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Practical Application of On-Load Tap Changer Vibro-Acoustic Fingerprinting and Diagnostic

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SUMMARY

The on-load tap changer (OLTC) of a power transformer plays a vital role in maintaining a stable voltage level within the electrical grid. The OLTC is a mechanical switching device used to regulate the system voltage by adjusting the transformers turns ratio. Due to the thermal and mechanical stresses generated during the switching of the load current, various OLTC components such as the contacts and the drive can suffer wear and tear over their lifetime.

The paper at hand focuses on the practical application and benefits of a combined dynamic resistance (DRM) and vibro-acoustic measurement (VAM) for OLTC diagnostics. The DRM concentrates on electrical characteristics during the switching process. In contrast, the VAM measures the vibrations produced during the switching operation by means of acceleration sensors temporarily mounted on the transformer tank.

The VAM method offers the possibility to perform measurements on an energized transformer and, accordingly, provide valuable information on the condition of the OLTC without the need for outages. By recording a detailed vibration pattern and comparing it to a fingerprint, it becomes possible to detect and to track changes of the mechanical integrity of the OLTC. Since VAM can be performed without any outage, it lends itself to be integrated into routine inspections, i.e. in-between scheduled maintenance intervals. Such regular tests will provide information on the current OLTC condition and can prove invaluable for maintenance prioritization. Combining the complementary VAM and DRM method, additional insights into the switching sequence are obtained and individual diagnostic blind spots are eliminated. This article will show how VAM and DRM are effectively combined and demonstrate the approach by comparing the results of two sister units.

KEYWORDS

Vibro-acoustic measurement, On-load tap-changer, Condition assessment

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1. Introduction

The on-load tap-changer (OLTC) represents a key element to maintain a stable voltage level in the electrical grid. With the help of the OLTC the transformer turns ratio can be adjusted under load to account for voltage fluctuations. This mechanical switching process causes heating and arcing inside the OLTC. Consequently, various components will experience wear and tear over their lifetime. In order to reliably analyze and assess the condition of the OLTC, increasingly advanced diagnostic tools are developed.
In the following, a condition assessment based on the combination of a dynamic resistance measurement (DRM) and a vibro-acoustic measurement (VAM) is discussed. While the DRM concentrates on the electrical characteristics during the switching of the load current, the VAM focuses on the vibration pattern of the OLTC produced during the switching operation. The evaluation of the VAM results relies on the comparison with reference data such as a fingerprint or the comparison with sister units. This complementary approach covers some diagnostic blind spots of the individual methods and helps to achieve a comprehensive assessment of the OLTC.

2. Measurement Setup

The mechanical movements and the arcing during the OLTC switching operation produce vibrations in a wide frequency range. The VAM allows the analysis of these vibration patterns by comparison with reference data and enables an assessment of the mechanical condition of the tap-changer. The signals are sampled at 250 kHz by the measurement system using integrated electronics piezo-electric (IEPE) acceleration sensors. This way, a non-invasive measurement can be performed on the transformer. This is even possible while the transformer remains in operation throughout the whole process.
In case the VAM is performed on a de-energized power transformer, the sensors can be placed either on the transformer tank wall or on the OLTC cover, of which the latter was found to yield the best signal-to-noise ratio (SNR). In addition, it is possible to combine the vibro-acoustic measurement with a dynamic resistance measurement (DRM). This way, additional information on the OLTC timings, contact wear and tear and possible arcing can be obtained. The OLTC operation is triggered by the test device which automatically records the VAM and DRM data for all tap positions. On an energized transformer, the tank cover is not accessible, and the sensor has to be placed in a safe working area, e.g. on the transformer tank wall. In both cases, the motor current of the OLTC drive system is recorded as well. An overview on the possible test setups is given in Figure 1.

