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**NEW SENSORING TECHNIQUES FOR CONDITION MONITORING OF
POWER TRANSFORMERS**

Bachelor's thesis in Technology for the degree of Bachelor of Science in
Technology submitted for inspection in Vaasa, 9th of February, 2011.

Instructor

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SYMBOLS AND ABBREVIATIONS

DGA	Dissolved gas analysis
EFPI	Extrinsic Fabry-Perót Interferometer
FBG	Fiber Bragg Grating
FRA	Frequency response analysis
HV	High-voltage
IFPI	Intrinsic Fabry-Perót Interferometer
LV	Low-voltage
MEMS	Micro-Electro Mechanical Systems
OLTC	On load tap changer
PD	Partial discharge
PVA	Polyvinyl Acetate
RH	Relative Humidity
SCADA	Supervisory Control and Data Acquisition
SGEM	Smart Grids and Energy Markets
SNR	Signal-to-noise ratio
UHF	Ultra High Frequency

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ABSTRACT:

Transformers, one of the expensive equipment of an electrical grid, have a life span of several decades. During this time they often face defects, which can cause downtime during the service operation. With the help of proper condition monitoring, this downtime can be as short as possible, since the failures can be predicted earlier and proper actions can be done during regular service breaks.

Many different attributes of a transformer can be monitored, which require different type of sensors. This thesis introduces some modern sensor types for transformer condition monitoring. Many of these sensors are still being further researched, but even some commercially available products are demonstrated.

The most researched sensor type, partial discharge sensors, has also a big role in this thesis, but also e.g. moisture measuring sensors and temperature sensors are introduced. The popularity of partial discharge sensors is based on the fact, that by monitoring partial discharges many different faults can be detected before they harm the transformer badly.

Any of these sensors improve the transformer condition monitoring compared to the situation with no condition monitoring sensors, but to pick out the perfect setup for each transformer with the minimum costs is the difficult task.

KEYWORDS: Transformers, Condition monitoring, Sensors

1. INTRODUCTION

This study is a part of the research program SGEM (Smart Grids and Energy Markets) arranged by CLEEN ltd (Cluster for Energy and Environment). The topic of the thesis belongs to the work package 4.5 (Condition management as real-time process), and the aim is to examine modern sensor techniques for transformer condition monitoring. The topic was suggested by Professor Erkki Antila from the Department of Electrical and Energy Engineering at the University of Vaasa.

This research focuses on large power and distribution transformers. Being very expensive and important devices on a substation, transformers should be well monitored and maintained to avoid expensive malfunctions. New monitoring techniques and sensors are developed all the time, in order to reduce the costs and damages caused by transformer failures. This thesis examines the modern sensor techniques of transformer condition monitoring.

The study consists of five chapters, whereby the next chapter describes briefly the basics of a transformer. In the third chapter, different condition monitoring measurements are described and explained, and in the fourth chapter different sensor techniques for transformer condition monitoring are demonstrated. The main focus of the study is in the latter chapter consisting of some modern sensor techniques. The last chapter is to make some conclusions about the different sensors and techniques.

2. TRANSFORMER

Every time a voltage level needs to be changed, a transformer is needed. The installed transformer capacity is several times the installed generator capacity. The big amount of transformers in service is divided into two basic types in high-voltage (HV) systems: generator transformers, which convert the generators voltage upwards to a suitable level in order to feed the power to high-voltage overhead lines, and substation transformers, which couple together several different voltage levels of the electric grid. Transformer efficiency is at the moment rising towards 100 percent, since transformers don't have any moving parts. (Gallagher & Pearmain 1983: 8–11.)

Power transformers are big and expensive, and because of that they are well taken care of. This begins already at the factory, where transformers are tested before they are shipped at site. After the transformers have been installed, they are tested again on site to fulfill all the requirements. When these tests have been done, they can be taken into use and their work as a part of the electric grid begins. (Transformer Handbook 2004: 6–7.)

Transformer lifetime can be significantly increased by using condition monitoring, regular inspections and maintenance operations. Transformers lose some of their features as they get older, however by monitoring these changes properly, correct actions can be done in order to lengthen their lifetime. Such actions may include for example changing the transformer oil or adjusting the load concerning the transformer. Regular inspections are more comprehensive than condition monitoring, so they give an even better picture of the current status of the transformer.

2.1. Transformer structure

Transformers are basically electrical devices with two (or more) windings, which transform alternating voltage and current by electromagnetic induction to a lower or a higher level. The transformers that transform the voltage upwards are called step-up transformers, where the windings on the incoming side make up the low-voltage (LV) side, and respectively the windings that feed the power onwards make up the high-voltage (HV) side. The most common way to arrange the windings is to have them connected in delta on the low-voltage side and in star on the high-voltage side. Transformers which provide large amounts of power need proper insulation between the different parts of their windings.

Most power transformers have special types of thin magnetic steel plates within the core, which make it possible to achieve the desired, strong magnetic field. This is possible because of the magnetic features of iron. The materials are also usually the same in most of the power transformers, conductor materials in the windings are usually copper or aluminum, and cellulose products such as high density paper or pressboard are usually used as insulation materials. Insulating oil typically is mineral oil, which also works as a part of the transformers cooling system. (Gallagher etc. 1983: 8–11; Transformer Handbook 2004: 8–9.)

The basic design of a transformer can be divided into two major types, core type and shell type. Using or servicing a transformer isn't significantly different between these two major types, but the manufacturing process is. This can be seen from the figure below. Each manufacturer produces the type of transformers they find suitable for their production facilities, and often the whole range of one manufacturer's transformers are of the same type. Briefly it

can be said, that in the core type transformers most of the windings are visible and the core is hidden, whereas in the shell type transformers the windings are mostly hidden behind the visible core. (Transformer Handbook 2004: 8–9.)

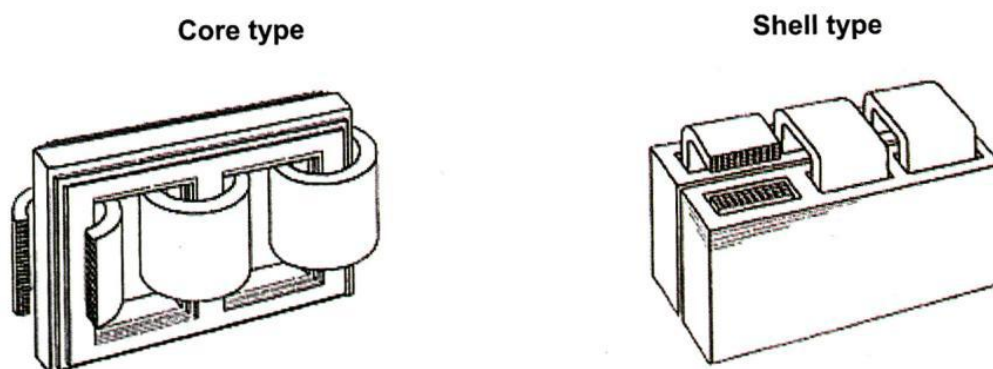


Figure 1. Core and shell type transformers (Transformer Handbook 2004).

One major issue when constructing large transformers is its cooling. Cooling is usually being done by oil-air or oil-water systems. Forced oil forced water cooling is the most effective cooling system. When water is used instead of air, the size of the heat exchanger can be kept small. Power stations usually can provide enough cooling water, and therefore the described cooling method is superior especially when large cooling capacity is needed. The evolution of cooling systems hasn't though been the main reason for the increase of output from transformers. The biggest single reason appears to be the improvement in the quality of the silicon steel, which is used for the core laminations. (Gallagher etc. 1983: 8–11.)

