UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

ELECTRICAL ENGINEERING

Lasse Pakka

MANAGEMENT OF TRANSFORMER CONDITION MONITORING DATA

Bachelor’s thesis in Technology for the degree of Bachelor of Science in Technology submitted for inspection in Vaasa, 11 of may, 2012

Instructor Professor Erkki Antila

ACKNOWLEDGEMENTS

I would like to thank my supervisor Kimmo Kauhaniemi and my instructor Erkki Antila for suggesting this interesting topic for my candidate thesis and all the guidance and support for the past few months.

CONTENTS

ABBREVIATIONS AND SYMBOLS

A/D	Analogy / Digital
ABB	Asea Brown Boveri
CDMA	Code Division Multiple Access
CH_4	Methane
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CLEEN	Cluster for Energy and Environment
DC	Direct Current
EMC	Electromagnetic Compatibility
FRA	Frequency response analysis
GSM	Global System for Mobile Communications
H_2	Hydrogen
I/O	Input/Ouptut
MCU	Master Control Unit
N_2	Nitrogen
OECD	Organisation for Economic Cooperation and Development
O_2	Oxygen
PD	Partial Discharge
PPM	Parts per million
PSTN	Public Switched Telephone Network

SCADA	Supervisory Control And Data Acquisition
SCU	Slave Control Unit
SGEM	Smart Grids Energy Markets
TDM	Time Division Multiplexing
UHF	Ultra High Frequency
USB	Universal Serial Bus

UNIVERSITY OF VAASA
Faculty of technology

Author:	Lasse Pakka
Topicd of the Thesis:	Management of condition monitoring data
Supervisor:	Professor Kimmo Kauhaniemi
Instructor:	Professor Erkki Antila
Degree:	Bachelor of Science in Technology
Department:	Department of Electrical Engineering and Energy Technology
Degree Programme:	Electrical and Energy Engineering
Year of Entering the University:	2006
Year of Completing the Thesis:	2012 **Pages:** 47

ABSTRACT

Transformers are critical components in electricity transmission. It is important that they operate continuously. Transformers are reliable and long life components but the older the transformer is, the more sensitive it is about to fail. Condition monitoring provides improved data on the condition of transformer. With on-line condition monitoring is possible to detect developing failures and then a corrective action can be made in time.

This thesis focuses on management of transformer condition monitoring data. The aim is to study about different condition monitoring methods and examine about fault resolving from sensor data.

In the beginning the study focuses on transformer basics. The study finds out different transformer condition monitoring methods. The most common of the traditional off-line methods and most of the modern on-line techniques are introduced. The main focus is on the condition monitoring data. Sensors feed different data that needs to be processed, analysed and monitored. Sensor type is related to used condition monitoring method. The sensor data must be usually processed in order to filter disturbances and made it suitable for data acquisition. This data is analysed on computer with specific fault diagnosing techniques.

There are a lot of issues among transformer condition monitoring that needs for research. This thesis could be continued for researching what information is needed in different management functions in sustainable power grid.

KEYWORDS: transformer, condition monitoring, on-line, off-line, data management.

1. INTRODUCTION

Power transformers are important components of electricity transmission and power transmission system and often the most valuable device in a substation. System abnormalities in loading or switching and ambient condition speeds the aging of transformer and can cause a sudden failure, which could lead to blackout. Therefore, the condition of transformers must be monitored.

This research is a part of research program SGEM (Smart Grids Energy Markets) arranged by CLEEN (Cluster for Energy and Environment). Research program consists of several work tasks. This research belongs to task 6.12 (Proactive condition monitoring) and the objective is to research data types for transformer condition monitoring. The topic was suggested by professor Erkki Antila from the Department of Electrical Engineering and Energy Technology at the University of Vaasa.

This study focuses on transformer condition monitoring data. Condition monitoring sensors offer a certain kind data that needs to be processed in a specific format, which can be analysed, saved and monitored.

This thesis consists of five chapters: Introduction, transformer, condition monitoring methods, data types for condition monitoring. The next chapter explains the transformer structure and the basic operating. Basics of condition monitoring are described in the third chapter. The main focus is on the fourth chapter where condition monitoring data processing is researched. The last chapter is for conclusion part.

2. TRANSFORMER

Transformer is over a hundred years old device, which is still being developed. With a transformer it is possible to change alternating voltage and current levels. Transformer can also be used as a protection for some device by isolating it from grid galvanically. Transformers can be used for change measured current or voltage to be suitable for measuring devices.

Power transformers can be classified in a few types depending on the operation presented in Table 1. (Mörsky 1994)

Table 1. Transformer types (Mörsky 1994).

Transformer type	Used for
Power and distribution	Changing voltage level to be suitable for power and distribution transfer
Isolating	Protection. Isolating transformer creates a galvanic isolation between the powered device and the power source.
Instrument	Changing voltage or current levels suitable for measuring devices.

This study focuses on power and distribution transformers which are essential parts of energy transmission grid.

Power transformers are used between the generator and the distribution circuits, and these are usually rated at 500 kVA and above. Power system may consist of a large number of generation locations, distribution points, and interconnections within the power system or with nearby power systems, such as a neighboring utility. (Harlow 2004)

Distribution transformer takes voltage from a primary distribution circuit and “steps down” or reduces it to a secondary distribution circuit or a consumer’s service circuit. (Harlow 2004)

In energy transmission, transformers are used to change voltage level suitable for different needs. A transmission line is a wiring connection which has always a resistive component. Thereby a part of transferred energy will be lost in transmission line. With a higher voltage level the same size of power can be transferred with a lower current level and thus the losses are smaller in transmission. (Hietalahti 2011)

For power and distribution transformers there is coming a new technique that bases on power electronics. The device is called electronic power transformer or power electronic transformer. The advantage of this electronic power transformer is that the magnitude and phase angle of voltage can be controlled in real-time. With the electronic power transformer flexible current and power regulations can be achieved. So the device works as a transformer with functions of flexible ac transmission system. (Lu 2009)

2.1. Definition

A transformer “is a static device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for inducing mutual coupling between circuits. Transformers are used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually changed values of voltage and current.” (IEEE Std. 100-1972)

2.2. Structure

Basic operation of transformer relies on electromagnetics whether or not the transformer has a magnetic core and windings. Transformer is built from several rounds of shaped conductors with the iron core inside. Iron cores are constructed of laminated plates for minimize eddy currents caused by alternating electric grid. (Hietalahti 2011)

Power and distribution transformers can be made for single-phase and multi-phase but most of them are three phase transformers. This chapter describes the main parts of a transformer.

2.2.1. Core

In three phase transformers the windings for each phase are placed on their own limb. Those three limbs are magnetically coupled together by the upper and lower yokes. In normal symmetric operation of the transformer the sum of voltages and the sum of currents are continually equal to zero. The sum of fluxes, $\varphi_{1,2,3}$ in three limbs is also equal to zero. In the limb the flux varies sinusoidally, like the voltage. In Figure 1 a three-phase three-limb core is presented. The cross section of the yokes is the same as of the limbs because yokes must be able to carry the same flux as in the limbs. (ABB)

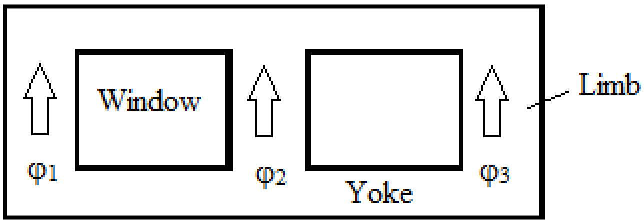

Figure 1. Three-phase three-limb transformer core (ABB).