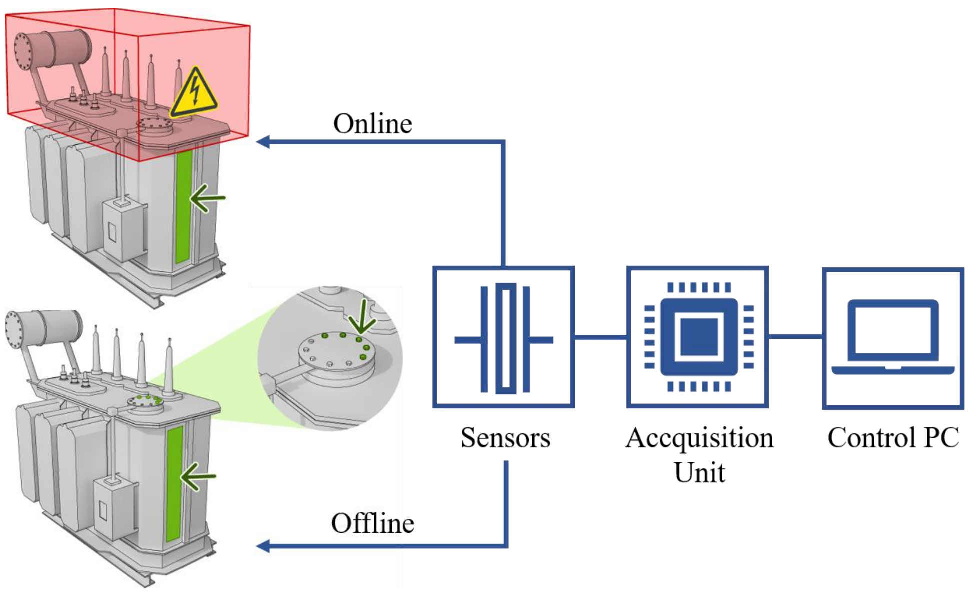

Figure 1 Connection setup of the VAM sensors and the acquisition unit for an online and offline measurement.

The green areas mark recommended locations to place the acceleration sensors. Up to three sensors can be mounted either via magnets on the transformer tank wall or on top of the OLTC cover using screw adapters. While the screw adapter provides the most rigid connection and best signal quality, the magnetic adapters offer higher flexibility and can be placed on any suitable position of the transformer tank. Additionally, it is recommended to use silicon grease on the mounting magnets to improve the signal coupling [1]. The sensor

placement plays a vital role since the obtained data quality is affected by the location of the sensor. It is advisable to place the sensor as close as possible to the OLTC, but far from other acoustic noise sources such as the motor drive, pumps or fans of the transformer. Additionally, sensor positions should be well documented ideally using photos to allow simple reproduction of the results.
In the following, the post-processing of the raw signals and the evaluation of the different result representations are discussed in more detail.

3. VAM Data Evaluation

The signal recording covers the entire tap switch operation from motor start to finish [2]. The strongest signal is obtained during the diverter switch operation. Figure 2 depicts a typical raw signal shape of a diver-switch OLTC and the recorded motor current.

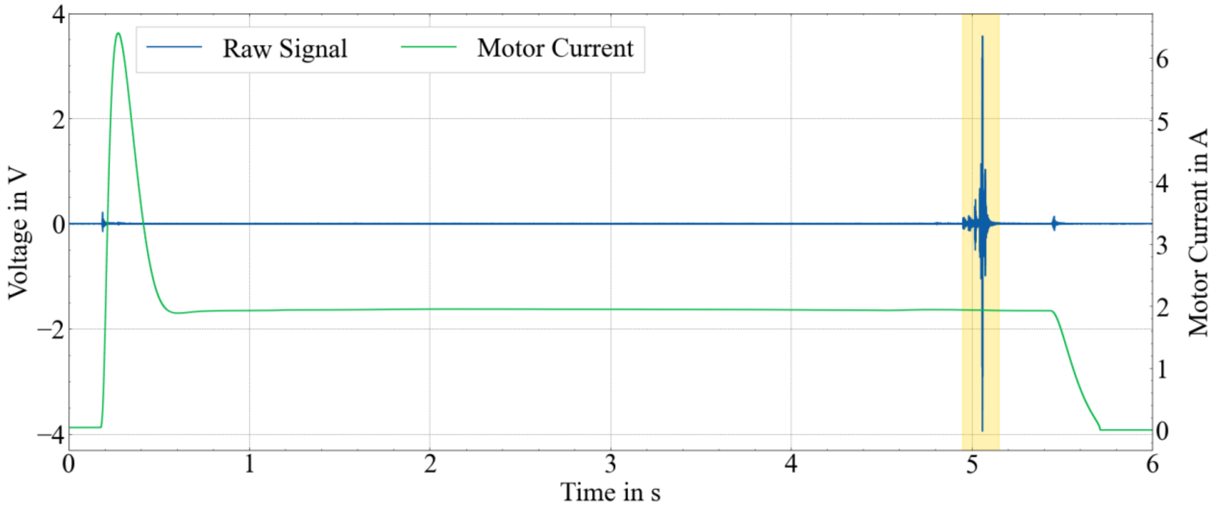

Figure 2 Raw sensor signal (blue) and motor current (green), diverter switch operation highlighted at around 5 s (shaded).