One significant issue affecting transformer designing has been the development of computers. With the help of modern technology, complicated calculations in the designing process can be performed quickly, and the computer with the help of sophisticated software can demonstrate the best possible solutions to the

user. Even the effectiveness of the manufacturing process has improved, with the help of precision and speed achieved by the automated processes as well as the development of materials. (Kulkarni & Khaparde 2004: 3–4.)

2.2. Transformer monitoring

Many standards organizations consider the transformer life to be around 20 to 25 years. This estimate is based on the fact that the transformer is constantly being run at its rated load, and that the average ambient temperature is 40 °C. The estimate also assumes, that the transformer is being maintained properly during its lifetime (Transformer Maintenance 2000: 1). 20 years doesn't sound like a lot, but the lifetimes are often longer, since transformers seldom are operated constantly at rated load and in 40 °C. So, since the expected lifetime often is longer than 20 to 25 years, it is important to service and monitor the transformer properly.

Transformer cooling system has a crucial effect on transformer lifetime. If the transformer is being used at 10 °C over the rated temperature, its lifetime can be reduced by 50%. This heat can be caused by internal losses due to loading, high ambient temperature, and solar radiation. Therefore, a properly working, effective cooling system is a vital part of a well-working transformer. The most effective cooling system uses oil as a conducting medium, and therefore this thesis focuses only on oil-filled transformers.

Thorough inspections and data gathering are the keys to a well-working transformer. Some of the desired data can be gathered by doing regular inspections (e.g. weekly inspections of oil level and temperature) and some can

even be gathered with the SCADA (Supervisory Control and Data Acquisition) systems. Nevertheless, properly trained maintenance people will always be needed in order to expand the transformers lifetime and to forecast the needed service operations.

The most important indicator of transformer condition is the transformer oil. Not only does it tell us the current condition of the transformer, but it also works as an insulator, part of the cooling system and kills the arcs. Most of the information regarding the transformers health is gathered from the dissolved gas analysis (DGA) of the transformer oil. One could say that conventional transformer oil is the heart of the transformer, vital and informative. (Transformer Maintenance 2000: 13–14.)

3. TRANSFORMER CONDITION MONITORING MEASUREMENTS

On-line monitoring of a transformer can be implemented with several different monitoring methods, e.g. temperature monitoring, dissolved gas analysis, partial discharge (PD) detection, frequency response analysis (FRA), acoustic monitoring etc. Since all the monitoring methods add costs to the monitored system, accurate calculations are made in each case in order to get the most probable faults covered with the implemented monitoring systems. (Sparling & Aubin 2007: 1.)

3.1. Dissolved gas analysis

Dissolved gas analysis is, as previously mentioned, one of the most effective monitoring methods. After performing a DGA, there is no easy way to decide what actions should be done according to the test results, if any. Every transformer is unique, and the possible actions to be performed need to be closely considered based on the trend analysis of previous dissolved gas analysis and expert opinions. Probably the most important aspects when deciding what actions should be performed are the analysis of the historical data of the examined transformer and its previous DGA. Since transformer aging, chemical actions and reactions, electric and magnetic fields, thermal contraction and expansion, load variations, gravity etc. all have their own impact on the DGA results, the historic data and precise documentation should be carefully recorded and analyzed.

The transformer oil contains the following key gases: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2),

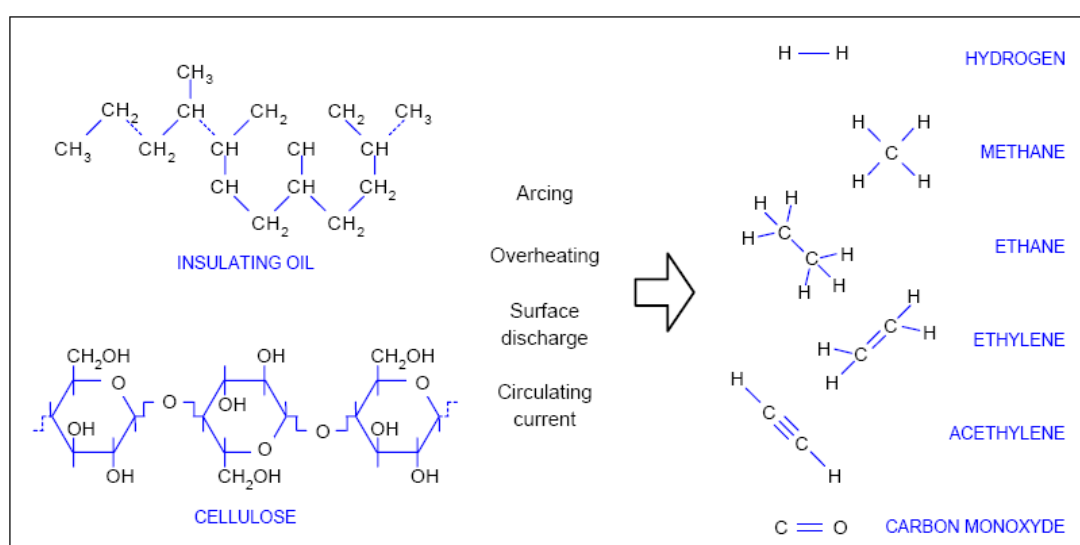
carbon monoxide (CO) and oxygen (O₂). The absolute values of different gases aren't the most important values of interest, but the relation between different gases and the relations compared to previous measurements are. The relation between different gases can tell us the type of the possible fault, and the trend analysis compared to the previous measurements makes it easier to predict the faults to come. There are also devices that e.g. once a day analyze one or more gas components, in order to have a more up-to-date picture of the transformers current condition. (Etto 1998: 7–8.)

The DGA can be done either in a laboratory or directly on site, with a portable device or with one, that is permanently attached to the transformer. Also these portable devices give close enough results compared to the real values and inform which transformers are malfunctioning and which oil samples have to be analyzed more closely in a laboratory. The relation between different gases in the transformer oil isn't the only major interest regarding the oil samples. Partial discharge is the other crucial attribute. As the transformer oil has the function of an insulator, its partial discharge voltage should be as high as possible. If water or small particles of any material get into the transformer oil, its partial discharge voltage decreases. Especially, if the water isn't dissolved in the gas but appears as drops, the partial discharge voltage of the oil collapses and makes the transformer extremely vulnerable. (Heinonen 2008.)

When the transformer oil is exposed to high temperatures or electric discharges, the oil reacts chemically with the cellulose paper forming new molecules. Concentrations of each molecule are monitored, and once the monitoring system detects a high concentration of some molecule or an unusual ratio between different molecules, it can alert the operator before the malfunction of the transformer leads to a bigger defect.

Table 1. Different gases formed in some fault types (Jakob 2009: 3).

Gases	Indication
Hydrogen	Partial discharge, heating, arcing
Methane, Ethane, Ethylene	“Hot Metal” gases
Acetylene	Arcing
Carbon Oxides	Cellulose insulation degradation

**Figure 2.** Molecules formed from insulating oil and cellulose paper (Sparling etc. 2007).

Typical malfunctions, which can cause these molecular changes, are moisture formation, current circulation in the core, overheated connections and winding overheating. There is one common aspect for all of these malfunctions: large amounts of hydrogen and carbon monoxide are generated in all the cases. (Sparling etc. 2007: 3–4.) Therefore, by monitoring only these two gases, it is possible to state whether the transformer is not working properly. When the alarm by hydrogen or carbon monoxide is triggered, a closer examination of the

insulating oil should be done in order to find out the reason for the malfunction and its severity. This is economically an effective way to avoid the need to run specific tests to the transformer too often, only when faulty behavior is detected. (Sparling etc. 2007: 3–4; Jakob 2009: 2.)

