UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

ELECTRICAL ENGINEERING

Lasse Pakka

UTILISATION OF TRANSFORMER CONDITION MONITORING DATA

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Vaasa, 8 of November, 2013.

Supervisor	Erkki Antila
Instructor	Kimmo Kauhaniemi

ACKNOWLEDGEMENT

This thesis has been done for Cleen's (Cluster for Energy and Environment) SGEM (Smart Grids Energy Markets) research project. The thesis will provide new perspectives for utilization of transformer condition monitoring in the power system management.

The study revealed me a lot of transformers, data communications and management of power systems. The topic was challenging and also very interesting.

I'm thanking my supervisor Erkki Antila and instructor Kimmo Kauhaniemi for good advices and guidance.

In Vaasa 8.11.2013

TABLE OF CONTENTS

ABBREVIATIONS AND SYMBOLS

A/D	Analog to Digital converter
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:	Utilisation of transformer condition monitoring data
Supervisor:	Professor Erkki Antila
Instructor:	Professor Kimmo Kauhaniemi
Degree:	Master 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:	2013 **Pages: 87**

ABSTRACT

Electricity grids are getting older and demand of electricity is rising. The critical components in electricity transmission systems should be monitored for assessing the need for maintenance. The electricity grid works more reliable when the condition information of important components are available continuously and thus larger catastrophic failures are preventable.

Transformers are one of the 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 it is possible to detect developing failures and then a corrective action can be made in time.

This study focuses on the utilization of transformer condition monitoring system in traditional grid and in upcoming smart grid. The aim is to find out, where the condition monitoring data is needed in electricity transmission and distribution system management and how it is possible to carry the information to right place.

This thesis introduces first the basics of a power system, the construction of a transformer, transformer condition monitoring methods and condition monitoring data process. After that the management of a power system within traditional and smart grid is analyzed. The asset management process of both type power systems is explored through case study of transformer failure situations. In traditional power system the transformer maintenance bases mostly on time scheduled inspections. In smart grid the management is all time aware on the condition information of transformers which allows using of better fault prevention strategies.

KEYWORDS: transformer, condition monitoring, management processes.

VAASAN YLIOPISTO
Teknillinen tiedekunta

Tekijä:	Lasse Pakka
Tutkielman nimi:	Utilisation of transformer condition monitoring data
Esimies:	Professori Kimmo Kauhaniemi
Ohjaaja:	Professori Erkki Antila
Tutkinto:	Diplomityö
Koulutusohjelma:	Sähkö- ja energiatekniikan koulutusohjelma
Suunta:	Sähkötekniikka
Opintojen aloitusvuosi:	2006
Tutkielman valmistumisvuosi:	2013 **Pages: 87**

TIIVISTELMÄ

Sähköverkot ikääntyvät ja sähkön tarve on kasvamassa. Verkon kriittisiä komponentteja sähkön siirron kannalta tulisi valvoa, jotta voidaan arvioida huoltotarvetta eri komponenteille. Kun kunnonvalvontatietoa saadaan jatkuvasti, voidaan verkosta saada paljon luotettavampi, kun tiedetään, missä kunnossa verkon tärkeät komponentit ovat.

Muuntajat ovat kriittisimpiä komponentteja sähkönsiirrossa ja on tärkeää, että ne ovat jatkuvasti toimintakunnossa. Yleisesti muuntajat ovat luotettavia ja pitkäikäisiä komponentteja, mutta mitä pitempään muuntaja on käytössä, sitä herkempi se on vioille. Muuntajien kunnonvalvonnalla voidaan saada tarkka tieto muuntajan kunnosta. On-line kunnonvalvonnalla saadaan jatkuvaa kunnonvalvontatietoa, josta voidaan huomata kehittyvä vika tarpeeksi aikaisessa vaiheessa, jolloin voidaan tehdä myös korjaava toimenpide ajoissa.

Tämä tutkimus keskittyy muuntajan kunnonvalvonta järjestelmän hyödyntämiseen nykyisessä sekä tulevassa älyverkossa. Tavoitteena suunnitella, miten kunnon-valvontatietoa hyödynnetään sähkönverkon hallinnassa ja kuinka oikea tieto saadaan oikeaan paikkaan.

Työssä käydään aluksi läpi sähköverkon perusasioita, muuntajan rakennetta, muuntajan on-line kunnonvalvontamenetelmiä sekä kunnonvalvontajärjestelmään liittyvää dataprosessia. Sähköverkon hallintaa esitellään sekä perinteisessä että älyverkossa. Case tutkimuksen avulla käydään läpi muuntajan vikaantuminen kummassakin verkkotyypissä ja selvitetään, kuinka omaisuuden hallinta toimii eri tapauksissa. Perinteisessä verkossa muuntajien kunnonvalvonta perustuu yleensä tietyin aikavälein tehtäviin tarkastuksiin. Älyverkossa hallinta on jatkuvasti tietoinen muuntajien kunnosta ja tämä mahdollistaa tehokkaamman kunnonvaolvontamallin käytön.

AVAINSANAT: Muuntaja, kunnonvalvonta, sähköverkon hallinta.

1 INTRODUCTION

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

Transformers are not the only group of critical devices in power transmission. There are also other devices in the power transmission chain that need maintaining and condition monitoring. In sustainable power transmission system, the idea is to make the power transmission system to work better. Condition monitoring of components in power system is one step further towards sustainability in power supply.

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 packages and tasks. This research belongs to task 6.12 (Proactive condition monitoring) and the objective is to examine the utilization of various types of transformer condition monitoring data for traditional and smart grid asset management processes. 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 in sustainable power system. Condition monitoring sensors offer a certain kind data that needs to be processed in a specific format, which can be analyzed, saved and monitored. One task is to map the different condition monitoring data and to analyze, where the certain data is needed in power system management.

This thesis consists of six chapters: Introduction, Research methods, Electric power system, Transformer condition monitoring, Power system management and summary. The next chapter explains the research method and materials used in the thesis. The structure and devices and the maintenance of power system are introduced in chapter three. In fourth chapter the transformer condition monitoring technology is explored. The chapter includes modern on-line condition monitoring methods and the data process is also examined from sensor raw data into transformer lifespan predictions. The main focus is on the fifth chapter in which the power system maintenance process is studied. The chapter discusses on utilization of transformer condition monitoring within the power system maintenance process. Management process within traditional and smart grid is studied by using a case study of different types of transformer failure. The last chapter is for conclusion and summary part. In witch the basic issue is reviewed and discussed on the possibilities of transformer condition monitoring in a power system.

2 RESEARCH METHOD

The research bases mostly on previous literary researches. Basing on those researches the main aim is studied by case study of transformer failure situations. The automation level of power system is country specific. In some countries the level of automation in power system is minimal. In this research those systems are called traditional power systems. More developed power systems with high level of automation are called smart grids.

There is difference within power system management either a transformer fails in a traditional or in a smart grid. The power system management differs a lot between traditional and smart grid in which it is more advanced. Therefore in point of view of transformer failure in power system is studied through case study in both power system types in order to realize the difference.

The management process of power system is divided into four sections in accordance with Erkki Antilas (2009) study:

- Safety and protection management
- Operation management
- Asset management
- Business management

Case study is one type of qualitative research strategies in which the researched issue is studied individually by collection of detailed information from various sources. (Creswell 2009: 13) In this research the studied issues are the actions in power system management due to transformer failure. The study is limited to cover only asset management processes. For further research this topic could be expand to cover also other management processes like safety and protection management, operation management and business management.

3 ELECTRIC POWER SYSTEM

Electrical energy is the most universal form of energy because it can be transported easily at high efficiency and reasonable costs. (Murty 2011:1)

Supply of electricity is important in modern society. Since the invention of incandescent light bulb, the electricity consumption has been growing in whole world. The electricity is needed in everywhere within households as industry. Electricity has become a commodity that is expected to be available at all times regardless the ambient weather conditions, changes in energy consumption, production and other factors. Providing electricity with high quality is a challenging task for power system.

Electricity transmission and distribution networks are a part of the infrastructure. Reliability and quality of electricity are determined by properties of distribution networks. (Lakervi 2009: 9)

A power system consists of:

- Power transmission lines
- Power distribution lines
- Substations
    - Transformers for changing voltage levels.
    - Protection devices
    - Measuring devices

Power transmission systems function is to carry electricity from power plants over long distances for distribution networks and possibly directly to consumer like industry. The electricity is transferred with high voltage for avoiding power losses during transfer. Power distribution systems function is to carry electricity from power transmission system to end user. There can also be power plants connected to distribution network.

The power is usually transferred in transmission and distribution lines as three-phase alternating current by frequency of 50 or 60 Hz. Alternating current can be changed with a transformer. Induction motor can be driven by alternating current. The power can also be transferred with direct current. In this case the advance is that there is no need to transfer the reactive power.

3.1 Structure of power system

The primary aim of power system is to meet the customer's demands for energy. The system consists of generation, transmission system and distribution system. Power is generated with a variety of methods depending on the economics and the energy demands. The transmission system is used to carry the energy from the generation points to major load centers. The distribution system transfers the energy to customers with a suitable voltage level. (Holmes 1996:1)

In Figure 1. is presented a structure of a power system. From up to down there is generation units, step up-transformer, transmission lines, feeders, transformers between power systems, step-down transformers, generation unit and step-up transformer, step-down transformers, feeders and load.

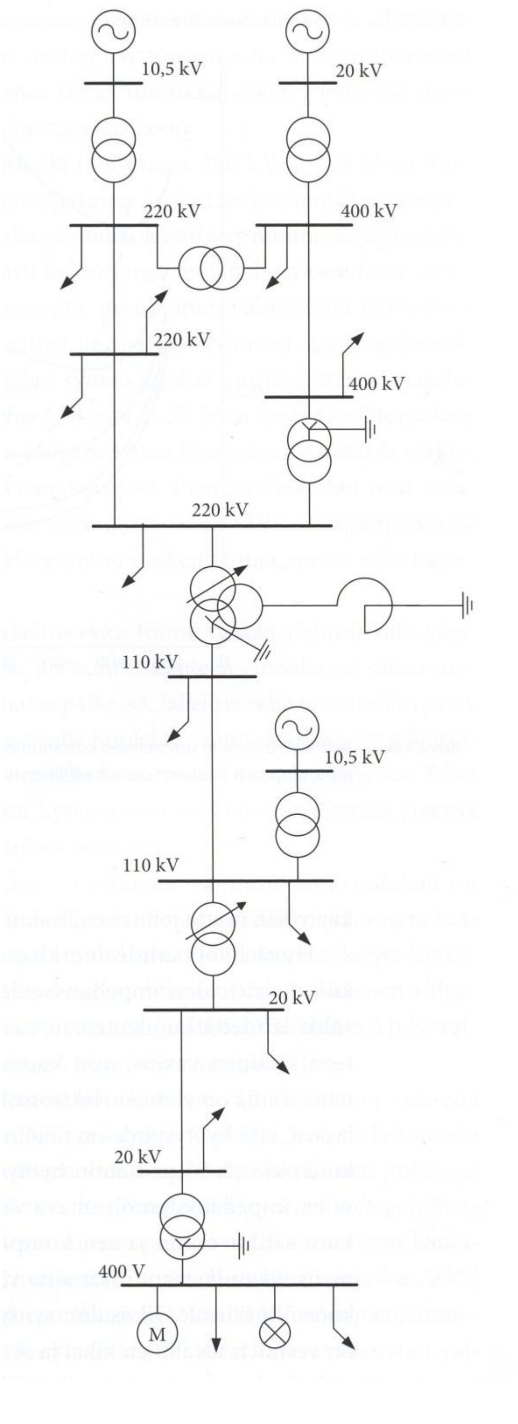


Figure 1. Power system (Elovaara 2011a: 55).

Power generation

Because the energy consumption varies and it cannot be significantly stored, the power generation and consumption should be equal continuously. The capacity of power generation should be so high that the power can be delivered even at the maximum consumption moments. There should also be power in reserve for preparing for a failure situation in power system. (Elovaara 2011a: 29)

Electric power is generated by changing a physical phenomenon into electrical energy. Power generation methods can be defined by the generator type or the use of production capacity.