In this case, the raw signal (blue) shows the motor start and stop instances as well as the diverter switch operation (highlighted). The simultaneously recorded motor current is depicted in green.
As stated before, the evaluation procedure is based on comparison with reference data. For that purpose, additional signal-processing is introduced to facilitate the visual comparison and make the results more robust against the influence of external disturbances.

Frequency Time Diagram

In a first post-processing step, a time-frequency analysis is conducted by applying a continuous wavelet transformation to the raw data [3]. The sensor signal is displayed both in time and frequency domain, as indicated by the heat diagram (also *ft-diagram*) in Figure 3.

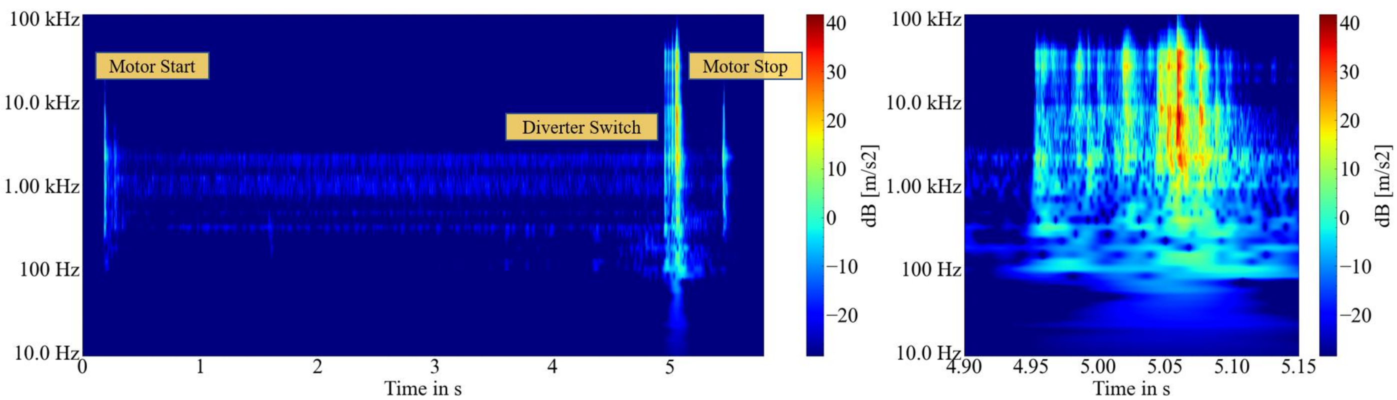

Figure 3 Frequency-time diagram depicting start and stop of the motor and the diverter switch operation (left) and detailed view of diverter switch operation (right).

The x-axis shows the measurement time in seconds, while the y-axis represents the frequency range from 10 Hz up to 100 kHz. The color coding represents the signal level in decibel related to m/s^2 of the individual frequency components. This representation allows to identify the main events of the switching operation such as the start and stop of the drive system, as well as the operation of the tap selector and the diverter switch. In addition, some anomalies such as vibrations caused by pumps or fans, as well as some types of EMC interference can be easily identified observing the f/t-diagram. Such anomalies do not necessarily pose a threat to the OLTC but can make further evaluation of the data more difficult. During online measurements, the transformer core vibrations can be picked up as well.

Envelope curve

In addition to the frequency-time diagram, an envelope curve is derived by integration in a typical frequency range of 10 kHz to 100 kHz and a subsequent Gaussian filtering. The resulting curve reflects the energy of the raw signal in the defined frequency range and can be used for comparison with reference data such as factory fingerprints or data of sister units [4]. Figure 4 illustrates the raw signal of the sensor and the corresponding envelope curve in dB over time.