Three-phase five-limb transformer has three main limbs with windings and two outer side limbs. These outer limbs are returning path for flux and therefore the cross section of yokes and the side limbs is on half of the cross section of main limbs. It gives the designer the possibility to reduce the total height of the core. These kinds of transformers have extremely high zero sequence impedance unless a delta connected winding is provided. (ABB)

Transformer cores are specially manufactured from thin steel sheets. Core steel has low carbon content <0,1 %. Carbon has a harmful influence on the hysteresis losses as well as the aging properties. Core steel is alloyed with silicon that increases the specific electrical resistance which reduces the eddy current losses in the core. But increased silicon content makes the core brittle. Therefore the silicone content is kept below 3 %. (ABB)

Grain-oriented steel is used nowadays. By rolling the steel sheets, the magnetic area in the sheet will tend to be oriented in the rolling direction. In this way, very good loss properties can be achieved in the rolling direction but poor loss properties in the traversal direction. Grain oriented steel is a mixture of silicon-iron that is rolled during fabrication in such a way that the permeability is higher and the hysteresis losses are lower when the flux is in the direction of the grain. (Winders, 2002)

The sheets must be insulated from each other to minimize the eddy current losses. The insulation should be an inorganic material compatible with transformer oil and it should also be corrosion and temperature resist. (ABB)

It is also possible use three single-phased transformers instead of using one three phase transformer (ABB).

2.2.2. Windings

The windings consist of conductors wound around the sections of the core. These conductors must be properly insulated, supported, and cooled to withstand operational and test conditions. (Harlow 2004)

The commonly used circular windings have inherently higher mechanical strength than rectangular windings, whereas rectangular coils can have lower associated material and labor costs. Rectangular windings permits a more efficient use of space, but their use is limited to small and medium size power transformers where the internal forces are not extremely high. As the transformer power rating increases, the forces increases significantly and there is need for added strength in the windings, so circular coils, or shell-form constructions are used. (Harlow 2004)

In Figure 2 it is presented a schematics of single-phased transformer core-form construction. There are two windings, other is high-voltage and other is low-voltage. The windings are placed in their own limb. In Figure 3 it is presented the same schematics for three-phased transformer. High-voltage and low-voltage windings are placed in same limb, but it is possible to place the windings on own limbs.

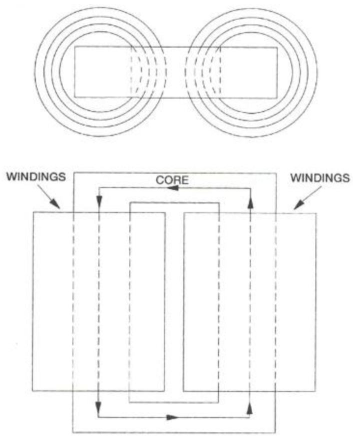

Figure 2. Shematics of single-phased transformer core-form construction (Harlow 2004).

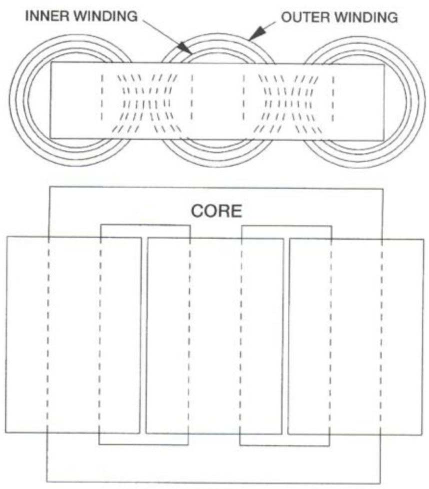

Figure 3. Shematics of three-phased transformer core-form construction (Harlow 2004).

2.2.3. Tap-changer

Tapped windings makes possible to adjust the transforming ratio safely and easily to system conditions. With a tap-changer the ratio of power transformers can be changed gradually. There are two types of tap-changer: One is on-load tap-changer where power ratio can be changed in loaded transformer. The other is off-load tap-changer where the transformer must be disconnected when changing the power ratio. (Siemens)

2.2.4. Cooling

An ideal transformer transforms the voltage level to another with no losses. Because of different losses a real transformer produces heat in operation. Most of the heat comes is generated in windings where alternating magnetic field influences. Heat can also be generated in internal metal structures in transformer. Method of removing this heat depends on the application, the size of the transformer, and the amount of heat that needs to be dissipated. (Harlow 2004)

In proximity of the heat sources it is important to have proper cooling channels where the cooling medium can flow by so that the heat can be effectively removed from the transformer. The heat is carried by the insulating medium until it is transferred through the transformer tank wall to the radiator. Radiators provide an increase in the surface area available for heat transfer by convection without increasing the size of the tank. Transformer surface area is also convecting the heat to the surrounding medium. Integral tubular sides or fins provide an increase in surface area and therefore convection can be more efficient. Fans can be installed to increase the volume of air moving across the cooling surfaces, thus increasing the rate of heat dissipation. Larger transformers that cannot be effectively cooled using only radiators and fans rely on circulating pumps that circulates the oil through the transformer and through external heat exchangers, or coolers, which can use air or water as a secondary cooling medium. (Harlow 2004)

2.2.5. Oil

The most of distribution transformers on utility systems nowadays are liquid-filled. Liquid-filled transformers offer the advantages of smaller size, lower cost, and greater overload capabilities compared with dry types of transformer of the same rating. (Harlow 2004)

Traditionally, the insulation system of power transformers consists of mineral oil, cellulose paper, and pressboard. In recent years, there has been an increase in the use of environmentally-friendly fluids such as synthetic esters and natural esters in place of using mineral oil. (Imad 2007)

Mineral oil is a mixture of hydrocarbons and is refined from crude oil. Mineral oil has a low biological degradability resulting in the need to construct bund walls around large transformers for prevent the oil escaping into the environment if a leak occurs in transformer. In the case of an oil leak to environment, significant financial penalties would be nominated by environmental enforcement agencies. In contrast to mineral oil, esters are very biodegradable, and they conform to the readily biological degradable definition according to the OECD (Organisation for Economic Cooperation and Development) 301 series of tests. (Imad 2007)

3. CONDITION MONITORING METHODS, DEVICES AND SYSTEMS

Power transformer is one of the most expensive equipment in a substation and it can act as a critical part of grid within electricity transfer. If a transformer fails, it may lead to a power failure, material damages, personal injury or oil spill to nature. Not to mention the financial loss, it is cheaper to maintain the condition of the transformer by monitoring it than using the transformer until it breaks down. According to Han (2003) Condition monitoring has the potential to reduce operating costs, improve the reliability of operation, and enhance power supply and service to customers.

Tang (2011) says that the normal life expectance of a power transformer is around 40 years. Because the investment boom after the 1970s the percentage of transformers operated in many power systems more than 30 years is increasing. Therefore the failure rate of transformers is expected to rise sharply in the coming years. Transformer failures are sometimes catastrophic and almost always include irreversible internal damage in transformer. Therefore, all the key power transformers in a power system should be monitored closely and continuously in order to ensure their maximum operation time. Generally, there are four main aspects of transformer condition monitoring and estimation, including thermal dynamics, dissolved gas, partial discharge and winding deformation, which should be monitored closely in order to determine power transformer conditions.

Because a fault can occur at any time in the transformer, it is best that defect becomes known as early as possible for the necessary action so the transformer can be kept operational.

Power transformers have sensitive and critical part in power transfer, if a transformer failures it causes stopping of all electrical devices that are connected under the transformer. Most of power transformer failures causes large economical damage, especially in industry area. By using condition monitoring system it is possible to prevent unwanted transformer failure and decrease the time of transformer failure to repairs. (Abniki 2010)

Traditional off-line condition monitoring techniques have been shown to be very effective to detect and identify faults. The methods that are used in transformer condition monitoring can be divided in two general groups which are off-line and on-line methods. The meaning of off-line methods is that the condition monitoring tests are made occasionally on field. With on-line methods the data recording is performed continuously. (Abniki 2010)

3.1. Off-line condition monitoring

With off-line condition monitoring techniques a transformer is tested on site occasionally. Some of tests are performed in off-loaded and others in loaded transformers as shown in Table 2.

Table 2. Off-line condition monitoring techniques.

