Effects of aging processes and varying humidity on the breakdown voltage of mineral oil in switchgear

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Master of Science Thesis

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谨以此文献给我的爸爸和妈妈

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List of Abbreviations

LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
OIS	Oil-insulated Switchgear
BDV	Breakdown Voltage
TRV	Transient Recovery Voltage
TAN	Total Acidity Number

List of Symbols

μs	microsecond
λ	electron mean free path
ε	permittivity
ε_{liq}	permittivity of dielectric liquid
hv	the quantum of energy lost in ionizing the molecule
v	velocity
k	Boltzmann's constant
kV	kilovolt

Abstract

Previous research has shown that in non-hermetically sealed medium voltage oil insulated switchgear (MV OIS), the insulating oil will absorb water from the ambient air. The humidity of oil highly influences the breakdown voltage of oil. The humidity of oil, in turn, is influenced by the acidity of oil which will change during the aging processes of oil. Moreover, experience on the influence of copper due to switching actions of switchgear on the chemical and electrical aging process of oil is rare. Chemical and electrical aging of oil can influence the humidity and breakdown voltage (BDV) of oil.

To address this situation, it is necessary to determine the influence of changing properties of oil on the BDV of said oil in switchgear. The goal of the research is to reduce the risk of breakdown of oil in OIS. Therefore, this thesis focuses on the BDV of insulating oil and quantifies the influence of related factors on the BDV of oil. Stedin can apply this knowledge in order to reduce the risk of failures related to the breakdown of insulating oil.

Chapter 2 introduces and discusses various constructions of MV OIS, arc interruption and dielectric measurement theory of oil insulation. Section 2.1 introduces COQ MV OIS and its construction. In section 2.2, switching arcs will be introduced together with arc interruption technologies, where oil as an interruption material will be given extra attention. In section 2.3, breakdown phenomena in oil and principles of tan δ tests of insulating oil will be discussed. Chapter 3 introduces the process of oil sampling, preconditioning of oil and experimental setups and testing procedures.

Chapter 4 gives data analysis to quantify the relationship between the following parameters:
tan δ vs. aging time, tan δ vs. copper, tan δ vs. Breakdown voltage(BDV), acidity vs. aging time, acidity vs. copper, acidity vs. BDV, BDV vs. copper, BDV vs. humidity and humidity vs. acidity.

The results shows that tan δ and acidity increase during the accelerated aging test but do not significantly influence the BDV of oil when the humidity of oil is constant. Varying humidity, however, does highly influence the BDV of oil. Acidity affects the varying humidity of oil of which the effects can be observed in the condensing process.

Chapter 5 will be the conclusions and recommendations. To reduce the risk of breakdown in oil, humidity of oil should be monitored. Acidity will increase during the service life of oil and influence the condensing process of oil.

Content

ACKNOWLEDGEMENTS V

LIST OF ABBREVIATIONS VII

LIST OF SYMBOLS VIII

ABSTRACT IX

CHAPTER 1 INTRODUCTION 1

1.1 What is switchgear? 2

1.2 Goal of the master thesis 4

1.2.1 Background information 4

1.2.2 Research objectives 5

1.2.3 Scientific challenge 5

1.2.4 Thesis approach 6

1.3 Thesis outline 7

CHAPTER 2 LITERATURE STUDY 9

2.1 Introduction of oil insulated switchgear 9

2.1.1 Functions of switchgear 9

2.1.2 Constructions of oil insulated switchgear 10

2.2 Arc interruption techniques 12

2.3 Breakdown of oil 15

2.3.1 Intrinsic breakdown of oil 15

2.3.2 Breakdown in practice 16

2.4 Factors influencing the BDV of oil 16

2.4.1 Aging of oil in general 16

2.4.1.1 Dielectric Dissipation Factor (tan δ) 18

2.4.1.2 Acidity of oil 21
2.4.2 Humidity 22

2.5 Conclusions 24

CHAPTER 3 EXPERIMENT DESIGN AND TEST SETUP 25

3.1 Preparation of the tests 25
3.1.1 Sampling of the oil 25
3.1.2 Preconditioning of the oil samples 28

3.2 Experimental design and setup 29
3.2.1 Accelerated aging test 29
3.2.2 Tan δ test 31
3.2.2.1 Test setup 33
3.2.2.2 Test procedure 36
3.2.3 Acidity test 37
3.2.4 Humidity test 37
3.2.5 Breakdown test 38
3.2.5.1 Test setup 38
3.2.5.2 Test procedure 39
3.2.6 Condensing test 40
3.2.6.1 Preparation 40
3.2.6.2 Test set up 40

3.3 Conclusions 41

CHAPTER 4 TEST RESULTS AND INTERPRETATION 43

4.1 Introduction 44
4.1.1 Definition 44
4.1.2 Timescale of accelerated aging test 44

4.2 Visual inspection 44

4.3 Tan δ vs. aging time regarding the influence of copper 45
4.3.1 Tan δ vs. applied voltage 46
4.3.2 Tan δ vs. aging time & copper 48

4.3.3 Time scale of accelerated aging test 51

4.4 Acidity vs. aging time 53

4.4.1 Acidity of oil from switchgear 53

4.4.2 Acidity of oil from aging test without copper 54

4.4.3 Acidity of oil from aging test with copper 55

4.5 Breakdown voltage of oil 58

4.5.1 BDV vs. tan δ 58

4.5.2 BDV comparison: oil with copper vs. oil without copper 59

4.5.3 BDV vs. acidity of oil 61

4.5.4 BDV vs. humidity 62

4.6 Condensing test 66

4.6.1 Condensing process of new oil 66

4.6.2 Condensing process of service aged oil 67

4.6.3 Condensing of accelerated aged oil 68

4.6.4 The influence of acidity on condensing process of oil 69

4.6.5 Humidity of oil vs. humidity of ambient air at fixed temperature 71

4.7 Conclusions 73

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS 77

5.1 Conclusions 77

5.2 Recommendations 79

REFERENCES 83

APPENDIX A 87

APPENDIX B 91

APPENDIX C 93

APPENDIX D 95

Chapter 1 Introduction

In the transport of electricity from generation to end-user, the electricity distribution part is the final stage in the delivery of electricity before it reaches the end-user. The network of a distribution system carries electricity from the transmission system and delivers it to consumers as can be seen in Figure 1.1 [1]. Typically, the network would include medium-voltage (MV) (less than 50 kV) power lines, electrical substations, low-voltage (less than 1 kV) distribution wiring and sometimes electricity meters.

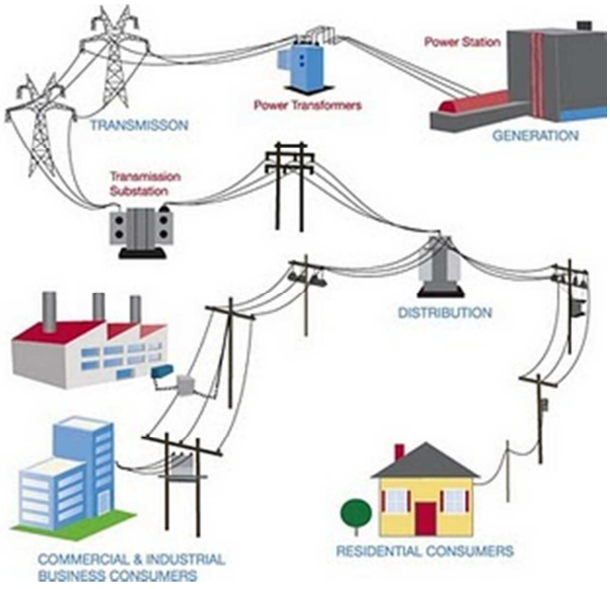


Figure 1.1 An electric grid overview with generation, transmission and distribution levels [1].

Distribution operators are directly related to medium-voltage networks. In case of any problem in this network, customers may experience significant problems due to outage. Important components in the distribution network are MV switchgear which are considered the back-bone. A reliable and efficient MV switchgear system translates to a high quality distribution network [2].

Nowadays, in order to meet the fast growth of electricity consumption, power distribution utilities are required to provide more electricity while maintaining a high level of reliability and quality. At the same time, in order to remain competitive, they need to operate in a cost efficient way by e.g. reducing material costs.