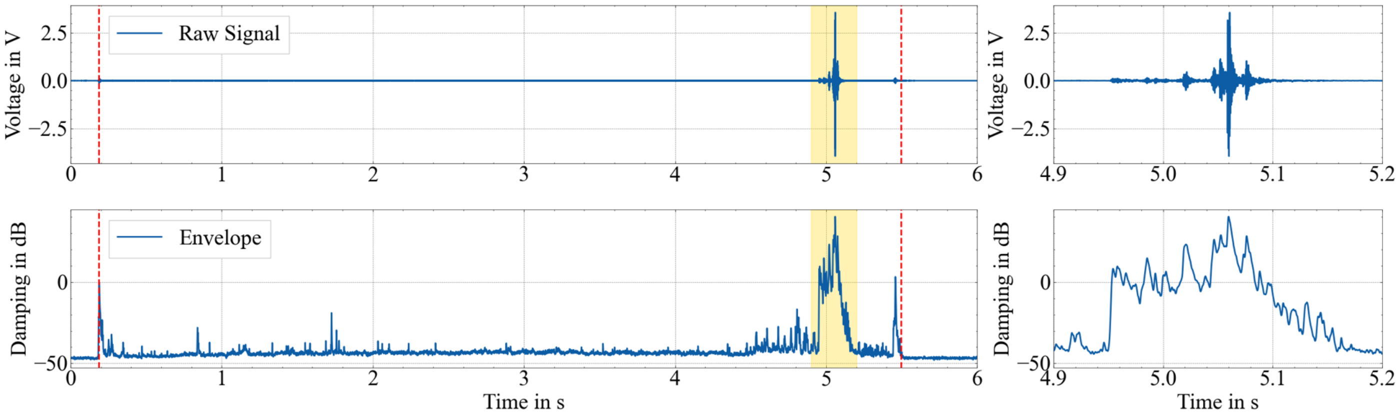

Figure 4 Top: Raw signal of OLTC operation (left) and detailed diverter switch operation (right). Bottom: Corresponding envelope curve.

Similar to the raw signal, the envelope curve reflects the main switching events like the motor starting and stopping, the tap selector movement and the diverter switch operation. Figure 4 shows a detailed view of the diverter switch operation (highlighted). In order to identify possible mechanical changes in the OLTC, attention should be paid mainly to a shifting of peaks and less to a change in amplitude between the reference and the actual envelope curve. The analysis of the switching timings based on the envelope curve process shows a considerably higher tolerance to external influences, which makes it much more suitable for comparison.

Combining VAM and DRM

The VAM and DRM measurements on an OLTC represent mechanical and electrical time sequences, respectively, and provide an opportunity for combined evaluation producing complementary data. By combining the two approaches, blind spots of the individual methods are compensated. Thus, parts of the ft-diagram or the envelope curve can be mapped to individual movements such as the opening or closing of the contacts. Using the vibro-acoustic measurement, all OLTC components that produce sufficient vibrations can be considered for the overall evaluation. However, some operations do not produce any recordable pattern. Consequently, they are not or only barely reflected in the VAM trace. In contrast, a dynamic resistance measurement is only affected by operations that cause a change in the test current. Figure 5 shows the synchronous measurement result of an envelope curve and the corresponding DRM curve.

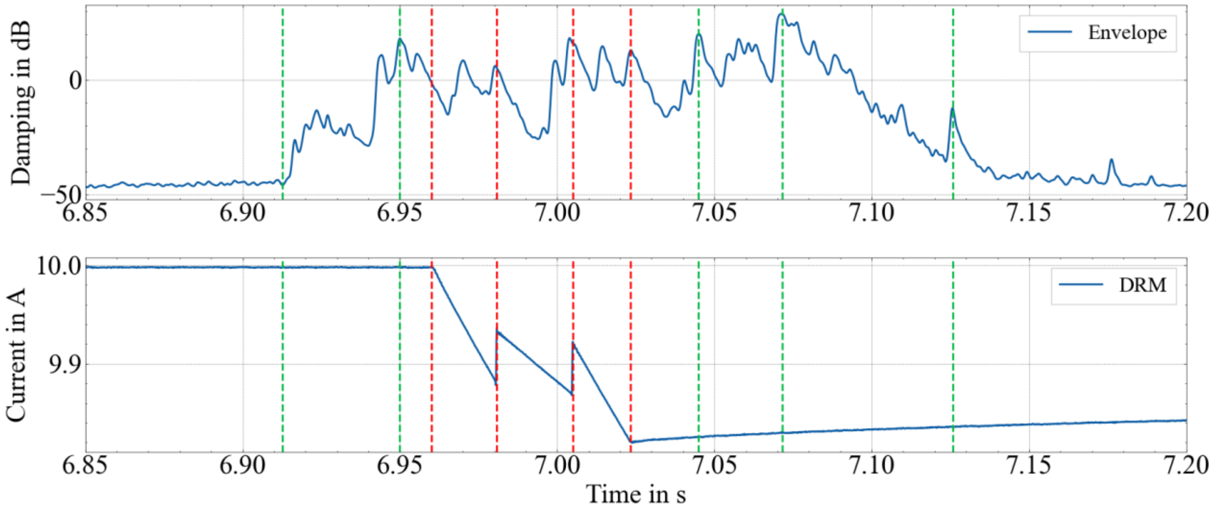

Figure 5 Top: Envelope curve of diverter switch operation. Bottom: Corresponding DRM curve.