Transmission systems

Tendency to high efficiency in power transmission signifies low transmission and distribution losses. The losses in power transfer, P_{losses} can be presented through equation.

$$P_{losses} = RI^2 \tag{1}$$

Where R is the resistance and I is the current of the power transmission system. So the losses due to transmission are increased quadratically by the level of current. The transferred power, P can be presented by equation.

$$P = UI \tag{2}$$

Where U is the voltage level of the power transmission. The higher the level of transmission voltage is the more power can be transmitted. Long transmission distance increases the resistance of transmission lines, so the transmission over long distance is better to be carried with high voltage for avoiding high power losses. When transferring a lot of power with a high level of voltage the device costs are high. (Elovaara 2011a: 54)

Commonly followed principle is that the relation of transmission voltage level between sequential networks is at least two. Especially this principle is followed when building new transmission systems. In Finland voltages of 24 kV / 400 V, 110 kV / 24 kV and 420 kV / 110 kV are used between sequential networks. So the relation between sequential networks is typically 4 - 6. There are also some old networks with special voltage level that are still maintained. With those networks the relation can be fewer than two. (Elovaara 2011a: 54)

The efficiency within power transmission is intended to be over 95 %. Therefore the impedance of load must be much higher than impedance of transmission system. Hence the short circuit currents are much higher than load currents. Short circuit is a normal fault in power system and it can occur at any voltage level. Possible causes of short circuit are thunder, faulty connection or insulation fault. When designing a power system, fault currents must be taken into account. (Elovaara 2011a: 56)

In transmission systems the power lines are usually constructed to shape of mesh or loop thus substations can be connected to several transmission lines which increases reliability. (Elovaara 2011a: 57)

In high voltage (400 kV and 220 kV) transmission system the closed loop network configuration is applied for better reliability, lower losses and voltage drop. But the downside is that the protection relays are much more expensive in closed loop systems than in radial systems. If two parallel lines with different voltages levels are connected to each other through a transformer and feeds power forward and there occurs a failure in other line which leads to a relay tripping the remaining line could be overloaded in this situation especially if the voltage of the tripped line is higher than the remaining line. For this reason the looped networks in 110 kV and 20 kV systems are kept open and loop connections are used only when changing network configuration and for troubleshooting. (Elovaara 2011a: 57)

Distribution networks typically transfers the power in one direction. If there are generation in distribution network the generated power must be consumed at the same place. Distribution network can’t transfer the power to transmission network with old protection devices. When fault occurs the fault current can come from both directions. Distribution networks need updates to work properly when distributed generation is connected. (Elovaara 2011a: 57)

The tree-phase alternating current is most commonly used in transmission and distribution networks. In Europe the frequency of 50 Hz is used in power systems but in United States, South-America and in some places in Japan it is used the frequency of 60 Hz. The advantages of ac electricity are the facility to transform the level of voltage to another level with a transformer. The difference between one-phase system is that there are no need for return conductor in the three-phase system. (Elovaara 2011a: 57)

Substations

Substations are nodes between networks. Task is to transfer or feed the power. The construction depends on whether there is generation unit or is it just switching station or is it for changing the voltage level. (Elovaara 2011b: 96)

In distribution networks the most important components of the grid are substations. Substations location and size defines the MV lines length, values for operation and probably back-up connections. (Lakervi 2009: 119)

Substation between HV network and MV network may consist of HV switchgear, one or more power transformer, MV switchgear and auxiliary voltage systems for auxiliaries. In countryside the substation devices are traditionally isolated from each other by air. Air-insulated devices need relatively a lot of space around. In urban areas the switchgears are commonly gas insulated systems for reasons of small space requirements. (Lakervi 2009: 119)

A high voltage substation can have multiple feeders which allows to change feeding directions and depending on the busbar system it may be possible to link radial system to meshed or looped system. For maintenance and fault condition there can also be back-up feeders. (Lakervi 2009: 119)

Transformer is most expensive component in a substation. Transformers rated power affects MV networks short-circuit currents in fault situation. The higher the rated power of transformer is the lower is the impedance of transformer and with low impedance the short-circuit current is higher. In substations the transformers are selected so that the actual power taken of the transformer is below the rated power thus the transformer has reserve capacity which is needed in failure situations. If a transformer failures nearby it is possible to use the other transformers with higher loading. (Lakervi 2009: 121)

MV switchgear substation is switching point between the main transformer and MV feeders. There can be different system of busbars in substation. In substations with a single transformer it is usual to apply a single busbar scheme or a main and auxilary busbar scheme. The feeders are connected to main busbar. In every feeder there is circuit breaker and disconnector on both sides of the circuit breaker. In substations with main busbar and auxiliary busbar the circuit breaker and disconnectors can be bypassed with the auxiliary busbars disconnector. The feeder circuit breaker can be serviced when the power is transferred through auxiliary busbar. (Lakervi 2009: 121)

3.2 Components in substation

The main components in a substation are:

- Circuit breakers
- Disconnectors
- Instrument transformers
- Compensation devices
- Surge arresters
- Transformers

3.2.1 Circuit breaker

Circuit breaker is a switch that is used to control the transfer route of electricity or to separate a failing part of grid of the operating grid. Circuit breaker has two operation modes. In conducting mode the circuit breaker conducts the load current through with low losses and in breaking mode the circuit breaker changes the conductor into insulation. (Elovaara 2011b: 161-162)

Circuit breaker can be controlled manually or automatically through relay. Usually the relay gives the command to disconnect due to overcurrent. The relay receives the measurement data from instrument transformers. The reconnection can also be made automatically for example by the relays reclosing system. (Elovaara 2011b: 162-163)

The circuit breakers operation can be defined so that the breaker can without any damages connect and disconnect a circuit in which the level of the current is many times higher than the nominal current of the circuit breaker. (Elovaara 2011b: 162-163)

3.2.2 Disconnector

When it is time to service some part of the power system, it is important that the serviced part is disconnected from power supply. This is possible by disconnector that was mentioned in previous chapter. The function of disconnector is to form safe opening between the circuit and the other facility of substation. And it has to be able to unenergize the certain parts for safe working. (Elovaara 2011b: 190)

The difference between circuit-breaker and disconnector is that the circuit-breaker is designed to break high currents whereas the disconnector is designed to connect or disconnect unloaded circuit. Therefore the high breaking capacity is not required for the disconnectors. But the short circuit currents and normal loading current must be conducted through closed disconnector without problems. For security reasons the disconnector has to be able to be locked in the open position in order to prevent the risk of causing danger to worker. In disconnector the opening gap between circuits must be extremely trustworthy because of the functions of the disconnector. For safety reasons there has to be visible indicator of the operation mode in order to see is there energized parts in the system. Also for safety reasons the voltages withstand for open disconnector must be higher than surrounding insulations for example between phase and ground in order to prevent breakthrough through the disconnector which may cause personal injury. (Elovaara 2011b: 190)

3.2.3 Instrument transformer

Instrument transformers are intentend to be used for measuring of voltage or current. Its functions is to isolate the measuring circuit galvanically from the main circuit. With suitable transformation ratio the measured signal allows to standardizing of the measure and protection devices for certain rating values. Also the instrument transformer protects the measuring devices for overloading. Instrument transformer makes it possible to place the measuring devices and relays far from the actual measuring point for centralized measuring. (Elovaara 2011b: 198)

The function of instrument transformer can be studied by equivalend circuit for normal transformer. The main difference is on the secondary windings, in current transformer it is almost short-circuited and in voltage transformer it is nearly unloaded. The function of instrument transformer is to convey the measured voltage or current on the normal range with good quality. (Elovaara 2011b: 198)

Most of the instrument transformers operation bases on electromagnetic induction but also capacitive instrument transformers are used. Optoelectronics based transformers are economically compatible within voltage rating of 400-500 kV. (Elovaara 2011b: 198)

3.2.4 Compensation devices

When a power system is compensated, it means that the reactive power is produced nearby where it is needed and therefore the reactive power is not needed to be transferred through power lines and the transmission capacity may be used almost for transmission of active power. (Elovaara 2011b: 225)

Reactive power in distribution system is typically produced by shunt capacitor banks. For transmission system in addition to shunt capacitor banks the reactive power is also produced by shunt reactors. The reactors are used to compensate the reactive power that is generated by transmission lines with low loading. (Elovaara 2011b: 225)

3.2.5 Surge arrester

Surge arrester is used for overvoltage protection on all voltage levels in transmission and distribution systems. Those can be used for locally reducing the transient overvoltage. To provide a comprehensive protection of overvoltage on power system using surge arrester at several point in power system is required. So the overvoltage protection must be taken in to account in designing of power system. The surge arrester doesn't protect from overvoltages with frequency near to network frequency but it provides good protection against thunder strikes. (Elovaara 2011b: 237)

3.3 Transformer

According to IEEE:s definition of transformer 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)

Benefits of the mutual coupling between circuits are:

- Direct current isolation between circuits
- Changin the level of voltage or current to be suitable in order to match two different circuits.
- According to the coupling of transformer it is possibility to make phase-shifting from primary to secondary circuit.

In power system, transformers are used to link together two or more power systems of different voltage levels. In order to carry the power through the transformer current must also be changed with changed voltage level according to transforming ratio. The frequency between primary and secondary windings will be same. Depending on the coupling of transformer there can be phase shifting in current between primary and secondary windings. (2011b: 141)

Power transformers are used in transmission system between a generator and transmission lines to raise the level of voltage to suitable for transmission. Transformers can be classified in accordance to the power rating. Transformers with power rating of 500 kVA and above are used usually called as power transformers. Smaller are used in distribution systems for lowering the voltage level from transmission system or distribution system to secondary distribution system or to a consumer's service circuit.

Electronic power transformer

As power and distribution transformers, a new type of transformer, electronic power transformer is coming. It is based on power electronics and the advances are that magnitude and phase angle of voltage can be controlled in real-time. A further advance with the electronic power transformer is that flexible current and power regulations may be achieved so that the device has the functions of flexible ac transmission system. (Lu 2009)

Phase shift transformer

One special type of power transformers is phase shift transformer which can be used for controlling the power flow by changing the angle of voltage. This type of transformer can be implemented with a tap-changer or with a tyristor controlled device. Phase shift transformer with tap-changer can be used in continuous state for controlling the power flow but it cannot be used for rapid adjustment of power. Phase shiftin transformers are used in power systems for controlling power flow between parallel power lines. Addition to normal control, tyristor controlled phase shift transformer can be used for controlling the dynamical features of the power system but there may be more power losses with tyristor controlled system. (Elovaara 2011a: 343)

Transformer structure

According to definition, Transformer is a static device in which the basic operation relies on the mutual coupling between windings with or without a magnetic core. Usually the power transformers are built with the magnetic iron core consisting of laminated plates for better efficiency and minimising of eddy current losses. (Hietalahti 2011)

Most of the power and distribution transformers are three-phase transformers but also, single-phase or multi-phase transformers can be made. (ABB Group 2004)

A winding in a transformer consists of conductor that is wounded around a section of the core. The conductor must be well insulated, supported, and cooled for withstanding mechanical and electrical strain. (Harlow 2004)

Schematic of structure of single-phased transformer is presented in Figure 2. The transformer consist of two windings, both with own limbs, first is the primary side and the other is the secondary side of the windings. Three phase-transformers differs from this single-phased transformer so that in addition to the number of phases, the primary and secondary windings are usually wounded at same limb. Schematic of the structure of three-phase transformer is presented in Figure 3.

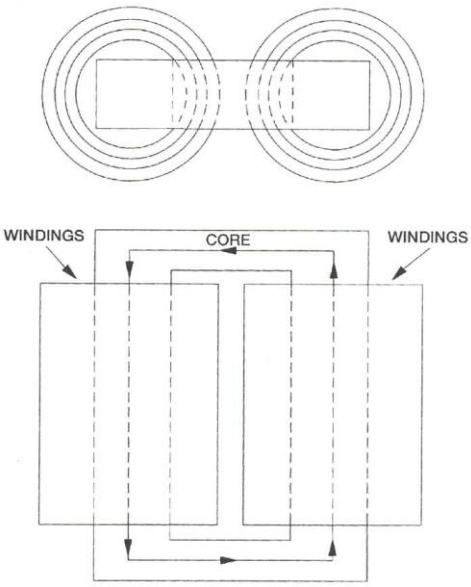


Figure 2. Shematic of single-phased transformer core-form construction (Harlow 2004).

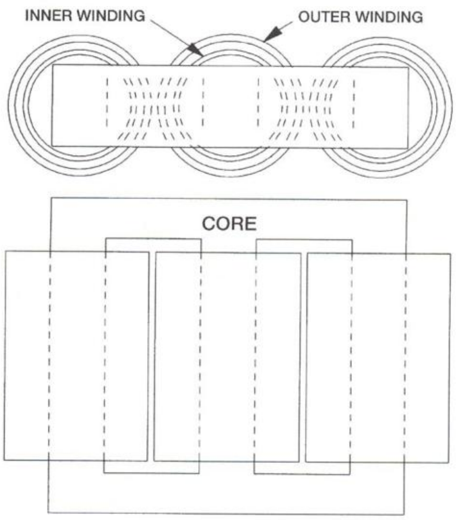


Figure 3. Shematic of three-phased transformer core-form construction (Harlow 2004).

3.3.1 Transformer components

Tap-changer

Tap-changer allows to adjusting the voltage output of transformer by connecting extra turns to the secondary windings. This also changes the transformer ratio. A tap-changer can be driven manually via a switch or with a motor. Tap-changer switching devices are usually mounted separately on the side of a transformer tank with own insulation medium but it is also possible to mount a tap-changer inside a transformer tank. Separate installation provides easier maintenance whereas the merged installation provides a compact transformer design and keeps costs down. (Bayliss 1996: 497)

Cooling

An ideal transformer changes voltage from primary to secondary without losses. But such a transformer is impossible to implement because of alternating magnetic fields in the transformer system. This influences everywhere in the transformer making forces, heat, sound and possible other phenomena these are reflected to transformer losses.

Heat is one of significant part of the losses. Most of the heat is generated in windings and transformer core by influence of alternating magnetic field. The temperature of the transformer is designed to be within specific limits so usually a transformer needs also some kind of cooling system which depends on transformer type, size and temperature requirements. (Harlow 2004)

Simplest cooling method is radiation from transformer tank. Oil acts as heat exchange medium that conducts the heat to the transformer tank where the heat is radiated to surrounding air. This usually works only with smallest distribution transformers. Bigger transformers need radiators for properly heat dissipation. With higher ratings a transformer may need external cooler banks where the oil circulates and exchanges heat. The oil circulation can be as “natural” meaning that the oil circulates by the temperature difference. Cool oil comes down and hot oil goes up. If cooling efficiency needs to be increased it is possible to use fans with radiators for moving cooling air through the radiator surfaces. Also the “natural” oil circulation can be boosted with oil pumps for effective heat exchange to cooling devices. (Baylis 1996: 526-528)

3.3.2 Aging of transformer

As a transformer ages the probability of failure is higher and the repair time is longer until the transformer reaches its end of life. In accordance with Abu-Elanien et al (2010: 460) there are three different concept of power transformer lifespan. One is the physical lifespan, other is technical lifespan and the third is economic lifespan. Physical lifespan comprises the lifespan from start point of the transformer until the point when the transformer cannot be used anymore in its normal operation conditions despite any repair action. Technical lifespan represents a lifespan if the transformer needs to be replaced due to technical reasons like the lack of spare parts. In this case the transformer may not reach the end of physical lifespan. Economic lifespan depends on the condition of the transformer. Every year the capital value of transformer is depreciated. Once the capital value of transformer reaches zero, the transformer is at the end of economic lifespan despite that the transformer is not at the end of the physical lifespan.

