows. Analytical techniques have been developed using a large variety of functionality from *The Mathworks Matlab* software and a number of its toolboxes [7]. Through comparing the numerical and visual trends in the analysis results of similar and dissimilar type OLTCs, before and after maintenance, a number of predictions can be made about the condition of an OLTCs contacts and drive mechanism.

4.1.Quantitative Curve

The idea behind the *Quantitative Curve* technique is that as contacts wear, the sound made as the copper contacts connect becomes less 'soft' and more 'sharp', causing an increase in higher frequency content in the waveforms. In addition, as carbon deposits on the contacts build up, it coats the contacts and creates a 'duller' sound, causing the mid frequency band to increase in content. Finally, as the drive mechanism begins to breakdown and become worn, there will be an increase in the low frequency content of the waveform.

Quantitative curves are created using a 3 step process. The first step involves performing low pass filtering of the raw waveform at a number of pre-determined frequencies between 3000 and 50Hz. The upper frequency of 3000Hz is selected as the magnitude of the frequency content falls and remains below -30dB of the 0Hz amplitude and is determined to be noise. Next, the raw waveform is Moving Average (MA) filtered at an order of one fiftieth of the raw waveform's sampling frequency (f_s) as this will decrease the random noise to only 3% of the defining signal. The final step is to calculate the difference between the raw and low-pass filtered waveform magnitudes with the MA waveform magnitudes and averaged to a single data point. The resultant values are then plotted as shown in Figure 4 below.

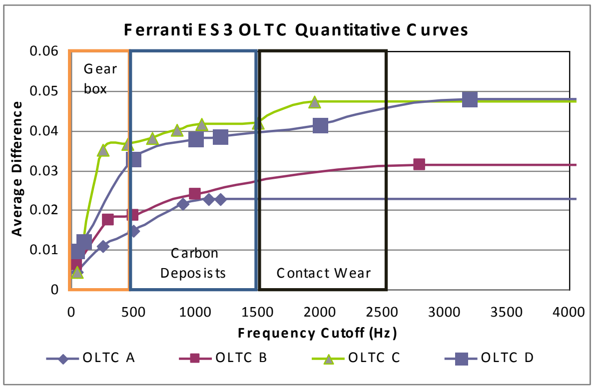


Figure 4 - Quantitative Curves of four Ferranti ES3 OLTCs

As mentioned earlier, it has been found that there exist three frequency regions that experience a change in content from the breakdown of an OLTC contacts or drive mechanism. Using Figure 4 as an example, it can be observed that the OLTC with the more worn drive mechanism has a greater increase in content in the 50 to 500Hz region. Next it can be seen that the OLTCs requiring an oil change and their contacts to be cleaned have a significant increase in content in the 500 to 1500Hz region due to carbon deposits. Finally, by observing the 1500Hz to 2500Hz region it can be seen the OLTC with contact wear shows an increase in content in this region. It is also important to draw attention to the 2500Hz onwards region of the quantitative curve. The fact that this line remains flat until $f_s/2$, confirms the previous statement that only minuet 'noise' data exists in frequency above 3000Hz.

4.2.Wigner-Ville Spectrum Analysis

The Smoothed Pseudo Wigner-Ville Spectrum (SPWVS) is often used for time-frequency characterizations of signals. Unlike a Fourier Spectrum of a waveform which tells us nothing about the evolution in time domain of the frequency content, the SPWVS provides almost perfect localisation of a signal in the time-frequency plane [8]. Figure 5 below shows the SPWVS of a healthy Reinhausen VIII type OLTC. In this plot it can be observed there is a large increase in energy across all frequencies at the moment the tap change takes place, 4.2 to 4.5 seconds, and at the starting and stopping of the motor.