A straightforward way to reduce material cost is to make better use of the assets than in the past by developing a more effective strategy of inspecting and maintaining old instruments such as oil

insulated switchgear (OIS). This is in contrast to simply replacing them with a new type of switchgear at fixed time intervals. A rough comparison is shown in Figure 1.2 where a tester and a tank of oil are involved for inspecting and maintaining 5 OIS. In (a), the tester can measure the humidity and breakdown voltage (BDV) of oil. Then the asset manager of the OIS can decide whether to replace the oil in the OIS. In (b), a new type of switchgear can be used to replace the OIS. This new switchgear does not use oil as the insulating medium. Therefore, the consideration of the influence of varying property of oil on the BDV is not necessary anymore.



Tester (6,219 Euro) **Oil (600 Euro)** **New switchgear (5*11,000 Euro=55,000)**

Figure 1.2 A rough comparison of material cost of two ways which can both obtain electricity supply with high level of reliability. (a) Using a tester [4] to inspect oil insulation in switchgear with a good strategy and replacing the oil [5] if necessary versus (b) A new type of air insulated MV switchgear (Unigear550) [6]. Here we assume the cost of paying people to perform the inspection and maintaining are similar between (a) and (b).

From Figure 1.2 we can see it can be economical to develop a reliable strategy of inspecting and maintaining OIS, which is challenging because the relation between oil properties and the BDV of switchgear is still unclear. Figure 1.2 only considers material cost of the two methods. For a more accurate economical comparison, additional costs for training to perform inspection and maintenance, and fees of developing new strategy of inspection and maintenance should be taken into consideration.

Before we move to details of this subject, we will explain what switchgear is in Section 1.1. Section 1.2 contains the goal of the thesis and background information which puts it in context. Finally, the thesis outline is displayed in section 1.3.

1.1 What is switchgear?

The term switchgear refers to the combination of electrical disconnectors, fuses and/or circuit breakers used to isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream. This type of equipment is important because it is directly linked to the reliability of the electricity supply.



(a) **(b)** **(c)**

Figure 1.3 Types of switchgear. (a) oil insulated switchgear. (b) AEG GIS gas insulated switchgear up to 420 kV. (c) Switchgear with Vacuum Circuit Breaker.

The earliest central power stations used simple open knife switches, mounted on insulating panels of marble or asbestos. Power levels and voltages rapidly increased, making open manually-operated switches too dangerous to use for isolation of a de-energized circuit. Oil-filled equipment allowed arc energy to be contained and safely controlled. By the early 20th century, a switchgear line-up would be a metal-enclosed structure with electrically-operated switching elements, using oil circuit breakers. There are several brands of switchgear and the more well-known manufacturers are GE, ABB, and Siemens. The completed installation of OIS under research in this thesis contains several switchgear, circuit breaker and other related components. The OIS is named ‘COQ’ and produced by COQ Utrecht which today is part of EATON B.V. and Siemens Germany.

Switchgear are categorized according to the extinguishing medium in the interrupting chamber in which an arc is formed such as oil, air-blast, SF_6 and vacuum switchgear. This arc can be interrupted by oil and will result in heat, gas and/or pressure generation.

Moreover, melting of copper contacts and erosion can occur. This will introduce copper particles into the oil and may decrease the dielectric strength of the oil insulation. Little experience exists with the influence of copper on the BDV of oil. Thus, in this thesis, special attention is paid to copper.

Today, oil-filled equipment has largely been replaced by air-blast, vacuum or SF6 equipment, allowing large currents and power levels to be safely controlled by automatic equipment incorporating digital controls, protection, metering and communications. In Figure 1.3, various types of switchgear are shown.

Although the manufacturing of oil switchgear has been discontinued in favor of non-oil types, there are still large numbers of oil insulated switchgear nowadays being used and they provide service of interrupting fault currents when necessary in MV network. The constructions and working principles of switchgear will be discussed in detail in Chapter 2.

1.2 Goal of the master thesis

1.2.1 Background information

This master thesis project is part of the Stedin talent student scholarship program and was fully performed at Delft University of Technology at the faculty of Electrical Engineering, Mathematics and Computer Science in the research group High Voltage Technology and Management.

Stedin is a regional grid operator in, amongst others, the area of Rotterdam, the Hague and Utrecht. Stedin has about 500 OIS COQ which contains several switchgear, circuit breaker and other related components in operation. These switchgear have generally been in operation for many years (20-50 years).

This thesis starts from the report ‘Invloed oliekwaliteit op de betrouwbaarheid van een oliegeïsoleerde schakelinstallatie (COQ NR)’ or ‘Influence of oil quality on the reliability of an oil insulated switchgear’ from KEMA. This report gives some recommendations for future research concerning the effect of varying value of acidity on the steepness of condensing curve of insulating oil. It is part of the research objectives of this thesis to quantify the influence of acidity on the BDV and condensing process of the oil used in COQ .

Previous research shows that in non-hermetically sealed MV OIS, the insulating oil will adopt the relative humidity of the ambient air within a limited period of time (weeks) [7]. In transformers this may take several years [7]. Therefore, a different approach for maintenance compared to transformers is required and additional procedures for operating the switchgear with special concerns of humidity of oil should be developed.
Another important issue is the lack of experience with respect to the influence of copper on the aging processes of oil and BDV. It is necessary to investigate this influence of copper since switching actions are affecting the oil because copper particles are scraped off of the contacts due to this switching.

It is necessary to determine the influence of changing properties of oil on the BDV of oil in switchgear. This thesis focuses on:

1. if and how the breakdown of insulating oil is affected by water content in the oil.
2. if and how the condensing process of insulating oil is affected by acidity of the oil.

1.2.2 Research objectives

The goals of this thesis are to quantify:

1. the influence of copper on chemical and electrical aging process.
2. the influence of copper on the BDV of oil.
3. the relationship between the measured dielectric losses and humidity with the BDV of oil.
4. the effect of varying value of acidity on the steepness of condensing curve of insulating oil.

In order to achieve these goals, the following research questions are proposed:

1. Which factors influence the dielectric strength of oil insulation?
2. What is the influence of humidity on the BDV of oil insulation?
3. What is the influence of chemical and electrical aging processes on the BDV of oil insulation?
4. What is the influence of copper on the chemical and electrical aging processes of oil insulation?
5. What is the influence of copper on the BDV of oil insulation?
6. What is the influence of acidity on the steepness of condensing curve of insulating oil?

1.2.3 Scientific challenge

There is a wealth of experience available regarding the interpretation of oil analysis and failure behavior of power transformers [8]. However, for MV OIS, defining a maintenance strategy is a challenge because it is not clear how failure behavior is affected by varying properties of insulating oil, even though a similar kind of insulating oil is used as in transformers.

MV OIS differs significantly from power transformers in both their operating conditions and construction. The main difference in the construction of MV OIS is that the insulating oil is not hermetically sealed off from the environment. The effect of the open construction that is used in the MV OIS on the dielectric strength of oil is unknown. Moreover, the influence of copper due to

switching actions of switchgear on the aging processes and BDV of oil is also not clear. Therefore, when oil analysis for MV switchgear is performed, it is still unclear how to interpret the results.

The tests of determine which factors highly influence the BDV of oil is difficult to design and perform.

Due to the limitation of oil samples, only 0.5 and 5 year-service aged oil are involved in this research. To make the research conclusions accurate and reliable, an accelerated aging test procedure is designed. However, while experience on defining the timescale of such test for transformers is readily present, experience for switchgear is not. This thesis solves this problem by using tan δ to help decide the correct length of accelerated aging test.

Water dissolved in the oil is hard to control and humidity of oil is needed to be adjusted to certain value for research purpose. This thesis solves this problem by wetting the oil in a special way which will be introduced in chapter 3.

1.2.4 Thesis approach

The first step is to perform a literature study on the work completed in this area so far. After this, it is possible to identify the most important parameters related to oil breakdown behavior and further design the experiment that will be performed on the oil samples.

Following tests will be performed on the oil samples in the high voltage lab:

1. Tan δ test to measure the dielectric losses of oil
2. Humidity test
3. Accelerated aging test with copper in the oil samples
4. Accelerated aging test without copper in the oil samples
5. Acidity test
6. Breakdown test
7. Condensing test

These tests will be explained in more detail in Chapter 3.

The final step is to perform data analysis and quantify the effect of chemical and electrical aging processes and humidity on the BDV of oil insulation of switchgear.

1.3 Thesis outline

Chapter 2 will discuss the literature study. It will explain in detail the construction and function of switchgear, arc interruption technology, breakdown behavior and factors influencing the BDV of oil.