The top part of Figure 5 shows the envelope curve of the diverter switch operation while the bottom part depicts the DRM current. The dashed lines mark all events that are either detected by the VAM or the DRM current. The red lines indicate events based on the DRM curve such as the opening and closing of the main and auxiliary contacts. In contrast, the envelope curve clearly shows that numerous mechanical events are picked up during the diverter switch operation (green dashed lines) that are not represented in the DRM curve. When comparing these events, it stands out that the last three DRM events coincide with peaks of the envelope curve, the first event of the DRM curve however is not visible in the envelope curve. The first event to cause a change in resistance and thus affect the DRM curve is the opening of the main contact. As opening a contact may cause less vibrations than closing one, it is likely that this instance is only represented in the DRM curve. Additionally, the comparison shows that the actual start of the diverter switch operation is picked up only by the envelope curve (at approx. 6.90 s).
This comparison shows that the combination of both measurement types provides an opportunity to assess the mechanical integrity of the OLTC in detail. In addition, linking DRM and VAM data offers the possibility to identify individual peaks and monitor possible changes in between maintenance intervals by performing online VAM measurements.

3. Influence of Sensor Placement

As indicated before, the positioning of the sensors should be carefully considered. The signal strength can vary significantly depending on the placement of the sensors. The best signal quality has been recorded from sensors mounted directly on the cover of the OLTC using screw adapters. In addition, positions close to the tap-changer and near rigid structures of the transformer tank wall yield a high signal strength. On the other hand, the signal strength will decrease with increasing distance between sensor position and tap-changer. Furthermore, external disturbances can be picked up if the sensor is placed in the vicinity of the drive shaft or other noise sources. Figure 6 depicts the influence of the sensor placement on the raw signal strength and shape.

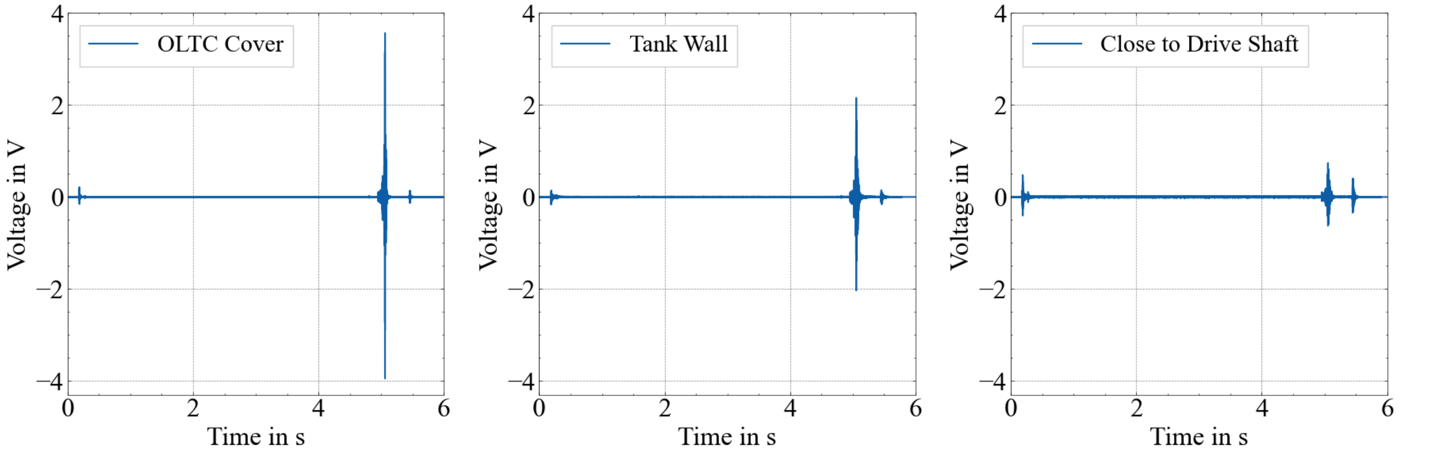

Figure 6 Influence of sensor positioning on raw signal strength. From left to right: OLTC cover, tank wall and close to drive shaft.