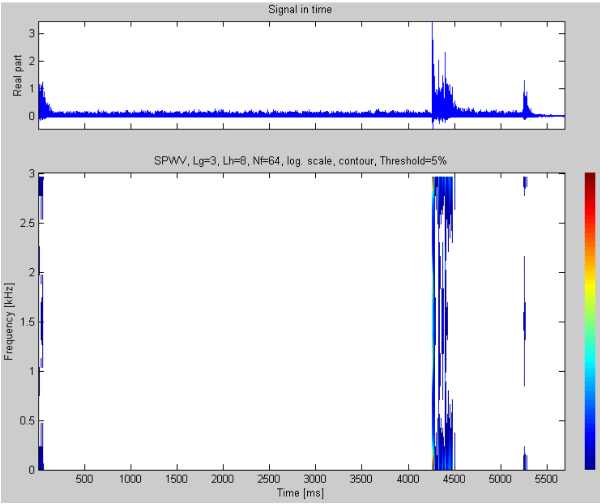


Figure 5 - SPWVS of healthy Reinhausen VIII type OLTC

Now comparing the SPWVS of an unhealthy Reinhausen VIII type OLTC, Figure 6 below, it can be observed that anomalies are present between 2.5 to 3.5 seconds of the unhealthy OLTC plot. This anomaly occurs during the pre-tap change phase of the switching sequence and signifies mechanical breakdown of either the spring charging process or slippage on the drive shaft, both of which are events that can lead to catastrophic failure if not rectified.

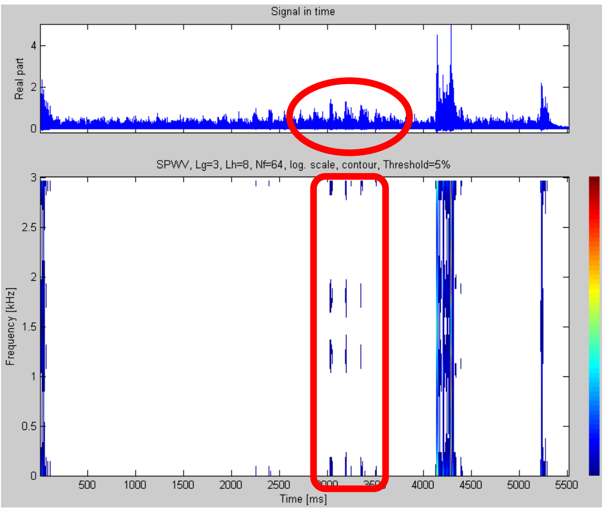


Figure 6 - SPWVS of unhealthy Reinhausen VIII type OLTC

4.3.Denoised Waveform Analysis

The Discrete Wavelet Transform (DWT) decomposes a signal into a set of frequency bands by projecting the signal onto an element of a wavelet, allowing for effective de-noising of waveforms. For the analysis of OLTC acoustic switching waveforms, the b-splines biorthogonal wavelet with a reconstruction and decomposition wavelet of order 3 is used as it meets the requirements necessary to allow for a speedy yet accurate decomposition of the acoustic waveforms with no distortion.

The denoised waveform is created by incorporating information from each of the decomposition waveforms at threshold levels determined by Equation 1, shown below:

$$Threshold = \sqrt{k \frac{1}{N-1} \sum_{i=1}^{N} (Dc_i - \overline{Dc})^2}$$

Equation 1 [9]

$$\text{where } k = \text{the crest factor}$$
$$= \frac{peak\_value}{RMS\_value}$$

The subsequent result is a waveform that incorporates only significant data from raw waveform, across all frequencies. As an example, Figure 7 below shows a healthy Reinhausen VIII type OLTC's raw waveform and Figure 8 below shows the subsequent denoised waveform.