The solid insulations of a transformer are usually based on cellulose. The cellulose insulation is continuously affected with heat, oxygen, water and other chemicals causing the insulation to degrade as electrical and mechanical aspects. This degradation of the insulation can be considered as the main reason for transformer aging. Abnormal operation conditions like overloading for a longer period or non-sinusoidal loads or failure situation in the power system may speed up the aging process. The physical aging can be divided into intransitive aging and transitive aging. (Abu-Elanien 2010: 460)

Intransitive aging comprises the aging of solid insulation material due to normal operation conditions. The solid insulation material has ability to withstand the designed stresses like electrical, mechanical or thermal effect for a period of time. The insulation ability of the solid insulation decreases over time until the transformer is not anymore in operation conditions. (Abu-Elanien 2010: 460)

Transitive aging of a transformer comprises a situation in which the transformer is subjected to abnormal operation conditions such as overloading, supplying non-sinusoidal loads, or exposure to high temperature. The hot spot temperature is the main reason for acceleration of the aging process. (Abu-Elanien 2010: 461)

3.4 Power system automation

The power system is designed to be operated as remote-controlled system in which the measurements can be read remotely, devices can be operated remotely and local operations can be automated. Relay protection is a typical automated local operation. Nowadays the substations are not occupied and the operations at substation are remote controlled and monitored. (Elovaara 2011b: 385)

The power transmission and distribution grids are located in a wide area so the centralized remote control of the system needs to be aware of the quality of the grid and the level of technical operation for example supply reliability and failure duration. The remote control can be used for controlling, measuring, adjusting, configuring and notificating. The remote-controlled system also contributes to savings in personnel costs. (Elovaara 2011b: 385)

The control system of power system is typically hierarchical system. In Finland the transmission system operator manages the whole 400 kV and 220 kV transmission grids and electricity transmission in those. It’s important to collect from the grids with lower voltage levels such information that may have effect on whole grid. One task is also controlling such devices in 110 kV power systems that may have effect on operation of whole power system. 110 kV power systems are usually managed by regional transmission system operator or transmission system operator. Within distribution grids the management is similar to the higher voltage levels and it’s the responsibility of distribution system operators. In any case the controlling and monitoring of devices is carried out by remote controlling system or local controlling. (Elovaara 2011b: 385)

The main task of the power system management is to take care of the energy transmission process with assistance of monitoring and controlling operations. Those management functions consist of balancing the produced and consumed power and to control the electricity to be transferred by most economical and reliable route. This requires gathering and processing of data and also data exchange between operators. The amount of collected data is huge. It consists of voltages in different locations in grids, currents through wires, power losses in wires, states and operations of switchgear. This wide data collection system is called supervisory control and data acquisition – system (SCADA). (Elovaara 2011b: 386)

Substation automation system

Substation automation system is commonly capable to

- Provide local or remote access to system.
- Permits locally manually and automatically operations
- Takes care of the communication link, connections, and codes the signals in accordance to specific protocol so that communication between different devices would be possible.

Substation controlling is based on controlling of electrical devices through control-reset switches. Substation is divided into feeder bays. Each feeder bay has own electrical cabinet in which it is gathered information about the state of the feeder from every device in the feeder bay. In traditional substation the gathered information is in analogical format. Basically all the protection relays are in cabinet according to feeder bay, but in some cases several relays can be in same cabinet like in some bus bar protections. Local data is used to operate feeder by controlling and adjusting (for example adjusting voltage and controlling of reactive power), for feeder bay and larger area protection, as well as for disturbance and event recording. Remote terminal unit (RTU) is the substations communication terminal which sends the required information to SCADA-system. RTU features multiple inputs and outputs. (Elovaara 2011b: 388)

The advantages of digital system is that the aging processor doesn't distort the data like aging parts in analogical circuits. If the analog to digital converter works properly the converted data can be more accurate and it can be saved so that it remains longer. Data transmission is most simply implemented by transferring the data in serial form. In this case the data transmission could be carried out by a fiber-optic cable. The data transmission is also possible in parallel form in which case there is needed parallel wires or fiber-optic cables. Efficient processors and large capacity of memory enables to carrying out various functions. It can be used to automated monitoring and controlling which improves the reliability and usability if a failure is detected at early stages. Reverse side of digital system is that data transmission in serial form causes delays. The surrounding magnetic and electric fields may generate disturbance so the automation system and data transmission system must be well designed. It may be problematic to link devices from different manufacturer because of some of the manufacturer use their own standards. Nowadays the standard series IEC-61850 has improved the device compatibility. (Elovaara 2011b: 388)

Digital substation automation system collects and stores information that is associated to the substation or its devices and the surrounding power system. The data is coded in communication interface with certain protocol for data transmission between devices and systems. The automation system calibrates the device clocks usually with the GPS-system (Global Positioning System) since all devices should operate on real-time and the time stamps should be comparable. (Elovaara 2011b: 389)

In future the substation automation could be totally digitalised system in which the data exchange between processes is implemented through I/O-units, smart sensors and actuators via process bus. Process bus is connected to feeder based control and protection devices: intelligent electronic devices (IED). Intelligent electronic devices exchange data between each other and upper levels (server) via interbay bus. The substation devices are connected to substation bus for communication between other substations and upper level monitoring systems. (Elovaara 2011b: 390)

Remote operating system

The power system automation can be divided into steps by their functions. Those steps form a hierarchical system in which there is central operator, areal operator, substations and power plants. It depends on electricity supplier how the remote system is used. Remote control connections are generally designed to carry the data in both directions.

3.5 Power system maintenance

The power system consists of a lot of components each of which has a specific task. Power reliability and quality depends mostly on the condition of switchgear, power lines, transformers, circuit-breakers, disconnectors etc. To ensure that all the devices works correctly there have to be a maintenance strategy. Maintenance strategy can be classified into corrective maintenance and preventive maintenance strategies. (Ahmad 2012:135)

Corrective maintenance is a strategy that is utilised to restore some equipment to its required function after failure. In accordance with corrective maintenance a typical maintenance function is to repair or replace a broken device. The strategy leads to high levels of machine downtime and maintenance costs. (Ahmad 2012: 135)

Preventive maintenance is an alternative strategy to the corrective maintenance strategy. With preventive maintenance the objective is to reduce the failure rate of the equipment and it aims to minimising failure costs and machine downtime and increasing product quality. Preventive maintenance strategy can be performed on experience or equipment manufacturer recommendations. Usually the preventive maintenance is performed at regular time intervals. (Ahmad 2012: 135)

This chapter focuses more on the preventive maintenance strategies which are utilised on the asset management of power and distribution transformers.

3.5.1 Time-based maintenance strategy

Time-based maintenance decisions are decided based on failure time analyses. Within time-based maintenance it is assumed that the failure behavior of the equipment is predictable and it is based on failure rate trends. (Ahmad 2012: 136)

As shown in Figure 4 the failure rate trend is divided into three sections: burn-in, useful life, and wear-out. It is assumed that failure rate is high at beginning of the device life cycle and then constant at useful lifetime and the end of life cycle the failure rate becomes high. (Ahmad 2012: 136)

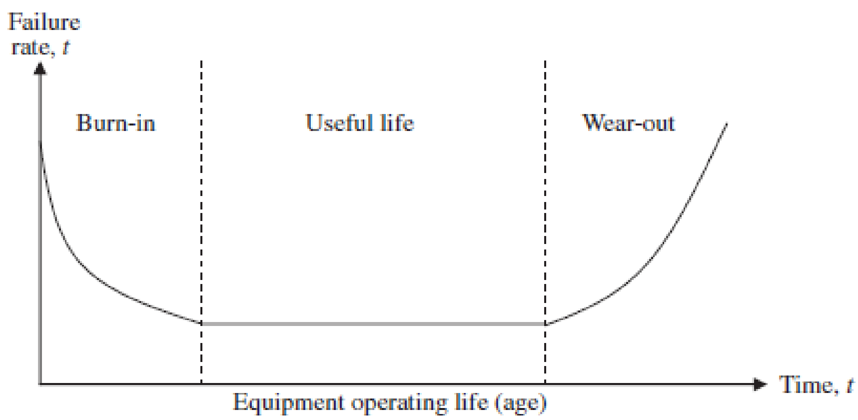


Figure 4. Equipment operating lifespan (Ahmad 2012: 136)

The Time-based maintenance process can be divided in two parts, one is failure data analysis/modelling and maintenance decision making. The purpose of the analysis/modelling process is to examine the failure characteristics of the equipment based on the gathered failure time data. (Ahmad 2012: 136)

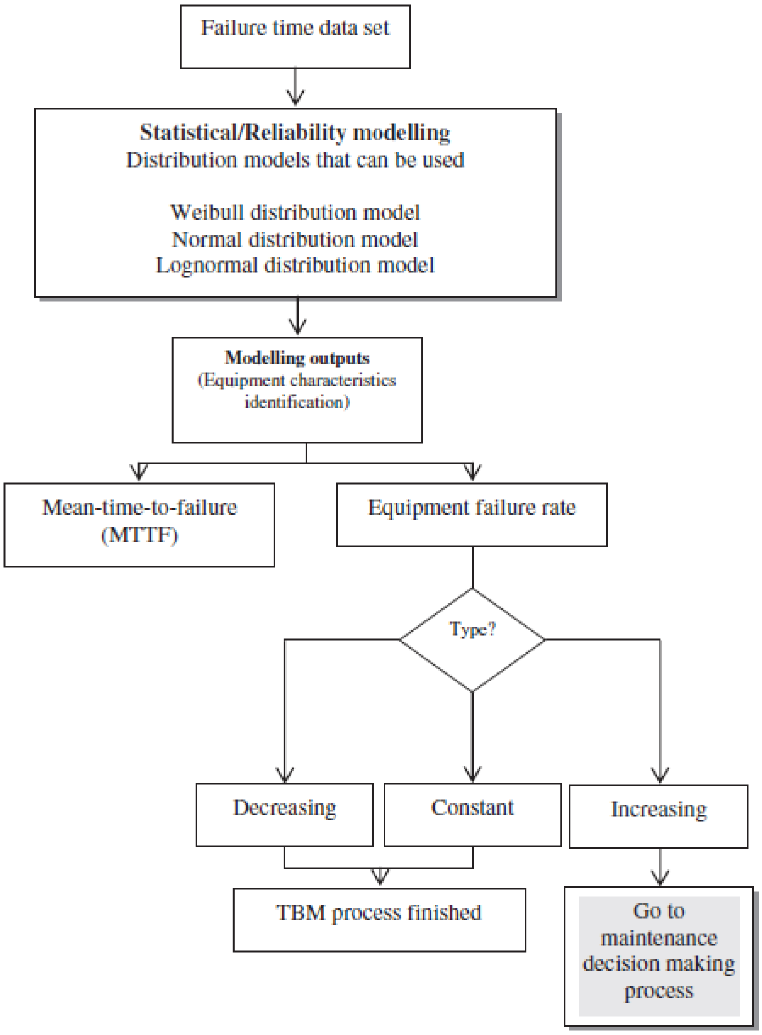


Figure 5. Failure data analysis. (Ahmad 2012: 137)

The failure data will be analysed through statistical/reliability modelling to indentify the failure characteristics of the equipment. That includes mean time to failure estimation and the trend of the equipment failure rate. There are mentioned different statistic tools for analysis like Weibull distribution, normal distribution and lognormal distribution model. Weibull distribution model is the mostly used to model the failures of several materials because of its ability to model various aging classes of lifespan distribution rates. If failure rate increases it is time to go to maintenance decision making process. (Ahmad 2012: 137)

Maintenance decision making is the next step of time-based maintenance process. The main objective is to find optimal maintenance policies that aim to provide optimum system reliability or availability and safety performance at the lowest possible maintenance costs. The decision making process consists of two sections. First task is to assess the total costs of preventive maintenance and failure costs. Second task is to assess that is the device repairable or non-repairable which depends on the device structure. (Ahmad 2012: 137)

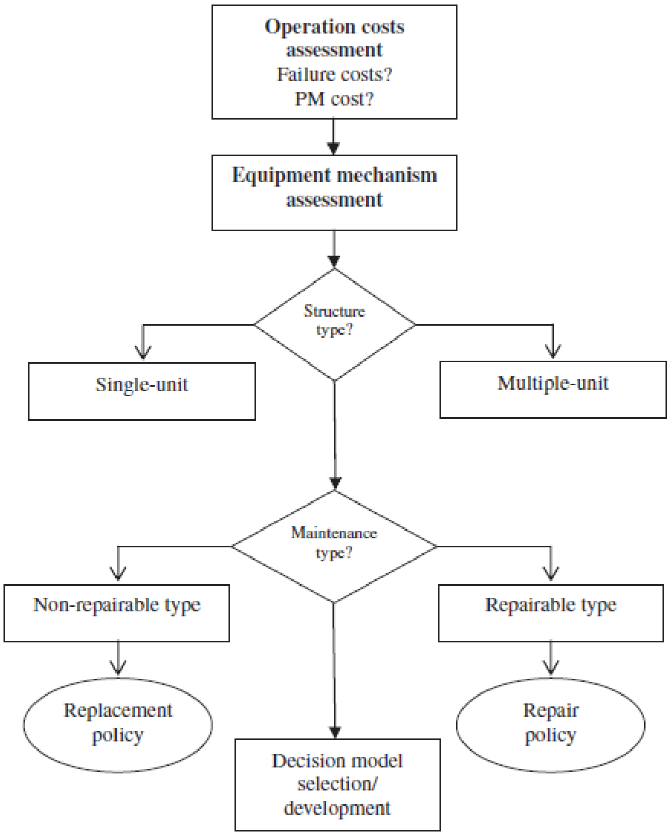


Figure 6. Maintenance decision process. (Ahmad 2012: 137)

Appropriate maintenance function can be selected after the structure of device has been identified. For non-repairable devices, the replacement policy is used and for repairable devices, the repair policy. (Ahmad 2012: 137)

Within time-based preventive maintenance strategy the actions are carried out at a certain intervals for example every 1000 hour or every 10 days based on recommendations. This is not usually effective for minimising operation costs or maximising machine performance since of each machine works in a different environment and would therefore need different maintenance schedules. Other reason is that the designer may not have the experience on machine failures like the maintenance engineers and technicians have. Also the original equipment manufacturer may have own objective for maximising the spare parts replacement through frequent maintenance actions. (Ahmad 2012: 138)