3.2. Partial discharge detection

Partial discharges (PD) occur by air pocket's electrical breakdowns in the insulating oil. In a partial discharge, a small current flows through the air pocket in the insulating oil. By measuring these small currents, the amount of PDs is found out. Firstly, PDs tell us when some maintenance operations must be performed, but secondly they also wear down the transformer and shorten the expected lifetime of the transformer, so it's important to detect them as soon as they start to occur. (Wilson 2004.)

There are a lot of different measurable phenomena in PD. One can measure the electromagnetic field, voltage drop, current impulse, acoustic shock-wave, light flash or chemical decomposition. Some of the measurements require connections to the circuit (e.g. voltage drop), some are based on frequency (acoustic shock-wave), some on light (light flash) and some on gas analysis (chemical decomposition). (Russwurm 2001.) For on-line PD-monitoring, the frequency-based acoustic devices are at the moment the most preferable and most studied techniques.

When the transformer is operating, it emits always noise at different frequencies. The high frequency components of this noise have a short wavelength, and the signal is usually also quite directional. By filtering the

lower frequencies from the noise, the location of the noise-emitter (in this case the partial discharge) can be located accurately and proper actions can be done before any significant fault or damage occurs. (Wilson 2004.)

Airborne ultrasound instruments, or ultrasonic translators, as the frequency sensor devices often are called, can provide information in two ways: qualitatively through headphones, i.e. the frequency is modified to a range where human ear can hear it, and secondly quantitatively by showing the measured readings on a meter. Although meters provide accurate readings that can be compared to previous measurements and examined closely, the qualitative measurement data often is more useful, as specialists can instantly tell what the problem is and where it is located. (Wilson 2004.)

Some benefits of the frequency based ultrasound measuring systems are, that no connection to the high voltage line is needed, the transformer can be operating while measurement is being done and measurements can be taken through a steel tank. If the measuring system is a digital one, then the data can be shown on a screen real-time and also be stored on a hard drive, allowing the comparison to previous measuring data and enabling the preparation of proper trend analysis. (Russwurm 2001.)

3.3. Frequency response analysis

As the transformer is operating, its windings have to deal with large forces, caused by the currents flowing through them. These currents may cause some winding movements and deformations as well as insulation damage. Another reason for these faults can be the aging insulation paper. Nevertheless, these

faults are difficult to detect with conventional methods, but because the changes in the windings result in some noticeable changes in the windings internal capacitance and inductance, the Frequency Response Analysis (FRA) method is the correct method to detect them. (Nirgude, Gunasekaran, Channakeshava, Rajkumar & Singh 2004.)

The FRA measurement technique itself, as described in the source (Rahman, Hashim & Gosh 2003), is based on measuring the impedances of the windings over a large range of frequencies (e.g. 5 Hz to 10 MHz). The measured values are compared to the historic values of the same transformer or its sister transformer, and based on the comparison the decision whether the transformer is faulty or not can be done. Because of the frequency behavior of an RLC circuit, the fault location can be accurately determined and proper actions can be done, but still a thorough analysis of the measurement data is in a key role.

Monitoring with the FRA method when the transformer isn't energized is an old but widely used method. Using FRA method when the transformer is operating isn't as usual, but according to the source (Birlasekaran & Fetherston 1999) it is a very reliable and informative type of transformer monitoring. Birlasekaran tested the method by sending a perturbing chirp signal at the primary of a transformer, along with the energizing 50 Hz HV signal, and then monitored at the secondary the transferred signal together with the 50 Hz HV signal. The tests were performed at three different load types. The test results show that, compared to the de-energized tests, this method produced more exact data of the fault location. Also, the fault didn't have to be a major one to be detected, therefore minor faults were noticed as well.

3.4. Thermal analysis

Often an error in the operating transformer causes a temperature change. Higher transformer operating temperatures, both the hotspot as well as the oil temperature, shortens the expected lifetime of the transformer significantly. Monitoring the temperature changes can be done either by predicting the transformer temperatures with the help of artificial intelligence, or by predicting the thermal behavior of the transformer by using a thermal model. (Abu-Elainin & Salama 2007.)

According to Abu-Elainin etc. (2007), artificial neural network can predict the transformer hotspot and the top oil temperatures very well. Using as inputs the transformer's three phase currents as well as the surrounding weather conditions, the prediction is already quite accurate. By adding other inputs to the artificial neural network the accuracy of the predictions can be increased.

The thermal model can be built with many different techniques, but according to Abe-Elainin the thermal model can be built based on the relation between the thermal dynamics of the transformer and the electric circuits. The thermal model inputs were solved by using Genetic Algorithms instead of measurements, because of the difficulty of these measurements. This thermal model can even be used as an on-line condition monitoring technique. Thermal models can also determine the transformer insulation condition by determining the water in oil, water in paper and the temperature calculation of the transformer.

Both the artificial intelligence techniques as well as the thermal models are already functional thermal analysis techniques. By developing and researching

the thermal models, even more accurate results can be achieved, but already at this point they are inexpensive and often used monitoring techniques.

3.5. Vibration analysis

Vibration analysis, being a relatively new transformer condition monitoring technique, is used to monitor the health of the transformer core and windings as well as the on load tap changer (OLTC). The tank vibrations are divided into two types, core and winding vibrations. The vibrations are measured at the transformer walls, where the vibrations caused by core or winding travel through the transformer oil. Accelerometer mounted on the transformer walls collect the vibration signals, and after signal analyzing with e.g. Fourier transform conclusions can be made that the transient signals mainly appear between 10 and 2000 Hz. (Abu-Elainen etc. 2007.)

Because the vibration analysis method still is quite new, much more research is needed for the complete breakthrough. At the moment, most of the research has been concerning the health of the OLTC. When more research has been done, vibration analysis becomes a good competitor to the FRA method in detecting the deformations in transformers windings. (Abu-Elainen etc. 2007; Garcia, Burgos & Alonso 2006.)

3.6. Moisture monitoring

Moisture in a transformer decreases both the electrical and the mechanical strength of it. Moisture can cause electrical discharges because of low partial

discharge inception voltage and higher partial discharge intensity. The problems with moisture in transformers have been known since 1920s so a lot of research has been done regarding the matter.

The possible ways for moisture to enter the transformer oil from the surroundings are as a vapor in the air or via a leakage in the sealing. Apart from these sources, moisture is also formed by the breakdown of the insulating paper, so it is obvious that the moisture level of insulating oil always increases as the transformer gets older. (Lord & Hodge 2007.)

It is important to know the moisture amount in the insulation, but direct measurements of it are very difficult. The direct measurements are nowadays done during a repair or tear down work, when a paper sample can be taken and its moisture can be measured. Therefore, many different curve sets have been published, which give a value of moisture in insulation based on the measured value of moisture in oil, measured typically with RH (Relative Humidity) sensors. The problem with these curves seems to be their reliability. One of the problems with the measurement of transformer moisture levels is that moisture in the transformer oil doesn't necessarily mean that the insulation paper would be moist. (Du, Zahn, Lesieutre, Mamishev & Lindgren 1999; Oommen, Thompson & Ward 2004.)

So, even though the moisture levels are important information and easy to monitor through on-line measurements from the transformer oil, the assumptions of the moisture levels in the insulation paper aren't totally reliable and the results must thus be considered with skepticism.