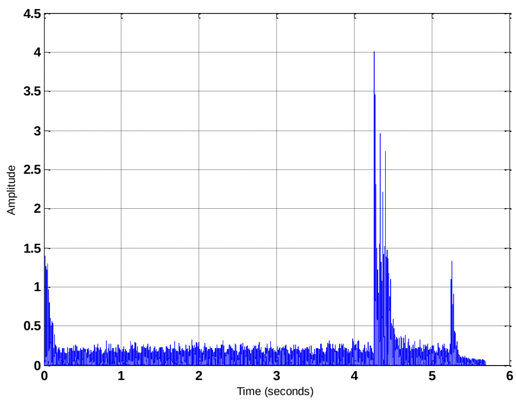


Figure 7 - Raw Reinhausen VIII OLTC Acoustic Waveform

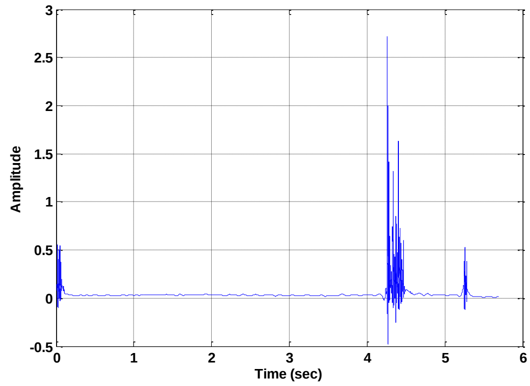


Figure 8 - Wavelet Denoised Reinhausen VIII OLTC Acoustic Waveform

Inspection of denoised waveforms allows for two types of diagnosis to be made. The first is to identify the occurrence of anomalies in the waveform and link to the OLTCs switching sequence to determine the deterioration of a part or process, similar to what is done with SPWVS. Figure 9 below shows the denoised waveform of the Reinhausen VIII type OLTC shown in Figure 8 earlier. Again the abnormal sharp spikes occurring between 2.5 to 3.5 seconds can be observed, signifying either breakdown of the spring charging process or drive shaft slippage.

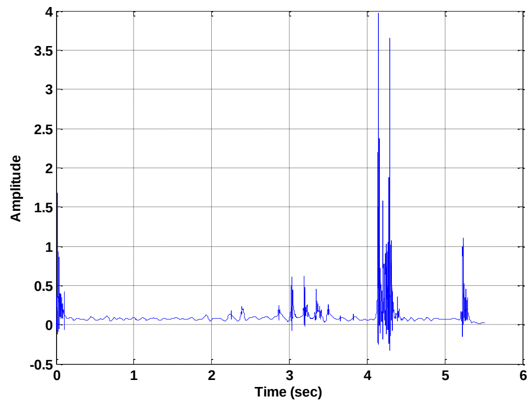


Figure 9 - Wavelet Denoised Unhealthy Reinhausen VIII OLTC Waveform

The second type diagnosis involves zooming in on time period where the actual tap change is made and identifying significant changes in the timing. In Figure 9 it can be seen that the tap change takes place between 4 to 4.5 seconds. Zooming in on this time period, shown in Figure 10 below, 5 time periods can be observed which aligns with the 5 steps in the tap change sequence, shown in Figure 11.

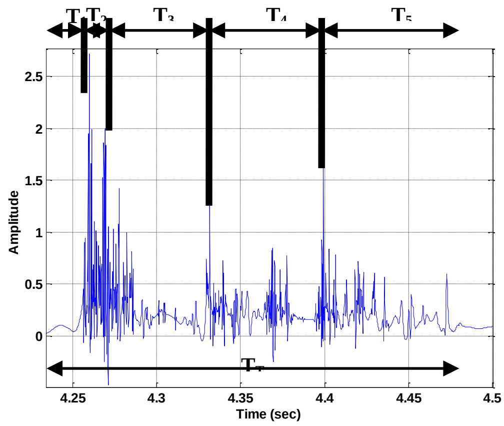
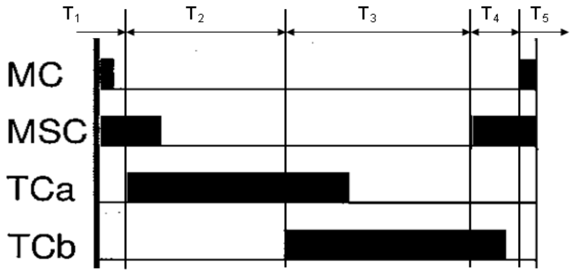


Figure 10 - Waveform form Figure 9 Zoomed in on Tap Change (4.2 to 4.5 seconds)



where:

MC – Main Contact
MSC – Main Switching Contact
TC – Transition Contact

Figure 11 - Tap Change Sequence of Reinhausen VIII type OLTC [10]

Issues such as severe contact wear and the occurrence of components sticking, will cause the timing of the tap change sequence to alter and can lead to catastrophic failure if not rectified.

5.Case Studies

In order to further verify the analytical capabilities of the developed OLTC diagnostic techniques, two case studies are presented in what follows. These studies were completed on two different makes of field based OLTCs that were due for maintenance. In both cases, data was collected before and after maintenance, in and out of service.

5.1.ATL AT317

The ATL AT317 OLTC studied was connected to a 15MVA, 66/11kV transformer. At time of data collection, the OLTC was 23 years old and underwent a mid-life overhaul. As per manufacturer's recommendations, the following maintenance work was carried out:

- Oil replaced and minor leaks repaired
- Gasket replaced
- All internal parts cleaned
- Moving scissor and fixed contact assemblies changed to ratchet contacts
- 3 main moving contact assemblies changed.