3.5.2 Condition based maintenance strategy

Condition-based maintenance is a type of predictive maintenance in which the maintenance functions are recommended based on the condition monitoring information collected through condition monitoring process. With condition monitoring process it is possible to monitor the device by various monitoring parameters like vibration, temperature, oil composition, discharges or noise levels. It is depending on the devices type which condition monitoring method is/are suitable. This thesis focuses on transformer condition monitoring and the most common monitoring methods are introduced in following chapter. Almost all of the equipment failures can be discovered beforehand with condition monitoring system making it possible to prepare for preventive action. Therefore condition monitoring based maintenance is needed for more efficient device management, lower life cycle cost, and preventing catastrophic failure. (Ahmad 2012: 140)

The main target of condition based maintenance is to make real-time assessment on the condition of equipment in order to carry out maintenance decisions. This reduces the unnecessary maintenance and related costs. (Ahmad 2012: 140)

The condition monitoring process can be divided in two parts. First, it is needed to collect the condition data of the equipment. Second, the condition monitoring data can be processed to increase the knowledge of the failure causes and effects and the characteristic deterioration of equipment. (Ahmad 2012: 140)

Condition monitoring process can be carry out into two ways depending on the operation state of equipment. Equipments on running state can be monitored by on-line condition monitoring techniques, while off-line condition monitoring techniques can be used when the equipment is not running. Condition monitoring can be performed either periodically or continuously. (Ahmad 2012: 140)

Maintenance decision making within condition monitoring based maintenance process can be classified in two parts: diagnosis and prognosis. Diagnosis is a process which is used to find the source of fault. Prognosis is a process which estimates when the failure may occur. (Ahmad 2012: 140)

The main purpose of diagnosis is to provide early warning signs to engineers when the monitored device is operating in abnormal conditions. The device running in abnormal conditions does not mean that the device has already failed. It may still be used for a certain amount of time before failure occurs. The main aim of prognosis is to make estimations about the devices life expectance or upcoming failure. With the prognosis information the preventive maintenance actions can be intensified in appropriate time just before device failure. (Ahmad 2012: 140)

Decision making can be performed based on two methods: current condition evaluation-based (CCEB) and future condition prediction-based (FCPB) method. The CCEB method estimates the current condition of equipment and the appropriate maintenance is carried out if needed. With the FCBP method it is intended to predict the future trend of the equipment condition and the appropriate maintenance is planned and scheduled if needed. (Ahmad 2012: 140)

Advantages of condition-based maintenance for transformer asset management are:

- Maintenance action is performed when it is needed.
- Savings on the costs of unnecessary inspections and manpower.
- Decreasing the unnecessary shutdowns of the system.
- Decreasing the probability of serious failure.

4 TRANSFORMER CONDITION MONITORING

Power transformers are one of the most important equipment in a substation and also the most expensive. Within electricity transmission a transformer has a significant role of changing voltage level from power system to be suitable for another. Power transformers are nodes between power systems. The key transformers in a power system should be monitored continuously in order to ensure their maximum operation time and keeping the power system in operation (Tang 2011).

Power transformers are sensitive and critical part in power transmission. If a transformer fails it may cause stopping of energy transmission for a certain area if there is not any back-up connection. Without back-up connections, electrical devices which are feeded only through the failed transformer, freezes. Usually a power transformer failure causes economical damage, particularly within industry area. Also a transformer failure may lead to a material damage, personal injury or oil spill to nature. (Abniki 2010: 1)

Life expectance of a power transformer is around 40 years. Investments made in 1970s in power systems causes that nowadays the percent of transformers operated more than 30 years is increasing. Therefore the transformer failure statistics is expected to rise in the coming years. Transformer failures are sometimes catastrophical and usually include irreversible damage in transformer. (Tang 2011)

The lifespan of transformer depends mostly on the condition of winding insulation, but also mechanical factors like core clamping and auxiliary devices like oil pump or radiator. The windings are affected by insulating oil, normal loading, and through going fault currents. For measuring the condition of transformer there have been developed different condition monitoring techniques which are introduced in following sections.

According to Han (2003: 4) condition monitoring has potential to

- Reduce operating costs
- Improve reliability of operation
- Enhance power supply

- Improve service to customers

By using condition monitoring system it is possible to prevent unwanted transformer failure. By detection of evolving fault at early stage makes possible to do necessary service actions in time. (Abniki 2010:1)

4.1 On-line condition monitoring methods

The online monitoring system will be an important component of the secondary system of the smart substations. It will be the primary data source of the status of primary equipments. In the following sections the most common and some interesting condition monitoring methods are introduced.

4.1.1 Dissolved gas analysis

If a transformer is going to have a failure it will provide information at an early stage by quantity of dissolved gases in oil. With dissolved gas analysis it is possible to determine if inside the transformer occurs arcing, oil overheating, corona, system leaks, over-pressurization, changes in pressure or temperature (Khan 2007: 5-6). Thermal aging produces dissolved gases in oil and thus provides an early indicator of an incipient fault (Gockenbach 2010: 28).

Traditional way to measure different gases is gas in oil analysis in which oil sample is taken and analysed in laboratory. This requires resources: transporting samples to laboratory, laboratory tests, documentation, and actions if something is found in oil sample. This could be intensified by performing the analyse near to transformer automatically. With on-line dissolved gas analysis technique it is possible. The oil sample is analysed periodically and the findings could be read in control room of the power system or probably in substation control room.

On-line dissolved gas analysis is modern way to analyse gas concentrations, condition, and ratios. The most common method is related to hydrocarbon gases which are methane, ethane, ethylene and acetylene. This method is based on combustion. Observation shows that hydrocarbon gases are produced during rapid temperature growth. (Abniki 2010: 3)

Another on-line dissolved gas analysis method is to compare the quantities of solution gases to each other basing on photo-acoustic technique (Abniki 2010: 3).

Gas concentrations, condition, and ratios of components can identify the reason for gas formation and indicate the necessity for further maintenance (Gockenbach 2010: 28-29). In Table 1 it is presented a variety of fault gases and problems that they indicate.

Table 1. Fault gases (Khan 2007: 6)

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 monoxide)	Overheated cellulose	Arcing if the fault involves cellulose
CO_2 (carbon dioxide)	-	Overheated cellulose, arcing if the fault involves cellulose
O_2 (oxygen)	-	Indicator of system leaks, overpressurization, or changes in pressure or temperature.
N_2 (nitrogen)	-	Indicator of system leaks, overpressurization, or changes in pressure or temperature.

4.1.2 Partial discharge detection

Insulation condition is a large factor in transformer lifetime expectations. An insulation material decomposes a little bit in normal operation and more by influence of through going fault currents or high temperature that may be caused of high loading of transformer or auxiliary faults. Partial discharge detection is one of the effective methods of diagnosing insulation faults (Abniki 2010:4). The insulation material decomposes for a long time until insulation damage is severe.

Every time when partial discharge occurs, it deteriorates the insulations material. Partial discharge affects the insulation material by high-energy electrons that cause a chemical reaction in insulation material. During the chemical reaction in insulation there will be emitted noise with ultra-high frequency. Most of incipient dielectric failure generates discharges for a long time before the catastrophic failure but it is also possible that the catastrophic failure happens suddenly and the occurrence of partial discharge may appear just a little before. If the occurrence of partial discharges increases it can be concluded that an insulation fault is upcoming. (Norick 2004)

There are three techniques for partial discharge detection

- Ultra-high frequency detector
- Acoustic wave detector
- Fiber optic sensor

During an insulation failure, partial discharge produces waves from 300-1500 MHz that can be detected by ultra-high frequency detector. Also the partial discharge affects to transformer oil by emitting pressure waves which are transmitted through the oil. With acoustic wave detector is possible to detect the waves. The advantage of these two techniques is that the fault point can be located exactly by placing several sensors around the transformer. Disadvantage of these techniques is that the sensors are affected by the electromagnetic interference of the substation environment. In order to reach reliable measurements the signal to noise ratio should be improve by signal processing techniques. Fiber optic sensor uses a laser diode and fiber optic coupler to detect partial discharge. In the coupler the air gap is changed by the pressure waves through oil. (Norick 2004)

4.1.3 Thermal analysis

Generally the power rating of electrical devices are determined based on the maximum withstand of temperature for isolation for certain period of time (Penman 2008). The life expectancy of transformer is related to thermal deterioration speed of isolation caused by the daily loading cycle (Tang 2011). In addition to daily loading cycle, faults in power system, inside transformer or transformer auxiliary affects also the temperature of transformer. Therefore, the monitoring of temperatures has an important role on transformer condition monitoring.

Temperature monitoring through thermal sensors is one of the simplest ways of transformer condition monitoring. Changes in temperature usually appear if there is a fault occurring in the transformer. Increase in temperature causes damage in the insulation of windings and dielectric constant of oil will be reduced. (Abniki 2010: 3-4)

There are three basic approaches to temperature monitoring

- Local temperature measurement from certain spots of the transformer.
- Thermal images to monitor the surface temperature of transformer.
- Distributed temperature measurements from the transformer body or bulk temperature of cooling fluid.

The local temperature measurements are performed at certain spots in the transformer windings or core, usually at the points where the temperature is highest. This can be carried out by using thermocouple sensor, resistance temperature detectors or embedded temperature detectors. The problem in winding temperature measurement is the insulation of the sensor from windings. So for winding temperature measurements the only way seems to be of using embedded temperature detectors like fiber optic sensing techniques. With the two other type of temperature sensors can be used for core temperature measurements. (Han 2003)

According to (Gockenbach (2010: 32), Thermovision is a non-contact monitoring method for fault detection in industrial system during operation and without interruption of the technological process. Thermo graph method provides information of temperature by monitoring the surface of transformer with infrared camera. Camera records the thermal field as infrared image where the temperature difference can be seen on the surface. This technique could also be exploited for monitoring of all substation devices through controllable infrared camera.

Temperature measurements of the transformer body or bulk temperature of cooling fluid can be used to hot-spot calculations. The hot-spot temperature can be calculated from the ambient temperatures and the mixes top-oil temperature. (Han 2003, Tang 2011)

4.1.4 Vibration analysis

A transformer vibrates constantly during normal operation because of the influence of alternating magnetic field generated forces between the primary and the secondary windings. This is natural vibration of transformer and it cannot be eliminated. By monitoring the vibration level it is possible to detect if the transformer is not working properly. The level of vibration may be increased because of electrical or mechanical effect. Below it is listed a few possible reasons for high level of vibration: (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 analysis is newish method within transformer condition monitoring but it is more used in rotating electrical machines more. Measuring techniques can be divided into accelerometers and velocity meters. The sensor must be chosen for certain range of vibration for accurate measurement results. SKF provides a variety of different vibration sensors for condition monitoring purposes.

4.1.5 Moisture monitoring

Water in oil indicates the aging of cellulose insulation in transformer windings. In addition, the interaction of water and oxygen in transformer oil may act like a catalyst for degrading process of insulation. Moisture in transformer oil can also be used for concluding the deterioration degree of mineral oil. Deterioration of mineral oil results to decrease in dielectric constant which could lead to a flashover in the transformer. (Abniki 2010: 3)

4.1.6 Sound monitoring

In future, sound monitoring could be a competitive method for transformer on-line condition monitoring. This new technique is suggested by Erkki Antila on the beginning of its development stage. At guidance of this thesis, Antila explained the idea of the sound monitoring technique. The interview of Virtanen from ABB (Asea Brown Bover) revealed that there is interest on the device in the market.

The idea of the new technique is that transformer emits specific sound in operation and also in fault conditions of power system or malfunction of transformer. The sound is generated through forces in windings and core caused by alternating magnetic field between the primary and secondary windings. By listening to the operation sound of transformer it is possible to conclude the condition of transformer. The vibration sound would be at a certain level at a specific loading of transformer. It would have to find out whether the sound of transformer is dependable on the loading of transformer when outside factors are excluded. This technique could be implemented as taking reference sound samples at different loading levels and comparing the current operation sound to the reference sound. In this way it might be possible to find out if there have been some changes in transformer condition. Also, power system failure may cause through going short-circuit current that will generate a loud sound in the transformer during the failure of power system. This spike in the sound could be analysed with comparison to short-circuit current.

For recording technique, audio sensors like microphones will be needed and the recording could be operated as continuous so that sounds during through going short-circuit currents could be analysed also. This technique could be easy to install on transformers in operation.

4.2 Condition monitoring data

Transformer condition monitoring has been widely researched by different institutions and device manufacturers in recent years. Generally the idea is to get information on the condition of transformer. There are lot of condition monitoring methods developed for such purposes. The selection of method determines the available sensor types. The sensor raw data needs to be processed, analysed, stored and transferred to power system management. This section focuses on the condition monitoring data.

Han (2003: 5) defines an on-line condition monitoring system as it 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. According to Han (2003: 5), the condition monitoring system has four main parts:

1. Firstly the physical quantity needs to be converted into electrical signal. This is possible by certain **sensor**. The type of sensor depends on the selected condition monitoring method.
2. **Data acquisition module** collects, processes and converses the sensor signals into digitally form for data analysis computer.
3. **Data analysis** is used for assessment of the condition of transformer. This includes monitoring of signals and evaluation of the signals by certain algorithms. There are two approaches for data analysis. One is knowledge-based and the other is analytic-model based approach.
4. **Fault detection** is the section that post-processes the abnormal signals to be sure of the fault and get a detailed fault description for maintenance. Depending on

the data analysis model, the detection can be performed by computer or expert system.

4.2.1 Data types

Sensor is a part of condition monitoring system. The type of sensor depends on the used condition monitoring method. The function of a sensor is to convert a physical phenomenon of monitored parts into electrical signals that can be utilised into data processing and analyses. In Table 2 it is presented different monitoring techniques, sensor types, possible output data and the purpose of monitoring. (Norick 2004)

The process of converting a physical phenomenon into electrical signal consists broadly of a phenomenon, a sensor and sensor output signal. The phenomenon can be something that can be measured like oil composition, partial discharge, temperature, vibration, moisture and so on. The sensor can be technically very simple but there can be also much intelligence. A sensor may include pre-processing of the data but also data analysis and perhaps data communication to substation IED. First step in conversion is usually to change a phenomenon into analogical data signal and the other steps depends on the sensor.

Table 2. Different sensors and output data.

