CASE STUDY ON CONDITIONAL MONITORING OF 25MVA POWER TRANSFORMER

Project Stage-II
Report submitted
in
partial fulfillment of requirement
***for the award of* degree of**

Bachelor of Engineering
in
Electrical Engineering

Submitted by

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SHAIKH AASIF AKBAR	**17DEE63**
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Under The
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Department of Electrical Engineering
Anjuman-I-Islam's Kalsekar Technical Campus, Panvel
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CERTIFICATE

This is to certify that the dissertation titled **“CASE STUDY ON CONDITIONAL MONITORING OF 25MVA POWER TRANSFORMER”**, **w**hich is being submitted herewith for the award of the, **‘Bachelor of Engineering’** in **Electrical Engineering** of Anjuman-I-Islam's Kalsekar Technical Campus, New Panvel (M.S, India). This is the result of the original research work and contribution by **‘Mr. PATHAN ARBAZ, Mr. SHAIKH AASIF, Mr. SHAIKH HAMZA, Mr. SHAIKH SOHEL’** under my supervision and guidance. The work embodied in this dissertation has not formed earlier for the basis of award of any degree or compatible certificate or similar title of this for any other diploma/examining body or university to the best of knowledge and belief.

Place: panvel

Date: / /2020

Prof. Yakub Khan
Guide

Prof. Kaleem Syed
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Dr. Abdul Razzak Honnutagi
Director

Acknowledgement

It is indeed a matter of great pleasure and proud privilege to be able to present this project on **CASE STUDY ON CONDITIONAL MONITORING OF 25MVA POWER TRANSFORMER** The completion of the project work which is partial fulfillment of Degree academic works is a milestone in student's life and its execution is inevitable in the hands of guide. I am highly indebted to the project guide Prof. Yakub Khan for their invaluable guidance and appreciation for giving form and substance to this report. It is due to their enduring efforts, patience and enthusiasm which has given a sense of direction and purposefulness to this seminar report and ultimately made it success.

I would also like to express my deep regards and gratitude to my director, Dr. Abdul Razzak Honnutagi and Head of the Electrical Engineering Department, HOD Prof. Sayed Kaleem for moral support and considerate attitude towards my short comings if any.

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ABSTRACT

Our Power transformer is one of the most critical components for electrical network in power plants. This means that dependability has a big role. At the moment end users allocate resources to power transformer maintenance. Resources for on-line condition monitoring on the other hand are not very significant. Reason for this is that transformers are reliable and long life components. However, failure costs might be very significant and online monitoring is justified from that point of view.This Project focuses on power transformer online condition monitoring. The goal is to find cost-effective and integrated solution which provides good-enough transformer monitoring. The subject has been studied quite a lot which tells about increasing interest towards the subject and might indicate possible markets for transformer monitoring services.

In the beginning research will focus on describing maintenance and condition monitoring related terms. Also goals are defined for different stakeholders applying the Delphi method. The middle part of the work focus on power transformer structure, fault statistics, condition monitoring methods and measurement devices. Also possibilities of condition monitoring are covered.Research results are divided into two different categories. First part of the results will be related to requirements defined for power transformer condition monitoring. Results include requirements for three different ranges of transformer monitoring. Second part of the results contains a specification for pilot project to test power transformer condition monitoring methods and devices

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBERIVATION

ABB	Alsea Brown Boweri	IEC	International Electro technical Commission
CBM	Condition based maintenance	IED	Intelligent electronic device
CIGRE	International Council on Large Electric Systems	IMIA	International Association of Engineering Insurers
DGA	Dissolver Gas Analysis	LV	Low voltage
EMI	Electromagnetic interference	NCC	On load tap changer
EN	European Norm	OLTC	On load tap changer
EPRI	Electric Power Research Institute	ONAF	Oil Natural and Air Forced
HMI	Human machine interface	OPC	Open connectivity via open standards
HV	High voltage	OSA-CBM	Open Systems Architecture for Condition-Based Maintenance
HVDC	High-voltage direct current	OSA-EAI	Open System Architecture for Enterprise Application Integration
IEEE	Institute of Electrical and Electronics Engineers	PD	Partial discharge
GSU	Generator step-up	PLC	Programmable logic controller
RAM	Requirement Abstraction Model	RCM	Reliability Centered Maintenance

1. INTRODUCTION

1.1 Introduction:

Power transformers provide a vital link between generation and distribution of energy produced. These static equipments are subjected to abuse during operation at generation and distribution stations and leads to catastrophic failures. The existing condition monitoring techniques at generating and distributing stations involve DGA (dissolved gas analysis) and electrical/Physicochemical analysis of transformer oil. Transformers are also tested for various electrical parameters of windings during maintenance shutdown.

Maintenance process and maintenance strategies are getting more focus as electric utility companies tries to keep their profitability in increasing competition by putting more focus on maintenance actions. One purpose of maintenance is to balance costs and risks in daily operation. For that purpose maintenance needs different tools for correct decision making. These tools can be expert analyses, collected information (maintenance activities, running hours) or condition monitoring which can be done both on-line and off-line. This thesis is focused on automated on-line monitoring methods.

Power transformer is one of the most critical electrical network components in power plants. At the moment end users allocate resources for power transformer maintenance and it is on an acceptable level. Resources for on-line condition monitoring on the other hand are not very significant, despite that subject has been studied quite a lot and even very complex monitoring systems are available.

1.2 Condition Monitoring:

Condition monitoring of transformers is the process of acquisition and processing of data related to various parameters of transformer so as to predict and prevent the failure of a transformer. This is done by observing the deviation of the transformer parameters from their expected values. Transformers are the most critical assets of electrical transmission and distribution system. Transformer failures could cause power outages, personal and environmental hazards and expensive rerouting or purchase of power from other suppliers. Transformer failures can occur due to various causes. Transformer in-service interruptions and failures usually result from dielectric breakdown, winding distortion caused by short-circuit withstand, winding and magnetic circuit hot spot, electrical disturbances, deterioration of insulation, lightning, inadequate maintenance, loose connections, overloading, failure of accessories such as OLTCs, bushings, etc. Integrating the 'individual cause' monitoring allows for monitoring the overall condition of transformer.

1.3 Power Transformer:

A power transformer is a static machine used for transforming power from one circuit to another without changing frequency. This is a very basic definition of transformer. Since, there is no rotating or moving part, so a transformer is a static device. Transformer operates on an ac supply. A transformer works on the principle of mutual induction. Power transformer windings are insulated with multiple layers of Kraft paper and immersed in mineral oil. This paper insulation is required to withstand both electrical and mechanical stresses. The paper and oil insulation degrades over time at a rate depending on the moisture level, oxygen present and the operating temperature of the oil. The degradation of original properties and the production of by-products are elated in the deterioration process. The quantity of by-product derivatives and the degree of changes in properties are used to gauge the insulation condition in the power system

2. LITERATURE SURVEY

2.1 LITERATURE SURVEY:

In most power companies, for online monitoring of power transformers, use supervisory control and data acquisition (SCADA) system, but for online monitoring of power transformer, the extending the SCADA system is an expensive proposition. Power transformers are currently monitored manually, where a person visits a transformer site, for maintenance and taking records purpose. But main drawbacks of these systems are, it cannot provide information about overloads (Voltage & Current) and overheating of transformer oil & windings. Due to these , the transformer life is reduced. Abdul Rahman Al-ali et al. This paper presents design and implementation of a mobile embedded system to monitor and record key operation indictors of a distribution transformer like load currents, transformer oil and ambient temperature. The designed system is connected to a distribution transformer and is able to record and send abnormal operating parameters information to a mobile device using a GSM network Buyung Sofiarto Munir et al. In this paper several methods are evaluated to determine which method is better in provides consistent and reliable parameters to be used for transformation condition. Basically there are two evaluated methods are used with vibration signals taken sequentially. First used is fast Fourier transform (FFT) which is used to compute discrete Fourier transform. Second evaluated method is Hilbert Huang Transform (HHT) which is used for to separate vibration signal into a finite and a small number of intrinsic mode functions (IMF). Xiaohui Cheng et al. Here compares many combinations ways of internet of things and power, the oil based transformer monitoring system is analyzed, but it has high cost, loss data and feedback control of function. This system uses a single bus multi point temperature measurement method and GSM network remote control and data processing combined, so that speed of the temperature and its analysis becomes improved also accuracy of system is also improved, reducing the cost of temperature monitoring system and using the remote control module to avoid the failure of transformer. Drasko Furundzicet al. Neural networks are widespread technique for transformer health monitoring system. Neural networks ensembles are the most advanced neural technique, which improve the accuracy and reliability in the transformer health and failure prognosis. This paper describes the technique to identify causal relation of dissolved gases in transformer oil and current state of the transformers health Suraj Pardeshiet .It is solution for monitoring and automatic voltage regulation. It concluded that by developing modular and intelligent units results in cost effective solution for online monitoring of transformer card for processing various algorithms and taking control actions. This paper discuss about the combination of online monitoring and control. D S Sureshet have discussed about insulating oil in a transformer which can explain about the actual state of transformer and its longevity. This proposed work mainly forces on condition monitoring transformer oil by using PLC, SCADA with sensors for sensing parameters of oil like moisture , and temperature can be found. Also to monitoring of transformer is done using PLC system and wireless technology for sending the information through GSM Mallikarjun Sarsambaet have presented a monitoring of load and power lines using SMS based GSM technology. This methodology is design and implementation using embedded system to monitor and record load fluctuations with respect to current and voltage in power lines and it breaks the power lines during high loads. It provides flexible control of load accurately and also provides information about any abnormality in power lines using GSM networks. Monika Agarwal have discussed about and design and implementation of a mobile embedded system to monitor and record distribution transformer parameters like over voltage, over current, temp and fall of oil level. Use of a GSM technique provides speed of communication with distance independency and also it enables bidirectional communication as a message. To reduce the risk of unexpected failure and unscheduled outage. Satya Kumar Behera have discussed about a implementation of automatic control circuits which is used in PLC system to monitor the condition of transformer like load current, voltage, and transformer temperatures. This PLC monitoring system will help to detect the internal faults as well as external faults of transformer. The PLC system is used to monitor and control the voltage current and temperature of a distribution transformer. The PLC system is designed to monitor the transformer parameters continuously throughout its operation. Vishwanath R, have presented, this paper uses a temperature sensor, pic microcontroller ,LCD display GSM board and xbee which is used for send the message to electricity board. By using this system we can detect multiple faults of three phase transmission lines which one can monitor the temperature, voltage, current by GSM modem. In this paper a system is develop to monitor the transmission line faults using GSM network. Pathak A.K et al have discuss about an idea of online monitoring system integrates the GSM modem with a single chip microcontroller and sensors. It is implemented at the distribution transformer side. If any emergency situation can occurs the system sends the SMS to the mobile phones containing information about the abnormalities according to instructions which are programmed into microcontroller. Also this system to protect distribution transformers from overheating and overloading. . Mohamed Ahmed Eltayeb Ahmed Elmustafa Hayatiet al. have designed decision support system to grid operation engineers with information helps to estimate the loads , fix problems and identify week points in the grid. This paper suggested and implemented a method to remotely monitor a group of distribution transformers. This method was accomplished by design an interface circuits and software program. System is designed based on pic microcontroller which acts as a data acquisition and transmission system. Ravishankar Tularam Zanzad et al. This paper presents design and implementation of a system to monitor and record operations of a distribution transformer like over voltage, over current, temperature, rise or fall of oil level. This system is implemented at the distribution transformer site and measuring above parameters it will help to optimize transformers and identify problems before it failures. Kathe Mohan et al.[14] This paper discuss about to develop low cost solution for monitoring health conditions for remotely located transformer using GSM technology to prevent failures of transformer and improving reliability of transformer. We need not have to check all transformer and phase current and voltage and also recover system in less time. The time for receive MSG vary due to public GSM network traffic, still it is more effective than manual monitoring. Sachin Kumar B S et al.[15] have discuss about it proposes a compact design and development of remote monitoring system for a three phase transformer. Arduino microcontroller and zigbee based wireless device are used for monitoring the operating point of three phase transformer remotely. The arduino microcontroller helps in monitoring the three phase current, voltage, temperature, and power of the transformer. The processed parameters are displayed on LCD which makes the system user friendly. All sensors required to monitor three phase parameters by single microcontroller, which makes the system compact.