In addition the following was observed:

- Minor flat spots on roller contacts of moving scissor contact assemblies
- Minor flat spots on fixed contacts.
- Oil insulating resistance @ 500V = >200MΩ
- All moving parts found to be in good working order

Figure 12 below shows a comparison of the quantitative curves for the change between taps 5 to 6, before and after maintenance.

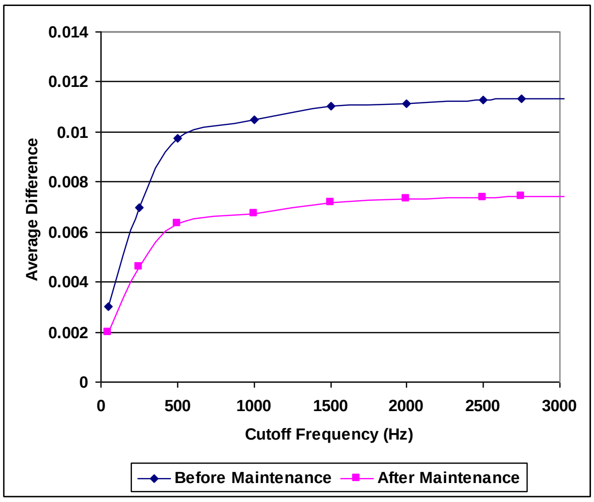


Figure 12 - Quantitative Curve results for change from tap 5 to 6

As expected, there is a significant reduction in the slope of the curve in the 0 to 500Hz range after maintenance due to the replacement of contacts assemblies and the cleaning of all moving parts. In the 500 to 1500Hz range there is little decrease in slope as although the oil was replaced, its insulating properties were still well above the required level. Finally in the 1500 to 2500Hz range, there is again little improvement in slope. This reflects the observations made that the contacts replaced had only minor flat spot wear and had the assembly not been changed, the contacts could have remained in place.

The SPWVS, before and after maintenance, for the change from tap 8 to 7 are shown in Figure 13 and Figure 14 respectively. Comparing the two, it is obvious that no significant anomaly occurs in the switching sequence of the OLTC pre-maintenance. This finding is expected given that all moving parts were found to be in good working order.

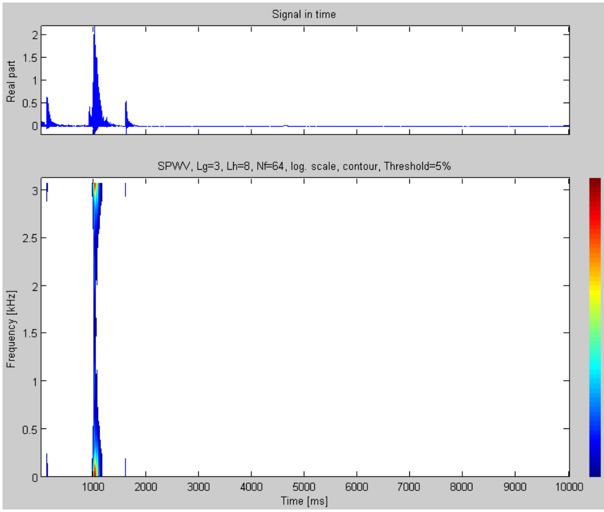


Figure 13 – Pre-maintenance SPWVS for change from tap 8 to 7

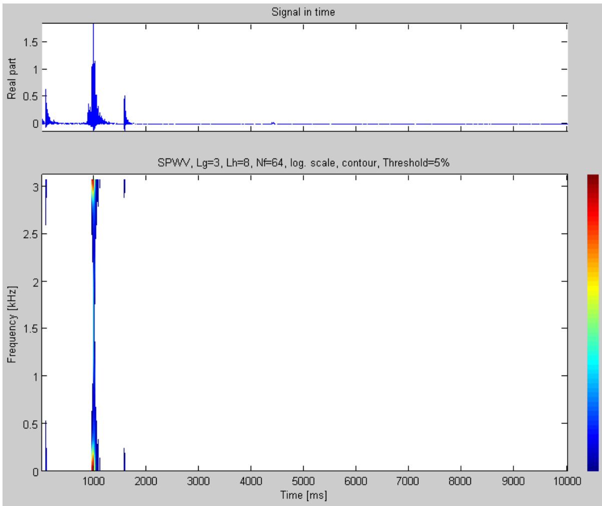


Figure 14 - Post-maintenance SPWVS for change from tap 8 to 7

Inspecting the entire switching sequence of the denoised waveform of the pre-maintenance switching sequence (Figure 15) and comparing to the post-maintenance waveform (Figure 16), the observations made with the SPWVS are again confirmed as no anomalies are found to be present. It is obvious however, that the actual tap change takes place between 0.5 to 1.5 seconds in the waveform. Figure 17 and Figure 18 below show the denoised waveforms zoomed in on this time period and time intervals to compare to the manufacturer's tap change sequence diagram in Figure 19 below.

