INVESTIGATIONS ON VIBRATIONS OF POWER TRANSFORMERS

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Abstract: Service reliability in electrical power networks is of crucial importance and depends on the quality and availability of electrical equipment. Operation resources like power transformers have to be considered, representing the intersections of energy networks. Regarding the age of power transformers e.g. used in the German grid surveillance is gaining importance. An approach for evaluating the transformer's status using vibrations is presented in this contribution discussing basic research of transformer vibrations. Vibrations are caused by voltage-dependent and load-dependent effects which lead to oscillations in mechanical structures like the active part of a power transformer. Vibrations are measured on the outside using accelerometers attached to the tank wall. In this contribution vibration measurement is performed at a 125 MVA power transformer using an acceleration sensor. Vibrations are recorded in time domain and analysed in frequency domain. Two approaches for vibration determination are presented. One regards the time depending trend of vibrations at different loads. The second uses statistical methods for comparison of measurements at comparable load conditions.

1 INTRODUCTION

Service reliability in electrical power networks is of crucial importance. Failures can cause considerable damage to the economy. Especially power transformers have to be considered. Changing demands of the European Grid require surveillance of its power transformers. The ongoing extension of renewable Energies with distributed generation leads increasing exposure on transformers. For basic research of transformer's vibrations data from onsite, online measurements provide the basis. Vibrations originated by the transformer's active part are analysed. Key issues of this investigation are correlations between vibrations and the actual loading rate of a power transformer.

2 PHYSICS OF VIBRATIONS

Vibrations are caused by voltage-dependent and load-dependent effects, which lead to oscillations in mechanical structures of power transformers.

2.1 Voltage-Dependent Vibrations

The voltage-dependent vibration is originated by magnetostriction leading to oscillations of the core (e.g. lamination sheets) [1,2]. The Weiss Domains in metal align themselves along the time-varying magnetic main flux induced by applied voltage [3]. Figure 1 illustrates the process. Weiss Domains are represented by elementary magnets. At the first step the magnetic flux density is assumed to be at its maximum, orientated to the left. All Weiss Domains are orientated accordingly. The changing magnetic flux density forces the Weiss Domains to follow the flux by rotation as shown in step 2. For Weiss Domains claim a certain area in the material, their movement result in a changing length of the whole material. Expanding and tightening lamination sheets causes mechanical vibration. In step 3 all Weiss Domains are aligned along the flux density at its opposite maximum. The difference considering length change along flux density orientation is Δl.

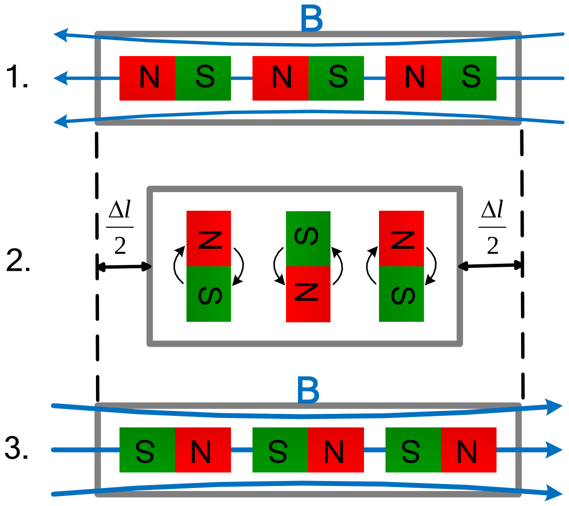

Figure 1: Deformation of ferromagnetic materials caused by magnetic fields

The mechanical orientation of the Weiss Domains in step one and three at the positive and negative maximum of the magnetic flux density is the same. Therefore, one electrical period leads to two maxima of material expansion. The basic oscillation is doubled electrical frequency. In European Network of Transmission System Operators for Electricity (ENTSOE) electric 50 Hz frequency leads to 100 Hz of mechanical basic oscillation. However, a core typically does not oscillate only with double electric frequency but also with harmonics. Considering no load condition, transformers often vibrate with 3rd harmonic at 300 Hz with amplitudes higher than basic oscillation.

2.2 Load-Dependent Vibrations

At load condition, current-related effects superimpose magnetostriction. Forces of the alternating magnetic field affect current-carrying windings leading to an oscillation also with doubled electrical frequency [3]. Also the magnetic leakage flux increases which causes magnetostriction in leakage flux shunts leading to vibration of shunts. The frequency spectrum of a transformer therefore consists of superimposed frequencies originated by its mechanics.