While the highest signal strength is obtained when the sensor is mounted on the OLTC cover using a screw adapter, the signal recorded via the transformer tank wall is still sufficiently strong and clearly defined. The sensor that was positioned close to the motor drive shows a comparatively high damping resulting in a signal strength that is only around 25% of the signal obtained on the OLTC cover. Additionally, the motor start and stop events are more prominent due to the vicinity of the sensor to the drive shaft. Consequently, the question arises what level of signal damping is still permissible. To illustrate the effect on the envelope curve, and thus the actual analysis, a comparison between a high- and a low-quality signal reading is depicted in Figure 7.

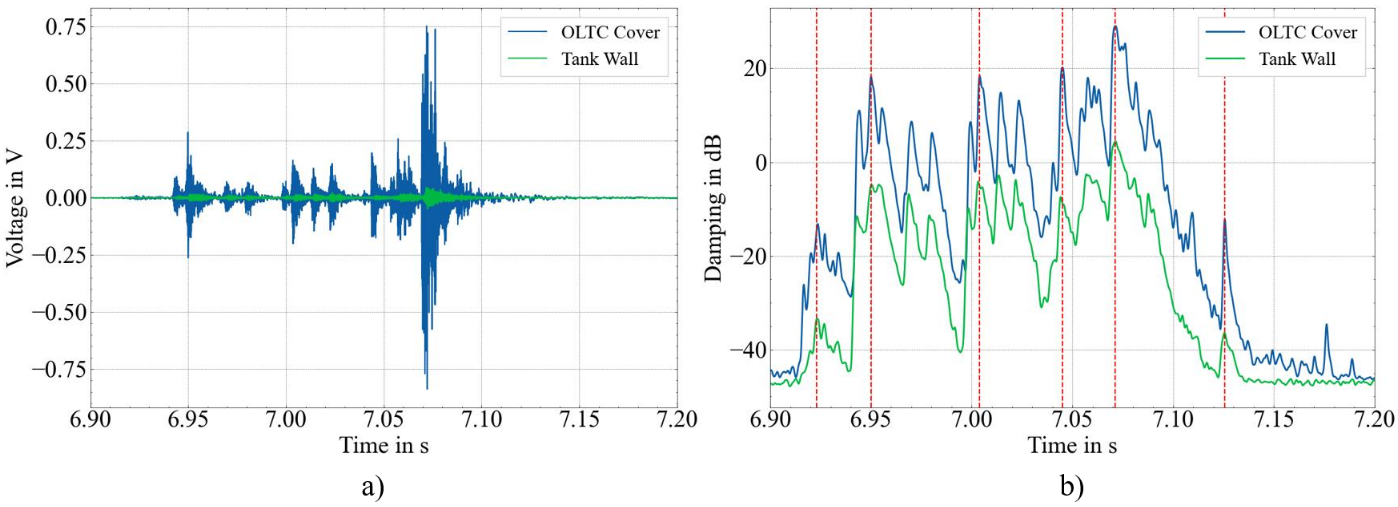

Figure 7 a) Raw sensor signals of high (blue) and low (green) signal strength. b) Corresponding envelope curves.

Figure 7.a) depicts two raw sensor signals with a high (blue) and quite low (green) signal strength, zoomed in on the diverter switch operation. The peak voltage of the blue curve is roughly 16-times higher compared to the green one. While the first one has been recorded on the OLTC cover, the second one has been recorded via a sensor mounted on the tank wall. Although the main events can be recognized in both signals, the green one seems to be lacking many details. However, when comparing the two corresponding envelope curves in Figure 7.b), the main features of both curves are quite similar in the number of discernable events and their timing. Again, the green curve is missing some smaller peaks, but in total the overall shape of the curves match, illustrated by the alignment of the peaks (red dashed lines).
This comparison shows that on the one hand the quality of the raw signal strongly depends on the sensor positioning. On the other hand, a high repeatability of the envelope curves is observed, even in case of a strong initial signal damping. Consequently, comparing online and offline results is feasible as well, even though the sensors might not be mounted in the same place due to a lack of accessibility.

4. Case Study - Comparison of Sister Units

In the following, the VAM results of two 410 kV / 27 kV transformers are discussed. Both units are equipped with *MR Oiltap® Type G* diverter switch on-load tap changers.