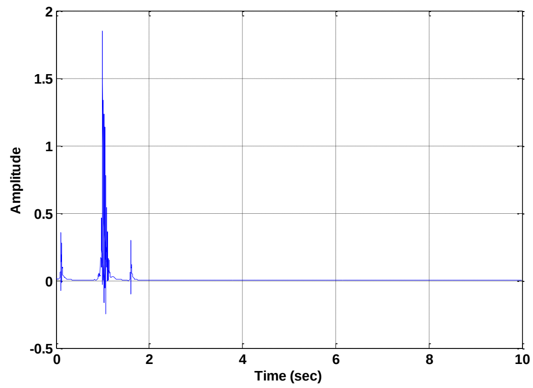


Figure 15 - Pre-maintenance Denoised Waveform for change from tap 8 to 7

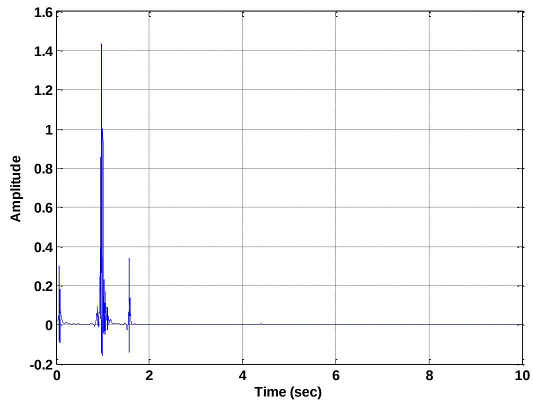


Figure 16 - Post-maintenance Denoised Waveform for change from tap 8 to 7

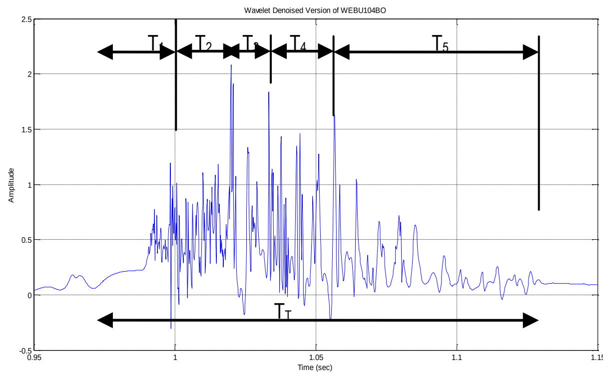


Figure 17 – OLTC Waveform from Figure 15 Zoomed in on Tap Change

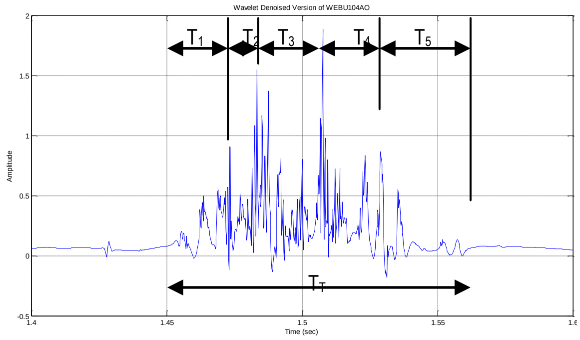


Figure 18 - OLTC Waveform from Figure 16 Zoomed in on Tap Change

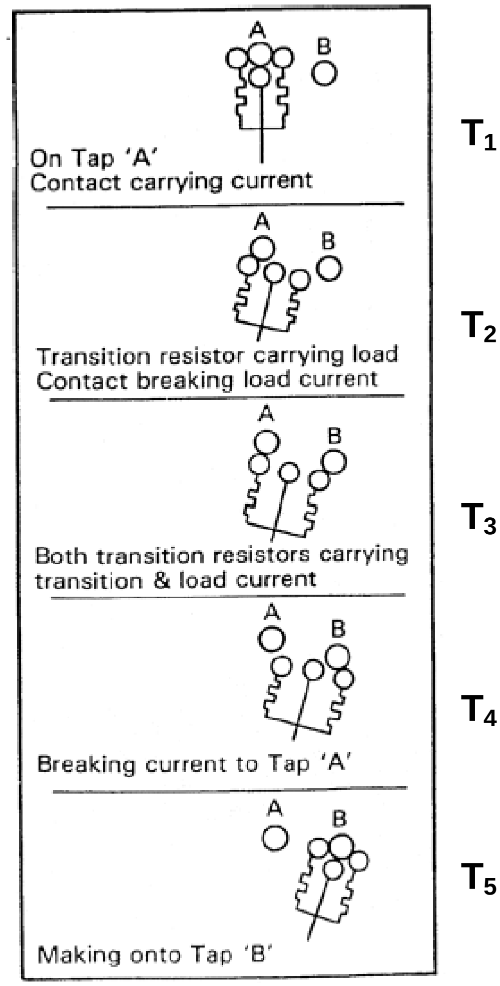


Figure 19 - ATL AT317 Tap Change Sequence [11]

Due to contact flat spots from uneven wear, in the pre-maintenance waveform T_2 is longer as a result of build up in tension of the spring resulting in a short T_3. Friction due to uneven wear also causes T_5 to be prolonged. During maintenance the contacts were replaced, resulting in the after maintenance results showing a reduction in the total switching time. A reduction in amplitude can also be seen post-maintenance due to the replacement of the assemblies.

5.2.Reinhausen HIII 400D

The Reinhausen HIII 400D OLTC studied was connected to a 36MVA, 132/66kV transformer. At the time of data collection, the OLTC was 9 years old and underwent routine maintenance which included:

- Oil replaced and minor leaks repaired
- Gasket replaced
- All internal parts cleaned