Monitoring method and sensor	Output data	Purpose of Monitoring
Dissolved gas analysis		Analysis of the oil samples. The fault location cannot be determined accurately. The monitoring information depends on the probing method.
Combustible		Insulation, overheated oil
Spectroscope	Digital	Insulation, overheated oil, system leaks, over-pressurization, or changes in pressure or temperature.
Partial discharge		Insulation: If there is partial discharge detected it is possible to locate the fault location accurately with using multiple sensors.
UHF sensor		
Acoustic wave sensor		
Fiber optic sensor	Digital	
Thermal analysis		Heat can indicate multiple faults.
PT100	Resistance	Oil temperature
Thermal camera	Digital	Surface temperatures
Fiber	Digital	Temperature direclty from windings
Vibration		Loose core clampings or bondning bolts.
SKF Acceleration sensor	Voltage	
Moisture		Insulation
Vaisala Humicap MMT318	Current	

The electromagnetic interference in a substation can be affected to some sensors extremely. Therefore signal processing techniques improves the efficiency of data signal. (Penman 2008)

Also, one option for avoiding the electromagnetic interference is to use high quality cables for data transmission. If multiple data cables coexist in the same cable channel the electromagnetic interference of the cables may cause disturbance to data signals. In order to avoid the electromagnetic interference between cables there have to be electromagnetic compatibility (EMC) isolated and power cables should be segregated from signal cables. EMC isolation may obtained by crossing the conductors in right angles inside cable. Proper EMC protection for certain frequency area of data transfer are as follows: (Penman 2008)

- Frequencies below 500 Hz, twin-screened twisted pairs
- Frequencies over 100 kHz, screened coaxial cable

Fiber optical cable is other alternative for avoiding electromagnetic disturbance. Some sensor techniques use fiber optical cables for such purposes. The sensor needs to be such that it works with optical data cable.

4.2.2 Data acquisition

Around the transformer there can be multiple different sensors with a lot of cables. The data from the cables need to be collected into connection box which could be mounted on the side of the transformer or near to transformer.

For that purpose, data acquisition module is a part of condition monitoring system that collects data from different sensors to processing unit. For example the functions of data acquisition module could be data receiving, processing, storing and transmitting the data to upper level of condition monitoring system. For upper level data analysis the signal data needs to be converted in digital form. In Figure 7 it is presented signal processing and analog to digital conversion blocks of data acquisition module. (Norick 2004)

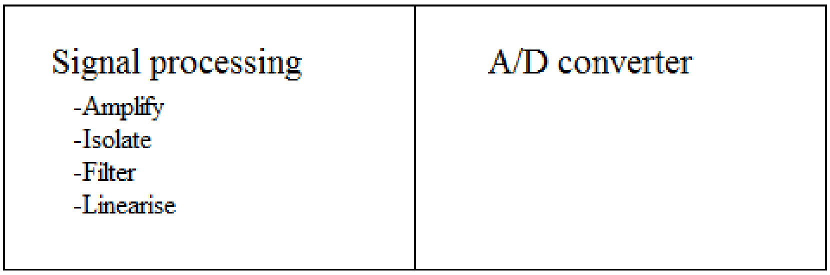


Figure 7. Diagram of data acquisition module. The data would be collected from sensors to module and then send to signal processing unit. After signal processing the data needs to be digitalised and send forward to data analysis.

According to Penman (2008) a data acquisition module consist of signal processing, multiplexing, anti-alias filtering, sample taking and analog to digital (A/D) converter. Every signal needs to be processed as similar type so that those are suitable for multiplexing. Multiplexing is a way to combine several signals into one. Signal levels should be adjusted to be in within certain values, usually in range 0 to 10 V. This adjustment can be carried out by amplifier if the signal is linear. Otherwise, if the sensor output signal is operating logarithmic, the signal must be linearized first.

Sensor data may include noise or disturbance by electromagnetic interference of transformer. The signal may be improved by removing unwanted frequencies through filtering techniques. For removing the unwanted frequencies there are filtering techniques like low-pass, high-pass and band-pass filtering. Low-pass filter cuts the high frequencies from the signal while the high-pass filter removes the low frequencies. Band-pass filter consists of both above filtering techniques so that there is a certain band that passes through the filter. A/D converter converts the analogical voltage signal into digital through sample taking and quantizing. The sample taking frequency may cause alias frequency in the output signal but by with properly selection of the frequency and filtering technique the effect of alias frequencies may be eliminated. (Penman 2008)

4.2.3 Data analysis

After data acquisition the digitalised sensor data needs to be analysed in order to monitoring the condition of transformer. Sensors give certain values that can be used to construing the operation of transformer, to detection of failure.

According to Norick (2004), data analysis is used for monitoring the condition of transformer and to detect evolving failures and to give alarm if necessary so that further actions may be executed. The fault diagnosis techniques can be divided into two areas:

- Knowledge-bases approach to fault detection.
- Analytic-model based approach to fault detection.

Knowledge-based model is based on the comparison of sensor value to defined limits. Those limits may be determined manually by experts or automatically by artificial intelligence. The final conclusion on the transformer condition is made by expert users. Analytic-model compares the measurements to predictions of sensor values through mathematical modeling of transformer. The model bases on mathematical expressions of a certain sections of the transformer system. A transformer may be modeled through linear or nonlinear system theory but the nonlinear has been proved to be better in modeling of transformer. The sections to model in transformer can be electrical, mechanical or thermal dynamics. The final conclusion on the condition of transformer may be performed by computer or through expert systems human operator. In Figure 8 there is a block diagram of both approaches for fault detection. (Norick 2004)

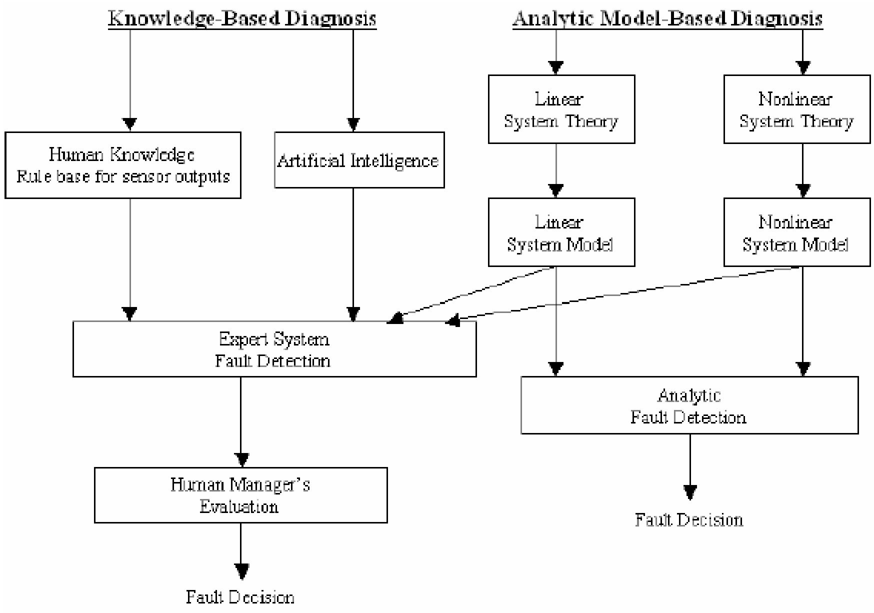


Figure 8. Different approaches to fault diagnosis

Human knowledge based diagnosis

The condition of a transformer can be best identified by experts who have worked with those. Human knowledge based fault diagnosis is based on comparison of monitored parameter to defined limits. The limits may be defined by the experts or with artificial intelligence. The final decisions on suspicious monitoring results are made by human experts. (Norick 2004)

Expert system is a tool in the condition monitoring system which makes the comparison process. The system consists of computer hardware and software that is used to make comparison of certain parameters against defined limits. In order to obtain reliable results and to minimize false diagnosis caused by sensor faults, the diagnosis should be based on several monitored quantities. Noricks (2004) example of IF/THEN algorithm in expert system as follows:

```
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
```

Analytic model based diagnosis

Other fault diagnosis approach is analytic based diagnosis in which the transformer is represented as analytic model through mathematical equations. For constructing the analytic model there are nonlinear and linear system theory of which the nonlinear has been proved better on describing the complexities of a transformer. (Norick 2004)

Analytic fault detection compares the actual measurements to predictions of the measurements made by analytic model. The actual parameters may constantly change over time by aging process of the transformer. The aging process may be taken into account by using adaptive filtering. In the comparison process of actual measurement and predictions from the model, the residuals from the comparison may be used to control the adaptive filtering. In Figure 9 there is presented a block diagram of analytic fault detection with adaptive filtration. Slow changes in monitored parameters may be normal aging but it can also reveal a slowly evolving fault. Rapid changes indicates usually developing fault. The age of transformer may be assessed by the speed of change in monitored parameters. (Norick 2004)

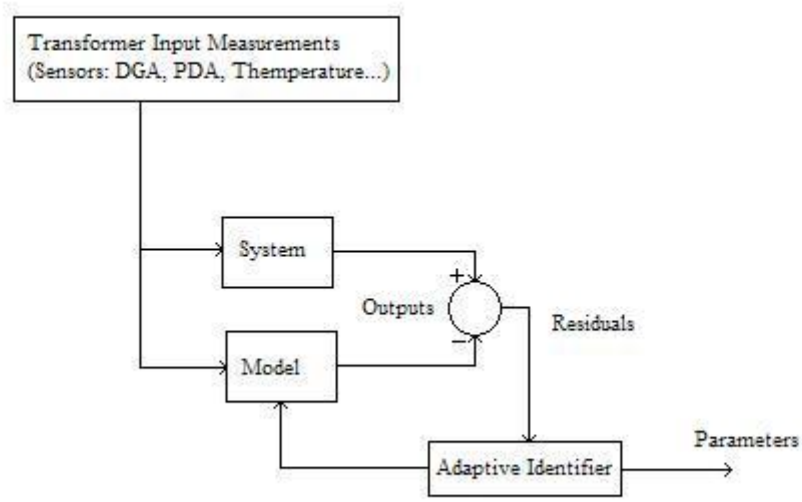


Figure 9. A schematic for analytic model based monitoring. (Norick 2004)

The complexities of transformer from the view point of modelling the system is difficult because the system consists a lot of factors like thermal, mechanical, fluid and chemical systems. Mathematically, the system is possible to be modelled by using linear or non-linear mathematical equations but the non-linear models appear to be more accurate within transformer modelling. On modelling aspect, most of the models are based on temperature calculations. In Table 3 it is presented various solutions for transformer modelling.

Table 3. Modelling possibilities.

System	**Modelling possibilities**
Thermal	• Top oil temperature rise over ambient • Top oil temperature measurements coordinated to dissolved 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 composition	• Transformer oil and its gas content.
Chemical	• Degree of polymerization and tensile strength of the insulation.

Nowadays the transformer condition monitoring data is mostly analysed at substation. There is remote access to analysis computer so the information is available at control center. But could it be more economical to place the analysis computer at control station for analysing several transformers in contrast to case where every single monitored transformer or transformer group have their own condition monitoring analysis computer. The signals could be transferred from transformer to control center by using the substation communication standard series IEC61850.

4.2.4 Data storage

With transformer condition monitoring it is possible to get a lot of data which may reveal an evolving fault by certain analyses. If necessary for post reviewing, the data needs to be stored in order to find out the history of the transformer for example if the transformer is malfunctioning. Also, the data may be used to improve the failure diagnosis detection.

Some condition monitoring techniques like frequency response analysis (off-line condition monitoring) requires the “finger print” of the transformer in order to compare the current measurements to original values. The “finger print” measurements can be done at the factory or at field.

Also, when the transformer is transported from factory to the location it can be exposed to impact forces during the transportation. The whole transportation is recorded with impact sensor. When the transformer is put into service, the impact measurements must be taken into account ensuring that the transformer is in good conditions. (Virtanen 2012)

As data storage, it needs to be considering that the storage capacity is not unlimited. From the view point of storage capacity, the data samples could be saved in certain intervals to conserve space. On the other hand, the stored data may be valuable information on the changes of a transformer. It’s also important to considering on how long history is needed or how dense. It could be also possible to save the condition monitoring data in two files:

- Short term data
- Long term data

In this way the short term data could cover only the recent time in transformer lifespan and in this file the data could be stored with higher sampling frequency in order to obtain the most accurate history on the transformer. Long term data could cover for example the whole transformer lifespan with low sampling frequency.

The location of data storage could be at substation computer or in control room of power system but it must be taken into consider that continuous data transmissions may load the bandwidth too much.

4.3 Condition monitoring with the standard series IEC 61850

"The goal of the IEC 61850 is the interoperability between IEDs (intelligent electronic devices) from different manufacturers in the substation automation system." (Baohong 2012)

The standard series IEC (International Electrotechnical Commission) 61850 is newish standard for data communication between devices in a power system. Previously manufacturers had their own standards for data communication but nowadays the use of IEC 61850 is extending. Without uniform standard a network company could be trapped in a single vendor due to compatibility problems between devices. Through IEC 61850 the compatibility between devices from different vendor has been improved.

According to Baohong (2012: 1) the IEC 61850 is the prime standard for smart substations. The online monitoring system is an important secondary equipment in a smart substation. The online monitoring system is the main data source of the state of a primary equipment. In order to utilise the condition monitoring system as a part of the smart substation, it must be compatible with the IEC 61850 standard.