3. CONDITION MONITORING

3.1. Condition Monitoring Related Definition:

Terms are defined in many different standards. This also gives problems to decide which definitions to use as there are plenty of differences between different standards. This chapter will define the terms used in this thesis and will not concentrate on the problem of several different definitions of terms.

3.1.1 Dependability:

According to IEC 60300-1 dependability is a combining term used to describe the availability performance and its influencing factors. These factors are reliability performance, maintainability performance and maintenance support performance. Relations between different terms and influencing factors are shown in Figure1.

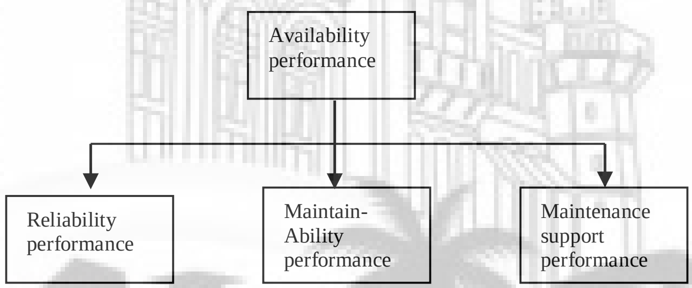


Figure 1. Dependability relationships (IEC 60300-1).

IEC 60300-1 also defines the dependability related factors. The definitions are following:

"Availability performance is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

Reliability performance is the ability of an item to perform a required function Maintainability performance is the ability of an item under given conditions of use, to be retained in, or restored to a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

Maintenance support performance is the ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy."

According to Järviö, Piispa, Parantainen condition monitoring is part of the maintainability performance. Maintainability performance is divided into maintainability, repairability and fault observation rate. Condition monitoring is included in fault observation rate.

3.1.2.Maintenance:

Maintenance is combination of all four terms defined in chapter 2.1. This means that condition monitoring is also a part of maintenance. SS-EN 13306 standard defines maintenance in the following way. "Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." SS-EN 13306 standard divides maintenance into preventive and corrective maintenance. Preventive maintenance is then divided into condition based and predetermined maintenance. Figure 2 shows the relationships between different terms.

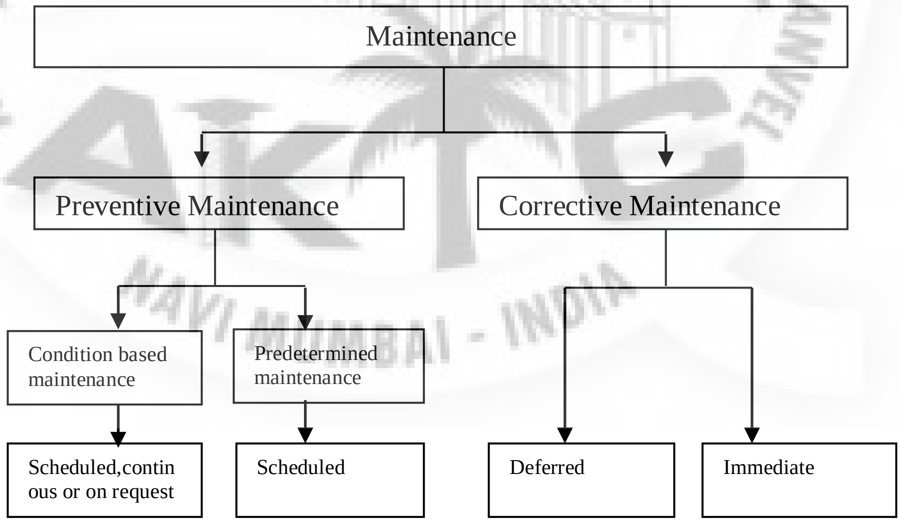


Figure 2. Overview of maintenance (SS-EN 13306).

Corrective maintenance is any maintenance activity which is required to fix a failure that has occurred or is in the process of occurring. This activity may consist of repair, restoration or replacement of components.

Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item. (SS-EN 13306.)

Pretermined maintenance is also known as time based maintenance. This is the most traditional way of handling maintenance. It means that running maintenance actions based on manufacturer's service guideline or valid a standard. This method can be slightly modified and this way it is possible to reduce maintenance costs. In practice this means stretching service intervals to longest possible and also only mandatory parts are serviced. (Lee Willis, Welch & Schreiber 2001: 373.) Time based maintenance is a traditional way of handling pretermined maintenance but it also has some problems. First of all labour costs are high as workload is big. Another problem is that faults between service actions are not noticed.

Condition based maintenance (CBM) is preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Performance and parameter monitoring may be scheduled, on request or continuous. (SS-EN 13306.)

Based on these definitions it can be clearly seen that we are focusing on condition based maintenance. As additional information predictive maintenance is also defined. This is carried out following a forecast derived from the analysis and evaluation of significant parameters of the degradation of the item (SS-EN 13306).

Reliability centered maintenance (RCM) is also shortly covered in here. Reliability Centered Maintenance analysis provides a structured framework for analyzing the functions and potential failures for a physical asset (such as an airplane, a manufacturing production line, etc.) with a focus on preserving system functions, rather than preserving equipment. RCM is used to develop scheduled maintenance plans that will provide an acceptable level of operability, with an acceptable level of risk, in an efficient and cost-effective manner.

Maintenance process must answer the following seven questions to be called a reliability centered maintenance process:

- What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
- In what ways can it fail to fulfill its functions (functional failures)?

- What causes each functional failure (failure modes)?
- What happens when each failure occurs (failure effects)?
- In what way does each failure matter (failure consequences)?
- What should be done to predict or prevent each failure (proactive tasks and task intervals)?
- What should be done if a suitable proactive task cannot be found (default actions)?

3.2 Condition Monitoring:

PSK 6201 standard defines condition monitoring in the following way. Condition monitoring determines the actual operating state of an item and assesses its development in order to determine the time of potential failure, service, or repair. Condition monitoring activities include inspections and monitoring performed either by sensing or by measuring devices, and analysis of measurement results. Condition monitoring provides initial data for planning preventive maintenance and repairs. (PSK 6201.) Condition monitoring activities include inspections and monitoring performed either by sensing or by measuring devices, and analysis of measurement results. Condition monitoring provides initial data for planning preventive maintenance and repairs. (PSK 6201.).

3.2.1. Off-line Condition Monitoring:

Off-line condition monitoring takes place during an outage, for maintenance or when an outage has occurred as the result of a transformer or network fault. Off-line monitoring can also include tests. Following parameters can be measured as an example:

- Winding resistances
- Magnetizing currents
- Impedance voltages
- Dielectric loss factor
- Insulation resistance, including core and yoke clamps to earth
- Inter-winding and winding to earth capacitance measurements

- Dielectric response, measurement of moisture in solid insulation (ABB 2004: 124.)

This thesis will not cover off-line condition monitoring methods as the goal is to achieve automated on-line condition monitoring system for power transformer.

3.2.2. On-line Condition Monitoring.

On-line condition monitoring takes place while machine is in operation. On-line monitoring can be divided into manual and automated condition monitoring. This study is especially focusing on automated condition monitoring solutions. On-line condition monitoring is not defined in standards but Electric Power Research Institute (EPRI) defines on-line condition monitoring as following: “Automated method of monitoring instrument performance and assessing instrument calibration while the plant is in operation and without disturbing the monitored channels.” (EPRI 2004: 2-1.)

Most of automatic monitoring methods are based on manual methods. Good example is dissolved gas analysis. It is traditional way of monitoring transformer oil and it is done manually usually once in a year. Last ten years have brought several devices which automatically take the oil samples and analyze the samples. This allows to take samples more often and to detect faults in much earlier phase. This method is described later in the thesis.

3.2.3 Condition Monitoring Based Goal.

It can be assumed that one of the primary goals for CBM and condition monitoring is cost saving. According these cost savings can be lower service costs compared to corrective maintenance, unrealized production and indirect costs. Järviö also claims that unplanned service is between four and twelve times more expensive than planned service actions. This research is more interested about the technical aspects which are supportive goals for condition monitoring but these are likely to affect non-technical aspects. As an example, wanted monitoring system output alone might not reduce costs but it decreases man hours which reduces costs and probably it also increases the staff motivation. Of course these technical goals should support the main goal.

Spare (2001) has studied a business case for condition based maintenance from electric utility point of view. According to Spare the expected benefits from condition based maintenance are divided into two different categories which are monetary and soft benefits. Listed benefits are following:

- Reduce maintenance costs
- Reduce catastrophic failures and collateral damage
- Defer replacement (extend life)
- Increase equipment utilization
- Reliability / availability
- Safety and environmental concerns

Last two of the benefits are categorized as soft values and rest of the benefits are monetary values. The benefits can also be thought as goals for maintenance. List clearly shows that these goals are all related to condition monitoring. This view is also supported as they have studied transformer condition monitoring in their article. According to their article condition monitoring is the technique served for condition based maintenance.

According to ABB (2000: 596-599) the goal for condition monitoring is to identify fault before major failures so maintenance activities can be planned. Another goal for condition monitoring is to give possibility to skip unnecessary maintenance breaks. Same source divides condition monitoring to detection, diagnosis and prognosis of fault, action proposal and root cause analysis.

ABB Transformer handbook (2004: 123) defines major goals for on-line monitoring system. The goals are to prevent major failures, to achieve better utilization of load capacity, optimize maintenance and to extend the remaining lifetime. These goals are more CBM related, which is supported by condition monitoring.