- Motor drive shaft seal changed

In addition the following was observed:

- Contacts have experienced 25% of acceptable level of wear
- Oil insulating resistance @ 500V = >200MΩ
- All moving parts found to be in good working order

Figure 20 below shows a comparison of the quantitative curves for the change between taps 7 to 8, before and after maintenance.

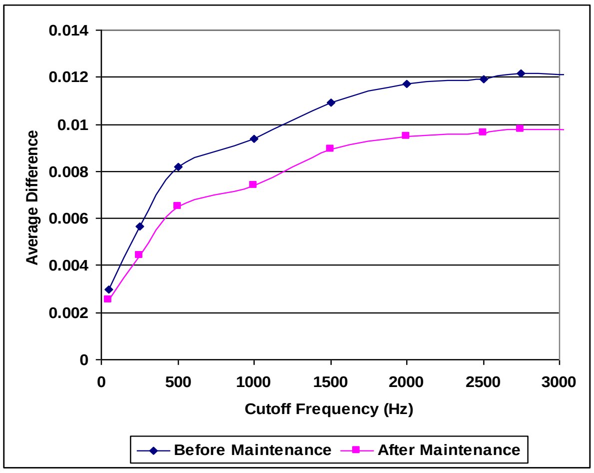


Figure 20 - Quantitative Curve Results for change from tap 7 to 8

Comparing the quantitative curves before and after maintenance, it can be observed that the 0 to 500Hz frequency range has a minor decrease of value as a result of the internal parts found to be in good working order and only requiring cleaning. Although the oil was replaced, there is only a small improvement in the slope of the curve in the 500 to 1500Hz region as the insulating property of the old oil was well above required level. Finally the 1500 to 2500Hz has no change in slope as the contacts weren't replaced.

The SPWVS, before and after maintenance, for the change from tap 8 to 7 are shown in Figure 21 and Figure 22 respectively. Comparing the two, it is again observed that no significant anomaly occurs in the switching sequence of the OLTC pre-maintenance. This finding is expected given that all moving parts were found to be in good working order.