The structure of the IEC 61850 bases on an object-oriented data model. The standard supports substation automation functions including: (IEC 61850-7-1 2011:16)

- Sampled value exchange for current and voltage transducers.
- Fast exchange of I/O data for protection and control
- Control signals
- Trip signals
- Engineering and configuration
- Monitoring and supervision

- Control-center communication
- Time-synchronisation

The IEC 61850 standard defines thousands of “signals” as data objects belonging to a certain data class and organised in logical nodes (Schwarz 2010:3). A logical device consists of logical nodes and it is always implemented in one IED. The logical device does not contain logical nodes from another IED. A physical device manages the communication means (specific communication service mapping, for example using of MMS, TCP/IP or Ethernet among other means). Figure 10 presents the structure of IEC 61850 data model. (Scwarz 2010:3, Baohong 2012:1)

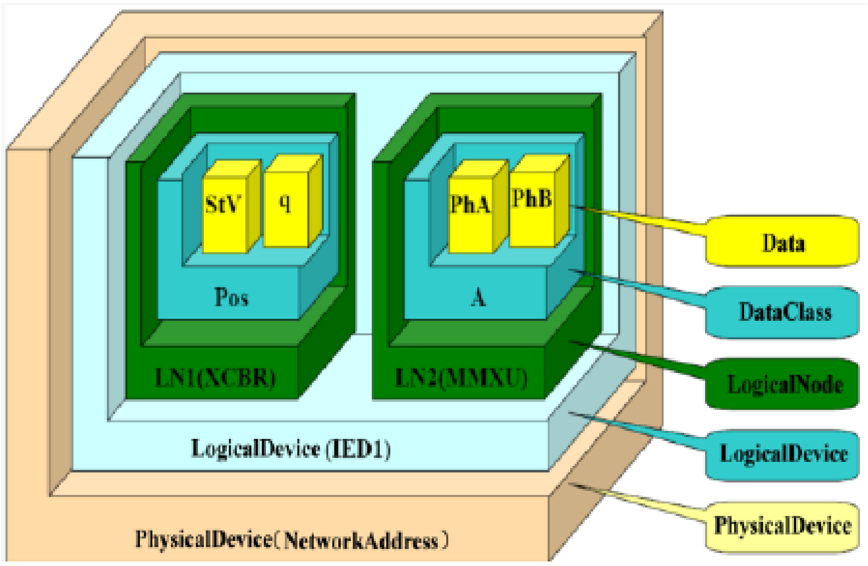


Figure 10. Structure of IEC 61850 data model. (Baohong 2012:1)

According to the standard definition, The IEC 61850 consists of ten parts of which each part consider a specific aspect of a substation IED:

- IEC 61850-1 Includes an introduction and overview of the standard.
- IEC 61850-2 Introduces terminology and definitions.
- IEC 61850-3 Specifies the general reguirements of communication network.
- IEC 61850-4 System and project management
- IEC 61850-5 Specifies the communication requirement for device and functions.
- IEC 61850-6 Configuration description language.
- IEC 61850-7

  - IEC 61850-7-2 Basic model, abstract services and basic types.
  - IEC 61850-7-3 Common data classes
  - IEC 61850-7-4 Compatible logical node and data classes
  - IEC 61850-7-5 Application quide

- IEC 61850-8-1 Mapping on network
- IEC 61850-9-2 Sample values mapping on network
- IEC 61850-10 Conformance testing

IEC 61850-7-4 Compatible logical node and data classes, is the part which includes logical nodes for supervision and monitoring purposes. The new edition 2 of the standard series has brought a lot of new functions. Some of the logical nodes contain only measurement data but some have more features.

According to Schwarz (2010), The edition 2 of IEC 61850 has been updated with new data objects for monitoring such as temperature measurements, oil level indication, gas densities and maximum number of connections. Those extensions can be used for condition monitoring purposes of equipment like switchgear, transformers, on-load tap changers, automatic voltage regulation devices, gas compartments, and lines, generators, gearboxes and towers in wind turbines, and communication infrastructure like Ethernet switches and routers.

IEC 61850-7-4 Compatible logical node and data classes

IEC 61850-7-4 standard contains the logical node group "S" which can be used for supervision and monitoring purposes. According to the paper of edition 2 of the standard, the standard has been updated with new logical nodes for those purposes mentioned above. In Table 4 there is presented the group of logical nodes for supervision and monitoring purposes. Column "Edition" refers to the edition of the standard serie. (IEC 61850-7-4)

Table 4. Logical nodes for monitoring and supervising.

	Logical node description	Name	Edition	CM of transformer
1	Monitoring and diagnostics for arcs	SARC	1	-
2	Circuit breaker supervision	SCBR	2	-
3	Insulation medium supervision (gas)	SIMG	1	Measurements
4	Insulation medium supervision (liquid)	SIML	1	Measurements
5	Tap changer supervision	SLTC	2	Status, measurements, controls
6	Supervision of operating mechanism	SOPM	2	-
7	Monitoring and diagnostics for partial discharges	SPDC	2	Status, measurements
8	Power transformer supervision	SPTR	2	Status, measurements, control
9	Circuit switch supervision	SSWI	2	
10	Temperature supervision	STMP	2	Status, measurements, controls, settings
11	Vibration supervision	SVBR	2	Status, measurements, controls, settings

According to the standard definition, the most suitable logical nodes for transformer condition monitoring purposes are introduced in the following.

Monitoring and diagnostics for arcs

SARC includes data objects as diagnostic of arcs like fault arc detection and arc detection during switching. The Logical node also includes operation counter, fault arc counter and switch arc counter. (IEC 61850-7-4 2010: 88)

Insulation medium supervision (gas)

Insulation medium supervision is for supervising of gas insulated (for example SF6) devices. This logical node includes data objects for status information, measurements and control. For information objects there are processes relating to the quality on the insulation, gas pressure alarm, density alarm, temperature alarm, level maximum and minimum. Measured values are gas pressure, density, temperature and calculation of the time untill blocking level is reached. (IEC 61850-7-4 2010: 89)

Insulation medium supervision (liquid)

Insulation medium supervision is for supervision of liquid (like oil) insulated devices like transformers and tap-changers. This logical node includes data objects for information status such as insulation state, temperature alarm, gas in liquid alarm and tripping function, liquid level minimum and maximum, H_2 alarm and warning, moisture alarm and warning. For measurement objects the node includes temperature, level, pressure measurements, composition of oil, also, measurements within relative saturation of moisture in insulation liquid, paper and air are included. The composition of oil covers measurements such as the amount of different hydrocarbons, nitrogen and oxygen in ppm and the total amount of dissolved gases and fault gas volume in Buchholz relay. (IEC 61850-7-4 2010: 90-91)

Tap changer supervision

The logical node of tap changer supervision can be utilised for assessing the condition of a tap changer. It includes status information objects like oil filtration status and tripping, motor drive overcurrent blocking and circuit status. For measurement the logical node includes motor torque, drive current, abrasion measurements of parts subjected to wear. (IEC 61850-7-4 2010: 91)

Monitoring and diagnostics for partial discharges

Monitoring and diagnostics for partial discharges is a logical node for insulation monitoring. The logical node includes data objects as alarm of partial discharge and operation counter. For measurements, the node contains acoustical measurements, apparent charge measurements, discharge current and ultra high frequency measurements of partial discharge. (IEC 61850-7-4 2010: 92-93)

Power transformer supervision

Power transformer supervision can be utilised to assess the condition of the power transformer. The node includes data objects for status information like winding hot spot temperature status, membrane alarm, core ground alarm and heater alarm. Measurements covers the aging rate, bottom oil temperature, core temperature and winding hotspot temperature calculations. (IEC 61850-7-4 2010: 93)

Temperature supervision

Temperature supervision node can be utilised for temperature monitoring purposes. This node provides alarm and trip/shutdown functions. (IEC 61850-7-4 2010: 94-95)

Vibration supervision

Vibration supervision node is for supervising the vibration in rotating devices like turbines, generators and other. The node includes data objects for alarm and trip/shutdown functions. For status information objects, there are vibration level functions. For measurement objects, there are vibration level and total axial displacement measurements. (IEC 61850-7-4 2010: 95)

5 POWER SYSTEM MANAGEMENT

Power distribution business is becoming more sensitive for various challenges of environmental changes. Those challenges as network automation, climatic changes, growing customer needs and aging power system, induces remarkable impacts on power system operation. (Brådd 2006: 1).

5.1 Power system operation

The operation of power system can be defined as daily switching and control operations. The intentions are to improve reliability and minimise power losses. Remote control and data transmission has important role within power system operation. (Lakervi 2009: 216)

Electricity Company's distribution grids have significant value and the intended lifetime is long. The systems has to be operated, maintained and developed continually. According to Lakervi (2009: 215), the management of the power system assets can be divided into three main processes like development planning, maintenance and the operation of power system. In Finnish legislation, it is defined as that the operation manager is responsible for operation of the power system including normal operation conditions and also fault situations (Brådd 2006: 5-6). Conformity with Brådd the main processes of power system operation are:

- Normal state management
  - Development planning
  - Control room activities
- Fault state management
- Preventive maintenance
- Other functions

Operation process seeks to maintain power quality, safety, customer service and economics in short period. Main focus in power system operation process is in safety and reliability. Economical requirements prescribe the limits on resource allocation and investment. The whole process is optimized between reliability and safety seeking to appropriate overall economy. (Lakervi 2009: 231)

For business aspects, the target of power system operation is continuously optimisation of operative costs, good power transmission capacity, customer service, occupational safety of electrical activities, and sufficient power quality. The optimisation decisions are made basing on cost and quality perspective. (Bådd 2008: 403)

The main processes, except other functions, are presented in the following sections. Other functions cover the customer service, purchasing, and the management of data systems. (Brådd 2006: 4)

5.1.1 Operation planning

Operation planning covers resource allocation on operations, assistive tools, fault current protection, connections during maintenance break and monitoring connections. Monitoring and controlling of the power system includes operation of protection and switching devices and monitoring the state of loading in power system. Power system is controlled by controlling switching devices from the control center remotely or locally on the field. Managing fault situations involves identification and locating of fault, disconnecting the faulted part from system, and energizing the back-up connections. The fault must also be repaired and the power system needs to be returned back to normal operation by fault management. One of the functions is the maintenance which consists of inspections, measurements and service actions. For field tasks operation management uses the same resources together as construction management. The distribution company may utilise its own resources or bought it as an external service. (Lakervi 2009: 232)

Operation actions in substations and medium voltage networks are typically executed through automation systems which allows to remote monitoring and controlling from a distribution company’s control center. In low-voltage network the automation level is lower but this design is changing through the utilisation of AMR (Automatic Meter Reading) technology which contains tools for low-voltage network monitoring. (Lakervi 2009: 232)

5.1.2 Power system development

Power system development planning is the basis for long period development of power system. The development planning process is performed by basis of the operation environment factors, calculation and principles, the current state of power system, and the future aspects. Development of power system seeks to keep the long term repair costs within limits and also maximise the profit of the capital investment. According to Lakervi, the basic of the strategy of power system development consists of the following definitions and descriptions: (Lakervi 2009: 215-216).

- Operating environment factors
    - Surrounding development factors has great effect on grid development basics and methods in long-run.
    - Client needs and regulation. Restrictions on interruptions and conditions on economic sanctions have also great influence on development of power system.
    - Environmental issues
    - Changes in loading. The changes are intended to be predicted for 15-30 years period at even substation level. This will facilitate the exploring of development needs.
- Defining the power systems calculation parameters and basic principles for planning.
    - Basic planning principles:
        - Target level in reliability
        - Grounding principle
        - Voltage levels
        - Structure of grid, components and automation system.
- The current state of power system on mechanical and electrical aspect.

- Electrical performance can be calculated of current measurements on the basis for assessing the impact of increase in loading on the system. Mechanical construction and condition are also important factors on grid development.
  - Voltage drop
  - Line capacity

- The main upcoming development actions in 10-20 years.
  - Power lines: Replacing or entirely new
  - Substations: Replacing or entirely new

5.1.3 Control room activities

Currently, a control room forms the central node of the information about power system. The information may be used for a basis for making investment decisions on processes like network planning, planning of maintenance, and construction of power system. The basic activity of control room is the remote-control of the grid. In practice the basic activities cover functions like monitor and maintain the electrical state of the grid, remote-controlling of switching, load prediction, surveillance of the substation environment, and remote control of power plants. Also, power quality is usually monitored in the control room. (Brådd 2006: 4)

5.1.4 Fault management

Fault management is comprised of fault related activities such as processing the alarm and fault information, analysing the event sequence, locating and isolating the faulty parts of the power system, providing an back-up connection, repairing the failure and restoring the power system into normal switching state. (Brådd 2006: 4)

5.1.5 Preventive maintenance

The maintenance strategies of power system aim to maintain the grid in working conditions. With proper maintenance functions the grid components service life can be extended. Maintenance can be executed through many ways but the extremities are corrective and preventive maintenance. (Lakervi 2009: 215)

In business environment, the costs have to be balanced between preventive and corrective maintenance activities. Operation and maintenance activities are usually operated with common resources. Preventive maintenance functions include condition monitoring, condition analysis of power system devices, preventive maintenance planning, maintenance actions, inspections, service and testing. (Brådd 2006: 4)

5.2 Data systems

The distribution system is a large entity in which electricity is transferred to wide area. To enhance and improve the process there has been developed assistive tool for the system management called distribution automation system. The automation system can be separated into parts like company, control center, substation, grid and client automation. Company automation bases on utilisation of data systems and management of the information flow. Following data systems are used to the management of the information. In Figure 11 it is presented the schematics of the data system.