Test type	Transformer loading	object
Megger	off	Paper and oil insulators
Power factor	on	oil insulation and winding losses
Short circuit impedance	off	Changes in winding structure
Frequence response analysis	off	Changes in core, windings and insulation
Oil	on/off	Insulation, moisture, oil dielectricy
Ultrasonic	on	Partial discharges
Thermovision	on	Faults that causes heating

3.1.1. Megger

The insulation resistivity of paper and oil can be measured by inputting DC (Direct Current) in winding and measuring the resistivity from winding to transformer body. The

DC voltage is proportionate to nominal voltage of windings. Measurement results are compared to standard values. (Abniki 2010)

3.1.2. Power factor

The quality of insulation of the transformer can be measured by Power factor or Dissipation factor test. The lower the power factor or dissipation factor the lower are the losses in the insulation and less energy is converted into heat. The condition of insulation deteriorates over time and water content in oil speeds up the aging process. Partial discharges also reduce the quality of insulation. (Omicron 2010)

In a particular frequency of 50 or 60 Hz the insulation can be presented by equivalent circuit that consists of an ideal capacitor and a resistance connected in parallel. Connecting a capacitor to ac voltage source, the angle of voltage and current will be 90 degrees. When the resistor is connected to voltage source, the angle between voltage and current is zero degrees. When these are connected parallel, the angle between voltage and current depends on the magnitude of resistance and capacitor. The power factor is the ratio of the current through the resistor of the total current. (Omicron 2010)

Tangent test is used for measuring the insulator loss that is a threshold for testing the degree of oil insulator and transformer armature winding losses. Measuring the insulator loss for transformer can be done by various voltages comparing by standard values. (Abniki 2010)

With the Power factor test is possible to detect the insulation integrity in windings, bushing, arrester, tank, and oil. Increased power factor may be caused of moisture in oil or polar and ionic compounds in the oil. (Gockenbach 2010)

3.1.3. Short circuit impedance

In this test the short circui impedance of windings are measured by applying the short circuit at high voltage side and using a percentage of nominal voltage at low-voltage side. This causes to the nominal current passing at high voltage side, and percent impedance is determined that it is proportional to mentioned voltage. Changes in impedance values express changes in structure of armature windings of transformer. (Abniki 2010)

3.1.4. Oil sample

Transformer oil quality is important factor for the transformer life extension. Moisture in transformer reduces the dielectricity of insulation system. The combination of moisture, heat and oxygen affects the decomposing rate of the cellulose isolations. The test include different physical and chemical tests such as moisture test, interfacial tension test, oxygen test, acidity test, and dielectricity of oil test. (Gockenbach 2010). It is also possible to measure the amount of particles in oil for to ascertain for example the condition of pump or fan bearings (Virtanen 2012).

3.1.5. Ultrasonic

When transformer insulation medium breaks down, it may cause a discharge in a transformer. Every time when discharge occurs it creates sound waves. Ultrasonic test is acoustical method for detecting discharges by using acoustical measurements with an ultrasonic sensor. With this test partial discharge and full discharge can be detected. It is also possible to detect other faults that emit acoustical waves. Increased core or coil noise refers to looseness, failing bearings in oil pump and fans causes also noise and nitrogen leaks in nitrogen-blanketed transformers can be detected. (Gockenbach 2010)

3.1.6. Frequency response analysis

If a protective relay has tripped or a through fault, short-circuit or ground fault has occurred this test may be helpful. When a transformer is subjected to high through fault currents, the mechanical structure and windings are exposed to mechanical stresses causing winding movement and deformations. It may also cause insulation damage and turn-to-turn faults. The deformation can also be caused of ageing of paper. As a transformer ages the insulation contract and the clamping pressure may be lost which decreases its withstand strength. Winding deformations in transformers are difficult to discover by conventional methods of diagnostic tests like ratio, impedance/inductance, magnetizing current etc. Deformation is shown in relative changes to the internal inductance and capacitance of the winding. These changes can be discovered externally by low voltage impulse method or FRA (Frequency response analysis) method. (Nirgude 2004, Gockenbach 2010)

Frequency response of each transformer is unique. For analysing the frequency response graph must be compared to the transformer fingerprint to state the change in transformer. In Figure 4 is graph of frequency response of 3 phase 16 MVA transformer. Specific frequencies provides information of certain parts of the transformer. (Omicron 2011)

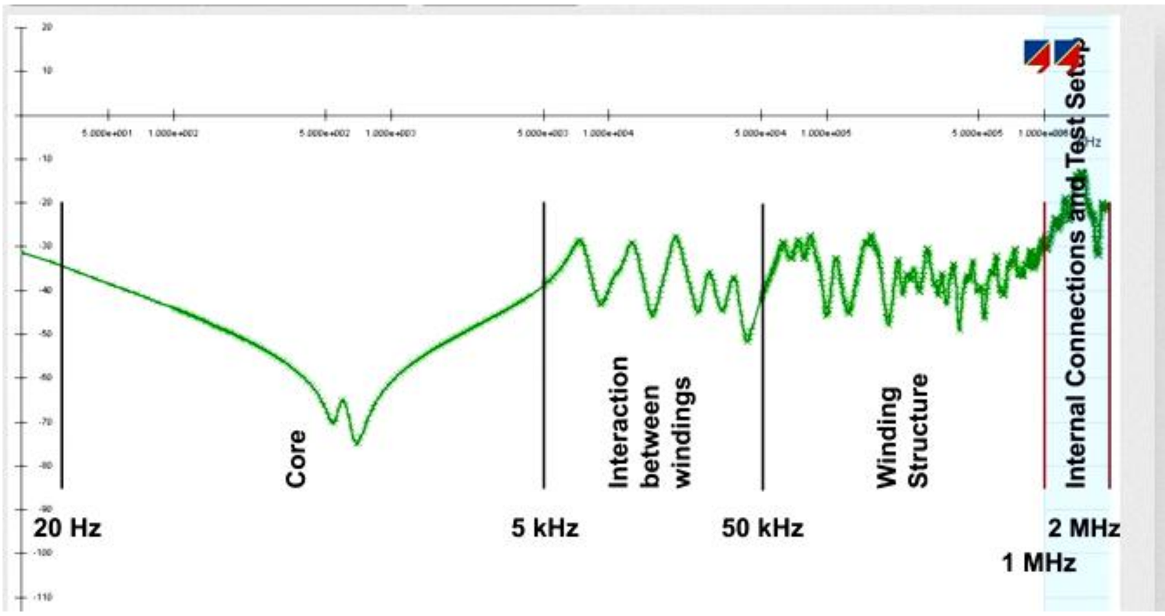

Figure 4. Frequency response analyse. (Omicron 2011)

3.1.7. Thermovision

An increase in temperature is usually caused of cooling problems or losses in the windings, core, bushings, tank, load tap changer or oil pump. The transformer aging process is correlated with the operation temperature. An increase of 6-8 °C to operation temperature doubles the rate of aging process. (Abniki 2010, Gockenbach 2010)

Every substance emits infrared radiation at a specific temperature. Thermovision test is based on the measurement of infrared radiation from surface of transfomer. With this test the gradient of temperature can be measured of the electrical and mechanical components. The infrared spectrum of a transformer is measured and converted to electrical signals. (Gockenbach 2010)

Unnormal thermal distribution reveals the fault. In Figure 5 it is presented a infrared image of defective bushing. (2010)

This method is possible to use also in on-line condition monitoring.