Frequencies at 50 Hz depend on the transformer type and are originated by ventilators and oil pumps, e.g. at oil forced and air forced (OFAF) transformers.

Frequencies of the active part and flux shunts, representing the considered vibrations reach from basic frequency at 100 Hz to harmonics up to 1 kHz, see Figure 2. As measurement shows, higher vibration frequencies are of low amplitude and will not be considered.

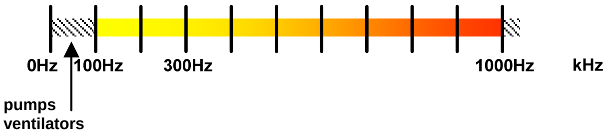

Figure 2: Frequency spectrum of transformer vibrations

2.3 Equivalent electrical circuit

An easy model for vibration characteristics delivers the transformer's simplified single phase equivalent circuit as shown in Figure 3.

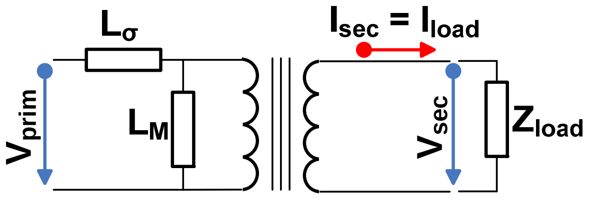

Figure 3: Simplified single-phase electrical circuit of a transformer

L_σ represents the inductivity caused by magnetic stray flux. L_M represents the inductivity of magnetic main flux. It yields through the active part's core and complex mechanical structure. Primary and secondary side couples by an ideal transformer. With rising load the voltage drop over L_M decreases. Thus magnetic main flux decreases according to law of induction.

Magnetic main flux is considered to be the main source of harmonics. Accordingly, harmonics rise with decreasing load.

Stray flux directly depends on the load. It is causing vibrations of windings and flux shunts. Both influence mainly basic frequency. Therefore basic frequency rises with load.

3 MEASUREMENT SETUP

Vibrations are usually measured on the outside tank using accelerometers attached to tank walls. Vibrations originated within the transformer travel through oil. Reaching the transformer's tank waves couple into metal and its longitudinal component can be measured as acceleration on the tank outside, shown in Figure 4. The voltage signal of the sensors is proportional to acceleration using an amplified conversion factor $k \cong 900\,mV/g$.

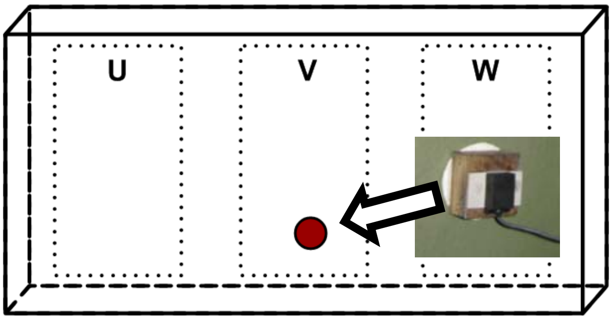

Figure 4: Accelerometer on outside tank wall

In this contribution vibrations are measured at a 125 MVA power transformer using one acceleration sensor and Matlab for recording data. The system was installed two years ago in 2009 and is working without issues ever since. For correlation transformer's load current (RMS value) is also constantly measured. If the transformer is online, recording is performed every 3 Minutes sampling data with 44.1 kHz. A section showing 50 ms of recording is presented in Figure 5. Data is measured at transformer's nominal load. The recorded vibration signal consists of superposition of basic frequency 100 Hz and harmonics.

For better discrimination signals are transformed in frequency domain using Fast Fourier Transformation (FFT). Figure 6 shows the frequency spectrum of the recorded vibration signal. Being of very low amplitude, frequencies greater 1 kHz are not considered.

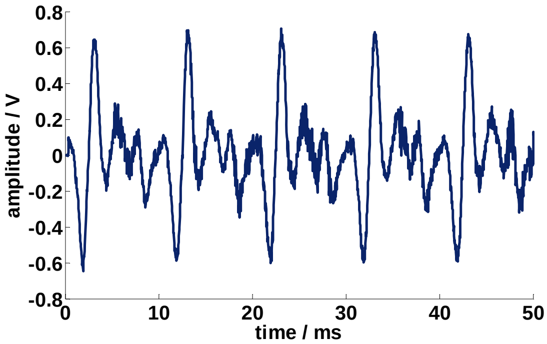

Figure 5: Continuous vibration signal in time domain

Basic frequency's amplitude is low compared to third harmonic at 300 Hz. Harmonics dominating the spectrum can be observed on most power transformers. Reason could be that active part mechanical resonance frequency matches the 3rd harmonic.