Chapter 3 will illustrate the preparation steps, experimental design and test setups of the performed tests including tan δ test, humidity test, accelerated aging test and breakdown test.

Chapter 4 will present the experimental data and interpretation. An analysis will be given to further quantify the effect of humidity and chemical aging on the BDV of oil insulation of MV OIS with special concern of copper.

In Chapter 5, conclusions and recommendations will be given.

Chapter 2 Literature Study

This chapter starts, in section 2.1, introducing functions and the construction of oil insulated switchgear (OIS). OIS will be then explained in detail with a special concern of current interruption components. Current interruption components provide functions of arc interruption that will be discussed in section 2.2.

In section 2.2, electric arcs will be introduced and the process of interrupting electric arcs will be explained. Examples of both a successful and a failed interruption will be given together with the main cause of the failure, namely breakdown in oil insulation.

In section 2.3, breakdown phenomena in oil will be firstly explained. With an understanding of breakdown in oil, we can list properties of oil that can influence the BDV of oil insulation. In section 2.4, with the experience of oil testing of transformers and the wide difference between transformers and switchgear, factors that can influence the properties of oil will be clarified. The properties that can mostly influence the BDV of oil insulation of switchgear will be chosen. The chosen properties will be measured to find the relationship between these properties and the BDV of oil insulation.

2.1 Introduction of oil insulated switchgear

2.1.1 Functions of switchgear

Under normal operating condition, an electrical system is in a steady-state condition. This steady-state condition continues until sudden changes take place in either the connected supply or the load circuit. Such sudden changes could be switching actions, either to connect or disconnect loads or to switch off faulted sections after a short-circuit, and disturbances from outside, such as a lightning stroke on or in the vicinity of a high-voltage transmission line [9] and can cause overload or short circuit. The components in the system can be subjected to high current and high-voltage peaks that can cause considerable damage due to the occurrence of these sudden changes. Switchgear is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit by switching circuits on and off.

All switchgear must be capable of both closing and opening an electrical circuit. Its basic function is to detect a fault condition and, by interrupting continuity, to immediately discontinue electrical flow. Unlike a fuse, which operates once and then has to be replaced, switchgear can be reset manually or automatically to resume normal operation.

Disconnectors are mechanical switches that, in closed position, are able to carry a defined rated normal and short-circuit current. In the open position, they must provide a defined level of insulation between their contacts. Switchgear also perform these functions.

The major difference between a disconnector and switchgear is that a disconnector is an off-load device intended to be opened only after current has been interrupted by some other control device (e.g. switchgear). Thus, in high voltage/high current installations such as in power stations or grid switching stations, the initial operation to isolate the circuit, whether planned or as a result of a fault, is performed by the circuit breaker/switchgear. After this event, the disconnector is then used to isolate the circuit breaker/switchgear for maintenance or repair.

2.1.2 Constructions of oil insulated switchgear

A simple single-phase diagram (Figure 2.1) illustrates the basic component functions within switchgear.

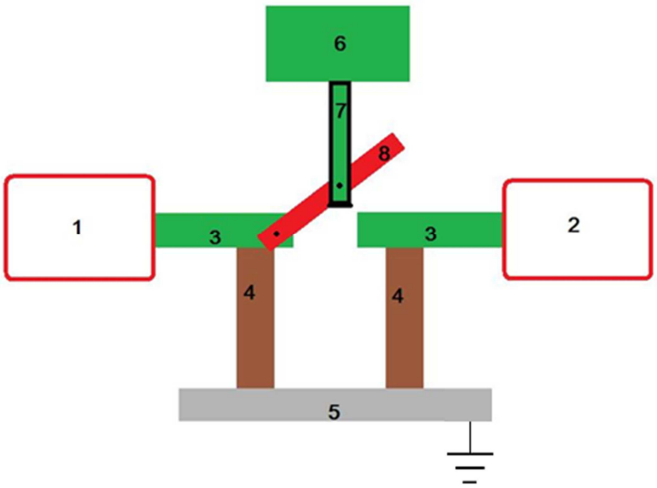


Figure 2.1 Basic components within switchgear. In the figure: 1 is supply side and 2 is the load side; 3 indicates the conductor; 4 is the insulation between 5 (earthing) and conductors; 6 is the operating mechanism to open and close 8 which is moving contact; 7 is insulation.

The conductors are required to carry electrical current. The insulators are required to provide electrical insulation to earth to withstand both the system voltage and any transient voltages which may be stressed upon the switchgear. The moving contact, like the conductors, will also be subjected to heat and mechanical forces. It is also the function of the moving contact to provide an insulating gap when in the open position. It is the function of the operating mechanism to drive the moving

contact between the open and closed positions, and to withstand the electromagnetic forces that can be generated when a short circuit occurs.

Not shown in Figure 2.1, but of great importance, is the means of extinguishing the arc (arcs will be introduced in section 2.2) that will always form when the moving contact is separated from its associated fixed contact while carrying current. The most important part of switchgear is a switching element having a variable impedance [23]. In most switchgear, this variable impedance is a high pressure arc, although, in some other switchgear, it may be a vacuum arc. The main factors that dictate the overall design parameters of the device are the interrupting and insulating medium, together with the methods that are utilized to achieve the proper interaction between the interrupting medium and the electric arc [24].

Switchgear can be categorized according to the extinguishing medium such as oil, air-blast, SF_6 and vacuum switchgear. The switchgear under investigation in this thesis is oil insulated switchgear (OIS) and is from N.V. COQ - Utrecht. The diagrammatic cross-section of the switchgear is shown in Figure 2.2; a schematic drawing of the drive of COQ switchgear is illustrated.

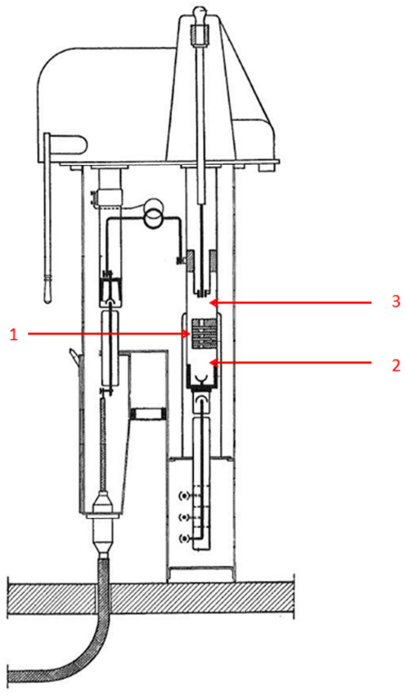


Figure 2.2 Schematic cross-section of COQ switchgear. The main parts are: 1. extinguishing chamber, 2. fixed contact, 3. moving contact [17].

The focus of this research is on oil insulation as insulation failure is the leading cause of switchgear failure [25]. The insulating oil being analyzed in this project is from NYNAS AB and the type name of the oil is NYNAS NYTRO LIBRA. The property of this oil is shown in Appendix C.

In OIS, oil serves three purposes; firstly, to insulate the switchgear contacts from the earthed metal tank, secondly, to provide an insulating barrier between the open contacts after the arc is extinguished and, thirdly, to produce hydrogen during the arcing period.

The oil is placed in the extinguishing chamber where two contacts are present. The two contacts, one fixed and the other moveable, are in the closed position under normal operation. The interrupting zone of the switchgear acts as a conductor. In order to interrupt the flow of current, this conductor must change its function to that of an electrical insulator. Due to the high voltage (up to 50 kV), the separation cannot be performed like a simple switch we use to turn off a light (220 V). An electric arc will occur between the two contacts and we need to use special insulating material to interrupt the arc. This change has to take place in the shortest possible time in order to minimize the effects of arcing. These effects may result in heat, gas and/or pressure generation. Moreover, melting of contacts and erosion can occur. Arc interrupting techniques will be discussed in section 2.2.

2.2 Arc interruption techniques

When performing analysis of simple switching transients and carrying out large system studies, it is often sufficient to model switchgear as an ideal switch. However, when studying arc–circuit interaction, the understanding of the influence of the electric arc on the system elements is important. Thus, a thorough knowledge about the physical processes between the switchgear contacts during current interruption is necessary [9].