All sources are well lined up and there are no major differences between sources. Now it can be clearly stated that goal for maintenance is to support availability performance and condition monitoring is the tool to provide information for condition based maintenance. To be more specific with condition monitoring goals it can be concluded that those should be early detection, diagnosis and prognosis of fault. Action proposals and root cause analysis are more advanced goals for condition monitoring. As it was defined in the introduction chapter this thesis will concentrate on early detection of faults.

4. POWER TRANSFORMER.

4.1.1. Transformer:

A transformer is a passive electrical device that transfers electrical energy from one electrical circuit to another or multiple circuits. A varying current in any one coil of the transformer produces a varying magnetic flux in the transformer's core, which induces a varying electromotive force across any other coils wound around the same core. Electrical energy can be transferred between separate coils without a metallic (conductive) connection between the two circuits. Faraday's law of induction, discovered in 1831, describes the induced voltage effect in any coil due to a changing magnetic flux encircled by the coil.

Transformers are most commonly used for increasing low AC voltages at high current (a step-up transformer) or decreasing high AC voltages at low current (a step-down transformer) in electric power applications, and for coupling the stages of signal processing circuits. Transformers can also be used for isolation, where the voltage in equals the voltage out, with separate coils not electrically bonded to one another.

Since the invention of the first constant-potential transformer in 1885, transformers have become essential for the transmission, distribution, and utilization of alternating current electric power. A wide range of transformer designs is encountered in electronic and electric power applications. Transformers range in size from RF transformers less than a cubic centimeter in volume, to units weighing hundreds of tons used to interconnect the power grid.

4.1.2. Types of Transformer:

There are various types of transformer used in the electrical power system for different purposes, like generation, distribution and transmission and utilization of electrical power. The different types of transformer are Step up and Step down Transformer, Power Transformer, Distribution Transformer, Instrument transformer comprising current and Potential Transformer, Single phase and Three phase transformer, Auto transformer, etc.

- Step up and Step-down Transformer
- Power Transformer

- Distribution Transformer
- Uses of Distribution Transformer
- Instrument Transformer
- Current Transformer
- Potential Transformer
- Single Phase Transformer
- Three Phase Transformer

4.2. Power Transformer:

4.2.1. Definition:

The Power transformer is a one kind of transformer, which is used to transfer electrical energy in any part of the electrical or electronic circuit between the generator and the distribution primary circuits. These transformers are used in distribution systems to interface step up and step down voltages. The common type of power transformer is liquid immersed and the life span of these transformers is around 30 years. Power transformers can be classified into three types based on the ranges. They are small power transformers, medium power transformers and large power transformers. The range of small power transformers can be from 500-7500kVA

- The range of medium power transformers can be from -100MVA
- The range of large power transformers can be from 100MVA & beyond
- The average life of a transformer is around 30 years

These transformers transform the voltage. It holds a low voltage, high current circuit at one side of the transformer and on the other side of the transformer it holds high voltage low current circuit. Power transformer depends on the principle of Faradays induction. They describe the power system into zones where every gear connected to the system is sized per the ratings set by the power transformer.

4.2.2. Construction.

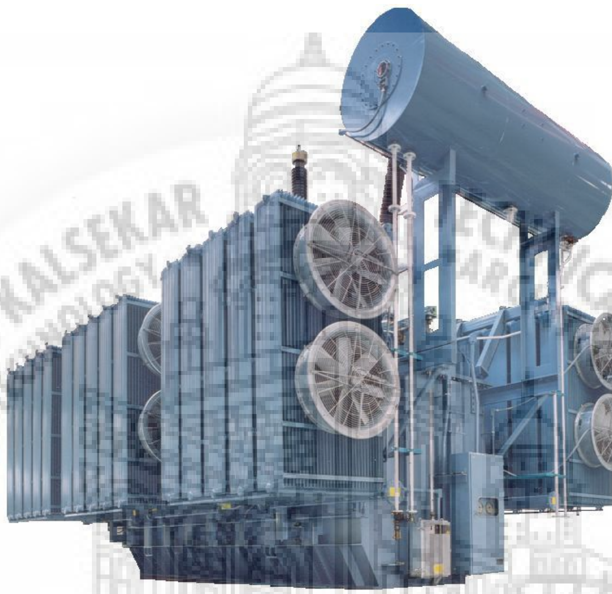


Figure 3. Picture of generator step up transformer (ABB 2010).

Generator step up (GSU) type power transformers are used on power plant applications. These transformers take voltage from the generator voltage level up to the transmission voltage level, which normally is around 110 kV. Figure 3 shows a picture of generator step-up transformer. According to ABB Transformer Handbook (2004: 18-19) step up transformers are usually Ynd-connected. It seems that there are many reasons why the low voltage winding should be connected in delta instead of star:

- The delta-connected winding keeps the zero sequence impedance of the transformer reasonably low.
- For large transformers the line current on the low voltage side is very high. In a delta–connected winding the current through the winding is equal to the line current divided by 3, which makes the winding work in the factory easier with a correspondingly smaller bundle of winding

The high voltage neutral is in most cases solidly earthed and the insulation in the high voltage winding is graded which means that the insulation level in the neutral is lower than in the phase end of the winding. (ABB Transformer Handbook: 18-19.)

According to this size of transformers normally use ONAF (oil natural and air forced) cooling. It means that fans are to used blow air on to the cooling surfaces of the radiators and oil is kept in circulation by the normal convection force in the closed-loop cooling system.

The skeleton of the power transformer is designed with metal which is laminated by sheets. It is fixed into either a core type or shell type. The skeletons of the transformer are wound and connected using conductors to make three 1-phase or one 3-phase transformer. Three 1-phase transformers require each bank isolated from the additional and thus offer continuity of service when one bank flops. A single 3-phase transformer, whether the shell or core type, will not function even with one bank out of service. The 3-phase transformer is inexpensive to make and it has a smaller footprint, and functions comparatively with higher efficiency.

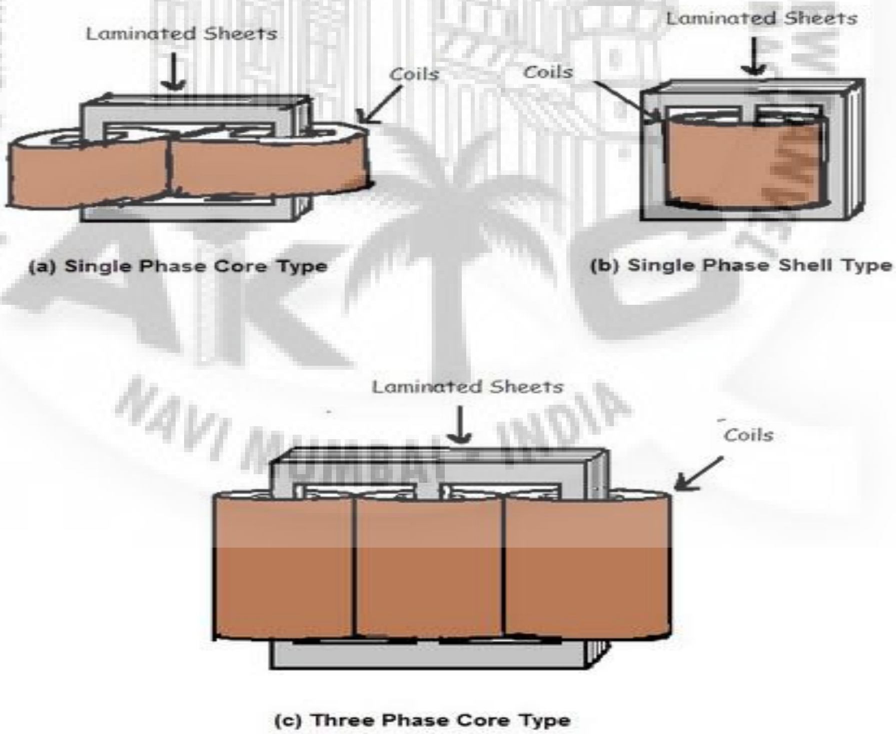


Figure 4 Transformer winding.

The skeleton of the transformer is absorbed in a fire retardant protecting oil inside a tank. The conservatory on top of the oil tank lets for the increasing oil to fall into it. The charger of the load taps to the side of the tank changes the no of turns on the high voltage-low current winding for superior voltage regulation. The bushings of the tank permit for conductors to carefully enter and exit the tank without stimulating the outer shell. The power transformer can be worked beyond its small rating as long as it stays within the 65ºC rise of the temperature. To allow the above nominal operation, transformers are built-in with a fan that cools the core of the transformer to a point below the indicated temperature.

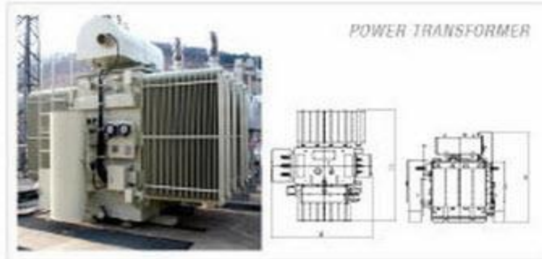
4.2.3. Power Transformer Specification.

Power transformers can be designed as either a single phase or a three phase configuration. There are numerous important specifications to identify when searching for power transformers. The specifications of power transformer include a maximum power rating, maximum secondary current rating, maximum voltage rating and o/p type. Power transformer specifications mainly include

- Phase is 3Ø
- Frequency if 60Hz,50Hz
- Primary Voltage is 22.9 kV
- Secondary Voltage is 6.6/3.3 kV
- Tap Voltage 23.9-R22.9-21.9-20.9-19.9kV
- Vector Dd0, Dyn11, etc.

▷ Transformer - Power Transformer

*Phase - 3φ
- Frequency : 60㎐, 50㎐
- Primary voltage : 22.9㎸
- Secondary voltage : 6.6/3.3㎸
- TAP Voltage : 23.9 - R22.9 - 21.9 - 20.9 - 19.9㎸
- Vector : Dd0, Dyn11.etc



CAPACITY (KVA)	Exciting Current Io(%)	Voltage Req. ε(%)	Eff n(%)	Dimension(mm)			Oil (ℓ)	Total Weight (㎏)
				W	D	H		
1000	4.5	1.3	98.4	2200	1950	1700	900	3500
1500	4.5	1.25	98.5	2600	2100	2600	1480	4800
2000	4.5	1.2	98.5	2900	2200	2800	1700	6200
2500	4	1.2	98.7	3100	2500	2900	2000	7300
3000	4	1.2	98.7	3100	2600	3050	2200	8000
5000	4	1.1	98.9	3200	3000	3100	3200	12000
7500	3.5	1	99.1	3400	3400	3300	4000	14500
10000	3.5	1	99.2	3600	3800	4000	5500	16500
12000	3	1.2	99	4250	3840	3830	5600	26500
14000	2.5	1.1	99.1	4300	3900	4070	7300	29000

Table 1. Power transformer specification

5. CONDITION MONITORING METHOD FOR POWER TRANSFORMER.

. According to Rudd, Catterson & McArthur several methods are needed to find out the fault as early as possible. This claim is in line with the results from earlier chapter as several different components or aspects can cause failures. This chapter will introduce different condition monitoring methods and make a link to which failures that specific method can be used.