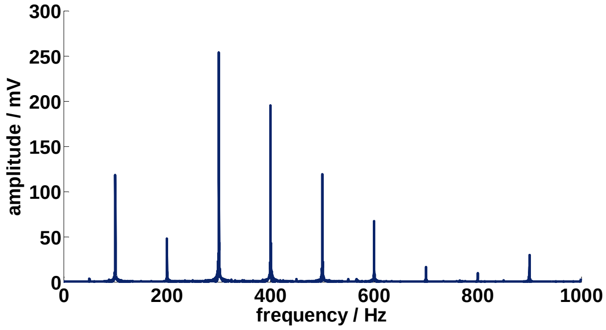

Figure 6: Frequency spectrum of continuous vibration signal

Vibration noises can origin from pumps and ventilators but are low compared to core vibration. Figure 7 shows 50 Hz component vibrations being approximately 20 times smaller than basic frequency. Therefore pumps and ventilators are considered to have no influence on active part vibration measurement.

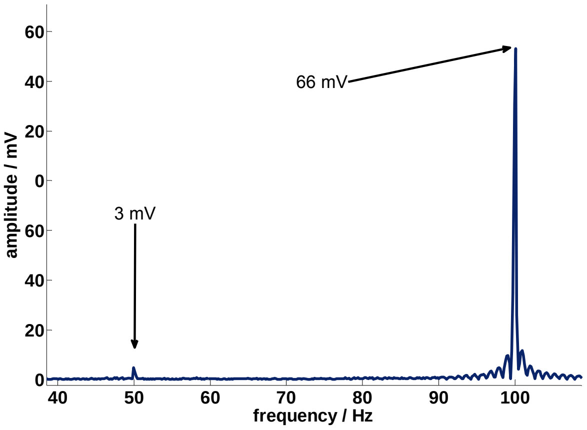

Figure 7: Vibrations of pumps and ventilators at 50 Hz compared to core basic vibration at 100 Hz

4 PERIODIC VIBRATION MEASUREMENT

Measuring both vibrations and load current, development of basic frequencies and harmonics can be observed depending on transformers load. For each vibration measurement FFT is performed and trends of frequencies can be plotted against time. Figure 8 shows vibrations of one day against time and load current. On the left y-axis the amplitude in Millivolts is plotted from basic frequency to 4th harmonic. On the right y-axis the RMS of load current is plotted in Ampere. Transformer's nominal load is at 600 A.

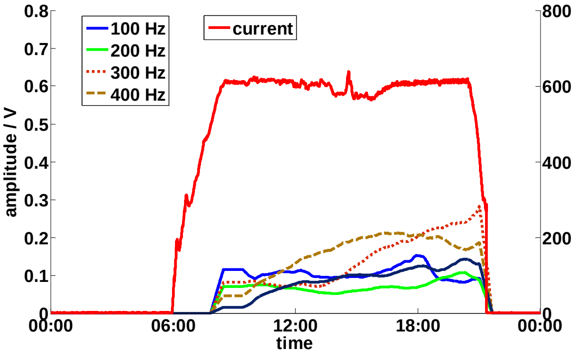

Figure 8: Trend of frequencies during one day

The considered unit generator transformer of a small coal power station is not online permanently in service. Typically, power station and thus transformer go online for several days in winter or spring.

Frequencies can be distinguished into two different transformer operating types: Behaviour at startup like shown in Figure 8 and behaviour during continuous service.

4.1 Vibration behaviour after startup

Due to core remanence, vibrations after startup differ from regular service. Caused by magnetic hysteresis at shutdown, the core holds a remanent magnetic flux. By applying sinusoidal voltage at startup, remanence slowly decreases within hours [4].

Regarding Figure 8, the transformer goes online at 6.00h in the morning and turns of about 22.00h at night. Vibrations are not measured from the startup due to the threshold level of the measurement system.

Basic frequency is dominant at the first hours of service. Amplitude is about 100 mV with one local maximum 12 hours after startup. 3rd and 4th harmonics rise after startup.

After approximately 12 h of service 4th harmonic reaches its maximum and declines afterwards. 3rd harmonic becomes dominant. Amplitude of 5th harmonic increases slowly. 2nd harmonic shows only little changes in amplitude.