The electric arc is a plasma channel between the switchgear contacts. The plasma channel is formed after a gas discharge in the extinguishing medium. The process of forming a plasma channel is shown in Appendix B. When a current is flowing through the contacts of switchgear, the contacts act as a conductor. When the contacts need to separate from each other, the magnetic energy stored in the inductances of the power system keeps the current to flow. Just before the separation of the two contacts, they touch each other at a very small area and the resulting high current density causes the contact material to melt. The melting contact material explodes and this will lead to a gas discharge in the surrounding medium, which is oil in this thesis.

The plasma channel is highly conducting because of the free electrons and the heavier positive ions in the plasma channel with high temperature [Appendix B]. In switchgear, the current interruption is performed by cooling the arc plasma. This cooling process can be achieved in different ways. Switchgears are categorized according to the extinguishing medium in the interrupting chamber in which the arc is formed such as oil, air-blast, SF_6 and vacuum switchgear.
Current interruption of switchgear occurs normally at current zero (the instantaneous point at which there is no voltage present) within a time frame of microseconds. Several processes take place at the same time in the process of current interruption.

After maintaining a constant value during the high current interval (shown in stage 1 in Figure 2.3), the arc voltage increases to a peak value (shown in stage 2 in Figure 2.3), the extinction peak, and then drops to zero with a very steep rate of decrease of voltage (in the order of 2000 V/μs). The current approaches its zero crossing with a more or less constant rate of change of current (in the order of 20 A/μs) but the current can be slightly distorted under the influence of the arc voltage. The arc is resistive and therefore the arc voltage and the current reach the zero crossing at the same instant. This process is illustrated in Figure 2.3.

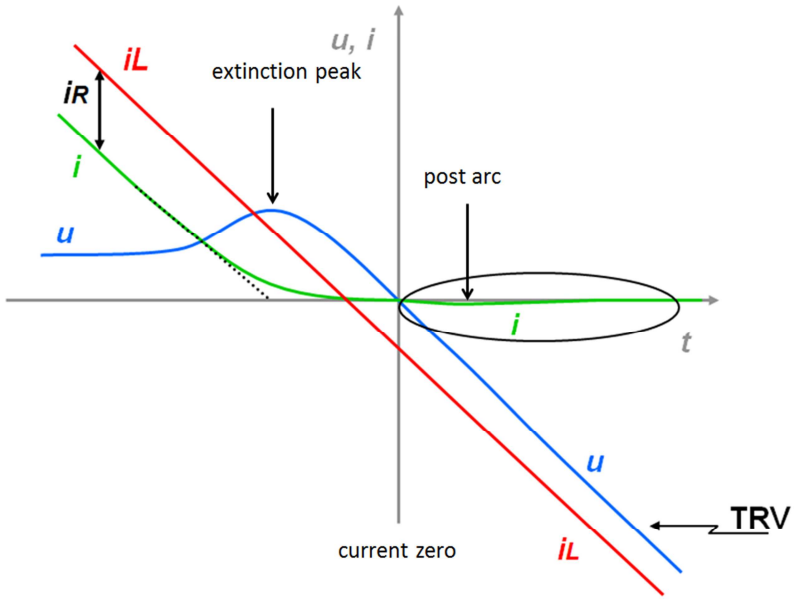


Figure 2.3 Current and voltage around current zero when switchgear interrupts a short-circuit current. The voltage and current reach zero crossing at the same time. The post-arc current, together with the TRV can result in thermal breakdown [9].

Around current zero, the energy input into the arc channel is rather low (at current zero, there is no energy input), and when the switchgear is designed is that the cooling by the extinguishing medium is at its maximum at current zero, the current can be interrupted successfully. After current interruption, the still-hot gas between the contacts is stressed by a steep rate of rise of the recovery voltage. In the resulting electric field, the present charged particles start to drift and cause a hardly measurable so-called post-arc current. The post-arc current, together with the transient recovery voltage (TRV), results in energy input in the still-hot gas channel (stage 3 in Figure 2.3). When the energy input is such that the individual gas molecules dissociate into free electrons and heavier positive ions, the plasma state is created again and current interruption has failed. This is called a thermal breakdown of the switchgear.

When the current interruption is successful, the hot gas channel cools down and the post-arc current disappears; still, a dielectric failure can occur when the dielectric strength of the gap between the contacts is not sufficient to withstand the TRV. The TRV across the breaker contacts after current interruption is formed by local voltage oscillations and reflected voltage waves. The steep increase of TRV is shown in Figure 2.4.

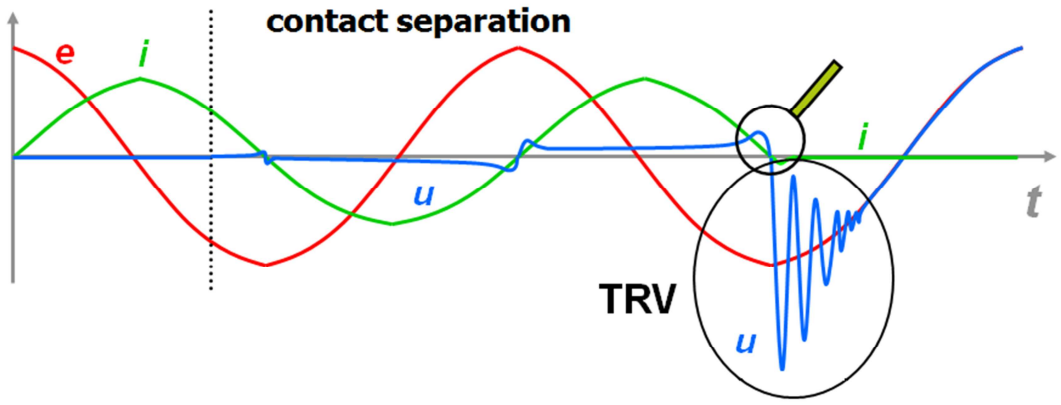
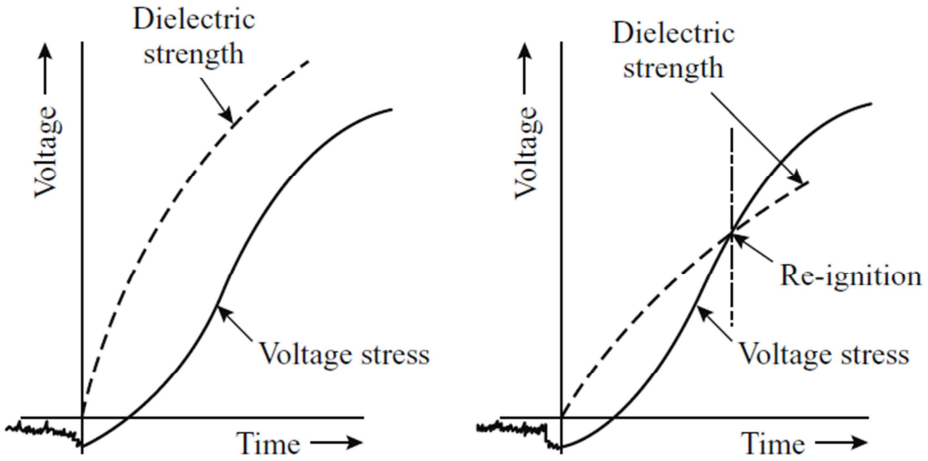


Figure 2.4 Switchgear interruptions with interaction. The TRV in this figure reaches to twice the peak value of rated voltage and can cause dielectric breakdown in oil insulation [9].

According to the theory of Slepian: ‘If, after current zero, the dielectric strength of the contact gap increases at a greater rate than the transient voltage, then the interruption will be successful.’, Examples of both a successful and a failed interruption are shown in Figure 2.5 [10].



(a) Interruption maintained **(b) Initial interruption followed by dielectric failure**

Figure 2.5 Slepian's theory. In (a) the dielectric strength of the contact gap increases at a greater rate than the transient voltage and the interruption of is successful. In (b) the dielectric strength of the contact gap fails to increase at a greater rate than the transient voltage and the interruption fails [10].

A successful interruption is shown in Figure 2.5(a) where the rate of increase of dielectric recovery exceeds the rate of increase of the TRV stress. Figure 2.5(b) shows a failure to clear as re-ignition occurs at a point where the impressed voltage exceeds the dielectric strength of the gap. We can conclude that breakdown is the main cause of the failure during arc interruption and therefore warrants more research. Thus, it is important to clarify factors that can influence the BDV of oil.