Abu-Elanien and Salama have studied different methods to handle transformer condition monitoring. Abu-Elanien & Salama have divided methods into five main categories. The categories are thermal analysis, vibration analysis, dissolved gas analysis, partial discharge analysis and frequency response analysis. According to the article the categories are based on several researches during past years. Methods listed are only covering the main tank but not the accessories. As mentioned earlier, the accessories are essential part of the transformer so we need to have monitoring method also for cooling and bushings. Abu-Elanien etc. have also included frequency response analysis which will be left out from this study as it is mainly used as an off-line method

Lord & Hodge have a slightly different approach to different condition monitoring as they are studying component monitoring rather than different methods. Lord etc. includes accessories in the components. Their condition monitoring subjects for the main tank are:

- Moisture in oil
- Oil signatures from winding connection issues
- Winding hot spot temperature
- Winding insulation degradation
- Core and winding geometry
- Main tank electrical and acoustic partial discharge (PD)

These subjects are mostly related to categorization. Moisture in oil and core and winding geometry are additions to the earlier categorization. For bushing monitoring Lord etc are suggesting tan delta monitoring as a good option. For cooling monitoring they are suggesting to monitor fans contactor operation at minimum level. Advanced option monitoring would include current measurement. All covered monitoring methods are suitable for automated transformer condition monitoring.

Any of these articles are not including loading as a condition monitoring method. One major failure cause was improper operation and overloading is included in this part so it would make sense to use loading information in condition monitoring. Following sections introduce most essential monitoring methods for this research and the methods are thermal analysis, vibration analysis, partial discharge analysis, dissolved gas analysis, moisture analysis and bushing monitoring.

5.1. Thermal analysis.

According to thermal analysis of the transformers can provide useful information about its condition and it is possible indicate any incipient fault inside it. Many of the incipient faults cause a change in the thermal behavior of the transformer. It is commonly accepted that transformer life can be affected very much for a continuous maximum hotspot temperature of 98°C on the paper insulation. Continues that from that point onwards it is assumed that the rate of ageing doubles for every increase of 6°C as explain. Also, the transformer oil is subjected to degradation due to direct thermal effects, and increased oil temperatures are likely to accelerate other ageing processes

Divides temperature analysis into two categories. The first category is related to artificial intelligence techniques to predict the transformer temperatures. The second category is about developing a thermal model to predict the thermal behavior of the transformer.

Abu-Elanien claims that artificial neural network is a very good predictor for the transformer hot spot and top oil temperatures. Assumed main inputs for the system to predict mentioned temperatures would be three phase currents measured from the transformer and surrounding weather conditions. More inputs to the software can be used to enhance the accuracy of the prediction of the top oil and hot spot temperatures like previous predictions. IEC defines hot-spot modeling in loading guide for oil-immersed power transformers (IEC 60076-7) and it is presented in Figure 9. It is a simplified model and it doesn't cover surrounded weather conditions or three phase currents. IEC (IEC 60076-7: 21) also notes that the hot-spot temperature should be referred to the adjacent oil temperature. Source assumes this to be the top-oil temperature inside the winding. According to same source measurements have shown that the top-oil temperature inside a winding might be up to 15 K higher than the mixed top-oil temperature inside the tank. For most transformers in service, the top-oil temperature inside a winding is not precisely known. On the other hand, the top-oil temperature at the top of the tank is usually well known either by measurement or by calculation. IEC (IEC 60076-7: 21.).

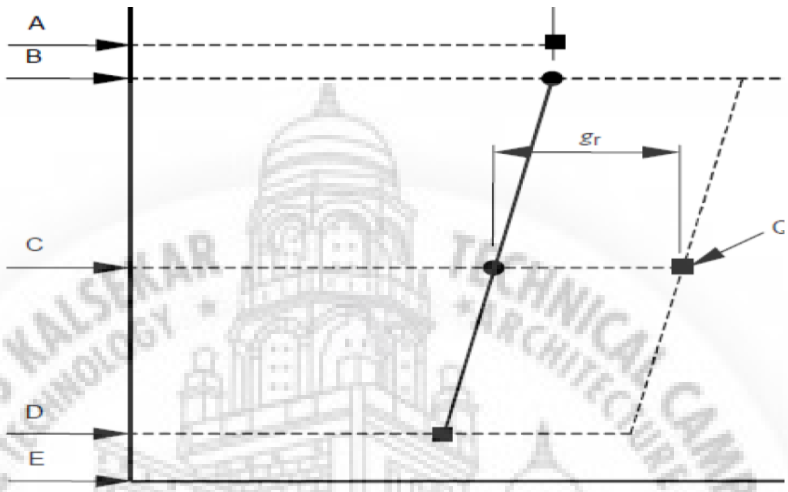


Figure 5. Thermal diagram for hot-spot modelling (IEC 60076-7: 22).

Second category is related to developing a thermal model for the evaluation of the transformer thermal behavior. claims that transformer thermal model was discussed in many publications with different accuracies and different building techniques. The source continues that there was a relation between the thermal and the electrical circuits. Source claims that this thermal model can be used to make on-site condition monitoring of the transformer and provide engineers with real time data monitoring. Model would determine the water in oil, water in paper and temperature calculation of the power transformer. Paper doesn't present any concrete examples or methods, so this second category should interpreted more carefully.

Temperature monitoring is a very cost-effective way of having transformer monitoring. This method is also already used. Biggest advantage for temperature monitoring is that it is very cheap and robust method. Main problem with the method is the sensitivity. Basically it means that temperature measurement is not sensitive for quickly evolving faults. For aging modeling, it is kept as a good method and also necessary. As mentioned Abu-Elanien claims that temperature monitoring could be used for on-line condition monitoring together with artificial intelligence. Using artificial intelligence needs more research but could be one option for the future.

5.3. Vibration Analysis.

According to the usage of the vibration signals in evaluating the transformer health is a relatively new technique and its research is under development compared to the other methods of the transformer condition monitoring. The health of the core, windings and on load tap changer can be assessed using vibration signature of transformer tank Garcia, Burgos & Alonso confirm this in their articles, which introduce a method to detect winding deformations. These articles doesn't cover core or on load tap changer but it is still clear that vibration analysis is one possible method for power transformer condition monitoring.

According to the tank vibration consists of two different types and those are core and winding vibrations. These generated vibrations travels through the transformer oil until reaching the transformer walls. The vibration of the transformer can be measured via accelerometers from transformer walls. The vibration signal is a series of decaying bursts and each of the bursts is the result of a combination of a finite number of decaying sinusoidal waveforms.

Vibration analysis is definitely an on-line monitoring method, which can be handled automatically. The method has been tested with pilot projects but it still needs more research before it's widely accepted. It is an interesting method but as explained in failure statistics the problems caused by windings and core are minimal. Garcia etc. presents a more detailed description about their method and also some results from a test environment.

5.4. Partial discharge analysis.

According to partial discharges occur in a transformer when the electric field strength exceeds the dielectric breakdown strength of a certain localized area. The insulation partially connects the conductors due to an electrical discharge or discharges. If consistent partial discharge activity is present for long periods of time, then the dielectric properties of the insulation may be reduced. This situation may result as a failure if the partial discharge activity remains. Researches into partial discharge phenomena in liquid dielectrics (such as oil) have been less common and are not as well understood as solid dielectrics Source also mentions that large number of insulation problems starts with partial discharge activity and continues that partial discharge is considered as raw data that is used to perform the transformer condition monitoring.

Mentions that on-line partial discharge measurement is usually affected by electromagnetic interference (EMI), which creates challenges when extracting the partial discharge signals from the measurement data. Source continues that this is because partial discharge signal magnitude is usually very low and the value of the partial discharge measurement signal from sensor is comparable with electromagnetic interference and cannot be distinguished by simple visual inspection.) says that it is required to apply some noise reduction techniques to achieve pure partial discharge signals. According to source the most common methods for de-noising are the Wavelet Transform, the gating method and the directional sensing.

According to the classification of a discharge depends on many factors but important features are the pulse amplitude, time of occurrence (point on wave) on the mains cycle, the number of discharges per second and the interval between discharges. continues that the partial discharge itself without interpretation is meaningless. It means that the data of partial discharge activity should be used to evaluate the condition of the transformer, to diagnose faults and to locate the origins of these faults. The partial discharge data is usually very large and because of that monitoring systems are often integrated with an artificial intelligence agent to sense the problem, identify its type and determine its location.

5.5. Dissolved gas analysis.

It was mentioned earlier that transformer insulation is made from cellulose paper or pressboard. The cellulose is impregnated with insulating oil. The chemical bounds within oil and cellulose molecules can break if the insulation is overstressed by high temperature or electric discharges. In that case new molecules will be created and that generates a variety of gasses that dissolve in the surrounding oil. 10 provides an overview of the chemical structure of insulating material and degradation secondary products.