The discussed behaviour of basic frequency and harmonics occur after every startup. Figure 9 shows startups of 3 successional days. Load current shows some differences but is close to nominal load $I_{nominal}$ = 600A.

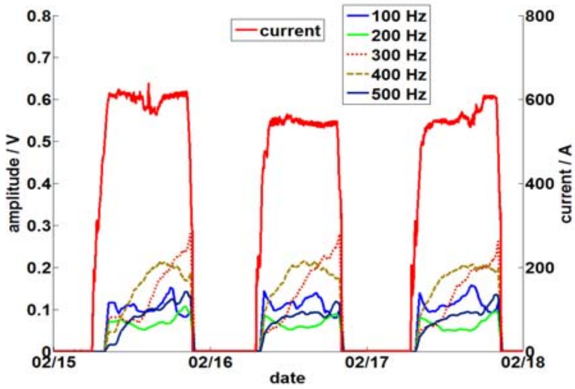

Figure 9: Vibrations at 3 sequent startups

In theory, remanence differs at each startup compared to the last one, because it depends on the voltage levels at each phase at shutdown. These differences do not seem to influence the considered vibrations with measurements starting approximately one hour after startup.

4.2 Vibration behaviour at continuous service

During service, vibrations can be correlated with the transformer's load current. Figure 10 shows load current and vibrations from basic frequency to 5th harmonic during 4 days of continuous service.

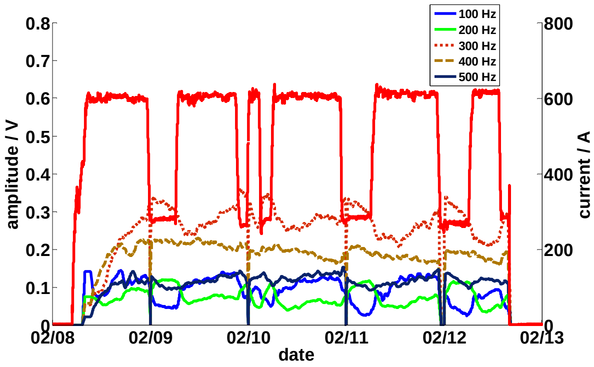

Figure 10: Vibrations at changing load current

On the first day vibrations depend on core remanence. On the second day remanence is abolished and vibrations depend mainly on load current. Load varies between nominal load $I_{nominal}$ = 600 A at daytimes and partial load $I_{partial}$ = 300 A at night.

Frequencies with high amplitudes like 3rd (250 mV to 350 mV range) and 4th harmonic (150 mV – 250 mV range) are dominating the spectrum. Basic frequency, 2nd and 5th harmonic range from 50 mV to 150 mV.

Basic frequency correlates with load current. At nominal load its amplitude is at 100 mV range. During partial load it decreases to 50 mV. 2nd harmonic shows inverse dependency on load current at comparable voltage range.

3rd harmonic being dominant frequency has a more complex dependency. Load drops from nominal to partial load cause 3rd harmonic to rise during the drop about 500 mV and to decrease when current level of partial load is reached. Load changes back to nominal load have no immediate effect. 4 to 6 hours after load rise the 3rd harmonic's local minimum occurs and its derivation becomes positive.

4th harmonic rises during load drops reaching its maxima level at 230 mV. Afterwards amplitude decreases with small derivation until the next load drop. Load rises do not affect 4th harmonic significantly.

5th harmonic dependency on load current is weak. It decreases with load drops and increases with load rises varying amplitude between 100 and 150 mV.

Harmonics of higher order are not considered in this contribution for their low amplitude. Signal drops at the beginning of each day are caused by automatic reinitialisation of the measurement system.

5 STATISTICAL EVALUATION

To determine the prospects of automated analysis statistical evaluation of vibration data is applied. The chosen approach clusters vibrations depending on its load current. Figure 11 illustrates the transition of time correlated vibration signals to clustering.