2.3 Breakdown of oil

According to IEC standard 60243, the definition of the breakdown voltage is:

- for continuously rising voltage test: The breakdown voltage is the voltage at which the specimen suffers breakdown under the test condition.
- for step-by-step test: The breakdown voltage is the highest voltage which a specimen withstands without breakdown for the duration of the time at the voltage level.

2.3.1 Intrinsic breakdown of oil

The intrinsic breakdown of oil can be reached if all interfering effects are prevented [28]. The intrinsic breakdown voltage is only realized in laboratory environment.

Electrons are emitted from the cathode and are accelerated until they have sufficient speed to ionize the molecules on collision. Avalanches are formed and the conductivity increases rapidly. A narrow channel arises in the oil somewhere the current concentrates, the temperature increases and the viscosity decreases [28]. This leads to a larger current and instability. Breakdown occurs as the oil evaporates locally. The breakdown path is highly luminescent; gas bubbles, traces of burnt oil and pressure waves are clearly observed.

2.3.2 Breakdown in practice

In practice, insulating oil is never free of impurities. Dust, particles, fibers, metal silvers and tiny air bubbles are always present [28]. The effect of these particles is not neglectable. The particles move towards areas of high field strength. The particles with high permittivity cause a field concentration by themselves and attract each other as well. Chains of particles are formed which may bridge the electrodes. These bridges are inferior dielectrics which are slightly conductive and built of impurities of low breakdown voltage. Moist particles especially show this phenomenon [28]. This is why the insulating oil is thoroughly dried.

2.4 Factors influencing the BDV of oil

With the knowledge from section 2.3, we know that the BDV is related to various properties of oil. Important properties are impurities (fibers or as dispersed solid particles), bubbles and water content of oil. These properties of oil are affected by changing environmental factors and will vary along aging processes of the oil. These factors are clarified in the following sections.

2.4.1 Aging of oil in general

New insulating oil is a clear, pale yellow liquid. After a period in service, the oil becomes darker and it is probable that oil insulating properties have deteriorated. Impurities in the oil will reduce its insulating properties. Insulating materials will deteriorate under normal operating conditions and the aging rate is influenced by several stresses: thermal, electrical, mechanical, and ambient stresses [11].

A wealth of experience has been obtained with aging processes of transformers. In a transformer, many aging processes take place. The transformer components age due to both electrical and environmental factors. In Figure 2.6, it can be seen that insulation suffers mainly from processes caused by environmental factors such as pyrolysis (thermal degradation), oxidation (oxygen in the oil) and hydrolysis (moisture in the oil).

Thermal stress can be recognized by the temperature gradient in the insulation during the long-term operation and especially the presence of hotspots. Electrical stress may lead to partial discharge, treeing and dielectric heating due to a lossy insulation or highly conductive contaminants. For mechanical stress, the aging process relies on the torsion, compression, tension or bending factors. Ambient stress is closely related to the environmental factors such as corrosive chemicals, petroleum fluids, high humidity, and ultraviolet radiation from the sun. The molecular structure of insulating materials can be decomposed by all of the stresses, leading to a situation in which the material eventually can no longer perform its insulation functions [19].

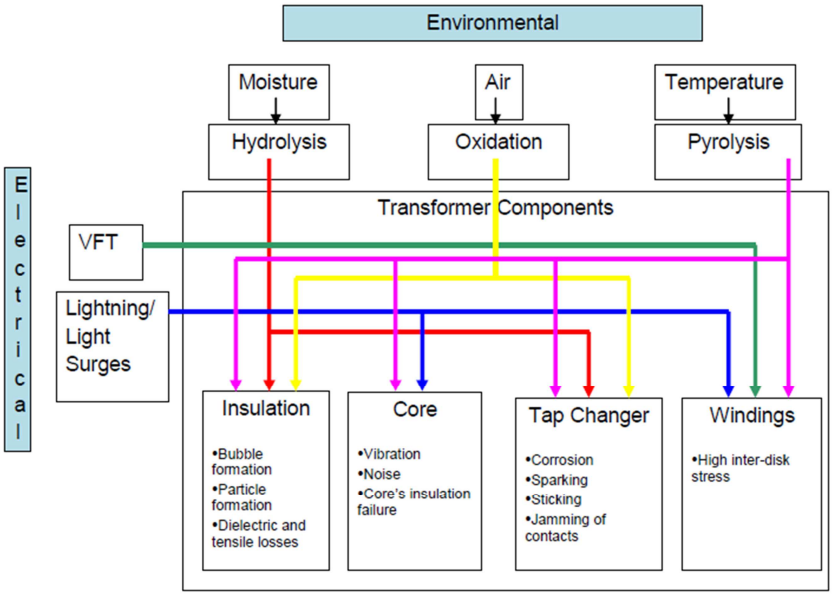


Figure 2.6 Electrical and environmental factors affect the aging of multiple transformers components. The main components affected are the insulation, core, tap changer and windings. When focusing on the insulation, it can be seen that hydrolysis, oxidation and pyrolysis are responsible for its degradation [15].

In switchgear, oil is used at ambient temperature. So the aging mechanisms that influence the insulating properties of oil are mainly chemical aging process and electrical stress. Additives, such copper, influence the total acidity number (TAN) and tan δ.

Although electrical aging, in isolation, has a limited effect, it can lead to a rapid increase in electrical losses within the oil, which, ultimately, will lead to failure of switchgear. The increase in electrical losses can be indicated by measuring dielectric dissipation factor or tan δ of oil.

Chemical aging of switchgear oil is caused by oxygen, copper and humidity. Switching actions of switchgear will result in heat, gas and/or pressure generation. Moreover, melting of contacts and erosion can possibly occur, which will add copper particle in the oil. These copper particles will interact with oxygen and water and further introduce by-product impurities. This will increase the acidity of oil.

Very little research has been performed on quantifying the influence of copper on chemical aging process of oil. Thus, in this thesis, the influence of copper on the chemical aging process and, consequently, on the BDV of oil will be analyzed.

As mentioned in section 2.3, impurities in oil will lead to decrease of BDV of oil. The chemical and electrical properties of insulating oil are affected by various factors. We have found these factors to be copper, oxygen and humidity.

Thus, factors such as copper, oxygen and humidity can be related to the aging of oil. The aging process of service oil in switchgear is simulated by accelerated aging test. Tan δ and acidity of oil will be measured and used as indicators of the aging level of insulating oil.

2.4.1.1 Dielectric Dissipation Factor (tan δ)

The dielectric loss factor tan δ is sensitive to the insulating ability and the aging degree of insulating oil, which is an important parameter to monitor the safe operation of transformer [27].

When oil is aged, the tan δ of the oil will normally increase and can be used as an indicator of aging level of oil. There are two fundamental parameters characterizing a dielectric material, the conductivity σ and the real part of the permittivity or dielectric constant ε'(or ε_R) [13].

The conductivity σ of a dielectric material is defined as the ratio of the leakage current density J_1 (in A cm^{-2}) to the applied electric field density E (in V cm^{-1}),

$$\sigma = \frac{J_1}{E} \tag{2.1}$$

It is also determined in terms of the measured insulation resistance *R* (in Ω) as

$$\sigma = \frac{d}{RA} \tag{2.2}$$

where *d* is the insulation thickness (in cm) and *A* is the surface area (in cm^2).

The dielectric constant ε' is defined as the amount of electrostatic energy which can be stored per unit volume per unit potential gradient. But it is also known as the real part of permittivity which is determined as the ratio of

$$\varepsilon' = \frac{C}{C_0} \tag{2.3}$$

where *C* is the measured capacitance (in F) and C_0 is the equivalent capacitance in vacuo. C_0 can be obtained from the same specimen geometry of

$$C_0 = \varepsilon_0 \frac{A}{d} \tag{2.4}$$

while ε_0 represents the permittivity in vacuo with the value of 8.854 x 10^{-14} F cm^{-1}. The value of ε_0 in free space is essentially equal to that in a gas (ε'_R of air = 1.000536).