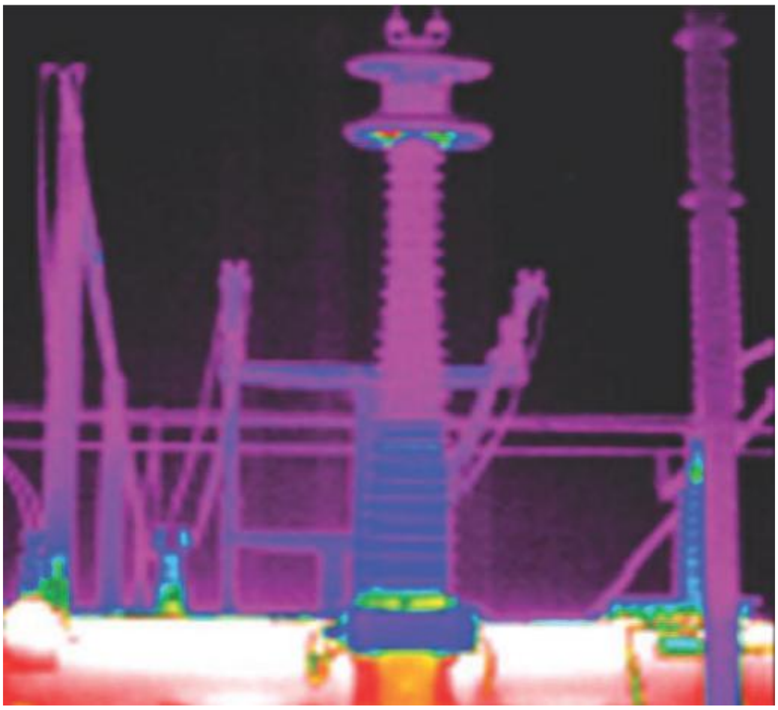

Figure 5. Defective bushing (Gockenbach 2010)

3.2. On-line condition monitoring

Increasing interest has been seen in on-line condition monitoring techniques. With on-line monitoring system, the condition of transformer can be monitored more effectively. The object of on-line condition monitoring is to detect developing failures and second goal is to minimise the need of maintenance. (Norick 2004)

There are several factors that affect the transformer life expectancy. Those factors includes electrical breakdown, lightning, dielectric fault, loose connections, moisture, overloading. Those parameters can be monitored on-line in order to obtain the information of the transformer condition. (Gockenbach 2010)

Defect can be detected at earlier stage than with the off-line condition monitoring techniques and thereby it is possible to make further actions earlier.

3.2.1. Dissolved gas analysis

Gas in oil analysis is the traditional way to monitor insulation condition. Dissolved gases in the oil produced by thermal ageing can provide an early indication of an incipient fault. Gases normally analyzed are hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane ethylene, and acetylene. Further analysis of concentrations, condition, and ratios of component gases can identify the reason for gas formation and indicate the necessity for further maintenance. (Gockenbach 2010)

In accordance to Abniki (2010), solution gas analysis is one of the commonest techniques for transformer monitoring. This technique bases on the fact that during faults, some gases are produced and dissolved in the oil. The densities of different fault gases are measured from transformer oil. Most of fault gases can apply for identification of different faults, but one of the commonest methods is related to hydrocarbon gas. Observation shows that gases like methane, ethane, ethylene and acetylene are produced during the rapid temperature growth. In Table 3 it is presented a variety of fault gases and problems that they indicate.

Another way for analyzing the fault gases is comparing the values of solution gases to each other. For example, when values of acetylene density to ethylene density are high, it can be stated that the transformer arcing occurs. (Abniki 2010)

Table 3. Fault gases (Khan 2007)

Fault gases	Key indicator	Secondary indicator
H_2 (hydrogen)	Corona	Arcing, overheated oil
CH_4 (methane)	-	Corona, arcing, and overheated oil
C_2H_6 (ethane)	-	Corona, overheated oil
C_2H_4 (ethylene)	Overheated oil	Corona, arcing
C_2H_2 (acetylene)	Arcing	Severely overheated oil
CO (carbon monox-ide)	Overheated cellulose	Arcing if the fault involves cellulose
CO_2 (carbon dioxide)	-	Overheated cellulose, arcing if the fault in-volves cellulose
O_2 (oxygen)	-	Indicator of system leaks, over-pressurization, or changes in pressure or temperature.
N_2 (nitrogen)	-	Indicator of system leaks, over-pressurization, or changes in pressure or temperature.

Dissolved gas can be analyzed with different methods. One is to find out the amount of hydrocarbon gases and other is comparing values of solution gases to each other.

An example of continuous on-line monitoring system of combustible gases is Hydran M2. It is a on-line monitoring system that measures the level of combustible gases and moisture in oil. Hydran M2 sensor is equipped with a gas detector that is sensitive to the four gases, hydrogen (H_2), carbon monoxide (CO), Ethylene (C_2H_4) and acetylene (C_2H_2) that are primary indicators of incipient faults in oil-filled transformer. Moisture is measured by a thin-film capacitive sensor. M2 has four type of optional I/O (Input/Ouptut) interface: 4 pcs 4-20 mA analog inputs, 0-1 mA analog output, 4-20 mA analog output and TDM (time division multiplexing) signal. Analog inputs can be used for monitoring various parameters. Outputs can be connected to SCADA (Supervisory Control and Data Acquisition) system for monitoring. The Hydran M2 can be used as a stand-alone unit or in a network with up to 32 hydran M2 through an isolated RS-485 link.

Inside the gas detector, the gases combine with oxygen to produce an electrical signal that is measured and converted to ppm. History capacity of measured parameters is

4760 and recording interval can be defined from one recording per day (13 years) up to logging rate of one recording per minute (79 Hours).

GE Energy provides a multi-gas on-line monitoring system called Kelman transfix. With the device is possible to monitor all significant fault gases using photo-aoustic detection technology. Those gases are hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide, carbon dioxide and oxygen. The device can also measure the moisture in oil and nitrogen. Sampling rate can be adjusted from one sample per hour to one sample for every fourth week. (Kelman Transfix Brochure)

It is possibility to connect analogical sensors to the transfix. There are five channels where the selected additional analogy input cards must be installed for using additional sensors. Options for analogical input card are 4-20 mA, additional load sensor and PT100. For special applications there are three optional outputs. Options for outputs are analogy or digital, communication protocol and connection. The supported communication protocols are MODBUS, MODBUS/TCP, DNP3.0 and IEC61850. Options for connections are RS232, RS485, Ethernet, PSTN (The public switched telephone network) modem and GSM (Global System for Mobile Communications) or CDMA (Code Division Multiple Access) wireless modems. Transfix have also channel for local USB (Universal Serial Bus) connection. (Kelman Transfix Brochure)

3.2.2. Partial discharge detection

Partial discharge detection is one of the effective methods of diagnosing fault that may have accumulated for a long time in electrical system. It happens when insulator is going to decompose until partial discharge. With the past techniques it took long time to identify the partial discharge, but nowadays a lot of ways are available to do this work in a shorter time. (Abniki 2010)

The insulation material deteriorates every time when partial discharge occurs. During partial discharge high-energy electrons causes a chemical reaction in insulation emitting ultra-high frequency. Most incipient dielectric failures will generate a lot of discharges before the catastrophic electric failure. Partial discharges may appear just before the catastrophic failure or in many years before any type of failure. A High occurrence of partial discharge indicates upcoming failure. (Norick 2004)

The techniques for detecting a partial discharge are ultra-high frequency detection, acoustic wave detector and fiber optic sensor. During the failure, partial discharges produces ultra-high frequency waves from 300-1500 MHz that can be detected by ultra-high frequency sensors. Acoustic wave sensors detect partial discharge by acoustic pressure waves that are emitted in partial discharge and transmitted through the transformer oil. Advantage of using these sensors is the ability to spot the location of the discharges. By placing several sensors around the transformer tank it is possible to calculate the exact partial discharge location. Disadvantage of these sensors are that they are greatly affected by the electromagnetic interference in the substation environment. In order to make the measurements effective, signal to noise ratio may be improved by signal processing techniques. Fiber optic sensor uses a laser diode and fiber optic coupler to detect partial discharge. Air gap changes inside the fiber optic coupler when partial discharge occurs. (Norick 2004)

The surrounding electromagnetic environment affects to measuring sensors adding noise to signal. Efforts for suppressing noise are to develop better sensors or to develop signal processing techniques and neural networks to eliminate noises from PD (partial discharge) data. Electrical noises can be divided into continuous periodic noises and pulse-shaped noises (Han 2003)

Qualitrol provides a partial discharge monitoring device for large (power and distribution) transformers called DMS PDMT. Product brochure states that partial discharge signals are detected by UHF couplers and carried to the master control unit where intelligent filtering is applied to reject interference. The amplitude and frequency is then digitalized, analysed and processed to produce the appropriate SCADA alarms and PD data outputs that are accessible through the local LAN (local area network) or via modem. A web-based viewer is also available.