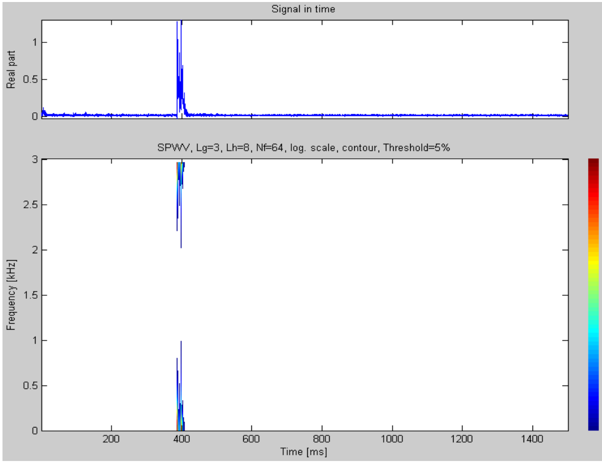


Figure 21 - Pre-maintenance SPWVS of change from tap 8 to 7

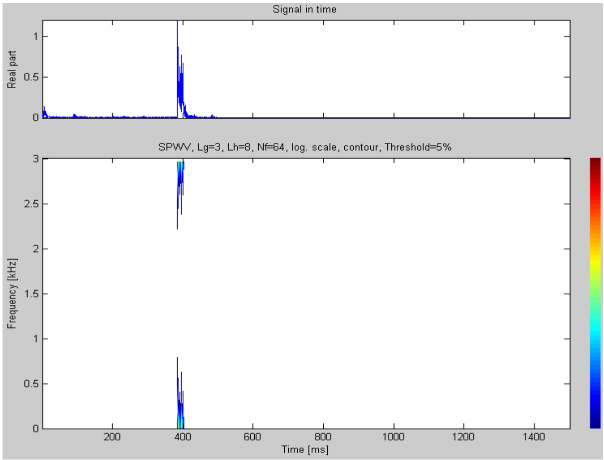


Figure 22 - Post maintenance change from tap 8 to 7

Comparison of the entire switching sequence of the denoised waveform of the pre-maintenance switching sequence (Figure 23) with that of the post-maintenance waveform (Figure 24), again shows no anomalies, confirming the observations of the SPWVS. In this type of OLTC, the actual tap change takes place between 3.5 to 4.2 seconds in the waveform. Figure 25 and Figure 26 below show the denoised waveforms zoomed in on this time period and time intervals to compare to the manufacturer's tap change sequence diagram in Figure 27 below.