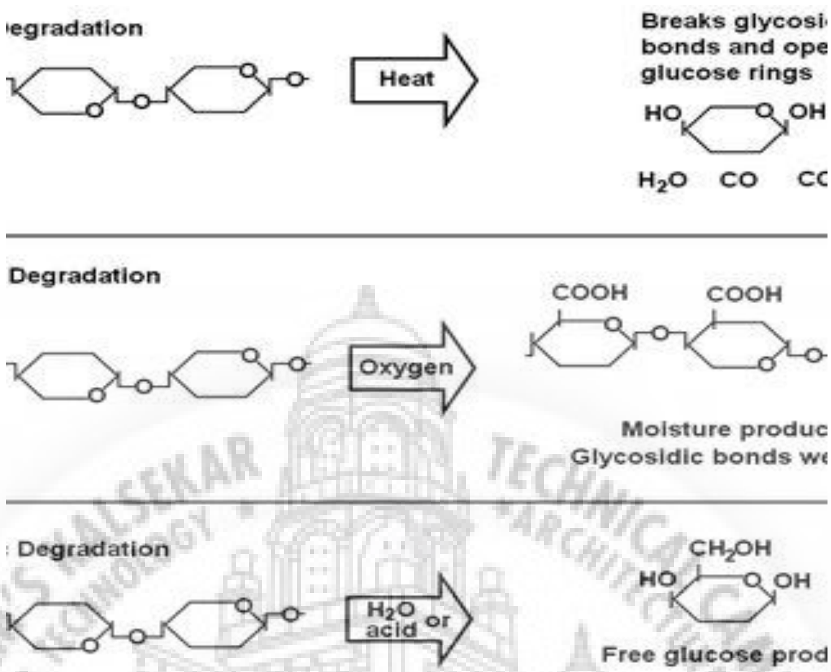


Figure 6. Chemistry of insulation degradation

According to Sparkling outcall developing problems in the winding insulation, in the connections, in the core or in the shields will generate a localized spot of high temperature or electric discharges. Those result decomposition of oil and/or paper. Source continues that different gasses are generated depending of the type and severity of the fault. According to all fault types are indicated by a variety of gases and not with just one individual gas. See Table 5 for details. This is also confirmed by Duval

Indication / Faults	H_2	CO	CO_2	CH_4	C_2H_2	C_2H_4	C_2H_6	O_2	H_2O
Cellulose aging		•	•						•
Mineral oil decomposition	•			•	•	•	•		
Leaks in oil expansion systems, gaskets, welds, etc.			•					•	•
Thermal faults – Cellulose	•	•	•	•				•	
Thermal faults in oil @ 150 °C – 300 °C	•			•		TRACE	•		
Thermal faults in oil @ 300 °C - 700 °C	•			•	TRACE	•	•		
Thermal faults in oil @ 700 °C	•			•	•	•			
Partial Discharge	•			•	TRACE				
Arcing	•			•	•	•			

Table 2. Produced fault gasses by failure causes

Duval says that there are several diagnostic methods and main methods are:

- The IEEE methods (Dornenburg, Rogers and key gases methods)
- The IEC ratio codes
- The Duval triangle

According to methods have different approaches for analyzing the oil. Gas ratios like CH4/H2, C2H2/C2H4 and C2H4/C2H6are compared by the Dornenburg, Rogers and IEC ratio codes methods. The key gas method is based on two or three formed main gases. The Duval Triangle depends on the relative proportions of three gases (CH4, C2H4 and C2H2). According to same source one disadvantage of the gas ratio methods is that some results of analysis may be outside the ratio codes and diagnosis is impossible to give (unresolved diagnoses). says that this does not happen with the Duval triangle method as it is a closed system instead of an open one.

Serveron have presented a comparison between different methods and the results . Data for the evaluation was from IEC data bank of inspected transformer failures and other reports.

Dissolved gas analysis is kept as best on-line monitoring method at the moment as mentioned in chapter 3.2. It can be very effective to detect quickly evolving faults so the sensitivity is very good. Downsides are more.

5.6 Moisture monitoring.

According to Davydov & Roizman the term moisture in the transformer industry is used to indicate absorbed water in the paper or dissolved in the oil. Source continues that the alternative terms for moisture are water or water content. Davydov etc. mentions that moisture can exist in different parts of the insulation system in a power transformer. Possible spots for moisture are solid insulation, be dissolved in oil or be found in the form of liquid water at the core or bottom of a transformer

Water may get mixed with the oil by leaking gaskets, poor handling techniques or from the product of insulating paper and oil degradation. As the paper degrades, it produces carbon dioxide and water and as the insulating oil ages, water, acids, sludge and other polar compounds are formed. So its presence is inevitable during the normal service life of a transformer. (Energy Services International.)

As explained earlier the moisture movement between the solid insulation and oil depends mainly on loading and temperature. Virtanen mentioned during interview that it is important to know the moisture level in insulation but it is very difficult to measure moisture directly from insulation. For this purpose there is an equilibrium curve which presents the moisture in solid insulation as percentage value. The charts have two parameters, which are temperature and moisture in oil. Du have studied and compared several different curves. Their conclusion is that all curves differ from measurement techniques, data sources and generating methods. That leads to a situation that caution should be taken when using any of the curves. Their claim is that Oommen's curves match best against the experimental data. See Figure 11 for an example of Oommen's curves for moisture for a paper-oil system. Oommen, Thompson & Ward says that these curves are unreliable as there are several problems are:

- Thermal equilibrium is rare
- Moisture distribution in insulation is uneven
- Type, grade and age of oil

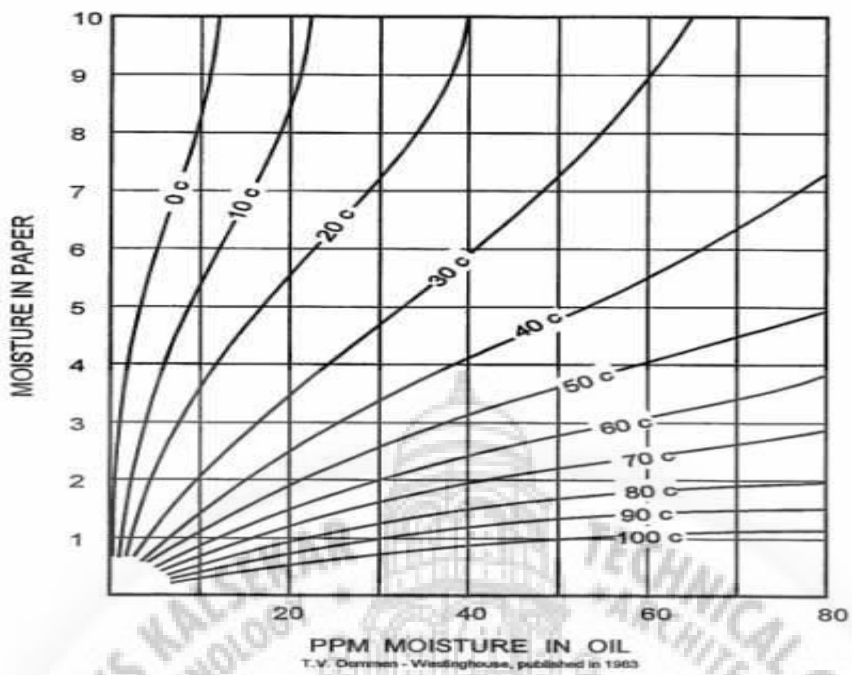


Figure 7. Oommen's curves for moisture equilibrium for a paper- oil system.

Unreliability seems to be known problem as there are proposed solutions for the problem from different sources like Oommen etc. (2004) and Zhou etc. (2009). These proposed solutions are not covered in this thesis.

In general it can be said that moisture is important part of transformer monitoring. It is easy to handle automatically with right sensors but there are challenges with reliability.

5.7.Bushing monitoring.

Lord etc. claims that tangent delta method can be used for monitoring current flows through bushing. According to Lord etc. it is best to determine the health of a bushing is by measuring the current that flows through the bushing insulation. This should be done at full system voltage. Lord etc. says that in healthy bushing this current is mostly capacitive with minor resistive component. The resistive current will cause heat losses in the dielectric of the insulation material According to one technique for tangent delta monitoring is using the vector sum of the leakage current. This is measured for the three bushings in a three-phase system. The three leakage currents are out of phase by approximately 120º. Usually leakage currents have the same magnitude. In ideal world all three bushings have similar capacitances and the voltages for the three phases are close to balanced. It means that the sum of the three leakage currents (Isum) is much smaller than any of the leakage currents taken individually and this is seen in Figure 12 (a). If there is a change in the capacitance and in the dissipation factor of the bushing on phase A, then leakage current on phase A also changes, as shown in Figure 12 (b). The change vector that expresses the displacement of current Ia from its initial value to its final value is also reflected in the sum current.

Change vector is then compared to the sum current (Isum) and this way the changes are detected which occurs in the impedance of the bushing. The method has some specific characteristics and those are:

- An initial reference must be determined for the system's currents
- Absolute values of capacitance and tangent delta of bushings are not measured, only variations occurred in these parameters are measured. Once each bushings

initial capacitance and tangent delta values are known (values present at the moment that the initial reference currents are is determined for the bushings), measuring their variations, allows current values to be calculated for capacitance and tangent delta;

- For new bushings, rated values for capacitance and tangent delta supplied by manufacturer of the equipment on the plaque can be used as the initial reference values.

According to bushing monitoring solutions are still very expensive which means tens of thousands in euros.

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5.2. Measuring devices for power transformer condition monitoring.

On line measurements gives the data for condition monitoring and for that measurement devices and sensors are needed. In this chapter few measurement devices types are introduced as an example

5.2.1. Transformer condition monitoring device.

There are devices on the market, which handle transformer condition monitoring. Usually these devices collect measurement data from several sensors, process the data and present the information for the maintenance personnel. Measurement methods might have some differences but the output and functionality from the device is very similar. As an example following monitoring functionality is usually seen in transformer condition monitoring device:

- Oil temperature
- Hot-spot temperature
- Load
- Currents
- Gas and moisture in transformer oil.
- Oil levels

As an example ABB provides transformer condition monitoring device called TEC (Transformer Electronic Control). The functionality is similar to the list above and also some other functions are available. As an example TEC has tap changer monitoring. Device has eight 4-20 mA, four Pt100 and twelve binary inputs. Additional input for tap changer position is also included. TEC has three binary outputs for alarms. (ABB 2008: 1.) This means that it is possible to attach external sensors to the device. TEC can communicate with upper level devices via OPC or XML files (ABB 2008: 1).

It is worth mentioning that TEC is quite extensive device and it is a good starting point for transformer condition monitoring. One major defect is that the system is completely external to transformer protection systems which are mandatory and this means higher costs (more devices, more complex installation and usability suffers). The functionality itself is enough for these kinds of devices but it should have tighter integration to other systems.

Another example is from Areva. They have several devices for transformer monitoring. These systems are also very extensive with modeling algorithms (Areva 2008). Price is very high for Areva systems. For example overall costs for monitoring device MS 3000 can be around 100000 euros.

5.2.1. Dissolved gas analysis device.

According dissolved gas analysis can be made with several different methods and devices are divided into two groups. These groups are combustible gas monitors and complete multi-gas monitors. Combustible gas method is rather old technique and depending on manufacturer, the sensitivity to different gases varies The important note here is that the sensor will report only one reading indicating the amount of gasses in the oil. continues that Multi-gas method is much recent technique and this one also has differences between manufacturers The principle is to give individual reading for each one of the measured gasses.

Hydran M2 is an example of combustible gas monitor. It is designed and manufactured by General Electric to analyze transformer oil in real time. Device monitors gas and moisture concentration from transformer oil. Hydran M2 is broadly sensitive to combustible gas. This means that a high content of acetylene and low hydrogen content can give the same reading as a low acetylene and high hydrogen. These different conditions cannot be easily resolved only with Hydran M2. Device can work as an independent condition monitoring unit or the measurement data can be transferred to another device. The data can be transferred by using 4-20 mA output. With optional communication card it possible to get four 4-20 mA inputs or four 4-20 mA outputs. Technical specification sheet (General Electric 2003) tells that it is possible to transfer sensor oil temperature, gas ppm, oil ppm and relative humidity % with 4-20 mA outputs. For 4-20 mA inputs it is possible to use for example temperature sensors. Communication can also happen with serial communication. Supported protocols are for example Modbus and DNP 3.0. According to Finnish importer of Hydran M2 (2009) the lifetime for the sensor unit is between eight and fourteen years and comments during interviews indicated even shorter lifecycle. The device itself costs around 8000 euros and replacing sensor unit costs around 1500 euros.