Signals are continuously captured in sets of one second and temporarily saved. Every 15 minutes all stored sets are analyzed by an automated classification system based on a range of analytical and statistical techniques, such as multiple neural networks, genetic algorithms and fuzzy logic. Device determines the condition of the transformer insulation. It alarms when the occurrence of partial discharge increases to critical rate.

The Master Control Unit (MCU) allows for up to 6 UHF sensors. Optional Slave Control Units (SCU's) allows extension for multiple transformer applications. With the SCU's, additional inputs can be added up to 250 sensors max. Remote software allows to observe all monitored units if the PDMT network expands over time and the management stays simple.

3.2.3. Thermal analysis

Generally the power ratings of electrical devices are determined by the maximum permissible temperature that the isolation can withstand (Penman 2008). Transformer life expectancy is related to the daily loading cycle that determines the thermal deterioration speed of isolation. (Tang 2011). According to Han (2003), overloading or local overheating causes always a hot-spot temperature. The monitoring of temperatures has an important note on transformer condition monitoring.

Monitoring of thermal sensors is one of the simplest ways of transformer condition monitoring. Thermal changes usually show if there occurs a fault in transformer. It is obvious that if a transformer heats up, insulation of windings will suffer and dielectric constant of oil will be reduced. (Abniki 2010)

There are three basic approaches to temperature monitoring. One is to measure local temperatures in the transformer using embedded temperature sensors. Other is to use thermal image to monitor the temperature of the surface of transformer. Third is to measure distributed temperature from the transformer body or bulk temperature of cooling fluid. (Penman 2008)

The local temperature is measured at a certain spot in the transformer. This can be done using thermocouples, resistance temperature detectors or embedded temperature detectors. The problem is that the measured temperatures are local so the place of a temperature sensor must be carefully considered. The problem in local temperature measuring from windings is the insulation of the sensor from windings. Using fiber optic temperature sensors seems the only way to get hot-spot temperature directly, but it is expensive. (Han 2003)

Another touch for thermal monitoring is thermograph method. As described in Chapter 3.1.8 this method can be used as an off-line and on-line method. Surface temperatures are measured from thermal images taken by infrared camera. Camera records infrared thermal field and temperature distribution on surface. Thermovision is a non-contact method that is useful for detecting faults in industrial system during operation, without interrupting the technological process. (Gockenbach 2010)

The commonly used method is to calculate hot-spot temperature through thermal model with measurements of oil temperatures and of load current. The hot-spot temperature can be calculated from the sum of ambient temperature, the mixed top-oil temperature rise above ambient and the hot-spot rise above the mixed top-oil temperature. (Han 2003, Tang 2011)

3.2.4. Vibration analysis

A transformer vibrates constantly in operation cause of alternating magnetic field that causes alternating forces between the primary and secondary windings. This is natural vibration of transformer. This vibration cannot be eliminated and does not indicate a problem under normal operational conditions. The level of vibration can increase in the windings or in the core may be caused of different reasons: (Booth 1998)

- Loose core clamping bolts or bolts bonding the core structure.
- Repeated switching of the transformer into circuits on no-load, particularly for transformers located close to a generating source.

- Heavy external short circuit faults subjects the transformer to short-term high mechanical stress that causes internal unbalanced in electromagnetic conditions.
- Rapidly fluctuating loads causes high levels of mechanical stress.

Vibration can be measured by accelerometer or velocity meter. There is a variety of motion sensors that can be used in measuring these parameters. The parameters are mathematically related, the acceleration is a derivative of the velocity. SKF provides different condition monitoring sensors for vibration measurement.

3.2.5. Moisture monitoring

Water in oil indicates the aging of cellulose insulation in power transformer. Water and oxygen in the mineral oil increases the insulation degrading. Water in oil is also a sign of deteriorating of the mineral oil and thence the dielectric constant of oil decreases that can lead to a flashover in the transformer. (Abniki 2010)

Vaisala Humicap produces different sensors for on-line condition monitoring. For moisture monitoring of the transformer oil they have MMT318. In addition to measure moisture in transformer oil the MMT318 can also be used for measuring moisture in all liquid hydrocarbons like lubrication or hydraulic oil. The device measures continuously the moisture in oil in terms of water activity and temperature. For transformer condition monitoring they have optional calculation that calculates the average mass concentration of water in mineral oil (ppm). Temperature measurement rate -70…+180 °C and water activity rate 0…1 AW. Two selectable and scalable analogy outputs: 0-20 mA and 4-20 mA. (Vaisala)

3.2.6. Sound monitoring

Sound monitoring is new method for monitoring transformer condition on-line. The new technique is still on beginning of development stage. Erkki Antila explained in guidance of the thesis about the sound monitoring technique. In the interview of Virtanen from ABB (Asea Brown Bover) revealed that there is interest on the device in the market.

In normal operation transformer produces specific sound that is generated in transformer windings. Alternating magnetic fields causes forces between windings and core that is resulting in vibration and noise. If fault current goes through transformer the forces inside the transformer changes and it changes the sound transformer at that moment. That fault-time sound is possible to be analysed and the condition of transformer can be defined.

For recording the transformer sound, audio sensors like microphones will be needed. The recording could be continuous time or just when the fault current passes through the transformer.

3.2.7. Complete systems

The goal of condition monitoring system is to prevent catastrophic failures and eliminate unnecessary maintenance. A complete condition monitoring system could be a device that collects data from a certain number of sensors. The sensors could be giving measuring signal in analogical as well as in digital type. Device could process the measured data to suitable form for analysing the measured data. The analysis algorithm could give a warning of impending failure.

ABB has a good example of complete condition monitoring system, TEC. The device is available for new transformers. According to device manual, the TEC operates as a control device; it monitors the measured data, and diagnoses problems. The different sensors are connected to the input boards of TEC unit. The TEC collects and process the data. To processing data, the device uses detailed mathematical algorithms including transformer fingerprint data from heat run test. The condition data can be transferred to the substation control system and/or viewed via a graphic web interface on PC.

TEC units input and output parameters:

- 8 insulated analog 4-20 mA inputs via terminals.
- 4 insulated Pt100 direct inputs.
- 12 insulated digital input via terminals.
- 1 input for the voltage measurement.
- 1 input for the tap-changer position.
- CAN bus possibility.
- PPS/PPM synchronization pulses.
- 5 output relays (ms), 3 used for warning alarm and trip signals.
- Up to 12 relays (s)
- Up to 6 relays for cooler control.

The system measures or estimates the following parameters:

- Transformer status
- Winding hot-spot temperature calculation
- Moisture content and bubbling temperature
- Cooling control
- Thermal ageing
- Overload capacity
- Short overload capacity
- Hot-spot forecast
- Tap-changer contact wear
- Hydrogen
- Moisture in transformer and tap-changer
- Transformer temperature balance
- Tap-changer temperature balance

4. CONDITION MONITORING DATA

Condition monitoring has been developed extensively in recent years. Different research institutions and device manufacturers have their own direction for condition monitoring for large power transformers. Most of such companies are dedicated to developing accurate transformer models and reliable transformer fault diagnosis systems. (Tang 2011)

In conformity to Han (2003) a condition monitoring system should be able to monitor the running machines with the existence of electrical interference, predict the need for maintenance before serious deterioration or breakdown occurs, identify and locate the defects in detail, and even estimate the life of machines. Four main parts should be contained in a condition monitoring system to practice these functions. Those are listed below Han (2003):

- Sensor is a converter that measures a physical quantity into an electrical signal that can be monitored. The monitored signals may reveal incipient faults long before failure occur. The used condition monitoring method determines the sensor type.
- A Data acquisition unit will be used for processing of the output signals from sensors and converting it from analogue to digital format. The processing may consist of filtering and amplifying techniques.
- Data analysis is used for identify upcoming failures. So that the alarm can be given and further actions can be executed. There are two different way for analysing the signals. On is knowledge-based and the other is analytic model-based approach to fault detection. Knowledge-based model is based on fault detection by comparing the measurements to specified limits. By using Analytic model-based way, fault is detected by comparing the measurements with predictions of mathematical models of transformer.
- The detected abnormal signals need to be post-processed to be sure about the fault and get a detailed fault description for maintenance. This can be done by

computer or experts. The fault description could include name and location of defect and status of transformer.