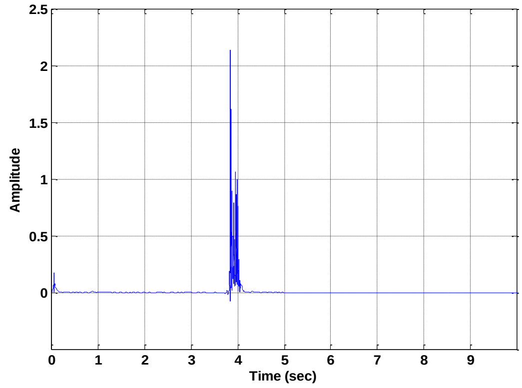


Figure 23 - Pre-maintenance Denoised Waveform for change from tap 8 to 7

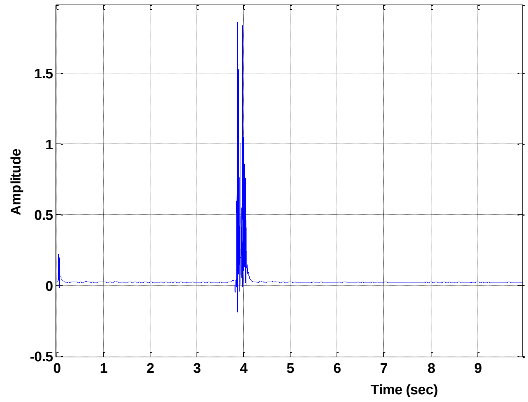


Figure 24 - Post-maintenance Denoised Waveform for change from tap 8 to 7

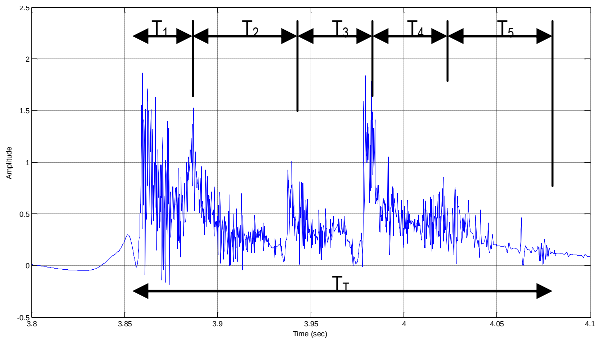


Figure 25 - OLTC Waveform from Figure 23 Zoomed in on Tap Change

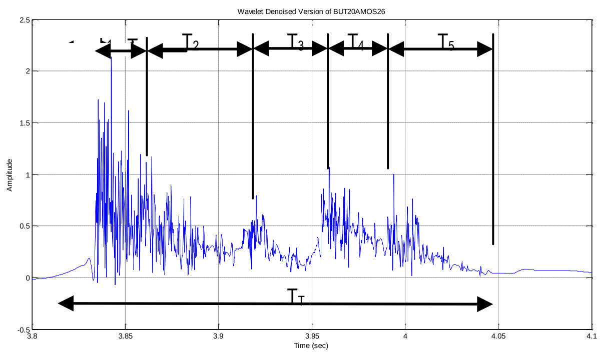


Figure 26 – OLTC Waveform from Figure 24 Zoomed in on Tap Change

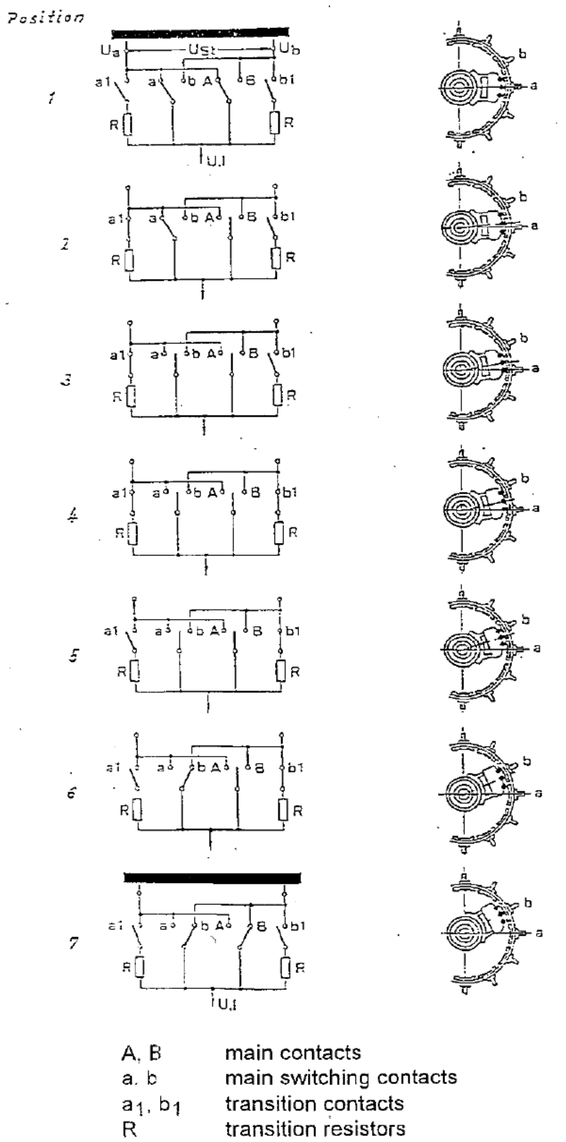


Figure 27 - Tap Change Sequence of Reinhausen H type OLTC [12]

Due to the maintenance of the mechanical parts consisting of nothing more then cleaning, comparison of the pre and post-maintenance denoised waveforms as expected showed no change in the duration of the time segments in the tap change sequence.

6.Conclusions

Non-intrusive diagnosis of OLTCs using acoustic monitoring still remains a difficult task as there are a number of makes and designs of OLTC, each of which contain numerous parts susceptible to wear and deterioration. The data acquisition system data collection process presented in this paper is effective, easy to use and safe to apply to the 9 makes of in service OLTCs tested. This has been shown by having successfully carried out data collection on 42 field based OLTCs.

The developed tap change waveform analysis techniques that have been presented in this paper are effective at identifying deterioration of an OLTC’s drive mechanism, contacts, insulating oil, and switching and tap change sequences. Based on the work completed to date, it is recommended that data capture be completed on new or newly maintained OLTCs as well as units requiring maintenance in order to determine maximum allowable deterioration characteristics. Identification of such characteristics will allow for maintenance workers to determine non-intrusively exactly when OLTC maintenance is required and what work is needed, reducing risks of catastrophic failures, as well as maintenance costs and outage times.

7.References

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8.Acknowledgements

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9.Biography

Donald McPhail – *BE (Electrical) Honours, GradIEAust* – is a Graduate Electrical Engineer at Ergon Energy presently working in the Network Planning and Development business unit. He graduated with honours from the University of Queensland, Australia, in 2008.