# Usability of Vibration Measurement for Power Transformer Diagnosis and Monitoring

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*Abstract*— This paper discusses the use of vibrations for power transformer surveillance. Therefore, basic research of transformer vibration is presented including the physical background of vibrations and methods of measurement in terms of sensor techniques comparing in-oil and outside tank wall measurement. A case study of an outside tank wall measurement performed on an aged generator step-up transformer presents first experiences in terms of long term measurement evaluating data of a 2-years period.A use case for vibration measurement is drawn for direct current (DC) detection in power transformers. DC can couple into 3 phase AC systems from nearby HVDC systems. The core's subsequent static magnetic field leads to increased core power losses and higher stress for the entire transformer.

#### Keywords - power Transformers Vibration Analysis, Diagnosis, Monitoring, HVDC

# I. INTRODUCTION

Service reliability in electrical power networks is of crucial importance. Power transformers are essential equipment concerning the availability of electrical energy networks. Therefore, the knowledge of transformers' health status is of main interest for grid provider. Vibration measurement represents an easy applicable, low cost and long-term measurement method being presented in the following.

# II. PHYSICAL BACKGROUND

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

# A. Voltage-dependent vibrations

The voltage-dependent vibration is originated by magnetostriction leading to oscillations of the core (e.g. lamination sheets). The Weiss Domains in metal align themselves along the time-varying magnetic main flux induced by applied voltage [1].

Fig.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  $\Delta L$ .

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 3<sup>rd</sup> harmonic at 300 Hz with amplitudes higher than basic oscillation.



Figure 1 Deformation of ferromagnetic materials caused by magnetic fields

# B. 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. Also the magnetic leakage flux increases, which causes magnetostriction in leakage flux traps leading to vibration of traps. The frequency spectrum of a transformer therefore consists of superimposed frequencies originated by its mechanics.

#### C. Equivalent electrical circuit

An easy electric model for vibration characteristics delivers the transformer's simplified single-phase equivalent circuit shown in Fig. 2.



Figure 2 Simplified single-phase electrical circuit of a transformer

 $L_{\sigma}$  represents the inductivity caused by magnetic stray flux.  $L_{M}$  represents the inductivity of magnetic main flux. 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 the main source of harmonics. It yields through core of the active part and its complex mechanical structure. 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.

#### III. MEASUREMENT OF VIBRATIONS

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, see Fig.3. The voltage signal of the sensors is proportional to acceleration using an amplified conversion factor.



Figure 3 Accelerometer sensor on outside tank wall on a transformer

Advantages of outside tank wall measurement are low equipment costs and easy and fast applicability. The influence of the tank on the signal has to be taken into consideration. Therefore, acceleration sensors and an in-oil sensor are compared in a laboratory setup. In a test tank vibrations of a small winding are excited with a shaker at a designated mechanical frequency, see Fig. 4.



Figure 4 Measuerment setup with excited winding part, in-oil sensor. Acceleration sensor on left oustide tank side (not shown)

Sonic waves are measured in oil by a hydrophone sensor and outside tank wall. The shown example uses a 700 Hz excitation. In-oil measurement detects changing oil-pressure using piezo-electric effects. FFT is performed on excitation signal and measured sensor signals. As Fig. 5 illustrates amplitudes between accelerometer and hydrophone differ, which is caused by different sensor sensitivity; signal amplification is identical. Also it can be noticed that the tank wall not does significantly change vibrations in terms of frequency distortion.

Nevertheless, practical experiences show that the sensor position on outside-tank wall and hence tank structure of power transformers also effect signal strength. Therefore it is advised to vary positions on an acceleration sensor setup for best performance.



Figure 5 Frequency spectrum of excitation, outside tank wall acceleration sensor and in-oil hydrophone.

In principle, in-oil measurement leads to higher SNR values and is independent from tank- wall structures. Its main disadvantages lies in the difficulty to apply sensors on power transformers, because only limited access by the number of available oil vales is given.

# IV. CASE STUDY

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 ago in 2009 and is working ever since. For correlation transformer's load current (RMS value) is also constantly recorded. If the transformer is online, recording is performed every 3 minutes sampling data with 44.1 kHz.