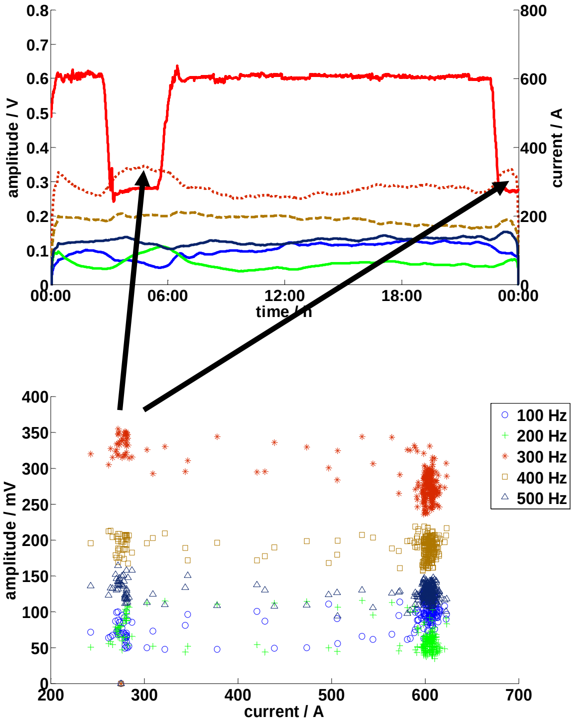

Figure 11: Clustering of vibration measurement at changing load current

Again, signals in time domain are transferred into frequency domain using FFT. For clustering basic frequency and harmonics of all measurements are plotted against corresponding load current.

For each frequency two clusters occur, see Figure 11. One occurs at nominal load, the other one at partial load. Changes of vibrations at constant load result in variation along y-axis. Some effects determined in chapter 4.2 can be observed using clustering. E.g. for 3rd harmonic amplitudes are higher at partial load, basic frequency's amplitude rises with load.

Clusters can be mathematically described by the mean amplitude of each cluster at certain load. Mean amplitude is calculated using the statistical median value over all measurements of one frequency.

In Figure 12 mean amplitudes are calculated for 11 days at nominal load in the year 2010. Partial load is not considered. Each dot represents one day of measurement. It can be observed that distribution of mean amplitudes is frequency dependent: Mean amplitudes of dominant 3rd harmonic varies between 225 mV and 275 mV. Basic frequency varies between 75 mV and 175 mV. For mean amplitudes of each frequency a typical area can be identified.

Basic idea of clustering is to use these areas as acoustic footprints for transformers. Further investigations will show if changes of the transformer's mechanical structure will result in changes of clusters.

Compared to time correlated vibration plots clustering provides reduced information but footprinting enables automated evaluation.

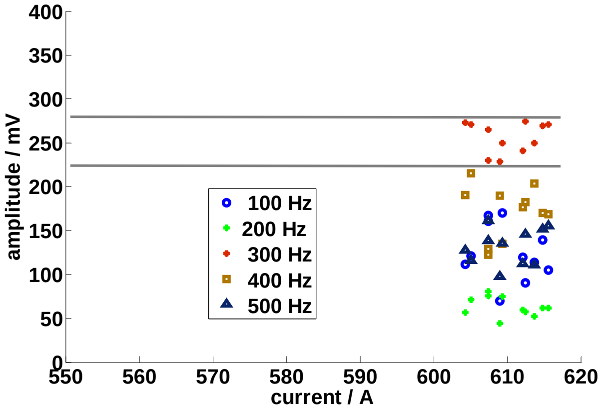

Figure 12: Medians of vibrations to 5th harmonic at nominal load, values of 11 days

6 CONCLUSION

Vibrations of power transformers correlate with different physical effects. Magnetostriction depends on the transformers actual voltage level. Load depended effects change with current. Basic dependencies can be described using a simplified single phase equivalent electrical circuit of the transformer. Basic frequency of vibration is doubled electrical frequency. In Europe transformers basic vibration frequency is 100 Hz. The active part's complex mechanical structure induces harmonics which may show higher amplitudes than basic frequency.

Vibrations can be long term measured reliably on outside tank wall using accelerometers. Data is recorded in time domain and transferred into frequency domain for analysis. Concerning vibration trends during service, two cases have to be discriminated. During startup the remanence of the core is dominating vibrations. Remanence dissolves after approximately one day of service. During continuous service vibrations mainly depend on load current. Basic frequency and harmonics show different dependencies on load current which can be observed by correlating current and frequencies over time.

For automated analysis clustering is used. By calculating mean amplitudes, clusters allow comparison of frequencies. Also measurements of different dates can be compared but variations of successional days are small. Therefore Clusters seem to be a suitable method to compare transformer vibrations on long term basis.

7 OUTLOOK

In this paper basic principles of vibration measurement on power transformer are discussed. First results suggest that vibrations can be used for transformer monitoring. Further investigations in this method have to take place. Using mean amplitude it might be possible to use vibration footprints as diagnoses and monitoring tool for power transformers. Reproducibility of clustering analysis has to be determined. Furthermore, the influence of mechanical changes of the active part on vibrations has to be examined.

8 REFERENCES

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