The relative permittivity definition from IEC 60247 is the ratio of capacitance C_x of a capacitor in which the space between and around the electrodes is entirely and exclusively filled with the insulating material, to the capacitance C_0 of the same configuration of electrodes in vacuum.

$$\varepsilon'_R = \frac{C_x}{C_0} \tag{2.5}$$

Dielectric losses can initially be caused by the movement of free charge carriers (electrons and ions), space charge polarization or dipole orientation. Most causes are influenced by the temperature, electric field strength, and are frequency dependent. A complex permittivity is defined as

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{2.6}$$

where ε'' is the imaginary value of permittivity and via measure of the dielectric loss contributed by the leakage current and the polarizations, ε is the complex permittivity and equal to the ratio of dielectric displacement vector $\bar{D}$ to the electric field vector $\bar{E}$. The losses determine the phase angle δ between vector $\bar{D}$ and $\bar{E}$. Based on the position in the vector, $\bar{D}$ and $\bar{E}$ should have the complex notation $D_0 exp[j(\omega t - \delta]$ and $E_0 \exp[j\omega t]$ with D_0 and E_0 as the vector magnitudes respectively. Thus, the following relations are obtained

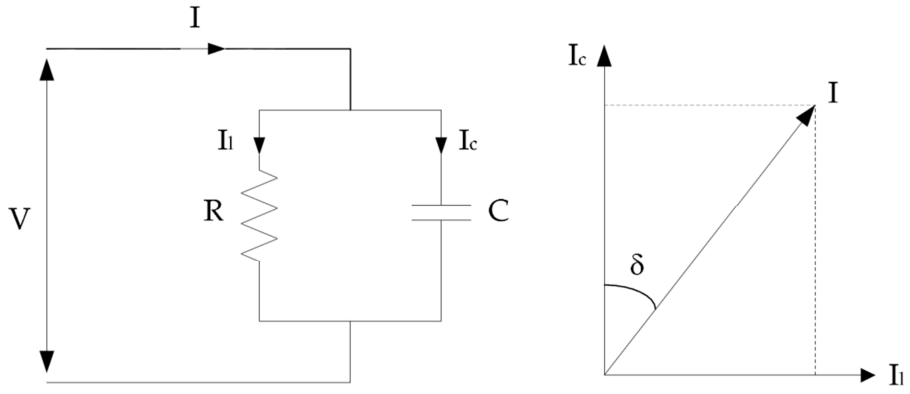
$$\varepsilon' = \frac{D_0}{E_0} cos\ \delta \tag{2.7}$$

$$\varepsilon'' = \frac{D_0}{E_0} sin\ \delta \tag{2.8}$$

The dielectric dissipation factor (tan δ) can be expressed as:

$$tan\ \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon''_{pol} + \frac{\sigma}{\omega}}{\varepsilon'} \tag{2.9}$$

The behavior of the losses of a dielectric can be determined from an equivalent electrical circuit. A parallel circuit as shown in Figure 2.7(a) is commonly used for analysis.



(a) **(b)**

Figure 2.7 The behavior of the losses of a dielectric can be determined from (a) Parallel circuit and (b) Phasor diagram

The behavior of equation (2.9) is commonly described in parallel circuit representation, with dielectric components such a capacitance *C* parallel with resistance *R*. When voltage *V* is applied over

a dielectric material, it generates a leakage current $I_1 = \frac{V}{R}$ and displacement current $I_C = j\omega CV$. From the phasor diagram in Figure 2.7 (b), we can derive the value of $tan\,\delta = \frac{I_l}{I_C}$. By applying the substitution on I_l and I_C , a final expression can be given as:

$$tan\,\delta = \frac{1}{\omega RC} \tag{2.10}$$

The definition of dielectric dissipation factor (tan δ) according to IEC 60247 is the tangent of the loss angle. The loss angle is described as the angle difference between applied voltage and the resulting current deviating from $\pi/2$ rad.

2.4.1.2 Acidity of oil

New oils contain practically no acids if properly refined. The acidity of oil is indicated by measuring the amount of acids formed oxidation. The oxidation products polymerize to form sludge which then precipitates out. Acids react with metals on the surfaces inside the tank and form metallic soaps, another form of sludge.

New oil has a total acidity number (TAN) of less than 0.05. The acid number (formerly referred to as neutralization number) is equal to the milligrams of KOH (potassium hydroxide) required to neutralize the acid contained in 1 gram of oil. It is uncertain whether oil that has deteriorated to the point where its acid number exceeds 0.6 can be put back into lasting good condition by a single renovation. The process of 'cleaning' used oil into its original condition is called renovation. An oil renovation plant can effectively remove colloid, oxide, acid, pitch, particles, impurities, water and gas in the used oil [31]. Specifically, it can restore the color of used oil and remove the scent rapidly. In this case, it is almost certain that two or more renovations will be required, spaced 6 months to 1 year apart. It is recommended to use an upper limit of 0.2 to determine when oil should be renovated, as a single renovation is then most likely to restore this oil to good condition. Oil showing an acid number of 0.15 or larger can be expected to show accelerated acid formation. Previous tests have been conducted which indicate that the acidity is proportional to the amount of oxygen absorbed by the oil [30]. It is estimated that if 0.0015 m^3/L of oxygen is absorbed in oil, then this will cause an acidity of about 0.4 mg of KOH, which is the acidity number at which sludging is assumed to start.

Acidity can also influence the condensing process of oil. The KEMA report mentioned in Chapter 1 recommends performing research on oil with different TAN other than 0.4 to quantify the effect of acidity on the BDV and condensing process of the oil. Thus, acidity test and condensing test need to be designed and performed.

2.4.2 Humidity

Water in oil is an unwanted substance and should be controlled as low as possible in the oil. It is generally accepted that water in microscopic amounts, not gallons, is the cause of electrical breakdowns more than any other impurity [26]. Humidity of oil does not only influence the oil properties by interacting with impurities in the chemical aging process, but it also directly influences the BDV of oil. Water is a polar liquid which has a high permittivity or dielectric constant. It is therefore attracted to areas of strong electric fields. Therefore, the internal moisture does not distribute uniformly, but in fact potentially concentrates in the most vulnerable and critical parts of the system.

In transformers, water can be introduced to the oil by leaking gaskets, poor handling techniques or from the product of natural insulating paper and oil degradation. As the paper degrades, it produces carbon dioxide and water and as the insulating oil ages, water, acids, sludge and other polar compounds are formed. Its presence is inevitable during the normal service life of a transformer [26].

One of the most significant differences between transformers and OIS is the method of storing insulating oil. In transformers, the oil is sealed off from the air and the varying moisture of oil mainly comes from the paper. Moisture can dissolve better in hot oil than in cold oil. Combined with the hot conductors in a transformer (due to high loads), this will drain the moisture out of the paper into the oil. However, in OIS, the oil is placed in a tank and the tank is directly exposed to the air (the tank of storing insulating oil will be illustrated in section 3.1). The varying moisture mainly comes from the ambient air and the process is fast and significant compared to transformers [7].

Water may be present in three possible forms in switchgear oil:

- Free water – water that has settled out of the oil in a separate layer. It is this water which is indicated by a low dielectric breakdown voltage.
- Emulsified water – water that is suspended and has not yet settled out into free water
- Water in solution – water dissolved in the oil.

The most dangerous and destructive effect of water content in oil is the loss of the oil insulating ability. This may occur during the following events:

- During periods of high load and at high ambient temperatures, dielectric breakdowns can result from the reduced oil strength with high absolute amounts of water.
- During sudden high loads, water can boil off conductor surfaces and the vapor bubbles can cause dielectric failures as they rise to the top.
- During the cool-down period after high load, water will precipitate out and greatly reduce the dielectric strength of the oil.

Water in oil will decrease the BDV of the insulating oil and can highly influence the reliability of switchgear, as even 0.001 % water content in insulating oil will reduce the electrical strength of the oil by 10 % [10]. When the temperature drops, water content will precipitate out and will condense and accumulate. As mentioned in the previous chapter, acidity can influence this process. Thus, condensing test should be performed to simulate this phenomenon and oil with different TAN should be included in the test.

As oil will float on water, any free water entering a switch tank will accumulate in the bottom of the tank. Some of this free water will be absorbed by the oil, reducing its electrical strength. Moreover, in its free state, this has been the cause of internal flashover and catastrophic failure of switchgear. This process is illustrated in Figure 2.8.

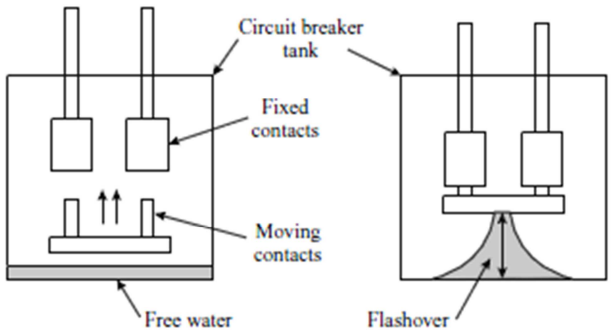


Figure 2.8 Electrical flashover due to free water in an oil circuit breaker tank [10].