4. SENSING TECHNIQUES FOR CONDITION MONITORING

In order to be able to monitor the desired attributes of a transformer, suitable sensors have to be used. Sensors can be wired or wireless, inside the transformer or on top of it, firmly attached to it or portable, several different variations exist. This chapter demonstrates some modern sensors used to monitor different attributes of the monitored transformer. Also, a wireless method to gather all the measurement data from different types of sensors is presented.

4.1. Acoustic monitoring of a transformer

A transformer that is operating emits to its surroundings acoustic vibrations. These vibrations are according to the source (Bartoletti, Desiderio, Di Carlo, Fazio, Muzi, Sacerdoti & Salvatori 2004) mainly caused by following phenomena:

- coil vibrations depending on the current amplitude and winding clamping compression
- core vibration depending on magnetostriction, the Barkhausen effect, and loosening of core clamping
- partial discharges either in insulating bushings or winding insulation
- movements of micro-metal chips
- effects due to magnetic shunts and related fasteners located in the stray magnetic flux.

These variables are transformer-specific, so it is important to have some reference values of similar new transformers or some average values of similar

transformers of the same age as the tested one, when the analyzing of the measured values begins.

Bartoletti etc. (2004) performed some tests according to the following set-up, which can be considered as an example how acoustic monitoring of a transformer can be implemented. Figure 3 shows where the acoustic sensors were placed. The received signals from the acoustic sensors were divided into substrings, which then were subsequently parameterized to find the significant parameters. *LabView* environment with implemented, specific software was being used for signal processing, and the various signals coming from different channels simultaneously were analyzed by the implemented *STUD* program. After the basic signal processing was done, the following operations were performed to the signal:

- fast Fourier transform (FFT) and discrete Fourier transform (DFT)
- cross correlation
- maximum and minimum evaluation.

The stored vectors can be further operated and then stored in several different formats, or even translated to “wave” format and submitted as audible information, that is (if necessary) frequency shifted to the audible range 20-20 000 Hz. (Bartoletti etc. 2004.)

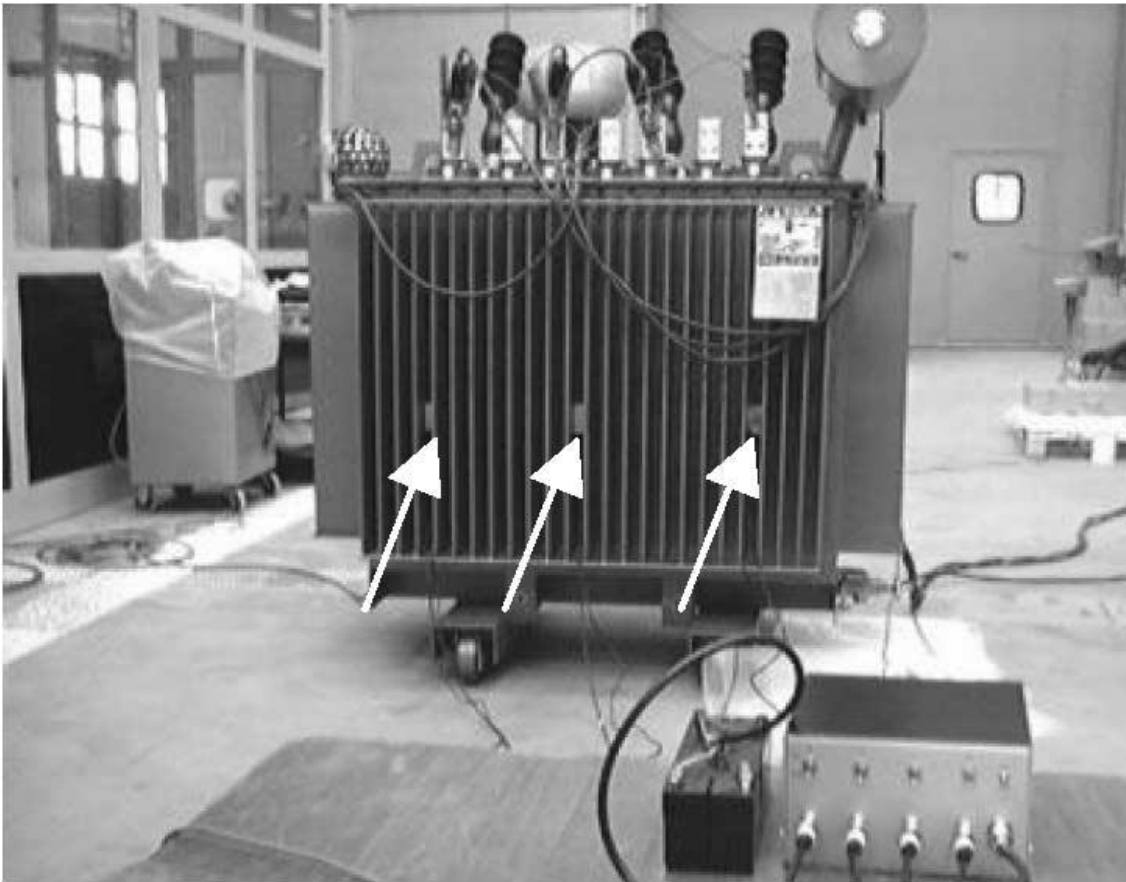


Figure 3. Locations of the sensors on a transformer (Bartoletti etc. 2004).

The frequency range emitted from a transformer is very wide, but in the test made by Bartoletti and his colleagues it was noticed, that a range of 50 Hz – 100 kHz was wide enough to detect the transformer condition. Even though the frequency range could be narrowed, different sensors had to be used for low and high frequencies. The higher frequencies (20 – 100 kHz) were detected with acoustic probes (PAC model R61), and the lower frequencies with two different types of sensors, the piezoelectric audio pick-up (Shadow SH – 2001, up to 15 kHz) and the vibrating accelerometer (Endevco 751 – 10, 1-15 000 Hz). The signals, of which the R61 and SH – 2001 signals were amplified up to 40 dB, were then fed to an acquisition card PCI – DAS4020/12.

Figure 4 below is trying to clarify the monitoring process: the acoustic sensors (=observer) start the process by measuring the vibro-acoustic signals from the transformer. Features extractor collects the relevant data from the acquired signals, which then is compared to the data found from the vocabulary (vocabulary = data storage, where reference data is being stored).

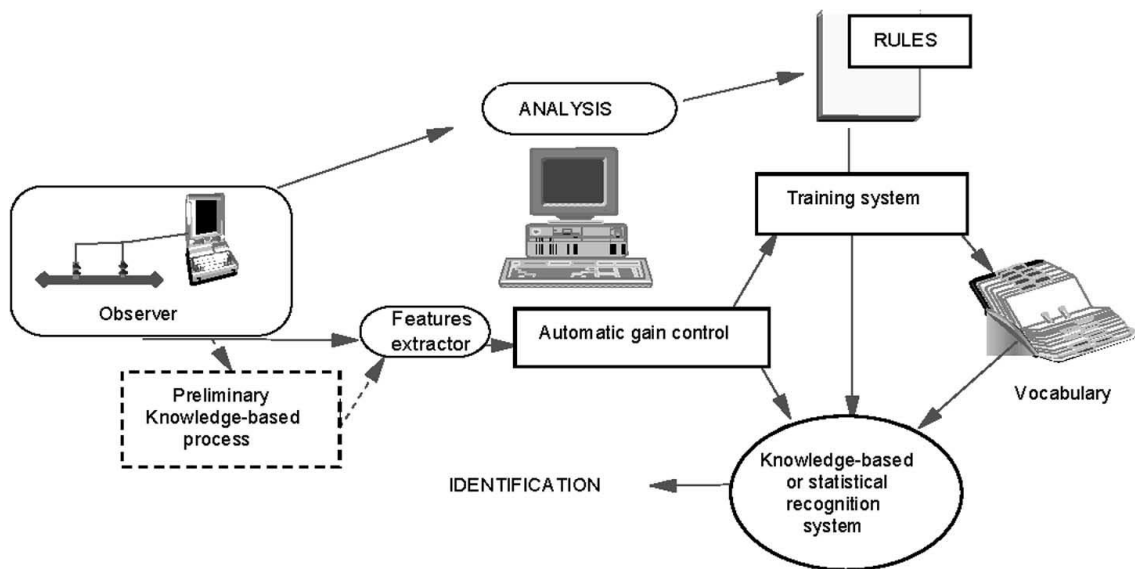


Figure 4. The set-up of the acoustic transformer monitoring system (Bartoletti etc. 2004).