Prior to the maintenance of the transformers, a VAM measurement is performed to analyze the OLTC condition. Since no fingerprints of the units under tests are available, a comparison of the two sister units is an effective approach to evaluate the results on a relative basis. The following evaluation will focus only on the diverter switch operation.

When comparing the raw signals, a time shift of 6 ms between the curves becomes obvious, Figure 8.

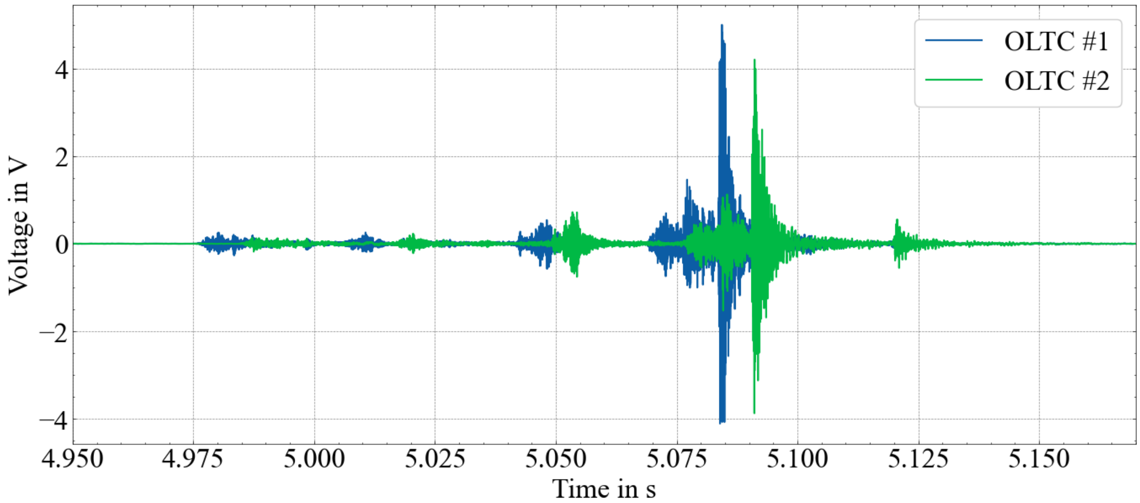

Figure 8 Comparison of the raw signals of the two sister OLTC.

Since the recording is triggered by the motor current, an offset correction can easily resolve the issue. Figure 8 shows that both signals seem to be quite similar in shape and amplitude. However, a detailed comparison based on the raw signals is not practical, as discussed earlier.

The comparison of the envelope curves reveals that the vibration pattern of the two sister units match almost perfectly, Figure 9. The offset between the individual curves has been eliminated to facilitate the comparison.

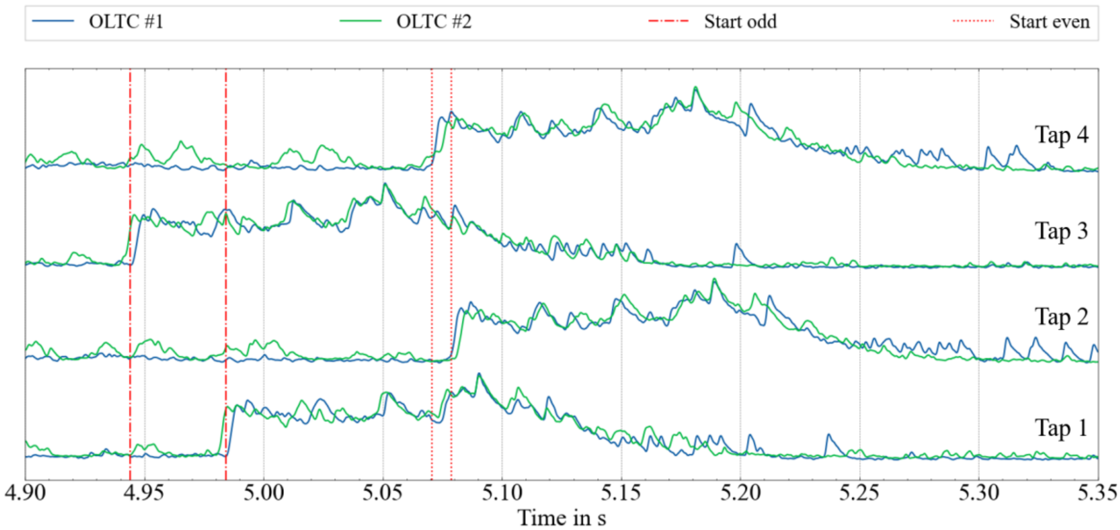

Figure 9 Comparison of the envelope curves for a) odd and even and b) up and down traces.