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



Figure 6 : Frequency spectrum of a teransformer vibration signal at nominal load

Measuring both vibrations and current, development of basic frequencies and harmonics can be observed depending on transformer's load. For each vibration measurement, FFT is performed and trend of frequencies can be plotted against time. Fig. 7 shows vibrations of one day against time and load current. On the left y-axis, the amplitude in mV is plotted of basic frequency up to 4th harmonic. On the right y-axis, the RMS of load current is plotted in Ampere. Transformer's nominal load current is at 600 A.



Figure 7 : Trend of frequencies during one day

The considered unit generator transformer of a small coal power station is not online permanently. Typically, power station and thus transformer go online on days with high prices per MWh. Frequencies can be distinguished into two different transformer operating types: Behaviour at start-up like shown in Fig.7 and behaviour during continuous service.

During service, vibrations can be correlated with the transformer's load current. Fig. 8 shows load current and vibrations from basic frequency to 5th harmonic during 4 days of continuous service.



Figure 8: Vibrations at changing load current

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

Frequencies with high amplitudes naming 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 to 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.

#### V. DC DETECTION USING VIBRATION MEASUREMENT

Direct currents on power transformer can be observed by vibration measurement. Reason for direct current in transformers are considered geomagnetically induced currents (GIC) or coupling effects between nearby AC and HVDC transmission lines.

For GIC, sun emitted streams of charged particles travel through the earth's atmosphere. Variations of the resulting geomagnetic field and the ionospheric currents lead, to variation of the electric field intensity penetrating the earth's surface [2]. Long high voltage overhead lines form a conductor loop with the earth ground through the power transformers at the end of these transmission lines. Because the variations of the electrical field are in the range of minutes, the currents can be regarded as quasi-stationary direct currents.

For electrons emitted by corona of HVDC lines nearby AC lines represent a near ground. Therefore, they can travel through the transformers neutral also causing DC.

# A. Measurement Setup

A 30 kVA YNyn6 distribution transformer with a maximum output voltage of 7.5 kV is used for the setup. Vibrations are recorded using acceleration sensors. A current source is injecting DC into the HV neutral. Each phase is supplied with 50 mA DC, which is about 50 % of the magnetizing current. Because lamination sheets are considered a major source of vibrations sensors are positioned directly on the yoke of the core. In this contribution, signals of one sensor being positioned over the middle limb, is used. Other sensor positions over outer limbs lead to similar results. After amplification signals are recorded using a DSO.

#### B. Vibrations of DC in Transformers

Direct currents change the magnetic flux of the core leading to changes of the flux and of correlated vibrations.

Fig. 9 shows the vibration signal in frequency domain. In the upper diagram the dotted signal is recorded at 2 kV AC voltage, applied 40 k $\Omega$  load per phase and no DC injection. With DC (lower diagram), the 100 Hz is superimposed with 50 Hz. The effect can also be recorded using acceleration sensors on the tank surface.



Figure 9 : Frequency spectrum of sensor 1, vibration signal without (dotted) and with DC (straight line)

# C. Physical Model

The DC dependent 50 Hz frequency is caused by half wave saturation effects of the core: DC represents a magnetising current I<sub>mag</sub> for the transformer and reduces its main inductivity  $L_M$  (see Fig. 2) in either positive or Simultaneously, negative half wave. the entire transformer's impedance is reduced and the AC source can drive a high current though the transformer. The frequency of the saturation effect is half the electrical frequency, e.g. in a 50 Hz system 25 Hz, see Fig. 10. With frequency doubling due to magnetostriction the result is a 50 Hz vibration as can be seen in the experiment.



Figure 10 : Principle of half wave saturation caused by positive DC

#### VI. CONCLUSION

Vibrations can be long term measured reliably on outside tank wall using accelerometers. 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.

Saturation effects caused by DC through transformer neutrals represent a threat because resulting high currents driven by the AC grid may cause damage to the equipment. Using vibration measurement DC in transformers can be detected by halved basic frequency, which only occurs in case of a DC superimposition. Therefore, vibration measurement can be helpful to ensure transformer's health in widespread systems coping with GIC or systems influenced by nearby HVDC lines.

# VII. REFERENCES

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