A comparison is made between the measured signal and the stored one, and based on the closeness of these two signals the recognition system defines the current condition of the transformer. The acquired data usually comes from six sensors located very accurately on the transformer tank, since by incorrect location of the sensors the values of vibration spectra and the signal magnitude are incorrect. It should also be noted, that the correct locations of the sensors vary significantly between the different transformer manufacturers. The measurements can be done two or three times a day, for both no-load and load conditions. The no-load condition can be measured when the load current is

less than 10 % of the rated current, and the load condition when the load current is above 50 % of the rated current. (Bartoletti etc. 2004.)

The transformer emits lots of different acoustic signals to its surroundings when operating, from some of them it was possible to define into which of the three classes the transformer belonged to; new, used or anomalous. By processing the measured signals and comparing them to the sample signals stored in the vocabulary, the class allocation could be done and possible further actions could be determined in order to lengthen the lifespan of the transformer.

4.2. Partial discharge measuring sensors

Partial discharge measuring is probably the most researched monitoring method, therefore several different sensor types for PD monitoring have been invented. Capacitive coupling sensors, which are more precisely described below, are known to have a good sensitivity, when again ultra high frequency sensors have a good signal-to-noise ratio (SNR). When looking only at these two parameters, the sensitivity is of higher interest, since the measured signal can be improved by using an amplifier. Thus, small amounts of partial discharges can't be measured with low sensitivity sensor types, such as ultra high frequency sensors. Below is described some of the different sensor types more accurately. (Lee, Chiu, Huang, Yen & Fan 2008.)

4.2.1. Capacitive coupling sensor

One new monitoring technique to detect partial discharges when the transformer is operating is the capacitive coupling sensor technique. Briefly, it

is done by attaching the sensor (consisting of two metal plates and a high frequency current transformer, HFCT) to the flange of the high voltage bushing of the transformer. All the components are either fixed or hang with a supporting arm that is highly insulated and thus allowing a safe installation of the sensor even when the transformer is operating. The capacitive coupling sensor allows a detection frequency of from 100 kHz to 100 MHz and a sensitivity of about 10 pC. (Chen, Urano, Song-bo & Jinno 2008a.)

Chen etc. (2008a) tested sensors at first in the laboratory, and after that on site. Factors affecting the received signal strength were the size of the coupling plate facing the bushings, the distances between the plate and the bushing flange as well as between the plate and the bushing ceramic ring, the inductance of the partial discharge circuit and the length of the connection wires. In the laboratory tests, PD pulses were fed to a 110 kV transformer bushing to confirm the characteristics of the sensing circuit. It was found out, that in laboratory conditions 50 pC sensitivity was detected successfully.

In the on-site tests, a portable partial discharge measurement (PDM) system was used and its four channels were connected to PDM sensors that were located at the high voltage (500 kV), medium voltage (220 kV), low voltage (35 kV) and the neutral terminal bushings. A pulse generator (PG) was used to simulate partial discharges fed into the transformer from the different bushings. During the tests, it was found out that the HV bushing could detect the signal fed in from the HV terminal but not the signal injected from the MV or LV terminal. This was, according to the document, because of the isolating coils in the voltage bushings. As a result of the test, the PDM sensitivity could be determined to be between 100 and 200 pC. (Chen etc. 2008a.)

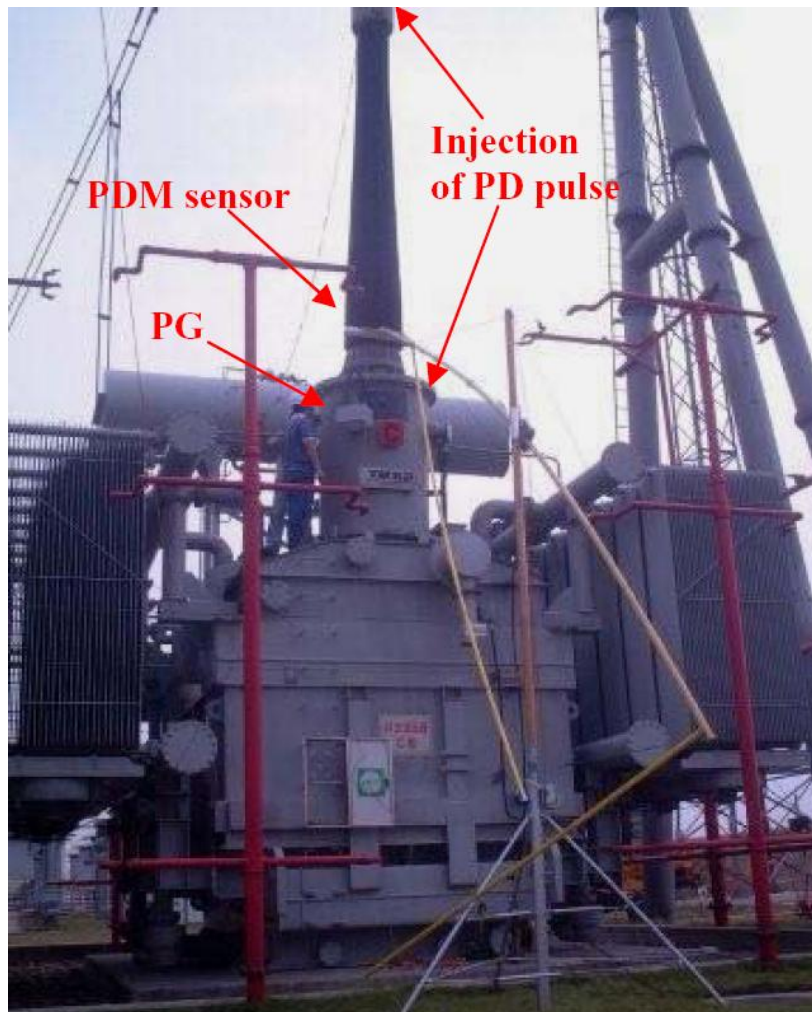


Figure 5. The test setup for on-site testing of capacitive coupling sensor (Chen etc. 2008a).

When the measuring devices were connected to three transformers in a substation, it was found out that detecting partial discharges using a short measuring period wasn't so straight forward. In the tests performed by Chen etc. (2008a) some easily detected corona signals were noticed from all the three transformers simultaneously, but on the other hand some signals reminding partial discharges were detected from two phases but couldn't be confirmed as partial discharges. Altogether, capacitive coupling sensors can be used to safely

measure partial discharges from transformers in operation, but in some cases further investigations must be done in order to make the correct judgments.