When the circuit breaker is open and at rest, as shown in the left-hand diagram of Figure 2.8, the free water in the bottom of the circuit breaker tank will not cause a flashover. However, during the closing action, the contacts will start to move in the direction of the arrows towards the position shown in the

right-hand diagram. During this movement, the pressure on the underside of the plunger bar is reduced causing the water to be drawn upwards, bridging the gap between the plunger bar and the circuit breaker tank which is at earth potential, causing an electrical flashover.

Thus the varying humidity of oil should be measured to determine the relationship between the humidity and the BDV of oil.

2.5 Conclusions

In order to interrupt the flow of current, the contacts of OIS should be separated. Due to the high level of voltage (up to 50 kV), an electric arc will occur between the two contacts and oil is needed to interrupt the arc. The interruption can fail if the BDV of oil is lower than the TRV.

For switchgear oil insulation, chemical and electrical aging process and the varying humidity of the oil can affect the BDV of oil.

The chemical aging process of oil is mainly caused by copper particles, oxygen and humidity introduced by switching actions and open air. This will increase the acidity of oil and can be indicated by measuring the TAN of oil. The increase in electrical losses caused by electrical aging can be indicated by measuring the dielectric dissipation factor (tan δ) of oil. TAN and tan δ are used as indicators of the aging level of oil in this thesis.

Little research has been performed on quantifying the influence of copper on chemical aging process of oil. Thus, in this thesis, the influence of copper on chemical aging process and further on the BDV of oil will be analyzed.

Water dissolved in the oil and free water both highly influence the BDV of oil. Humidity test together with breakdown test are needed to quantify the influence of dissolved water on the BDV of oil. Condensing test is needed to simulate the water precipitation due to decreasing temperature of oil after high load. Oil with different TAN will be involved in the condensing tests to determine the influence of acidity on the condensing process.

Chapter 3 Experiment design and test setup

In chapter 2, several factors were discussed that influence the BDV of oil insulation. These factors are oxygen, copper and humidity. With these conclusions, tests can be designed and performed to measure tan δ, humidity, acidity and BDV of oil. Accelerated aging tests will be designed and performed to simulate the influence of chemical aging process and electrical aging process of oil. To quantify the influence of copper on changing tan δ and acidity, new oil will be placed with and without copper during the accelerated aging test. Tan δ and acidity of service aged from switchgear will also be measured to compare with the data from accelerated aging tests.

Section 3.1 starts with a number preparation steps before building the test setup and performing the measurements. These preparation steps are the sampling and the preconditioning of oil and will be discussed in this section.

In section 3.2, 6 tests will be introduced. These tests are accelerated aging test, tan δ test, acidity test, humidity test, breakdown test and condensing test. The test setup and testing procedure of each test will be discussed in this section.

3.1 Preparations of the tests

3.1.1 Sampling of the oil

Oil samples are taken from the MV OIS COQ installations which are in service in the grid of Stedin. New oil and used oil of two different ages (0.5 year and 5 years) are taken separately. This part of work takes place in the building where the switchgear is situated, see Figure 3.1.



Figure 3.1 Front entrance of the building of keeping COQ inside. COQ OIS are indoor switchgear and the only influence of the environment is from the open air.

Drawn aluminum bottles are used to store and transport the oil. Before taking the oil samples these bottles are cleaned with alcohol and dried.



Figure 3.2 Drawn aluminum bottles are chosen to keep the oil samples and a crap can reject air from outside of the bottles.

According to IEC standard 60475, the sampling procedure includes the following steps:

1. Place a pump on the switchgear (tank) at fixed height to the bottle of the switchgear (tank).
2. Flush 2 liter of oil to a waste container to make sure the inside of pump only exists new oil from the tank or the oil from the switchgear.
3. Fill the bottle with 50-100 ml of oil and shake the bottle. Put this oil also to the waste container. This step must be performed twice before continuing.
4. Fill the bottle with this constant oil flow till 1 cm below the screw cap.
5. Close the bottle with the cap.



(a) Sampling new oil from oil tank which is just opened before the sampling starts



(b) Sampling aged oil from COQ switchgear

Figure 3.3 Sampling work

The construction and housing of COQ switchgear indicates the key difference of COQ switchgear and transformers: the oil tank of COQ switchgear is directly exposed to the air which can lead to humidity variance in insulating oil. For transformers, the oil is sealed off and the changes of properties of oil mainly come from the paper insulations. Figure 3.4 shows the constructions of oil tank.



Figure 3.4 Oil tank are directly exposed to the air and this can lead to humidity change of oil according to the humidity of air.

3.1.2 Preconditioning of the oil samples

A vacuum oven (in Figure 3.5) is used to precondition the oil samples to reduce the humidity of the oil. Using this method, the initial varying humidity of oil will not affect the result of tan δ. Therefore, the tan δ will only be dependent on the aging time. Before starting the planned tests in section 3.2, the oil samples must be preconditioned. Firstly, the glass sample bottles are cleaned and dried before filled with oil. Secondly, the oil samples are put inside the vacuum oven.

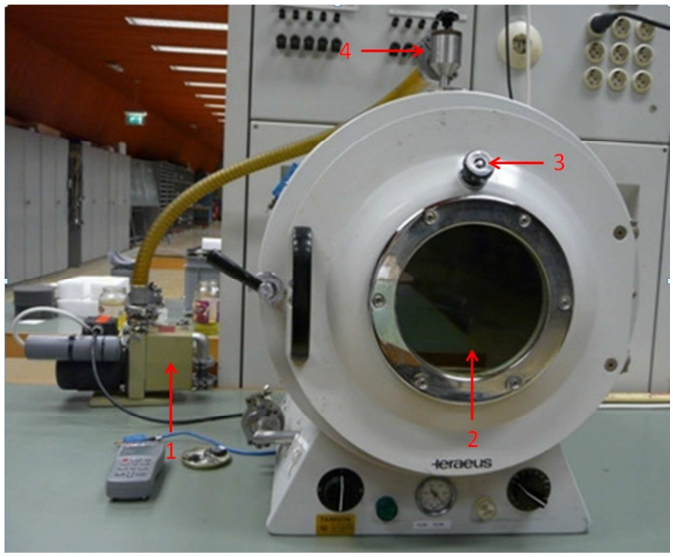


Figure 3.5 The vacuum oven has functions of both heating and drying samples inside the oven. 1. An air pump can pump the air outside the oven and make inside of the oven vacuum. 2. An air tight gate rejects the inside of oven off air. 3. An air switch can let air in when open the gate. 4. Through this air switch the air can be pumped outside the oven.

3.2 Experimental design and setup

3.2.1 Accelerated aging test

After preconditioning in the vacuum oven, the samples are placed in the normal oven without vacuum function to perform the thermal aging test. Oil with copper and without copper will be kept in glass bottles and heated at 130℃ inside the oven. For oil with copper, each bottle has 6 pieces of copper in the oil (shown in Figure 3.8). The test temperature, number and size of copper pieces are chosen with the help from referring to the test described in [8]. The test in [8] is designed for transformer oil and at 100 ℃ the test takes up to 2 months but the result does not show a significant difference. Using 130℃ as test temperature can accelerate the test and meanwhile still reach the requirement of safe operation.

The size of the copper piece is 2.5cm long and 2cm wide which is shown in Figure 3.6. Arrangement of the samples inside the oven is shown in Figure 3.7(a). The oven used for heating the samples is shown as Figure 3.7(b).