Figure 9 depicts exemplary the tap switches from tap one to tap four. The markers indicate the start of the diverter switch operation. There is a time shift of approx. 110 ms between odd and even tap positions, given that both curves are triggered by the motor current. Similar time offsets exist between up and down switching. The diverter switch of this type of OLTC has two different switching operations, switching from odd to even position and vice-versa. Therefore, the evaluation of the results is enhanced by separating the envelope curves by parity and direction. Ideally, each tap switch should be compared to its direct counterpart with the same parity and switching direction. Adding in the DRM data (Figure 10) helps to map some of the VAM peaks to certain events like the operation of the main and auxiliary contacts. Besides, it shows again that both OLTC units produce almost equal traces.

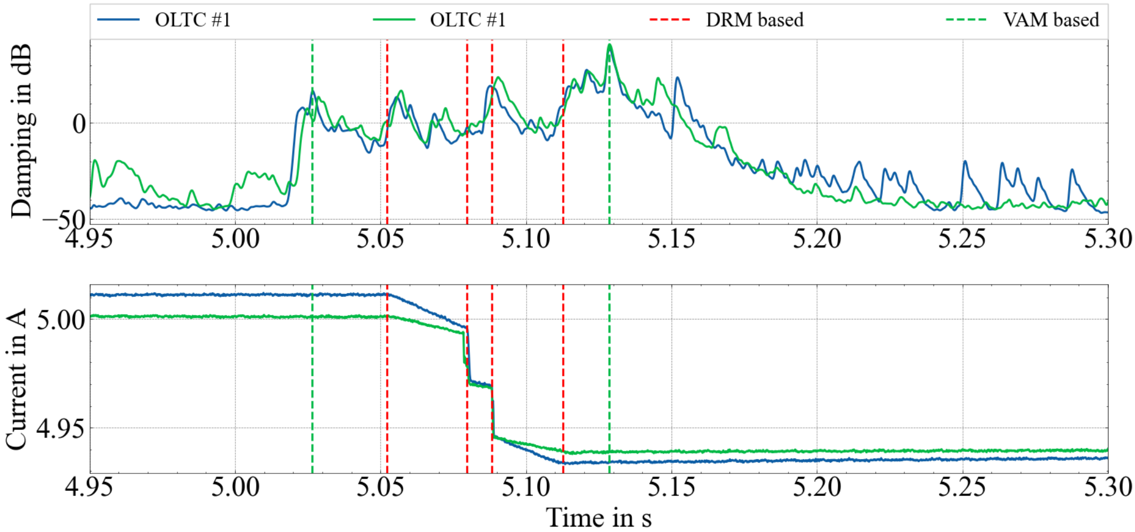

Figure 10 Combination of VAM and DRM data of both OTLC units.

For all 27 tap positions of the two units, the envelope curves of the two units match very well, both in amplitude and timings of the peaks. Only minor deviations within the OEM specifications could be observed throughout the measurements. These could be related to manufacturing tolerances, differential wear and other random fluctuations.

5. **Conclusion**

All in all, the combined approach of VAM and DRM proves to be a robust diagnostic tool that delivers repeatable results, even when similar OLTC units are compared, and varying sensor positions are used. Due to the advanced signal post-processing external influencing factors are mitigated. The additional insight into the OLTC enables the operator to further assess the mechanical condition of the OLTC under test. Apart from the comparison of similar units, the VAM data can be monitored for deviations in amplitude and timing by comparing it to previous measurement results. Additionally, if available, the VAM data can be checked against fingerprint data, ideally obtained from the OEM.

BIBLIOGRAPHY

[1] S. Mayo, L. Moisan “Effects of mounting on accelerometer performance” (Meggit, February 2011)
[2] T. Bengtsson “Acoustic Diagnosis of Tap Changers” (CIGRE 1996: 12-101)
[3] K. Viereck, A. Saveliev “Acoustic tap-changer analyses using continuous wavelet transformation” (IEEE, 2016)
[4] M. Foata, R. Beauchmin, K. Viereck, A. Saveliev and H. Hochmuth “"New Vibro-Acoustic Tap-Changer Diagnostic Method – First Results and Practical Experience" (CIGRE Session, Paris, 2016)

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