4.2.2. Wireless partial discharge monitoring

Monitoring partial discharges with wireless sensors isn't user friendly only because of the lacking power and sensor communication cables, but also because it is safer thanks to the galvanic isolation between the transformer and the user at the remote monitoring location. Adding to the above mentioned notes that wireless sensor network (WSN) can also reduce the overall costs, it seems like a very good sensor technique. (Hammoodi, Stewart, Kocian, McMeekin & Nesbit 2009.) Hammoodi etc. (2009) simulated in their research the WSN technique, with totally seven wireless sensor nodes. The seven nodes were connected to a power transformer, whereof six of them were at each HV and LV side of every phase of the transformer sensing the partial discharges and the seventh node was working as a coordinator. The coordinator node collects the measurement data from the six sensing nodes and stores the data until it is downloaded from the monitoring center.

According to Hammoodi etc. (2009) there are three different ways to move the data from the six sensing nodes to the coordinator node and to synchronize the different measurement data collected by the nodes. The first method is that when one sensing node informs to the coordinator, that its buffer is filled with data, the coordinator tells the other nodes to stop collecting data and downloads all measurement data from all the sensing nodes. In the second method the coordinator waits until it has received a message from all sensing nodes that their buffers are full, before it downloads the data from them. In the third method the communication channels don't allow data transmittal until the

buffer of the sensing node is filled, and after all the nodes have transmitted their data, the synchronization is done at the base station.

The ZigBee model used in the simulations made by Hammoodi etc. (2009) doesn't by default use any of the above described data transmittal methods, but it was modified to use a model as described as the third option. The coordinator node that collects the data from the sensing nodes could be placed near a power source, and the base station where the coordinator node sends all the PD measurement data can be located a few meters to kilometers from the sensing nodes. The data synchronization and data processing is done at the base station.

4.2.3. Fiber Fabry-Pérot sensors for acoustic detection of partial discharges

The fiber Fabry-Pérot interferometers are sensors to be placed inside the transformer tank to detect partial discharges, and thus to examine the health of the transformers insulation system. The acoustic waves created by the PDs are detected with the sensors, and since they are located inside the transformer tank, they can locate the partial discharges more precisely than the conventional acoustic sensors, which are placed on the outside of the transformer tank. (Sanderson, Frazão, Farias, Araújo, Ferreira, Santos & Miranda 2009.)

There are two types of Fabry-Perót sensors, the Extrinsic Fabry-Perót Interferometer (EFPI) and the Intrinsic Fabry-Perót Interferometer (IFPI). The details of an EFPI sensor can be seen in the figure below. The acoustic waves created by PDs in the transformer oil cause pressure to the diaphragm, which then in its turn changes the length of the air gap. A laser light is transmitted through the lead-in/-out fiber. When the laser faces the end of the lead-in/-out fiber, some of it (about 4 per cent) reflects back (R1) and the rest travels through

the air gap and faces the target fiber before it reflects back to the lead-in/-out fiber (R2). By measuring the difference between these two reflections, the length of the air gap and thus the acoustic wave can be determined. (Sanderson etc. 2009.)

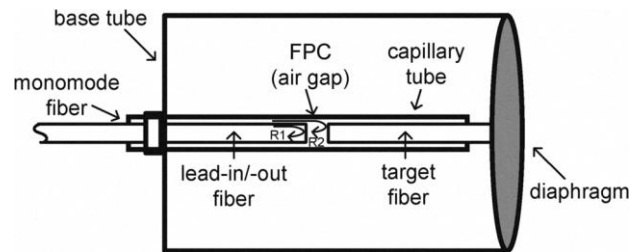


Figure 6. The details of an EFPI sensor (Sanderson etc. 2009).

In the IFPI sensor the basic principle of the measurement is similar to the EFPI, but the sensor itself looks a little different, as shown in the figure below. The FBG reflector reflects 40 per cent of the incoming light (R1), and the mirrored end-surface attached to the vibrating diaphragm reflects the rest of the transmitted light (R2). Again, the difference between the reflected signals and thus the movement of the diaphragm is determined. (Sanderson etc. 2009.)

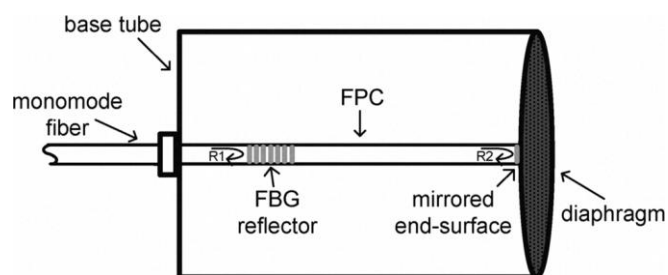


Figure 7. The details of an IFPI sensor (Sanderson etc. 2009).

In the test performed by Sanderson etc. (2009), the sensors were tested in air, immersed in water and immersed in oil. The oil-immersed tests show, that these sensors could be used to detect the partial discharges instead of using the

ones mounted on the outer walls of the transformer. Especially the test results of the EFPI sensor were promising. Still, some further research needs to be done in order to improve the process and to choose the most suitable materials for construction of the sensing heads. Sanderson *et al.* (2009) are hopeful, that after further investigation these sensors can produce a 3-dimensional picture of the acoustic phenomena inside the transformer oil tank and can provide a very accurate fault location when sensors are located correctly inside the oil tank.

4.2.4. New UHF transformer probe sensors

One method studied at the moment to measure partial discharges is the Ultra High Frequency (UHF) method. The UHF method measures the energy that is radiated from the discharge site because of the rapid acceleration of the charged particles. UHF method has been used quite a long time in gas insulated switchgear and has recently been applied to power transformers. The UHF sensors are easy to install in new transformers, and can also be installed into transformers in use, through the oil drainage valve. The only demand to the old transformer is that the valve has to be of gate or guillotine type. In this case, the probe has to be mechanically robust as well as highly sensitive, since their breakdown won't only stop the PD measurement, but will also affect directly to the transformer operation. (Reid, Judd & Johnstone 2009; Lopez-Roldan, Tang & Gaskin 2008.)

The sensors have to deal with several different challenges, such as vibration, high oil temperature and tough weather conditions, and in addition remain tight and sealed. The designers must take into consideration that the probe shouldn't be able to be installed too deep into the oil tank in order to avoid

close contact to the HV conductors. The probe should also be highly electrically sensitive. (Reid etc. 2009.)

The new UHF probe was compared by Reid etc. (2009) to a commercial probe and it was found out, as can also be seen from the figure below, that the new probe achieved significantly higher sensitivity at all mounting depths compared to the commercial one, and can thus achieve more accurate measurements even when not installed very deep in reference to the transformer tank wall. The ability to install the probe close to the wall helps to avoid any contact to the HV conductor that may be located close to the probe. It was also discovered, that the UHF sensors could with a high probability detect PDs at any frequencies they can occur, and thus increases the chances of detecting them.