Norick (2004) presents a prototype of the decentralized and distributed condition monitoring system described in Figure 6. This design divides the condition monitoring system in different zones to be analyzed separately and then interconnected. System consists of five zones consisting of sensors, data acquisition system, and a computer, which stores the data that is sent to a host computer for data analysis.

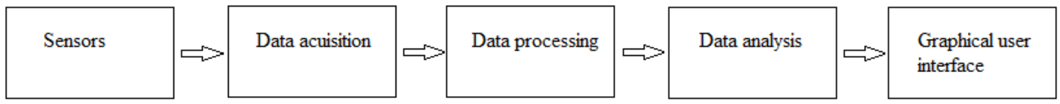

Figure 6. Decentralised system. (Norick 2004)

4.1. Data types

For condition monitoring, there needs to be a device to convert the physical phenomena of the machine to data that can be analysed. The system starts with getting signals from different sensors. For different phenomena there is a huge variety of sensors for giving information on the health of the transformer. In Table 4 examples of different sensors and output data is presented. Different condition monitoring methods were described in Chapter 3. These are dissolved gas analysis, partial discharge, thermal analysis, vibration analysis and moisture monitoring. (Norick 2004)

Table 4. Different sensors and output data.

	Output data
Dissolved gas analysis	
Combustible	
Spectroscope	Digital
Partial discharge	
UHF sensor	
Acoustic wave sensor	
Fiber optic sensor	Digital
Thermal analysis	
PT100	Resistance
Thermal camera	Digital
Fiber	Digital
Vibration	
SKF Acceleration sensor	Voltage
Moisture	
Vaisala Humicap MMT318	Current

When a physical quantity is transformed in electrical signal, it is always in analogical form. The output data depends on the type of sensor and the used technique. The analogical data are processed into digital form in some advanced sensors.

Some sensors are extremely affected by electromagnetic interference in the substation environment. With signal processing techniques the efficiency of measuring results can be improved. When transferring the data in digital format it is possible to reduce the disturbance by using certain protocol. (Penman 2008)

The cables used for data transfer should be of high quality to achieve good signal in substation environment. If many channels coexist in the same transmission canal the cables need to be shielded to avoid common impedance coupling between channels. The power cables could be separated from signal cables and the signal cables should be electromagnetic compatibility (EMC) isolated. EMC isolation is obtained by crossing the conductors inside cable in right angles. In most cases twin-screened twisted pairs should be used for data transfer in low frequency field <500 Hz to avoid induction. In high frequency fields >100 kHz screened coaxial cables are more suitable. When high resistance to noise is essential optical cables are frequently used alternative. (Penman 2008)

4.2. Data acquisition

The sensor data needs to be collected and changed suitable for data analysis. Data acquisition unit is the device of condition monitoring system that collects data from different sensors and sends the measurement data to an embedded processing unit. For example the functions of data acquisition system can be to receiving data, processing, storing, and transmitting the data. Sampling rate and number of samples to be received from each sensor must be chosen carefully. The data needs to be converted in digital form so that it can be analysed in computer. In Figure 7 it is presented a block diagram of data acquisition module. (Norick 2004)

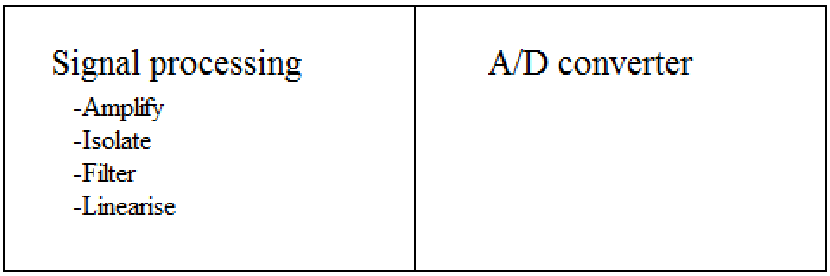

Figure 7. Data acquisition.

Data acquisition module could consist of signal processing, multiplexing, anti-alias filtering, sample taking, and A/D (Analogy/digital) converter. Sensor data must be processed suitable for multiplexing and for further processing. Signal levels should be adjusted within certain values, for example voltage levels 0 V and 10 V. If the sensor operates linearly the adjusting can be done by amplifying the signal. Amplifying can increase or decrease the signal level. If the sensor operates logarithmically, the signal must be linearized. In Figure 8 is electrical circuit drawing of a type of instrument amplifier. With this amplifier there is no need to match the sensor impedance to the measuring unit. Sensor is connected to U1 and U2 and the output is V_{out}. (Penman 2008)

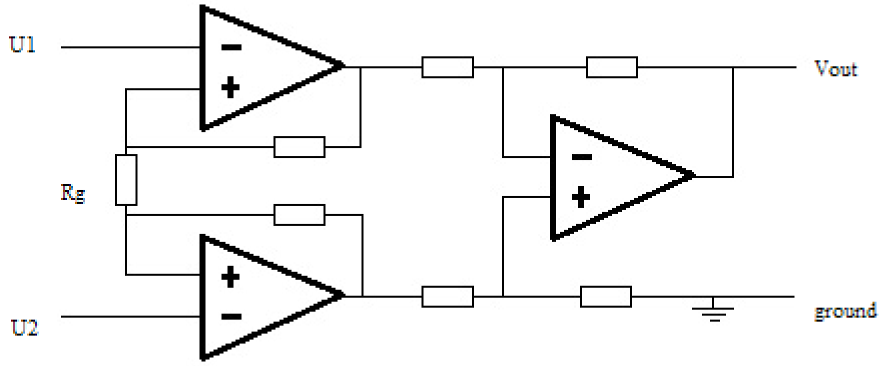

Figure 8. Instrument amplifier. A type of differential amplifier.

Raw data may include noise or disturbance that can be filtered of. Low-pass filter, high-pass filter or band-pass filter can be used to improve the signal by removing unwanted frequencies from the condition monitoring data signal. Low-pass filter eliminates high frequencies from the signal and high-pass filter removes low frequencies from the signal. Band-pass filter consists of low-pass filter and high-pass filter and it removes high and low frequencies from the signal. An analogue to digital converter transforms the analogical voltage signal into a digital numbers. The A/D converter consists of sample taking and quantizing. (Penman 2008)

4.3. Data analysis

This is the most important part of condition monitoring system. This part of system processes all the data that is transmitted by the data acquisition module into useful diagnostic information that can be used to detect failures and make assessments regarding the health of the transformer. (Norick 2004)

4.3.1. Fault diagnosis methods

There are many different methods for fault diagnosis. These methods can be classified in two categories described in Figure 9. One is knowledge-based and the other is analytic model-based approach to fault detection. Knowledge-based system bases on determined rules and decisions are made based on the rules. Rules for sensor outputs can be determined manually by human knowledge or automatically by using artificial intelligence. Experts who have worked with transformers makes the decisions of transformer condition based on different sensor values. (Norick 2004)

Analytic model-based system bases on mathematical expressions of the system. System can be modelled by using linear or nonlinear system theory. The mathematical system consists of different models that may be electrical, mechanical or thermal dynamics. Fault detection with analytical model can be executed by comparing the actual behaving of the system to estimated values. Fault detection can also be made by an expert system based on heuristic rules but the final fault decision will be made by human operator. (Norick 2004)