Kelman Transfix is an example of a multi-gas monitor. The device can measure eight gases and moisture. The analyzer is based on photo acoustic spectroscopy. The method is rather new in transformer monitoring but the technique is common from other industries. Biggest disadvantage for the device is price, which is around 35000 euros commissioned. This applies to all full scale multi-gas monitors

Kelman has also developed a limited version of Transfix that is called Minitrans. This device will measure three gasses and moisture. It is possible to detect critical arcing activity, general fault activity and rapid cellulose degradation. (GE Energy 2009.) Price is much lower as it is around 11000 euros commissioned.

Kelman products support wide range of communication protocols like Modbus, Modbus/TCP, DNP 3.0 and IEC 61850 (GE Energy 2009: 2). IEC 61850 protocol support is a great asset as it has important role in substation world

The biggest downsides at the moment with dissolved gas analysis are related to the measurement devices. These problems are high price and the technical problems. According to biggest problems are lifetime of the sensors and reliability of information. With multi-gas monitors the experience is quite limited at the moment and some problems, such as false alarms are noticed. It seems that sensor technology has longer lifetime but reliability of the devices is questionable. The results from questionnaire indicate that simple gas analyzing sensor would be preferred by several stakeholders. In other words it means that stakeholders are seeking a simple sensor, which would indicate evolving faults and costs would be reasonable. Of course reliability and lifetime should be good-enough. At the moment it is not possible with current devices but this should be the direction of the development.

5.2.2. Moisture measurement device.

Davydov says that polymer relative humidity and polymer relative saturation sensors are frequently used to evaluate water content in oil. Source continues that absolute moisture content expressed in parts per million (ppm) can be determined by measuring the relative saturation of oil. The water solubility characteristic for the specific oil must be known in advance for this method.

Daydov claims that several parameters effects measuring process of moisture assessment in a paper-oil insulation system. These are oil type, age and flow rate. Source continues that also sensor positioning has an effect to the accuracy of moisture assessment. Davydov says that water solubility in oil is required that installed moisture sensor can be calibrated. According to source water in paper activity was as is one factor when determining dryness in a power transformer.

As an example Vaisala Humicap MMT318 is a moisture measurement sensor for transformer monitoring. The MMT318 measures moisture in terms of the water activity and temperature. The calculation of water content in PPM is an option when the sensor is used with mineral transformer oil. It is also possible to get the transmitter with a ball valve set that enables insertion and removal of the moisture probe without having to empty the oil system. The MMT318 has two analog outputs and an RS232 serial output as communication interface. Price for one sensor is around 2000 euros.

According to experts moisture measurement is not kept very important in Finland. This is because climate is very good for transformers and moisture doesn't cause that many failures. The problem with moisture measurement is its measurement location. It should be measured directly from insulation paper rather than oil. Measurement through oil doesn't give reliable results as explained.

5.2.3. Partial discharge monitoring device.

Partial discharge monitoring is fairly new monitoring method and especially as an automated condition monitoring method for power transformers. These devices usually record measurement information from sensors. The sensors can be for example ultra high frequency type.

One example of partial discharge device is manufactured by Doble and it is called Transformer Guard. According to Transformer Guard brochure (Doble 2009) the system is designed for continuous partial discharge monitoring of high voltage equipment like generators, motors, and power transformers in the conventional range of frequency. The device supports four inputs and it can transfer the data outside through TCP/IP protocol. Monitoring device also supports UHF antennas so it can record partial discharge activity with range from 100 to 1000 MHz.

5.2.4. Vibration measurement device.

Vibration monitoring is very common with rotating machines condition monitoring. For transformer monitoring it is a relatively new method to monitor the condition. Different types of accelerometers are used for vibration analysis. Garcia have used piezoelectric charge accelerometers for the measurement of vibrations. According to Sanz-Bobi, Garcia-Cerrada, Palacios, Villar, Rolan & Moran charge type accelerometers cause less electrical noise than integrated circuit piezoelectric (ICP) type accelerometers. Garcia claims that their model calculates how the transformer tank should vibrate if it was healthy. The model compares the calculated and measured vibrations. Then it determines if something unusual is happening inside the transformer. Other option is to measure the vibration and compare it to the fingerprint measurement that is made at the transformer factory. Both of these methods needs post processing of the measurement data and at the moment there is no suitable device available for the purpose. The amount of accelerometers varies between different studies. The minimum amount of sensors was three and maximum amount of sensors was twelve.

As an example SKF creates accelerometers for machine monitoring and these could be used for transformer monitoring. SKF Machine Condition Transmitter (MCT) collects measurement data from accelerometers, processes the data and sends it forward in wanted format, e.g. 4-20 mA format. One transmitter can handle only one sensor. MCT products have different versions for speed, vibrations and temperature.

6. POSSIBLE FAULT OF CONDITION MONITORING.

6.1. Transformer Ageing.

Transformer aging is one reason why condition monitoring is researched. Aging will cause outages, which creates losses for power plant owner. According to ABB (2004:117) transformer aging is related cellulose materials as those undergo chemical degradation in service. Cellulose materials are used as dielectric around transformer windings. This chemical degradation basically means old paper breaking up into small flakes. The dielectric insulation properties are only slightly affected in this state. More relevant risk is mechanical rupture and metal-to-metal contact as a result of mechanical shocks and vibrations (ABB 2004: 117.)

According to Koltunowicz, Bajracharya & Djairam (2009:1) aging is influenced by several factors like temperature, humidity, loading and power quality. They see power quality as an increasing problem in form of very fast transients (VFT) and lightning surges. According to Koltunowicz etc. (2009) humidity is dangerous for the transformer as it deposit itself on the tank and slowly turn into rust and that can cause causing leakages. It can also penetrate into the insulation layer adding moisture to the oil paper insulation. The insulation has some moisture in the beginning. Elevated temperatures will cause this moisture to leave the paper and cold temperatures vice versa. With frequent fluctuations, the paper's ability to reabsorb the moisture decreases. Over time the permanent moisture level will increase leading to breakdown.

ABB (2004: 117) states that chemical deterioration process is doubled for each 6-7 ○C temperature rise and this rate is considerably increased by the presence of water molecules and free oxygen dissolved in the oil. It is also clear that transformers continuous load capacity varies at different ambient air temperatures. IEC have created a loading guide for oil-immersed transformers and the guide has identification number 60076-7.

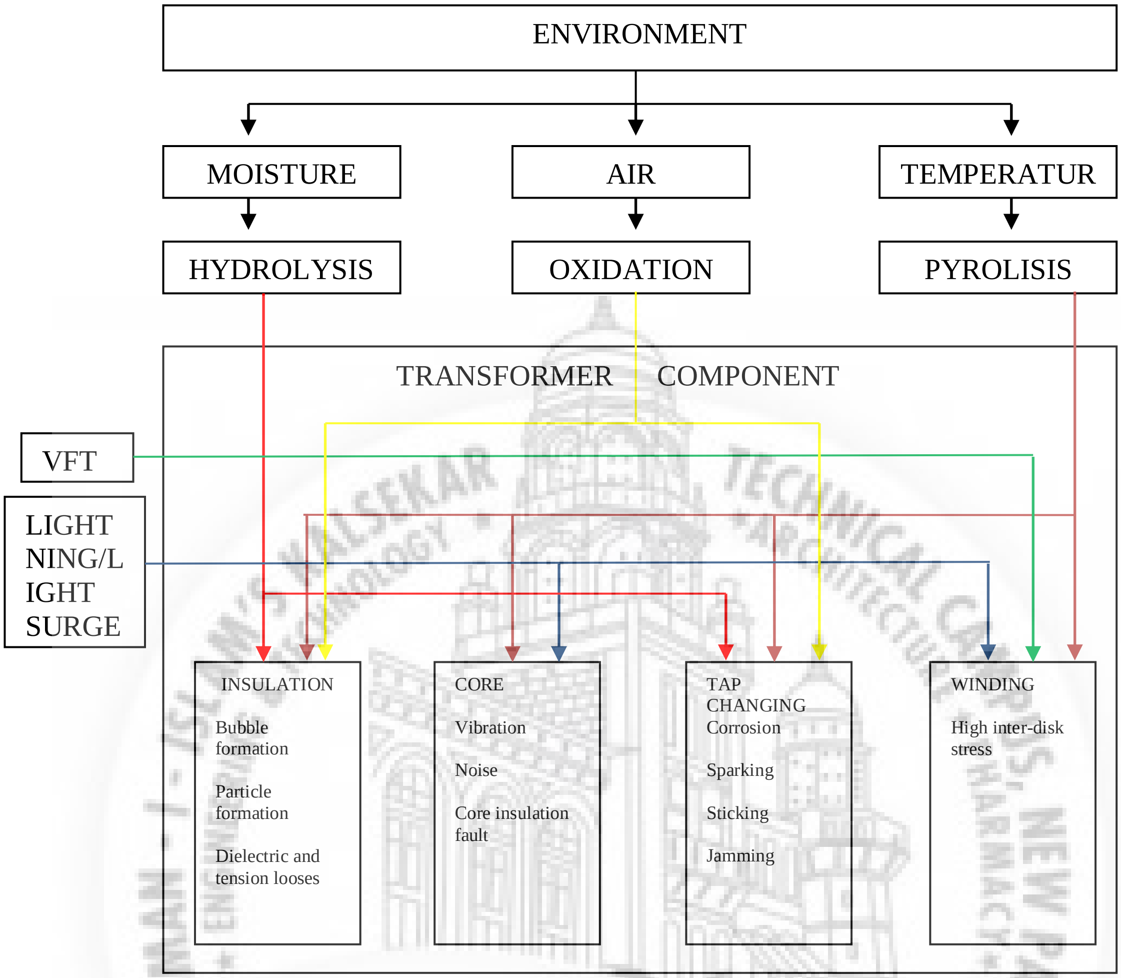

Figure 8. Aging factors and their effect on the main transformer components.

Koltunowicz etc. (2009) claims that fast switching functions used by power electronics cause serious harm to the insulation layers of capacitive objects such as the transformer's winding. For example AC/DC and DC/AC converters are common applications for power electronics and these converters are often used in wind farms and HVDC substations. Koltunowicz etc. (2009) base their claim on a test where two square waveforms of amplitude 4 kV and 5kV were applied to two wires with a layer.

6.2. Possible faults.

Several different parties have studied transformer failure statistics. Some of these are introduced here and the goal for this chapter is to define the major failure areas with power transformers.