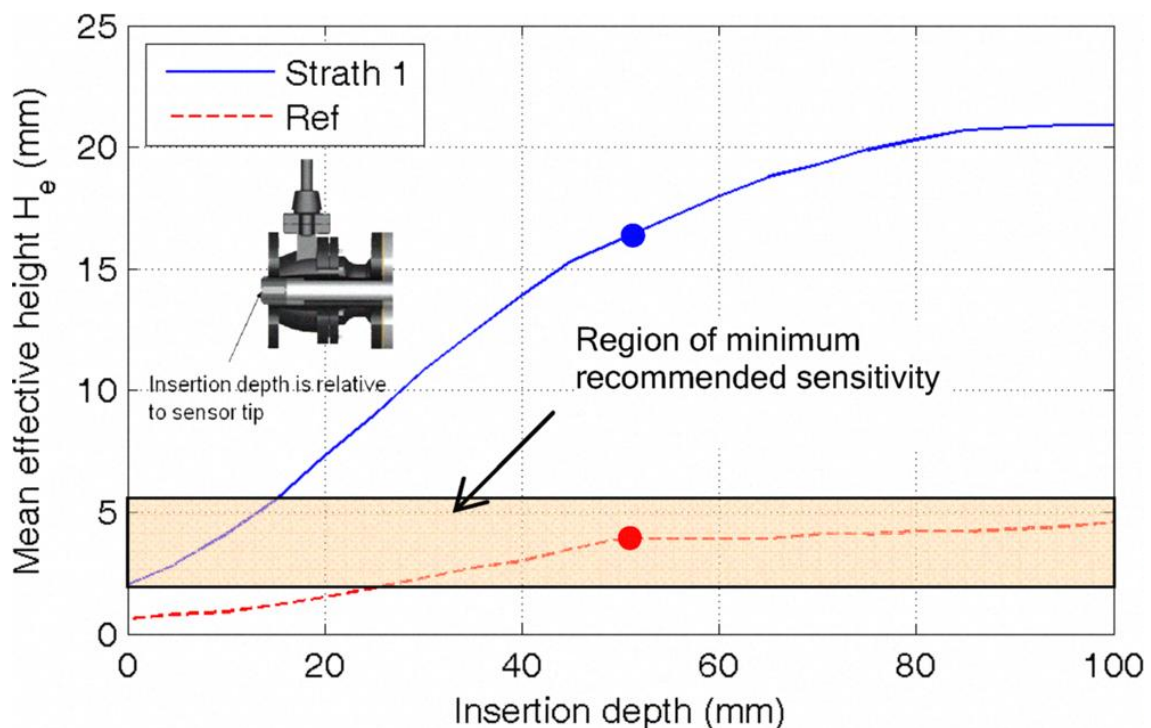


Figure 8. Comparison of sensitivity and installation depths of the new Strathclyde and commercial probe (Reid etc. 2009).

Lopez-Roldan etc. (2008) have examined the different antenna types for this purpose. In the document they claim that a long, conical shaped $\lambda/4$ monopole antenna is the best type for this purpose. They also confirm the results made by Reid etc. (2009) that the insertion depth significantly increases the antennas sensitivity, and thus improve the PD detection rate. Lopez-Roldan etc. (2008) also fitted the antenna in a 1500 MVA 330 kV/275 kV transformer that was known to have some PD activity inside it. Also these tests backed up the results achieved in laboratory conditions about the antennas properties, but still some further research must be performed to confirm that the test results are correct.

4.3. Temperature measuring sensors

Temperature measurement of a transformer can be performed with several different methods. At the moment, there are three main methods to perform these measurements: thermal simulation method, thermal model method and direct measurement method. The thermal simulation model tries to determine the coil temperature by using a thermal simulation thermometer, but has a large measurement error. The thermal model method is based on calculations made from the transformer parameters and known values, but it has to make some simplifications and thus produces some inaccurate results. The direct measurement method is the most accurate method of these three, because it bases on measurements of sensors located in or near the windings. The problem with this method is that the winding hot-spot is not known, so several sensors at different locations have to be installed to get accurate and reliable results. (Chen, Liu, Wang, Liang, Zhao & Yue 2008b.)

One sensor type for the direct measurement of winding temperature is the fiber-optic Fiber Bragg Grating (FBG) temperature sensor. The FBG sensors measure the temperature change using a modified version of a passive all-fiber demodulation scheme. The FBG sensors are located encapsulated in protective tubing, which are tightly sealed to the outer wall of the transformer ensuring that no oil leakages occur from the gland. The protective tube protects the sensors from the mechanical stress and possible transformer oil damage. (Chen etc. 2008b; Lobo Ribeiro, Eira, Sousa, Guerreiro & Salcedo 2008.)

In the test performed for FBG sensors by Chen etc. (2008b), it was found out that both during the constant load test as well as the varying load test, the FBG sensors were accurate and effective, and also responded quickly to the temperature changes in the transformer winding. Thus, FBG sensors are a very good option for continuous transformer winding hot-spot sensing.

4.4. Moisture measuring sensors

Transformer moisture is, as mentioned previously, an issue that has been known for a long time. This is one reason why moisture measuring sensors have been developed widely. The moisture measurement can also be done with several different methods. Below I present two moisture sensors which operate with different techniques.

4.4.1. Optical fiber moisture sensor

On-line moisture monitoring directly from the insulating paper isn't yet commonly used, but some research regarding moisture measuring sensors has

been done in order to correct this issue. One modern sensor type is an optical fiber moisture sensor, which is based on a polymer optical fiber covered by Polyvinyl Acetate PVA. These types of sensors can be of many different geometrical shapes, such as straight, tapered or bent. (Rodriguez-Rodriguez, Martinez-Pinon, Alvarez-Chavez & Jaramillo-Vigueras 2008.)

The moisture measurement requires at least two sensors, whereof one is located in contact with the insulation paper (where the moisture is measured) and the other one is located in the insulating oil giving a reference value. The moisture value of the oil is at least 500 times smaller than in the insulating paper, so the reference sensor can be considered to measure dry values compared to the other sensor. The measurements are done by entering light from one end of the sensor and measuring the reflected light from the other end. The PVA coating scatters the light, but if the coating is exposed to moisture, the light penetrating the coating layer can be scattered out of the coating. This means, that if the paper insulation that the sensor is in contact to has a high humidity, the light transmittal is significantly higher. So, by comparing the measured values of the reflected light from the two sensors, the moisture level of the paper insulation can be calculated. (Rodriguez- Rodriguez etc. 2008.)

4.4.2. Capacitive humidity sensor

As previously mentioned, moisture is often measured from the insulating oil, and the measured value is, with the help of calculations and curve sets, converted to discover the moisture level in the insulating paper. One possible sensor for this purpose is the capacitive humidity sensor. It's a polyimide based sensor that can stand both high and low temperatures and also has a strong chemical corrosion resistance. (Chen, Chen & Gu 2008c.)

The sensor is coated with a polyimide film and dropped into the transformer oil. When the moisture level in the oil change, the amount of water molecules in the polyimide film change accordingly, changing the relative dielectric constant and thus the capacitance of the sensor. This change of capacitance is converted to a signal that is entered to a computer and the change of moisture in insulating paper can be calculated. The sensor is very insensitive to the aging of different oils and also to additives in the oil, so the measured information about moisture in oil is usually very reliable. On the other hand, changes in the temperature changes the relations between moisture in oil and moisture in insulating paper, so in order to get reliable results regarding the moisture level in the insulating paper, a temperature sensor and the curve sets also have to be used. (Chen etc. 2008c.) Also, it has to be remembered, that moisture in the insulation oil doesn't necessarily mean that the insulation paper would contain moisture, so these measurements can't be considered bullet-proof.

4.5. MEMS sensors for gas detection

One way to discover the gas molecules formed in the transformer oil is to use the MEMS (Micro-Electro Mechanical Systems) sensors. The sensors that measure the gas formation in the insulation oil are installed around the windings to ensure maximal flow of oil and gas bubbles through the sensor, and by using multiple sensors the transformer can be seen as a three dimensional image. (Bhat, Oh & Hopkins 2010.)