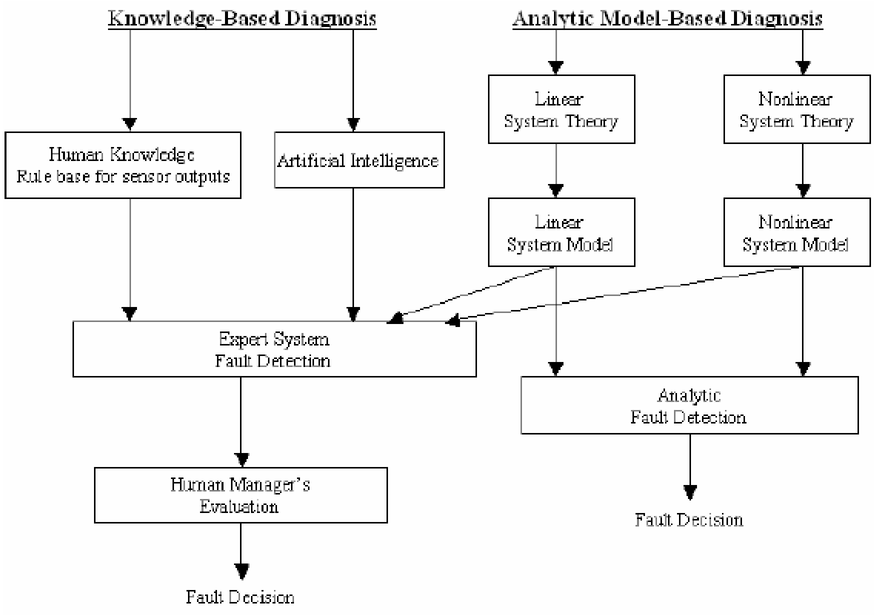

Figure 9. Different approaches to fault diagnosis

4.3.2. Human knowledge based diagnosis

The experts who have worked with transformers can best identify the condition of transformer. Human knowledge fault diagnosis is based on defined limits on monitored parameters. It is possible to use artificial intelligence to define the limits automatically. Decisions of transformer condition are made by human experts. (Norick 2004)

Expert systems have been developed for condition monitoring. The process consists of computer hardware and software that is used to compare certain parameters to defined limits. The system works better when the fault diagnosis is not based on a single measurement value. This has been taken into account by creating an IF/THEN model. In this case it possible to ascertain whether there is a transformer failure developing or is it just a sensor failuring. Below it is Noricks example of expert systems IF/THEN condition monitoring process. (Norick 2004)

```
IF (Temperature Above Reference) > 20 °C
THEN
       IF (Fan Bank Current) > 0,5 A
       THEN
             IF (Ethylene Concentration) > 100 ppm
             THEN
                  IF (Moisture Concentration) > 15 ppm
                  THEN
                         Transformer Overheating, Take Off-line
                         to Service
                  ELSE
                         Check DGA and Moisture Analyser for
                         Proper Functioning
             ELSE
                   Check Thermocouple Sensor
       ELSE
             Fan Bank not Operating Properly, Have Serviced
ELSE
       Transformers Operating Normally
```

4.3.3. Analytic model based diagnosis

Analytic models try to represent the system through mathematical equations. Nonlinear and linear models have been developed to build those mathematical models for analytic fault diagnosis. For modelling a transformer system, nonlinear models are needed in order to describe all the complexities of the system. (Norick 2004)

The model-based condition monitoring works in such way that the actual measurements are compared with predictions based on operating conditions and ambient temperatures for estimating the actual condition of transformer. (Norick 2004)

Measurements are compared with calculated model and actual system. The measured parameters may constantly change over time naturally. Those parameters cannot be directly compared but this can be done by taking the evolution of transformer into account. The difference between the system outputs and model outputs are calculated and residuals are used to control adaptive filtering as shown in Figure 10. The adaptive filtering parameters are used for recalculating the model parameters in order to obtain a model which is developing at the same rate with the transformer. (Norick 2004)

Rapid changes of model parameters indicate a developing fault. Slow changes in parameters may reveal a slow developing fault but it can be normal aging. The transformer life expectancy may be calculated of the change speed of parameters in normal operating conditions. (Norick 2004)

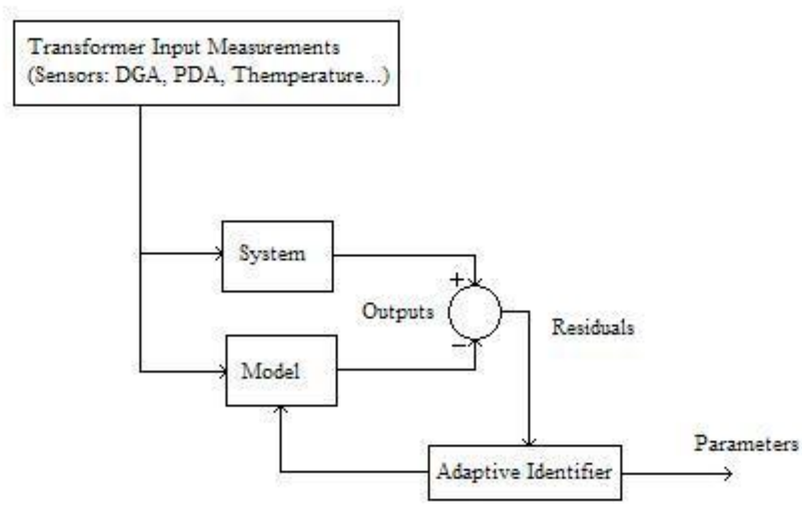

Figure 10. A schematic for analytic model based monitoring. (Norick 2004)

The transformer system is very complex for modelling cause it contains thermal, mechanical, electrical and fluid system. The mathematical models have been modelled using linear or nonlinear mathematical equations. The non-linear models have been proved more accurate in transformer modelling. (Norick 2004)

Most of estimation models are based to temperature calculations but there are also other models based on mechanical, fluid and chemical calculations. Examples of different models are described in Table 5.

Table 5. Modelling possibilities.

System	Modelling possibilities
Thermal	• Top oil temperature rise over ambient • Top oil temperature measurements coordinated to dis-solved gas content. • Hottest-spot conductor over top-oil temperature. • Hottest-spot winding temperature given at specific load. • Oil, tank and ambient temperatures combined with winding voltage and currents.
Mechanical • Mechanical stresses due to forces on the transformer windings.	• Short circuit currents • Transfer function between input and output voltage and current.
Fluid	• Transformer oil and its gas content.
Chemical	• Degree of polymerization and tensile strength of the in-sulation.

Neuro-fuzzy fault detection engine is analytical model that can be used to describe dynamics of the transformer system. In order to make accurate failure diagnoses, the entire transformer must be modelled. Artificial intelligence with accurate modelling of transformer makes possible to detect developing faults. The combination of neural networks and fuzzy logic is common in transformer condition monitoring systems. (Norick 2004)

4.4. Data storage

When a transformer is manufactured there is need to do certain tests to make “finger print” of the transformer. Some condition monitoring methods uses the fingerprint to comparing the measurement value for defining the condition of transformer.

When the transformer is transferred from factory to field the impact forces are measured during the transfer. These measurements can be utilized when the transformer is put into service. (Virtanen 2012)

The measurement data could be storage for further research. Measurements can be taken in short period of time but the data could be storaged in longer intervals. It’s also possible to store the condition monitoring data in two files, other is for short term and the other is for long term. There is a lot of information to storage and it has to be considered how long history is needed. Because transformers are individually devices, the condition monitoring data, fingerprints and other information should be storaged individually.

4.5. Sustainable power grid and condition monitoring

Antila (2009) have designed a data management model for electric power distribution that is taking sustainability into account. Environmental sustainability is focused on reducing carbon emission and utilization of renewable and distributed energy resources. Sustainability in the electric power distribution covers the whole grid on each relevant aspect of the area. (Antila 2009)

The efficient and well-controlled energy chain provides the basis for the sustainable energy services. Energy production, transmission and distribution process are the traditional aspects for evaluating the functionality of energy chain. For a sustainable use of energy there are also aspects in addition to these, such as the fuel and its transmission logistics, energy losses and controlled energy consumption. (Antila 2009)

Deregulated markets: Infrastructure of electric power distribution is split into four dedicated zones: Generation, Transmission, Distribution and sales. Consumers can freely choose supplier. Natural monopoly acts in distribution. Natural and regulated monopolies act in energy transmission. There are open markets in power generation that are limited by emissions. (Antila 2009)

In order for sustainable power grid effective communications network is needed between the various network managements as well as between different levels of power grid. Multi-services is required from equipment and subsystems for all applications. Different managements in sustainable power grid: Safety & protection management, operation management, asset management and business management. The model is described in Figure 11. (Antila 2009)

Transformer condition monitoring will be a part of sustainable electric power distribution. Transformers are included in power process in the model. Condition monitoring data would be needed within all management level.