- Network information system
- Customer information system
- Possible other information systems in company
- Distribution management system
- SCADA

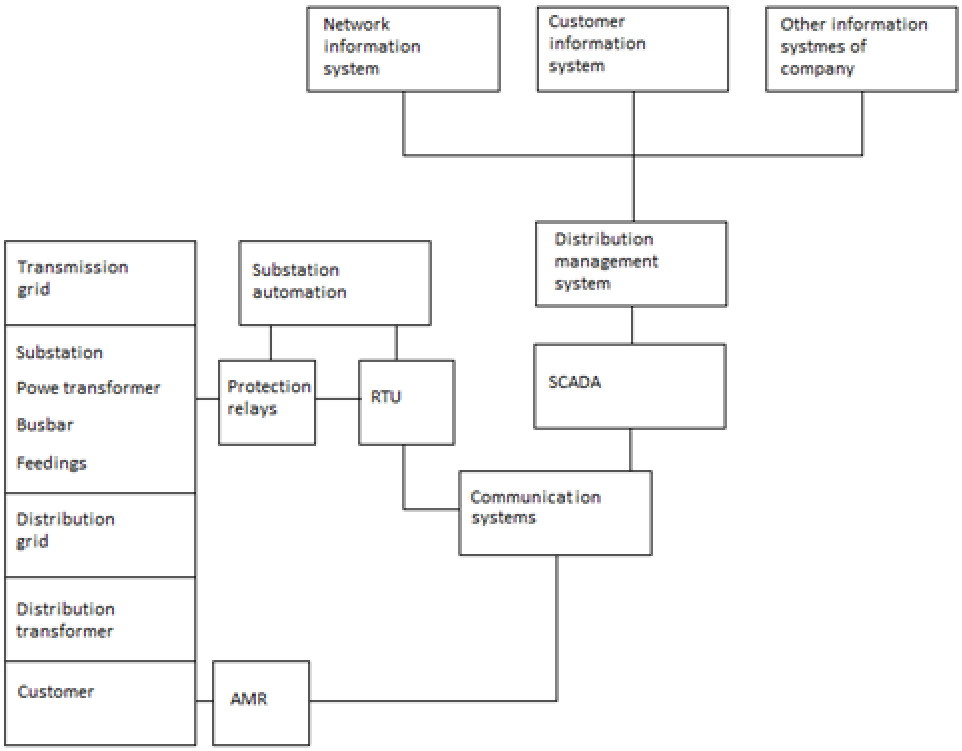


Figure 11. Schematics of data flow in power system. (Edited from Lakervi 2009: 233)

5.2.1 Distribution company automation

This automation level of power system consists of network information system, customer information system and other systems. The central functions of the company automation are for example planning a backup connection and protection during the use of the backup connection, planning of switching of the grid needed for service and maintenance actions and also energy measurements from customers. (Lakervi 2009: 234)

5.2.2 Control center automation

The central functions of control center automation are to monitor the electrical state of the grid and control it. Also, managing of the fault situations of the power system is one of the important functions. (Lakervi 2009: 234)

SCADA – Supervisory control and data acquisition provides control and monitoring functions of a power distribution grid. The main functions of SCADA are management of event data, management of switching situations, remote control, remote measurement, remote settings and reporting. So SCADA is a process computer that provides real-time information on distribution process and it is also used to control many critical operations. SCADA's database includes accurate information of substations and devices in those. Through the event data management, information on the operation of protection relays, events of switching devices and operation of fault indicators and tap-changers is available. According to event recording and power system information, the SCADA can maintain the information on switching status of distribution system. (Lakervi 2009: 235-236)

Typically, a SCADA based system consists of remote connections with field-located remote terminal units (RTU). At field, the RTUs can be connected to transmitters and actuators. RTU converts analogy measurements into digital form in order to transmit over the data network.

5.2.3 Substation automation

Substation automation covers the operation of protection relays, voltage and current measuring, control of switching devices, and regulating voltage by control of tap-changers. Also, there can be switching sequences for example isolating the power transformer of the system. The substation may be also operated locally by local automation system. (Lakervi 2009: 234-235)

5.2.4 Feeder automation

Feeder automation covers the remote control of disconnectors, measuring of currents and voltages, and data transmission of failure indicators. Also, local autonomic functions can be possible. (Lakervi 2009: 235)

5.2.5 Customer automation

Automatic meter reading (AMR) provides information on real time consumption of energy making it possible to charge customers by actual meter reading instead of estimated billing. The technology has been evolved and there are new features to be utilised such as an hour-based metering, real-time follow-up on the power quality, outage registration and remote disconnection of the power system. (Brådd 2009: 5)

5.3 Management processes related to transformers in traditional grids

In 1950's power system was supposed to offer a power supply for customers to keep the lights on. In the contemporary power system the power were produced by centralized plants that were feeding the electromechanical power system. The power flow was intended to be one-way. In the traditional grid the electricity consumption and production must be controlled as equal. Between customer and grid, there is not communication.

Today grids are usually something between traditional and smart grid. The amount of assistant device like automatic meter reading (AMR), substation automation and protection devices and other things are becoming more common in continually updated power system. The utilization of on-line condition monitoring of power system devices is low within current power system. Currently, maintenance strategies are based mostly on corrective and time-based preventive maintenance strategies.

Network companies have their own way to realize the management processes of power system but according to Antila et al. (2009) the management of power system can be divided in four sections according to main process:

- Safety and protection management
- Operation management
- Asset management
- Business management

Antila's (2009) idea is to create a management model in smart grid in order to gain the sustainability in power system. In the model the data communication between different management processes is the major factor. The model doesn't describe a management of traditional power system but in order to make comparison between traditional and smart grid, the management processes are divided in those four main processes. Those main processes include sub-processes which are needed for the main process. The sub-processes may differ between the management of traditional grid and smart grid. This study focuses on the power system management from the point of view of transformers in power system. So the transformer related management processes are explored in the following Table.

Table 5. Management processes in traditional power system.

Safety and Protection Management	Operation Management	Asset Management	Business Management
Measurements	Measurements	Measurements	Measurements
Parameter setting	Parameter setting	Planning of power system.	
Alarm reporting	Alarm reporting	Alarm reporting	Alarm reporting
Protection and disconnection	Isolation	Serviceability	Outage costs
Load shedding	Load control	Accessories and spare parts.	Balance management
Power restoration		Maintenance	

Safety and protection management includes all processes related to protection and operation during fault situation in traditional grid. This management area includes sub processes such as measurement, parameter setting, alarm reporting, protection and disconnection, load shedding and power restoration. Measurement includes measurement data for protection devices like relays. Parameter setting consists of configuration of relays. Alarm reporting is for sharing the information of possible fault situation for other management processes. Protection and disconnection is the part of the process that contains protection functions and disconnect the failed component of the power system for keeping the rest of the power system in operation. Also, in fault situation it may be required to utilize load shedding for maintaining the power quality. After the failure situation, when the device is repaired and ready for operation the power restoration is the process that is responsible for returning the power system into normal operation.

Operation management is the main process which takes care of the operation of power system in normal conditions. For the operation of transformers, this main process includes sub processes like measurements, parameter setting, alarm reporting, isolation and load control. The measurement process covers measurement like voltage for adjusting purposes. Parameter setting is a process in which the ratio of transformer tap-changer is controlled. Alarm reporting is for sharing the information of normal operation for other processes. If it is time to proceed a service for a device in power system, the device need to be disconnected of the system by isolation process. Load control process is for regulation of power flow through transformer by controlling the network configuration.

Asset management process can be described as maintenance and servicing process of power system. Sub processes related to transformers are measurement, alarm reporting, serviceability, accessories and spare parts, and maintenance. The measurement process includes mostly time-scheduled measurements but there can also be in some places on-line condition monitoring. Alarm reporting process is for sharing the condition information on transformers to other management processes. Service process is for servicing transformers. In order to perform services of transformer there have to be accessories, spare parts and even spare transformers available. This process is performed by accessories and spare parts process. Maintenance is the process that assesses the need for service for a transformer.

Business management process includes only processes within business area of the company. Its sub processes related to transformers are measurements, alarm reporting, outage costs and balance management. Measurement process consists of power measurements needed for balance management.

Asset management in traditional grids

The asset management in traditional power system is introduced through two cases of transformer failures. The two transformer failure cases considered include one with low level of urgency and another with high level of urgency. Because the power outage caused by transformer failure may influence the power systems reliability, the importance of the transformer through operation purpose can be estimated so that step-up transformer failure is usually more serious than transmission transformer failure and also with two power transformers, the one with higher loading is more influential than the other with a low loading (Fischer 2010). This may also affect to the asset management process by prioritizing the further actions. In these cases it is not taken into account whether the transformer is a step-up transformer or step-down transformer, and how high the transformer loading is.

In traditional power system the data communication is minimal and usually the use of condition monitoring devices is uncommon. So the indication of transformer fault is obtained through:

- Periodically performed inspections and measurements.

The most extensive protection system may consist of:

- Protection relay
    - Differential
    - Short-circuit and ground fault
    - Tap-changer protection
    - Gas relay
    - Oil level
    - Oil temperature
    - Winding temperature

Case one: Small amount of moisture in oil in the transformer.

The indication of moisture in oil may be determined through periodically performed oil samples. Water in oil refers to deterioration of isolation and the moisture in oil acts as a catalyst for the aging process of isolation and it also reduces the insulation ability of oil. Depending on the interval on the periodically inspections the water may have constituted there for undefined time from previous inspection. So the speed of the possible deterioration process of isolation is not known and so the remaining lifespan is also unspecified. But the amount of water in oil can be referred to urgency level. However, until the maintenance day the water affects in the transformer. Considering the minimizing the effect of water in oil, it may be for example necessary to lower the loading of the transformer in order to keep the temperature of windings at a lower level.

First action may be the planning of the transformer service including the maintenance day and actions. This could be oil change which is a large operation in which the transformer is taken into maintenance facility for oil change and possible other maintenances. This operation may require a spare transformer in order to change the degradable transformer for functional transformer and keep the power system as reliable as possible. So there have to be spare parts and spare transformer available.

The maintenance action of changing the transformer for a new one requires isolating at least the transformer from the power system. Also, depending on the purpose of the transformer in the power system, back-up connection may be possible to be used for maintain the required power supply in order to avoid power outage. If there are also other maintenance actions to be done at the same substation, those actions could also be scheduled according to the action of transformer change.

If the configuration of the power system is changed for the maintenance actions, the protection relays must be probably adjusted for the protecting the rest of the power system. After the maintenance actions the substation or the transformer can be connected to the power system. Thus the protection relays must also be adjusted back for protection of normal operation conditions of power system.

Case two: Transformer overheating

The indication of overheating may be determined through protection relay depending on the used relay. The reason for the rise in temperature may be several: Short-circuit in windings or low level of oil or partial discharges through isolations, overloading, cooler fault and other. In the best case with a specific protection algorithm, the cause of overheating may be discovered at early stage and the actions may be performed. But there is also possibility that the overheating will be noticed after the failure has become so bad that the transformer cannot be used. In this case the assumption is that there is a protection relay with oil temperature protection.

The immediate actions could be shutting down of the transformer and finding the problem. Also the back-up connection for the feeded area must be coupled if possible. For necessary power supply it could be also possible to load the other transformers more.

Because the temperature rise may be a result of several problems, it must be first to find out how serious the problem is; whether the transformer can be repaired or replaced. In order to perform the repairing or replacing actions there have to be spare parts and transformer available. After the maintenance actions the serviced system can be reconnected to power system.

5.4 Management processes related to transformers in smart grids

DENISE (Distribución Energética Inteligente, Segura y Eficiente) project defines the smart grid as follows:

"The Smart Grid integrates electricity and communications in an electric network that supports the new generation of interactive energy and communication services and supplies digital quality electricity for the final customer. In this sense, the electric network must be always available, live, interactive, interconnected and tightly coupled with the communications in a complex energy and information real time network." (Roncero 2008)

According to Hassan 2010 (Survey on smart grid), a real Smart Grid will integrate different technologies in order to maximize the benefits instead of keeping the different technologies separated. Smart Grid is a step of impovement for taking distribution networks forward. Smart grid technologies includes:

- Advanced digital meters
- Distribution automation
- Reactive power control based on intelligent coordination controls
- Reconfiguration schemes based on intellifent switching operations
- Low-cost communication systems
- Broadband communications for distribution applications
- Real-time angle and voltage stability and collapse detection
- Closed loop systems using advanced protection
- Fault analysis
- Distributed storage and generation
- Distributed energy resources

Transformers are critical components in smart grids as in traditionl grids but the operation of transformer may affect in different ways in various processes. According Antila's (2009) management model of sustainable power system, the management processes that are connected to transformers, are supplemented in Table 6. Some of the management processes are the same as in traditional grid management table but their content is developed. The most significantly changed sub-processes are highlighted with bolded text in the table.

Table 6. Transformer related Management processes in smart grid

Safety and Protection Management	Operation Management	Asset Management	Business Management
Measurements • Protection • Fault current	Measurements • Operation	**Measurements** • **On-line monitoring**	Measurements • Business
Parameter setting • Relays	Parameter setting • Tap-changer	**Maintenance** • **Lifespan calculations**	
		Planning of power system.	Outage costs
		Accessories and spare parts	Balance management
Adaptive protection and disconnection	Isolation	Serviceability	
Load shedding	Load control		
Back-up supply	**Reserve plants**		**Capacity planning**
Power restoration	**Demand side management (DSM)**		**Demand side management (DSM)**

Safety and Protection Management represents processes relating to fault situations, protection and also cyber protection. For transformer operations, it includes sub-processes like measurements, parameter setting, adaptive protection and disconnection, load shedding, back-up supply and power restoration. Measurement and parameter setting processes are for protection devices. Adaptive protection and disconnection process consists of protection devices that adapts into the condition of power system. For example, after a transformer failure, protection relay has disconnected the failured part of the power system and thus protection parameters need to be changed in order to protect the operating system. In a transformer failure conditions it may require to disconnect loads due to lower transmission capacity. This is done by load shedding process. After repair or replace of failed transformer, the power is connected back through power restoration process.

Operation Management represents the management processes of normally operating power system. For transformer operations, it consists of sub-processes like measurements, parameter setting, isolation, load control, reserve power plants and demand side management (DSM). Measurements and parameter setting are for control operations for adjusting tap-changer ratio and for changing coupling of transformer. A transformer may be isolated from the power system for servicing or maintenance or from other action through isolation process. The current flowing through transformers may be controlled through load control process. In a case where condition monitoring system indicates that the probability of fault in the transformer is going to rise the loading may be reduced in order to keep the transformer longer in operation. Also one possibility is using reserve power plants for feeding certain area to lower the loading of a transformer. This is managed by reserve plant process. Demand side management process is also for controlling loads. In a failure situation it may also be utilised in order to assure necessary power supply.

Asset Management can be described as maintenance, servicing and planning processes of the power system. For transformer operation the asset management process includes sub-processes as measurements, planning of power system, serviceability, accessories and spare parts, and maintenance. Measuring process consist of transformer condition monitoring measurements. Maintenance process performs the evaluation of service needs and asses the lifespan of a transformer. The condition of a transformer may also affect to the planning process of power system. For example if a transformer is aging in a substation it must be considered when the possible renovation is done and how widely. Service is the process that performs service for a transformer. In order to do servicing there have to be also accessories and spare parts available.