According to ABB Transformer Handbook (2004: 118) failure rate of large power transformers due to short circuit currents was very low, 3 failures per 25000 transformer service years. Of course this excludes all other failures causes, which likely have a major effect to the failure rate. Sokolov (2006: 1) says that many-sided observation on transformer reliability was presented in CIGRE survey at 1983. It summarized over 1,000 failures of power transformers rated 72 kV and above for the period 1968-1978. It was revealed that the annual failure rate for all power transformers was 2 %, and for extra high-voltage transformers it may be 5 %.

Insulation Failures - This category excludes those failures where there was evidence of a lightning or a line surge. According to Bartley's analysis there are four factors that are responsible for insulation deterioration: pyrolosis (heat), oxidation, acidity, and moisture. Moisture is reported separately. The average age of the transformers that failed due to insulation was 18 years.

- Design /Manufacturing Errors - This category includes conditions such as: loose or unsupported leads, loose blocking, poor brazing, inadequate core insulation, inferior short circuit strength and foreign objects left in the tank.
- Oil Contamination – This category includes those cases where oil contamination can be established as the cause of the failure.
- Overloading - Includes those cases where actual overloading could be established as the cause of the failure. It includes only those transformers that experienced a sustained load that exceeded the nameplate capacity.
- Fire /Explosion - This category includes cases where a fire or explosion outside the transformer can be established as the cause of the failure. This does not include internal failures that resulted in a fire or explosion.
- Line Surge - This category includes switching surges, voltage spikes, line faults/flashovers and other abnormalities.

- Maintenance/Operation - This category includes disconnected or improperly set controls, loss of coolant, accumulation of dirt & oil and corrosion. Inadequate maintenance has to take the blame for not discovering incipient troubles when there was enough time to fix it.
- Flood – The flood category includes failures caused by inundation of the transformer due to man-made or natural caused floods. It also includes mudslides.
- Loose Connections - This category includes workmanship and maintenance in making electrical connections. According to Bartley's analysis one problem is the improper mating of dissimilar metals, although this has decreased somewhat in recent years. Another problem is improper torquing of bolted connections. Bartley's analysis states that loose connections could be included in the maintenance category but it was reported separately.
- Lightning - Unless there is confirmation of a lightning strike, a surge type failure is categorized as "Line Surge".
- Moisture - The moisture category includes failures caused by leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil.

The original table is appended with proportion of failures column. This table is covering whole analysis data and it is not limited only to generator step up transformer failures. The table shows that the three biggest failure types are causing over 60 % of all failures. It can be also noted that 29 % of all failures cannot be predicted with condition monitoring system if we include external failures causes Unknown, Fire / Explosion, Line Surge, Flood and Lightning. Unknown can be either external or internal failure cause, so this adds uncertainty aspects to the 29 % and most likely the real value is significantly smaller.

Based on the figures in Table 2 a chart showing relation between amount of failures and cost can be created. Figure 6 shows the total risk between different fault types. Three highest are clearly the most important according to this study. These three are Insulation failure, Design/Material/Workmanship and Unknown.

Cause of Failure	Number	Proportion of failures
Insulation failure	24	26%
Design / Material / Workman ship	22	23%
Unknown	15	16%
Oil Contamination	4	4%
Overloading	5	5%
Fire / Explosion	3	3%
Line Surge	4	4%
Improper Maintenance / Operation	5	5%
Flood	2	2%
Loose Connection	6	6%
Lightning	3	3%
Moisture	1	1%
Total	94	100%

Table 3. Cause of failures

7. POSSIBILITIES OF ON-LINE MONITORING

Collecting the data is one part in condition monitoring and other parts are diagnosis and prognosis. Following sections are mainly related to the last two parts of condition monitoring

7.1. Transformer Predictive Ageing Model.

Prediction of the aging is one possible direction for transformer condition monitoring. There are two examples quite close to each other, so this could be a possible feature to be implemented in transformer monitoring system. First one is related to diagnosis and the second one is related to prognosis. These two examples are presented in the following.

7.1.1. Condition Monitoring Multi Ageing System. (COMMAS).

Rudd, etc. (2008) claims that an accurate transformer condition diagnosis would include many different data interpretation methods. They continue that most complete picture of transformer health is achieved with multiple types of sensor. They also mention that such a system requires a way of integrating different components, allowing sensors and interpretation techniques to be easily added and removed from the diagnosis process. Their solution for this is agent technology, where individual autonomous agents encapsulate different tasks. Figure 14 shows how agents would interact between each other to define transformer health

7.1.2. Transformer predictive health model.

Bajrachary, Koltunowicz, Meijer, Djairam, De Schutter & Smit (2009) proposes a health state prediction model to evaluate and predict aging of a transformer. The model predicts the future health state of the transformer based on the historical and present condition data.

According to Koltunowicz etc. (2009) the condition analysis incorporates the operating condition such as load, voltage, temperature and other monitoring data like results of partial discharge measurements. The monitoring system gives an indication of the present health state of the transformer. Any previously implemented or future management actions to improve the health state such as maintenance schemes are also considered in the model. The schematic of health state prediction model is presented in Figure 15. (Koltunowicz etc. 2009: 3-4)

The proposal of Bajrachary etc. (2009) also includes an optimization model for maintenance and it is presented in Figure 16. According to the source the optimal maintenance action balances the economical cost of the maintenance, the improvement of the health state, and the reduction in the failure rate of the equipment. Their optimization model uses the predicted health information to identify the required maintenance actions. Bajrachary etc. (2009) mentions that the model considers three different cost functions, while evaluating the performance of each of the actions provided by predictive health model. These three are usage and maintenance actions, cumulative stresses and failure rate, as shown in Figure 16. The usage and maintenance actions include the economical cost of the maintenance. The failure rate includes the cost associated with the failure of the equipment. The cumulative stresses take into account the cost of deterioration of the equipment. Bajrachary etc. (2009: 2) According to Koltunowicz etc. (2009: 4) the health state prediction model is also used to verify the effect of optimized actions on the health.

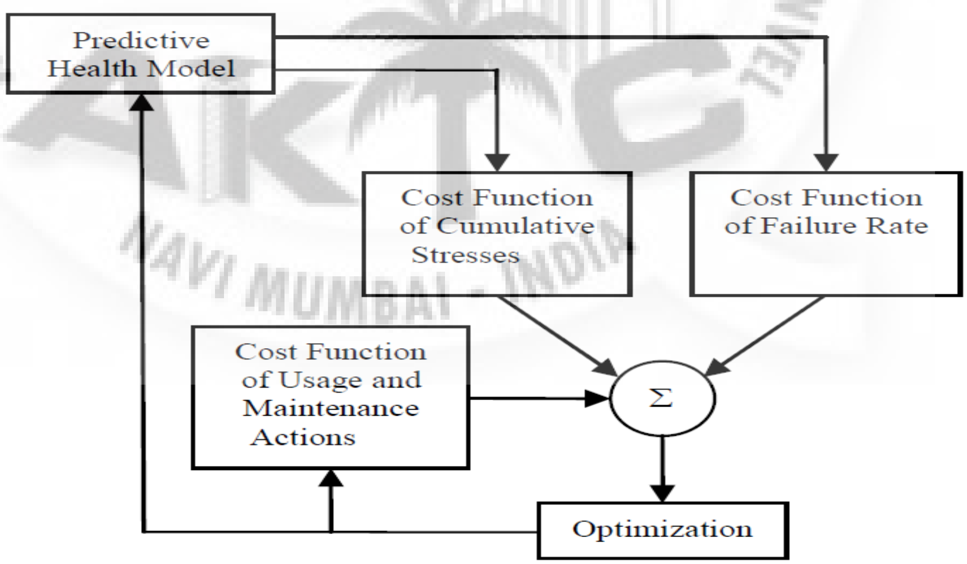

Figure 9. Optimization of maintenance.

7.2. MIMOSA standards.

Lack of standards was mentioned in the results of the questionnaire and its effect on slowing down the development of on-line condition monitoring. MIMOSA standards are introduced here as an example of a monitoring standard, but it is not commonly used among the industry.

MIMOSA is an alliance of Operations & Maintenance (O&M) solution providers and end-user companies who are focused on developing consensus-driven open data standards to enable Open Standards-based O&M Interoperability. Mimosa has two different standards, which are OSA-EAI and OSA-CBM. (Mimosa 2009.)

The MIMOSA OSA-EAI is a standard for data exchange of engineering asset management data. Interconnectivity of the islands of engineering, maintenance, operations, and reliability information is embodied in MIMOSA OSA-EAI specification. The "information network" is constructed by using OSA-EAI bridges to proprietary data stores to allow this information to be easily understood and utilized. (Mimosa 2009.) Figure 17 shows the architecture and components of MIMOSA OSA-EAI standard.

According to Mathew, Zhang, Zhang & Ma (2006) the MIMOSA OSA-EAI is a thorough and well constructed specification for asset management data. The CRIS (Common Relational Information Schema) provides a usable database implementation that can be populated by a comprehensive reference data set. With a few adjustments, the OSA-EAI is suitable for a condition monitoring database, covering the major aspects of condition monitoring, including asset and sensor registry management, measurement event management and storing raw and processed signals. The primary issues encountered for condition monitoring system development were the lack of documentation and the complexity of the data model. Peculiarities also arose in the reference data and certain sections of the data model. To support advanced trending and diagnostic functionality, additional tables were required. Although the MIMOSA OSA-EAI continues to be a work in progress, it provides a bright future for engineering asset management systems. (Mathew etc. 2006.) Referred review is over three years old so the situation with documentation might have changed in the last years. According to the history data Mathew etc. (2006) have used version 3.0 of the specification. At the moment valid version is 3.2.2.

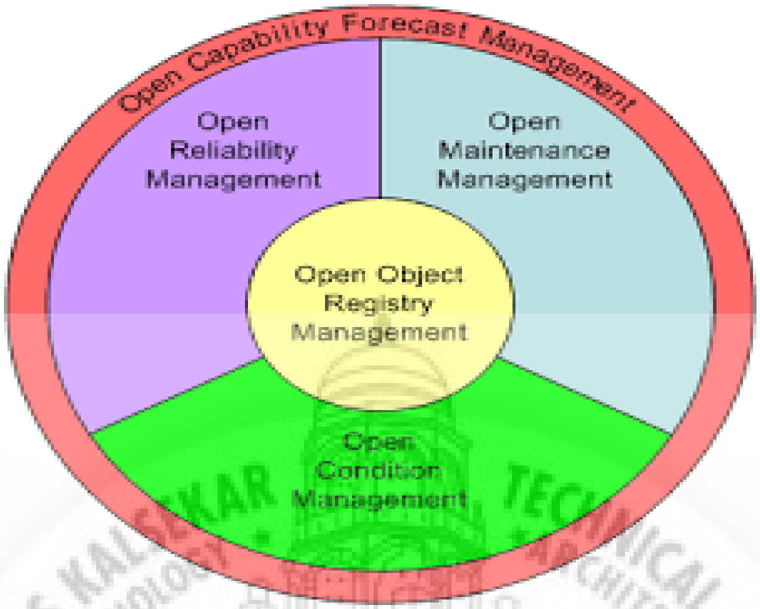

Figure 10. MIMOSA Open Systems Architecture for Enterprise Application Integration (OSA-EAI) (Mimosa 2009).