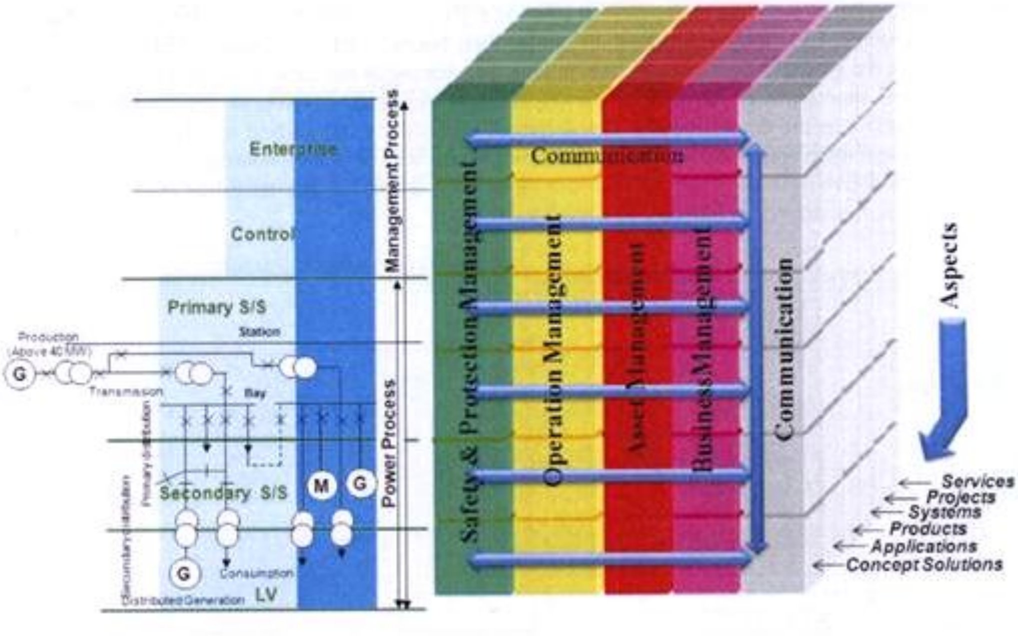

Figure 11. The three dimensional model for data access (Antila 2007)

When a transformer fails it is necessary to make a decision how to treat the fault. In some cases the corrective task is oil change but in worst case the whole transformer must be replaced. During the transformer failure it may be required to break the transformer from the grid. In such situations the information must flow to right places in different managements of sustainable power grid model. For further research there is a need to find out what information is needed in different management functions.

5. SUMMARY

With transformer condition monitoring systems it is possible to achieve more sustainable power grid. Condition monitoring system makes possible to prepare for evolving transformer failures beforehand and to make possible actions. The possibility of transformer failure increases with the aging process. It is important to monitor these transformers to ensure energy supply. Transformer condition monitoring will be demanded in future.

For condition monitoring of transformer it has been developed different techniques that are used to monitoring of certain parameters of the transformer. These parameters can be used for estimating the condition of the transformer. The condition monitoring methods can be divided in two groups according to the operation: off-line and on-line condition monitoring. The traditional off-line condition monitoring is still used a lot of. Specific test are made occasionally and the measuring results are analysed by an expert. The analysis can be done on site or in laboratory. Rapidly developing faults may be missed with off-line condition monitoring techniques. On-line methods can be used for condition monitoring to achieve more sustainable power grid. With on-line condition monitoring it is possible to be prepared for evolving failure and to make further actions at an early stage. When a possible evolving failure is detected there is need to make a decision for further action. The decision is made by human experts.

In sustainable power grid it is important to direct the maintenance resources effectively. With on-line condition monitoring the need of maintenance can be reduced from transformer off-line measurements and the main focus could be direct to maintaining and repairing transformers.

LÄHDELUETTELO

ABB Group (2004). Transformer Handbook. Geneva. 212 pages.

Abniki Hassan, H. Afsharirad, A. Mohseni, F. Khoshkhati, H. Monsef, & Sahmsi Pourya (2010). Effective On-line Parameters for Transformer Monitoring and Protection. North American Power Symposium (NAPS), 2010. IEEE. Teheran

Antila Erkki & Göran Wiklund (2007). Benefits of applying totally value-based segmentation of applications needed. Dubai: GCC CIGRE – P.O. Box 698 – Doha, Quatar, November, 2007. pp. 267-279.

Antila Erkki & Göran Wiklund (2009). Redefining sustainability in the electric power distribution context.

Booth C, McDonald J.R (1998). The use of artificial neural networks for condition monitoring of electrical power transformers. sciencedirect. Neurocumputing 23:1-3.

Gockenbach Ernst & Xiang Zhang (2008). Asset-Management of Transformers Based on Condition Monitoring and Standard Diagnosis. IEEE Electrical insulation magazine 24:4, 26-40.

Han Y. & Y. H. Song (2003). Condition Monitoring Techniques for Electrical Equipment—A Literature Survey. IEEE Transactions on Power Delivery 18:1, 4-13.

Hietalahti, Lauri (2011). Muuntajat ja sähkökoneet. Vantaa. ISBN 978-952-5491-72-2

Hydran M2 manual available: http://www.ekosinerji.com/pdf/Hydran_Manual_en.pdf

Imad Ullah Khan, Zhongdong Wang, Ian Cotton & S. Northcote (2007). Dissolved Gas Analysis of Alternative Fluids for Power Transformers. IEEE Electrical Insulation Magazine 23:5, 5-14.

Kelman Transfix Brochure. [Cited 2012-02.01] Available from Internet: <URL:http://www.gedigitalenergy.com/products/brochures/MD/TRANSFIX.pdf>

Lu Jiming, Chengxiong Mao, Dan Wang (2009). Operation and Control Mode of Electronic Power Transformer. *Conference on Sustainable Alternative Energy, 2009 PES/I.* Spain,Valencia. ISBN: 978-1-4244-4431-1

Mörsky, Jorma & Janne Mörsky (1994). Voimalaitosten yhteiskäytön tekniikka. Otatieto ISBN9516721842, 9789516721845

Nirgude, P.M., B. Gunasekaran, Channakeshava, A.D Rajkumar, B.P. Singh (2004). Frequency response analysis approach for condition monitoring of transformer. *Conference on Electrical Insulation and Dielectric Phenomena, 2004. CEIDP '04. 2004 Annual Report.* India, Hyderabad. ISBN: 0-7803-8584-5

Norick Tim, Rahmat Shoureshi & Ryan Swartzendruber (2004). Intelligent Transformer Monitoring System Utilizing Neuro-Fuzzy Technique Approach. Colorado. Available from Internet: <URL:http://www.pserc.wisc.edu/documents/publications/reports/2004_reports/shoureshi_intelligent_substation_report.pdf>

Omicron (2010). TanDelta/Power Factor Testing – Background. [Cited 2012-01-25]. Available from Internet: <URL:http://www.youtube.com/watch?v=D6eXTDPwLzo>

Omicron (2011). FRAnalyzer: Powerful & easy to use software. [Cited 2012-01-25] Available from Internet: <URL:http://www.youtube.com/watch?v=KS0t3-VmwpA>

Penman Jim, Li Ran, Howard Sedding & Peter Tavner (2008). Condition Monitoring of Rotating Electrical Machines. The Institution of Engineering and Technology. London. ISBN 978-0-86341-739-9.

Siemens (2012). [Cited 2012-01.10] Available from Internet: <URL:http://www.energy.siemens.com/hq/en/power-transmission/transformers/>

Tang W.H., Hu Wen (2011). Condition monitoring and assessment of power transformers using computational intelligence. London. ISBN 978-0857290519.

Vaisala Humicap MMT318 brochure. [Cited 2012-01.24] Available from Internet: <URL:http://www.hoskin.qc.ca/uploadpdf/Instrumentation/Vaisala/hoskin_MMT31840bf6dd7b2dfd.pdf>

Virtanen, Esa. ABB Muuntajat Oy. Vaasa. Interview. 13.2.2012.

Winders, John J. (2002). Power Transformers Principles and Applications. Pennsylvania, Allentown. ISBN: 0-8247-0766-4