The MEMS casing should be manufactured from e.g. ceramic and silicon dioxide, to withstand both electrical and mechanical stresses. The transducer section itself can be divided in four sections: the collection tube, MEMS turbine,

gearing and generator. The collection tube is accurately designed and calculated to ensure suitable flow of gas to the turbine. The turbine is the primary component of the transducer, and its purpose is to transfer the hydraulic energy captured from the gas bubbles into mechanical rotational energy. A gearing has to be used to increase the shaft speed to drive the generator at appropriate speed, which then in its turn transfers the mechanical energy to electrical output signal that represents the gas flow. The figure below describes the MEMS sensor and its working principle. By monitoring the relative differences in velocity, pressure and flow rate, some early stages of faults can be discovered before real damage to the transformer has occurred. (Bhat etc. 2010.)

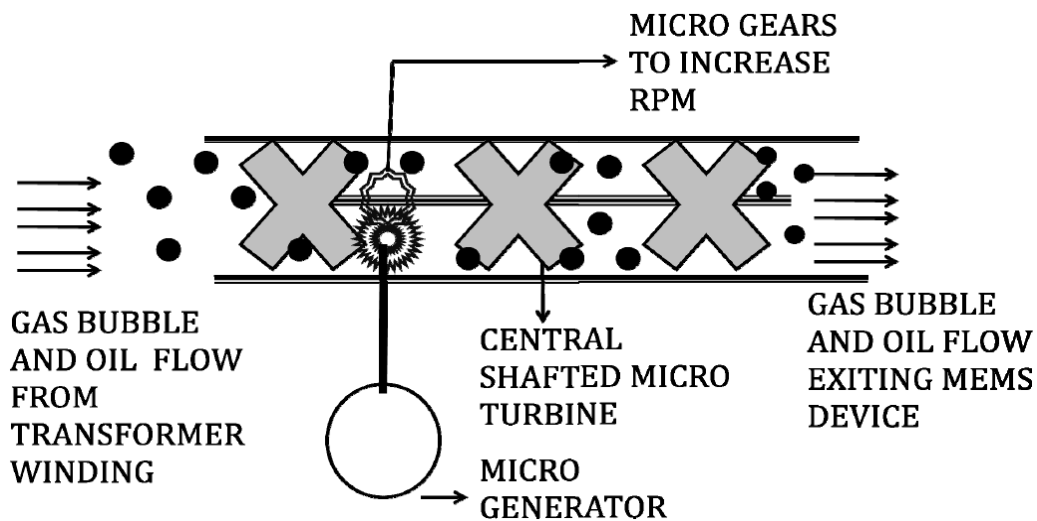


Figure 9. Construction and working principle of a MEMS sensor (Bhat etc. 2010).

By installing the sensor close to the windings, the possibility of fluid to run through the sensor increases. This large fluid volume transfers the energy to the turbine blades, which are closely designed to operate at low energy levels and with low rotational velocity. Already at this stage, even if the research hasn't been going on for long, the MEMS sensors appear to be a good replacement or

addition to the traditional monitoring sensors, but in order to be commercially available, more research needs to be done. (Bhat etc. 2010.)

4.6. Data gathering of monitoring sensors

The measured data of the transformer has to be, by one way or another, transported to the grid operator or controller. Exporting the measurement data separately from each sensor isn't very cost efficient and often makes it complicated for the operator to interpret the current situation. An easier way is to gather the data together already at the transformer, and then transmit the measurements to the controller.

One system under development for this kind of operation is the DAKSHITA™ real time operation system. It collects the measurement signals of different sensors, which are dissolved fault gas content (hydrogen), moisture in transformer oil, oil temperature and other temperature readings. The measurement signals are gathered from different sensors to a data acquisition and analysis hardware, which transfers the data to a central location with the help of GSM network using GPRS service. Thus, all the measurement data can be monitored from any location with the help of an internet connection. The weakness of the system, limited measurement signals, is also under development, and later on acoustic emission sensors for detecting partial discharges as well as individual fault gases detected by DGA will be available to monitor with the same system. (Wagle, Lobo, Santosh Kumar, Shubhangi & Venkatasami 2008.)

The DAKSHITA™ system also contains alarm-functions, so that when the system detects some measured values differing from the reference values, it triggers an alarm. With the help of this alarm function, the DAKSHITA™ system sounds very promising and hopefully its development goes on further and it along with its equivalent rivals becomes commercially profitable and quickly widespread.

5. CONCLUSIONS

Transformers are expensive equipment of an electrical grid and their lifespan is counted in decades. As they are critical components and operate most of their lifetime, the importance of proper condition monitoring is obvious. Even if the condition monitoring systems of a transformer improve the predictability of maintenance costs and helps to prevent some serious malfunctions and failures, the downside of it is that it adds more costs and complexity at the purchasing moment. Therefore, it is important that every transformer is equipped with a condition monitoring system designed specifically for the purpose, i.e. that no useless sensors are installed.

After a brief introduction of a transformer and an overview of different monitoring methods, I moved on to the main topic of the thesis, different sensor types. Thanks to constant research, studies of different sensor types could be found plenty. I tried to pick the ones of most interest and introduce them, with some basic technical description, and afterwards consider which were the most promising sensors.

Detecting partial discharges is an issue that has inspired many researchers. The methods to detect PDs are numerous, all of them having their pros and cons. Some methods require reference values of the same or a similar, healthy transformer, when others might not achieve totally reliable results without doing some further tests. In my opinion, the fiber Fabry-Pérot interferometers as well as the ultra high frequency sensors would appear to be two good PD measuring sensors. Both sensors are located in the oil tank and are thus in contact with the transformer oil, whereof vibrations caused by PDs can be measured. The Fabry-Pérot method can even locate the PD very accurately,

because of multiple sensors at different locations. The UHF sensors have already been used in switchgears, but in order to make them suitable for transformers, both sensor types still need some further research. Any PD measuring sensor installed in a transformer is better than none, because early detection of any PD activity can help to begin the maintenance actions in time and thus prevent any bigger failures.

Temperature measuring of a transformer can often be difficult, because the hotspots are rarely known and the installation of the sensors near a hotspot can be difficult. Often the temperature is simulated or modeled, but these methods can't obviously be very accurate. One good sensor for direct temperature measurement seems to be the Fiber Bragg Grating sensor which is accurate, sensitive, reacts quickly to any temperature changes and is already commercial. With the help of its protective tubing, it measures the temperature near the windings with reliable results.

Regarding moisture measurement, the optical fiber moisture sensor appears as a reliable sensor type. Because it is in contact with the insulating paper, the results are always truthful and real. The capacitive humidity sensors measure the moisture of the oil, and with the help of curve sets it is converted into the moisture value of the insulating paper. The problem with this technique is that moisture in oil doesn't always necessarily mean moisture in paper. But again, more research has to be done in order to obtain some reliable commercial products for direct moisture measurement from the insulating paper.

MEMS sensors are at an early development stage. At this point some promising results have been achieved and in the future they can be excellent fault detectors, but at this point it isn't possible to make further conclusions on them.

Altogether, development towards wireless technologies is a key point, even in transformer condition monitoring. Some sensors can operate wirelessly and transfer the data onwards without any permanent connections, but sending all the measurement data from the separate sensors to the control building collectively without wires is a big step. With efficient use of both GSM and GPRS, this is the modern technology of the near future, as proved by the DAKSHITA™ system.

As can be seen from the thesis, constant development of different sensors is ongoing. When new commercially available sensor types come on the market, some further research of their cost efficiency and final properties would be interesting. Also, some kind of minimum setup of different sensors to achieve a decent protection for a transformer with minimum costs would surely be of interest among the grid operators as well as the transformer manufacturers. With a basic sensor package, the condition monitoring system would be much easier to sell to the customer along with the transformer.

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