The OSA-CBM specification is a standard architecture for moving information in a condition-based maintenance system. OSA-CBM specifies a standard architecture and framework for implementing condition-based maintenance systems. Standard describes the six functional blocks of CBM systems, as well as the interfaces between those blocks. The standard provides a means to integrate many disparate components and eases the process by specifying the inputs and outputs between the components. Basically it describes a standardized information delivery system for condition based monitoring. It describes the information that is moved around and how to move it. It also has built in meta-data to describe the processing that is occurring. (Mimosa 2009.)

These standards could evolve to the point where those are accepted by the industry. At least these standards would give a good base to start developing industry approved standard. OSA-EAI seems to be more useful from electrical system point of view. IEC 61850 has a strong position in substation and edition 2.0 of the standard gives more options for condition monitoring. Communication between devices is in good shape because of IEC 61850 and this means that OSA-CBM is more or less useless. On the other hand OSA-EAI covers the communication between power plants and maintenance centers. It would make sense to study this standard more. As an example power plant maintenance personnel might not be experts analyzing electrical failures and then analysis should be done by external partner. Experts might be located in other parts of the world. Standardized data transfer protocol enables opportunities to develop condition monitoring. For example various experts can quickly reach data from various locations to solve problems.

7.3. Integrating monitoring framework to secondary system.

One possibility to develop condition monitoring and to limit possible costs is to integrate the condition monitoring functionality to existing secondary system. Transformer protection relays and terminals are always mandatory even if there is high range condition monitoring and maintenance system connected to the transformer. This increases the overall price for whole secondary system. There are also communication protocols like IEC 61850 which are field proven and even have support for condition monitoring. Some protection relays already have condition monitoring functionality implemented and most likely the functionality will increase in the near future. The major defect is related to data presentation. Either information value is low or finding the correct information is difficult.

Secondary system is usually having protection relays, communication gateway, instrument transformers, backup power supply and wiring. The idea is that protection relays would gather and measure the data for condition monitoring. Then the pre-processed information would be transferred to station automation device, which also works as a communication gateway. Station automation device would present processed information about transformer health with proper user interface or the data would be sent forward. Figure 18 shows an example structure of existing secondary system in power plant.

The combination of relay and station automation device should actually be a framework for condition monitoring, which is expandable with new features. As mentioned earlier the general opinion is not encouraging to use condition monitoring. Framework solution would allow customers to buy basic framework first together with protection relays, which could be expanded if better monitoring is needed.

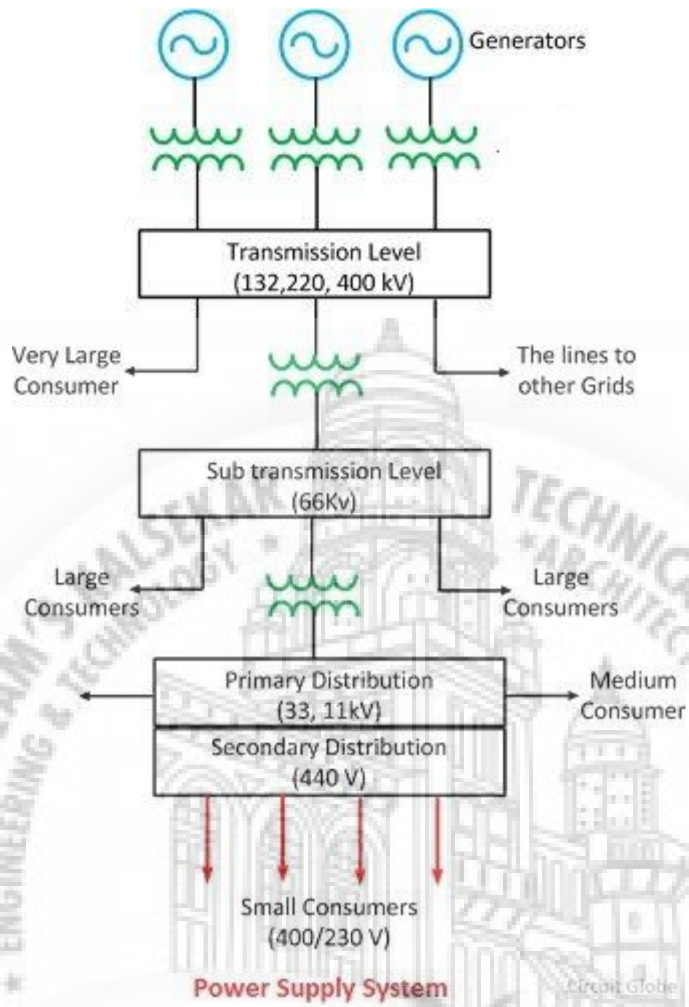

Figure 11. Typical secondary system in power plant.

Next sections will introduce transformer protection terminal and station automation device and current capabilities of these devices.

7.3.1. Transformer protection terminal.

High-end transformer protection relays have extensive functionality and these devices could be used as measurement data nodes, which collects the data from sensors and sends it to higher level, e.g. station automation device. Protection terminals main purpose is to protect transformer with appropriate functionality. With today's technology also control, measurement and condition monitoring functionality can be included in the same device. Normally protection terminals have flexible I/O interface and there are usually a 4-20 mA inputs available as an option. This way both position indication and measurement information can be gathered into one device. At the moment there are several manufacturers that provide this kind of devices.

As an example RET 54_ is transformer protection terminal manufactured by ABB. The device can also run other than protection functions. Device has some functionality for circuit breaker and secondary system condition monitoring. (ABB 2005.) It is important to notice that the device has a weak point, which is lack of direct functionality for transformer condition monitoring.

It is possible to add RTD/mA card to the device. This means that relay has 4-20 mA and Pt100 inputs. This gives possibilities to use external sensors and gives the possibility for transformer condition monitoring. One big asset of the RET 54_ is the communication possibilities to upper level devices. With use of PLC logics it is possible to combine data from different sensors. With the help of this information alarms and warnings can be sent. (ABB 2005.)

7.3.2. Station automation device.

Station automation device is normally located in a substation and its main purpose is to act as a communication gateway. With existing technology, other functionality can be added to the device. One example of this is to include data logger to the station automation device. Normally these devices have user interface to monitor the data provided by substation IEDs (intelligent electronic device).

COM600 is an example of station automation device manufactured by ABB. It can work as a communication gateway, automation platform and user interface solution for power plant. The gateway functionality provides connectivity between substation protection terminal and other IEDs. The gateway also connects network-level control and management systems. It has optional web browser based user interface. (ABB 2009: 13). Figure 19 shows a conceptual view of COM600 device. The figure presents the structure how data is transferred between different interfaces.

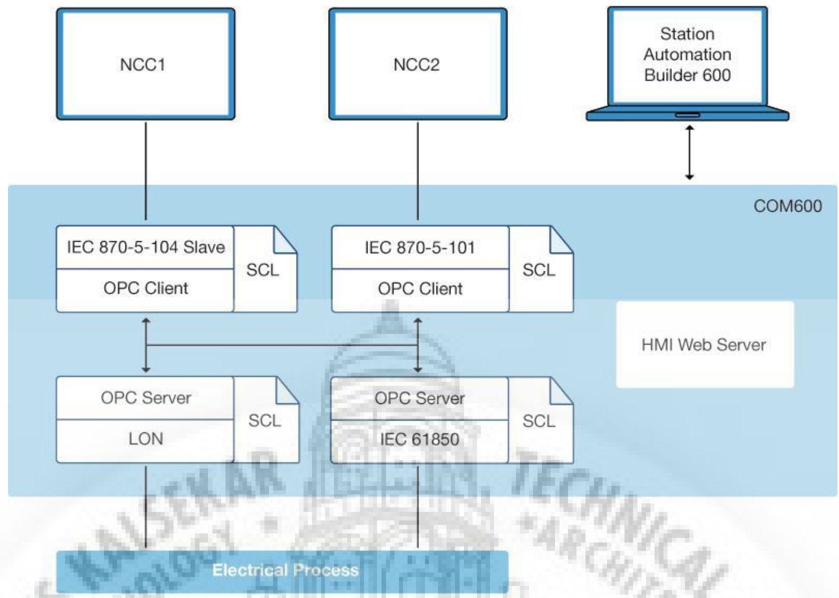

Figure 12. Conceptual view of station automation device COM600 (ABB 2009: 15).

8. CONCLUSION.

Power transformers are critical components in electrical networks and especially in power plants. The engines in the power plant might already have condition based maintenance but not the electrical circuit. This was the starting point for the thesis, which studies automated condition monitoring for power transformers. The goal was to achieve concept of good-enough condition monitoring system

Condition monitoring of power transformer chapter handled the structure of a transformer, aging process of transformer, possible faults and fault statistics, condition monitoring methods and examples of monitoring devices. The conclusion from statistics was that transformer condition monitoring is not justified by fault rate but it is justified when failure expenses are studied. Many of the failures are possible to discover with different monitoring methods. At the moment the most cost effective way is dissolved gas analysis. This handles both aging and quickly evolving faults. Temperature, moisture and loading are useful when aging process in the focus. There are other techniques, which are effective but are not industry proven, commercial measurement devices are missing or price is too high. One example of these is partial discharge.

Some possibilities of transformer condition monitoring now and in the future were also covered. This is divided into three sections, which are predictive aging model transformers, maintenance and condition monitoring standard MIMOSA and secondary system as framework for condition monitoring. Predictive aging model presents options how to have better utilization of monitoring data. These models predict transformer aging by using monitoring data and loading trends. Diagnosis and prognostics are the next step from monitoring where predictive aging models belong. Second section was about standards. In the questionnaire it was mentioned that one major challenge for maintenance and condition monitoring was lack of maintenance related standards. MIMOSA is one option for this and it is briefly introduced as a possible option to be used. Last section was related to monitoring framework. Secondary system is already having some monitoring functionalities integrated to protection relays and there are also solutions for data collecting. Problem is to collect and process the measurement data such way that it is easy to access and costs are acceptable. Integrating monitoring system to existing secondary system could create a proper framework and solution.

Quality and Reliability are a measure of the availability of the transformer for continuous operation throughout its stipulated life time.

• It is highly dependent upon the design and manufacture of the transformer, its materials and construction. It is also dependent on proper erection & commissioning and subsequent maintenance at site.

• In essence, it is a function of the interactions between the transformer and system.

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