Business Management represents the business processes of power system. For transformer operation, it contains sub-processes as measurements, outage costs, balance management, capacity planning and DSM. Measurement process is mostly power and energy measurements for business purposes. A transformer failure may lead into power outage. It affects the outage cost process. Balance management process is responsible of the energy balance between consumption and supply. Capacity planning process is intended to be a management tool of the capacity of the power system . There is certain capacity that may be used in power system but the capacity planning defines the amount of the available capacity in the future. Demand side management process is also for controlling loads through business aspects.

Asset management in smart grids

Similar examples of transformer failures that were studied in the chapter 5.1.1 within traditional power system are also studied with smart grid technology in order to see the difference between asset management processes.

According to the fact that smart grid is a self-healing systemit is beneficial that upcoming failures are prevented or mitigated by corrective actions based on predictions of evolving fault (Farhangi 2010: 23). So the condition monitoring of transformers is one important part of the smart grid. In following cases of transformer failures, the indication of faulty conditions is got through condition monitoring assets. The most common techniques for condition monitoring purposes are presented in Table 7.

Table 7. Condition monitoring techniques and indication

Condition monitoring	**Indication**
Dissolved gas analysis	Insulation, overheated oil, system leaks, over-pressurization, or changes in pressure or temperature.
Partial discharge detection	Insulation: locating the fault spot.
Thermal analysis	Heat can indicate multiple faults.
Vibration analysis	Loose core clampings or bonding bolts.
Moisture monitoring	Insulation

Case one: Small amount of moisture in oil in the transformer.

The indication of moisture in oil can be detected through several condition monitoring methods, directly or through another indication. At least the information of the moisture can be indicated with moisture monitoring, dissolved gas analysis, partial discharge detection and possibly through thermal analysis. The primary indications can be got through moisture and dissolved gas analysis. The other two indicates more of the consequences of the moisture in oil. But it is important that evolving fault is detected as early as possible in order to maintain the power system as self-healing system.

Comparing the techniques of fault detection in traditional power system and smart grid, the detection of fault can take place at earlier stage. So there is more time to prepare for upcoming failure and actions can be done more efficiently.

Firstly, when the moisture is indicated, the loading of the transformer may be considered to adjust in order to keep the transformer in operation until the maintenance actions. Also, with condition monitoring it is possible to estimate the residual lifespan of the transformer which is important information for planning the maintenance action.

The estimation of lifespan may affect to the planning process of power system for example by changing the timing of new investments in the system or changing the system into different kind, and considering whether the substation in that location is necessary anymore.

Similarly as within traditional power system, smart grid asset management must also to have spare parts and spare transformer available for maintenance actions.

For the considered maintenance action it may be required to isolate the transformer from the power system in order to repair or replace it. The adaptive protection changes the settings to relays when a part is isolated from grid during the maintenance. Also, back-up supply and reserve power could be used for ensure the necessary energy supply. After the maintenance actions, the isolated parts can be reconnected to the power system.

Case two: Transformer overheating

Depending on the reason of overheating, it is either rapidly raising or slowly evolving. With condition monitoring, the slowly evolved failures will be noticed at an early stage. So the assumption in this case is that the heating is rapidly rising until the level of overheat. By studying the condition history of the transformer and on basis of that, it is possible to rule out the possible causes of fault. Rapid change in temperature may refer to for example:

- Fracture in tank

- Overloading
- Through going short-circuit current
- Radiator failure
- Oil-pump failure
- Isolation damage

Firstly, according to temperature measurements, the protection relays must disconnect the transformer from the power system in order to avoid serious damages in the transformer. For the new connection of power system the adaptive protection does parameter adjustment for protecting the remaining power system during the transformer failure. Also, the back-up connection to the supply area could be connected automatically.

Depending on the used condition monitoring method or methods, the problem may be found out quickly unlike within the traditional power system. According to the reason of fault and the condition history the maintenance actions can be made. The maintenance actions may require the availability of spare parts or transformer. After the maintenance actions the power system may be restored back to use.

5.5 Data track to right management function in smart grid asset management

In the Table 8, the differences between smart grid and traditional power system are introduced. For data track, considering the data chain from sensor to management process, in traditional power system the data chain is hierarchical and in smart grid the data chain is of network type.

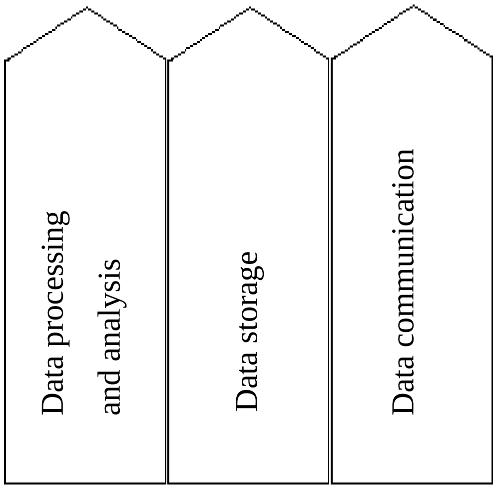
	Existing grid	**Smart grid**
Operation	Electromechanical	Digital
Data communication	One-way	two-way
Generation	Centralised	Distributed
Data system	Hierarchical	Network
Sensoring	Few sensors	Sensors throughout
Monitoring	Blind	Self-monitoring
Fault recover	Manual restoration	Self-healing
Sustainability in faulty conditions	Failures and blackouts	Adaptive and islanding
Equipment chek/test	Manual	Remote
Customer automation	Few customer choices	Many customer choises

Table 8. Smart grid compared to traditional power system. (Edited from Farhangi 2010: 20)

For transmitting the condition monitoring data from sensor to smart grid management, the process consists of several steps. Firstly, the data needs to be gathered from sensor for data analysis. The sensor can be a smart sensor in which there is a lot of intelligence and the sensor could be connected for example through a data bus cable. The sensor can also be only an analogical converter. The sensor data needs to be saved somewhere and the data analysis could be made for example at the substation or control room. If it is done in control room, it may take too much capacity of the communication network. The data from substation to SCADA is send by remote terminal unit. In Table 9. it is presented the data flow from sensor to asset management.

Table 9. Data flow from sensor to asset management process.

	Process
Asse manage-ment	Planning of power system
	Lifespan calculations
	Accessories and spare part planning
	Service planning
Control station	Alarm reporting
	Monitoring the measurements
	SCADA
Substation	RTU
	IED
	Data acquisition
	Sensor



The data flow from sensors to asset management process covers the data processing and analyzing, data storage and data communication. Data processing is the basic operation of improving an analogic signal and digitalising for data analysis. Data analysis, introduced in Chapter 5.2.3, can be implemented at substation or control room but also further analysis can be done in management level such as for example a transformer lifespan calculations. Data storage covers everything from the short term buffer of sensor data to asset management data system of long term data. The amount of needed data is different at each level of the power system. At substation the data storage may be only short-term type because of the delays in data transmissions. At control center the data storage could be of a longer period type for example controlling purposes. In asset management the long-term data history could be significant information for example lifespan calculation, service planning and planning of power system. For data communication, special protocols are required. In the following figure the generally used protocols are marked into the data process.

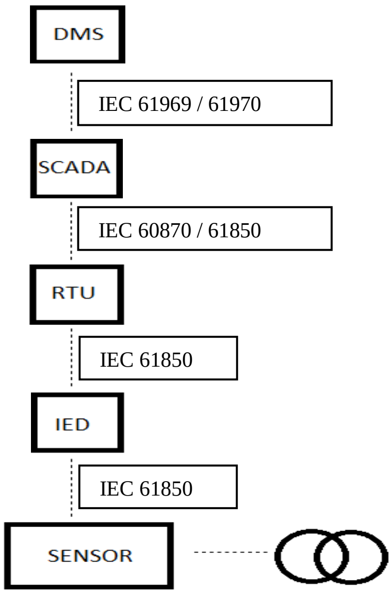


Figure 13. Data track.

For data communication between devices in transmission, distribution and substation automation systems the open standard IEC 61850 series are the most important protocols. The protocols were presented in Chapter 4.3. Data communication between RTU and SCADA can be implemented through standard series IEC 60870. From SCADA to DMS the data may be transferred through common information model in which the IEC 61969 works in the distribution domain and the IEC 61970 works in the transmission domain. (Cecati 2011: 7)

6 SUMMARY

The topic of this study was the utilisation of transformer condition monitoring data that is practically, combining a transformer condition monitoring system and power system asset management. Generally, there are two types of power systems: The other is traditional power system and the other is the more developed smart grid. In order to see how the condition monitoring data will be needed in smart grid and where it could be needed this study explored the issue through case study by comparing a transformer failure situation in both power system types.

Electrical energy is the most universal form of energy because it can be transported easily at high efficiency and reasonable costs (Murty 2011:1). The basic function of power system is to transfer the electrical energy from production to consumers. The supply of electricity has reached important role in modern society. Most of the people need electricity every day. The power quality has high expectations today. For example changes in frequency or voltage may lead to device failure at consumers. Power outages are also undesirable and may cause harm. The power system is designed to meet the requirements of power transmission with good efficiency and reliability. Power transformer is one of the most important equipment in a substation and also the most expensive device in a substation. Within electricity transmission a transformer has a significant role of changing voltage level from a power system to be suitable for another. (Abniki 2010:1)

Life expectance of a power transformer is around 40 years. Investments made in 1970s for power systems causes that nowadays the percent of transformers operated more than 30 years is increasing. Therefore the transformer failure statistics is expected to rise in the coming years. Transformer failures are sometimes catastrophical and usually include irreversible damage to the transformer. (Tang 2011)

The lifespan of transformer depends mostly on the condition of winding insulation, but also mechanical factors like core clamping and auxiliary devices like oil pump or radiator. The windings are affected by insulating oil, normal loading, and through going fault currents. For measuring the condition of transformer there have been developed different condition monitoring techniques. Gockenbach (2010 :1-2) describes a transformer condition monitoring system which aims to make evaluation of the operating conditions, finding the causes of aging, recommending measures to improve quality and the assessment of lifetime.

Different condition monitoring techniques has been developed by many institutions and companies. Generally, a condition monitoring system consists of sensors, a data acquisition module, a data analysis computer, a data storage and data communication to management system. Purpose is to monitor certain signals which are used to estimating the condition of transformer. Evolving faults may be found at early stage and corrective actions may be performed.

Maintaining Tangs (2011) expectations on service lifespan of transformer, the aging devices needs maintenance more and more in order to maintain reliable power supply. With on-line condition monitoring it is possible to detect evolving fault at early stage which could not be done with earlier techniques and maintenance strategy as effectively.

By condition-based maintenance strategy it is possible to reduce also the unnecessary maintenance actions like time-scheduled inspection, thus minimising the operating costs of transformer. Today, the power system maintenance bases mostly on corrective maintenance strategy but also time-based preventive maintenance is used.

The automation level of a power system is specific in each country and management of the power systems is also different. In this thesis the power system is outlined as traditional and smart grid. In traditional grid the automation level is low and the management is undeveloped compared to smart grid management. Smart grids are the grids of future applying high level of automation and highly developed management systems.

Asset management in both systems was compared through case study in previous chapter. The study pointed out that there are similarities and differences in management between the grid types. Upcoming transformer failure may be missed within traditional power system management and the fault may be evolved to catastrophic failure. With smart grid technology and management an upcoming transformer failure may be prevented. In traditional grid the transformer condition information can be collected through scheduled inspections. In order to have a sustainable grid it is important to get transformer condition monitoring data where it is needed. The need of condition monitoring data in the power system management depends on the type of the grid. There are several sub-processes where the information is needed.

For further research, this study could be expand to cover the whole management system in smart grid. In Erkki Antilas model of a power system management the system is divided into four sections: Safety and protection management, Operation management, Asset management and Business management. Processes in those are related to each other so there have to be more research about the effect of transformer condition monitoring information to those other management functions.

REFERENCES

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

Abu-Elaine Ahmed E.B. & M.M.A. Salama (2010). Asset management techniques for transformers. *Electric Power System Research,* April 2010, 80:4, 456-464.

Ahmad Rosmaini & Kamaruddin Shahrul (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering 63:1*. 135-149 p.

Antila Erkki & Göran Wiklund (2007). Benefits of applying totally value-based segmentation of applications needed. *Dubai: GCC CIGRE Doha, Quatar,* November, 2007. 267-279 p.

Antila Erkki & Göran Wiklund (2009). Redefining sustainability in the electric power distribution context. *CIGRE International Conference in Gulin, China. October 2009.*

Baylis Colin (1996). Transmission and distribution electrical engineering. Great Britain. ISBN0 7506 2287 3

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

Brådd, A., J. Lassila & J. Partanen (2006). The challenges of the network operation in the Nordic electricity distribution business heading for year 2030. *The IASTED International Conference on power, energy, and applications*, September 11-13, 2006. Gaborone, Botswana.

Brådd, A., J-P. Bergman, A., Jantunen, J.Partanen, J-M. Saksa & S. Viljanen (2008). The strategic activities of electricity network operators within changing electricity distribution industry. *International Journal of Energy Technology and Policy 6:4,* 395-412.

Elovaara, Jarmo & Liisa Haarla (2011a). Sähköverkot 1. Otatieto. 520 p. ISBN 9789516723603.

Elovaara, Jarmo & Liisa Haarla (2011b). Sähköverkot 2. Otatieto 550 p. ISBN 9789516723634

Farhangi, H (2010). The path of the smart grid. *IEEE Power and Energy Magazine 8:1*, 18-28.

Fischer Markus, Reinhold Haug, Michael Schäfer & Stefan Tenbohlen (2010). Determining power transformers' sequence of maintenance and repair in power grids. *Electrical Insulation (ISEI), Conference Record of the 2010 IEEEInternational Symposium on 6-9. June 2010.* San Diego, CA. ISBN: 978-1-4244-6298-8

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

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

Lakervi, Erkki & Jarmo Partanen 2009. Sähkönjakelutekniikka. 2. Ed. *Otatieto*. 295 p. ISBN 978-951-672-359-7

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

Murty, P.S.R. (2011). Operation and control in power systems. 2. ed. *Hyderabad: BS Publications; Leiden : CRC Press, 2011*. 428 p. ISBN 978-0-415-66565-0.

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>

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_MMT31 840bf6dd7b2dfd.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