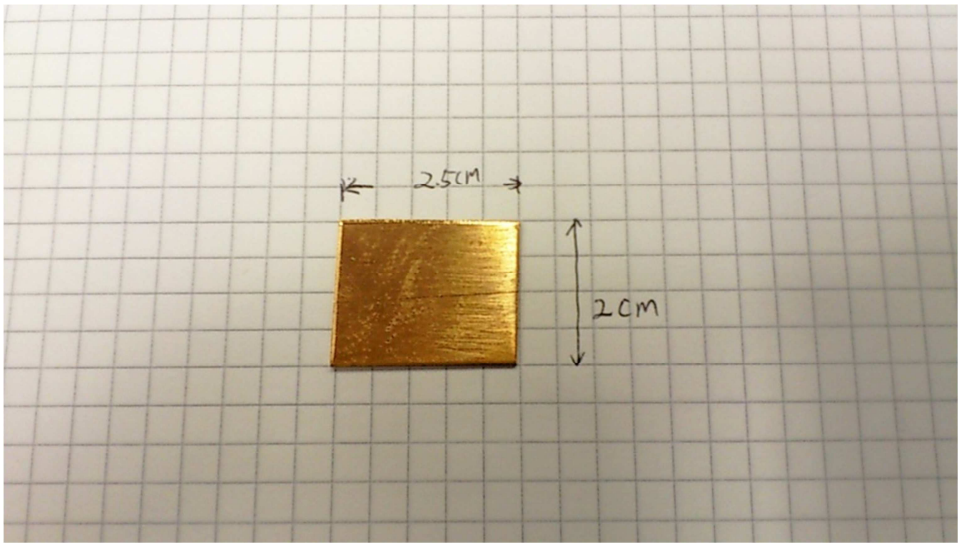


Figure 3.6 Dimensions of a piece of copper used in thermal aging test.

To ensure similar aging factors in each bottle and that the only changing parameter is the aging time, each bottle contains 1.1 liter of oil and will be kept enclosed with same volume of air at same temperature. Thus, the influence of oxygen and humidity of air on the chemical aging process is the same on the oil with and without copper.



(a) Arrangement of the samples in the oven during the thermal aging test.



(b) Oven used to perform the accelerated thermal aging test.

Figure 3.7 Inside and outside of the oven.



Figure 3.8 Pieces of copper in the oil.

The influence of copper on the chemical aging process and BDV of the oil can be then quantified by comparing the data of tan δ and BDV of oil between the samples with copper and the samples without copper.

After setting up the temperature of the oven at 130℃, the aging test starts. Tan δ will be measured to detect the aging level of the two groups of samples.

3.2.2 Tan δ test

One of the most commonly used methods for measuring 'loss tangent', tan δ, and capacitance with high precision is the Schering bridge, originally patented by P. Thomas in 1915 and introduced to HV measurements by H. Schering in 1920. The basic circuit arrangement is shown in Figure 3.9.

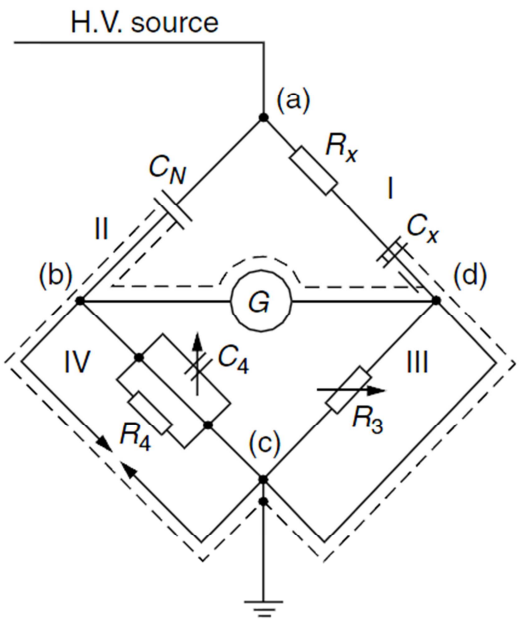


Figure 3.9 The principle drawing of Schering bridge. When the bridge is in balance, G shows no voltage potential between (b) and (d) [18].

The bridge measures the capacitance C_X and loss angle δ (i.e. tan δ) of a capacitor or any capacitance of a sample by comparing it with a gas-filled standard capacitor C_N which has very low and nearly negligible loss over a wide frequency range and can be built for test voltages up to the megavolt range. The 'I' HV arm (right-hand side) of the bridge consists of a sample, the dielectric loss and capacitance of which are to be measured. On account of the dielectric loss, the current through the capacitor leads the voltage by an angle (90 - δ) which is only slightly less than 90°. This current produces a voltage drop of usually less than 100V across the variable resistor R_3 of the low-voltage part of the bridge. The elements R_4 and C_4 of this part are necessary to balance the bridge. As seen from the circuit, the balance conditions are represented by considering that for the frequency applied a pure capacitance C_X is connected in series with a hypothetical resistance R_X, the power dissipated in the resistance simulating the power loss in the actual capacitor.

When G shows 0 which means the bridge in balance, tan δ is then obtained:

$$tan\,\delta = \omega R_4 C_4$$

3.2.2.1 Test setup

The dielectric dissipation factor (tan δ) measurement in this project follows the standard IEC 60247 including preparation of measurement tool. The design of the test cell has been slightly modified to reduce the complexity. Figure 3.10 shows the design of the test cell.



(a) Test cell dimension **(b) Low voltage electrode** **(c) High voltage electrode**

Figure 3.10 Test cell dimension and separated parts.

The test cell consists of high voltage (HV) and low voltage (LV) electrodes. Both electrodes are made of stainless steel with high heat resistance. The top part of LV electrode is made of epoxy as an insulator and equipped with a guard which is put inside it. The guard has a function to minimize the effect of any leakage current in the measurement. The guard is explained in detail in Appendix D. A small hole in top part of LV electrode and an air/oil rejection pipe connected on the side of HV electrode are designed to assure that no air will be trapped inside the test cell after it is fully filled with oil samples. The test cell has been measured with only air inside with the measured results of capacitance and $\tan\delta$ being 133.58 pF and 3.6×10^{-4} at 500 V. The connection of the test cell to the high voltage side and low voltage side is shown in Figure 3.11.

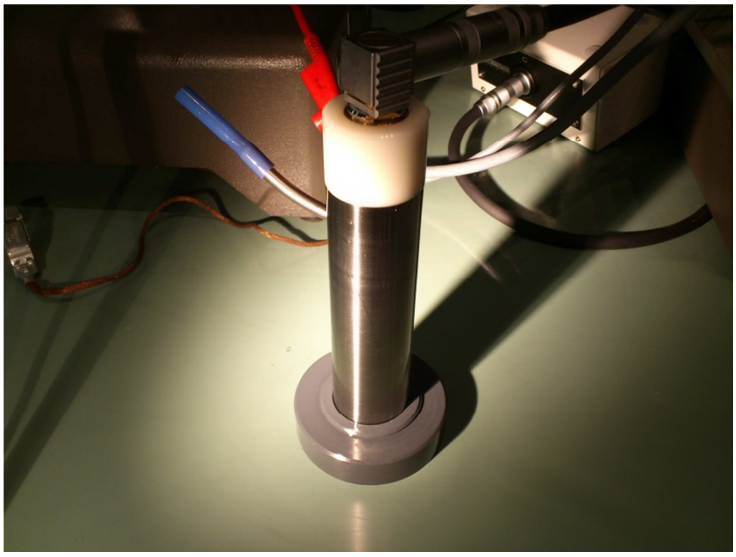


Figure 3.11 The test cell is connected to the high voltage side (power supply) and low voltage side (measuring instruments) via two cable. The red cable is connected to the high voltage side and the other cable on the top of the side is connected to the measuring side.

Tan δ of oil samples are measured with the Schering bridge and other equipment as described in a circuit diagram (Figure 3.12). Value of tan δ and capacitance will be measured and recorded by Tettex C,L & tan δ 2840.

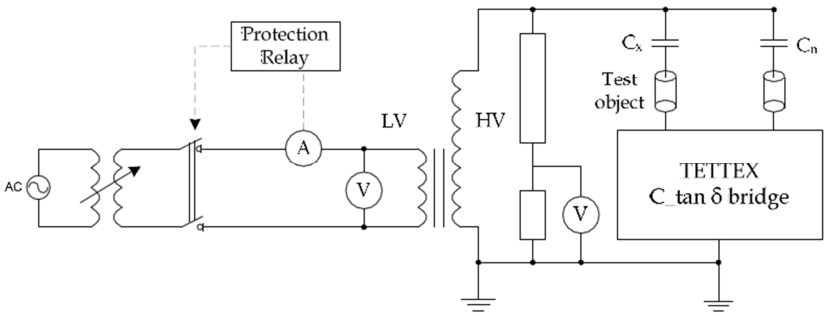


Figure 3.12 Circuit diagram of ta n δ measurement. Test object in the circuit refers to the oil samples and is placed inside the cell. The test cell is parallel connected to a standard capacitor C_N at the HV side which has a nominal value of 100 pF. It also connects to balanced detector Tettex at LV side.

The test arrangement is shown in Figure 3.13.

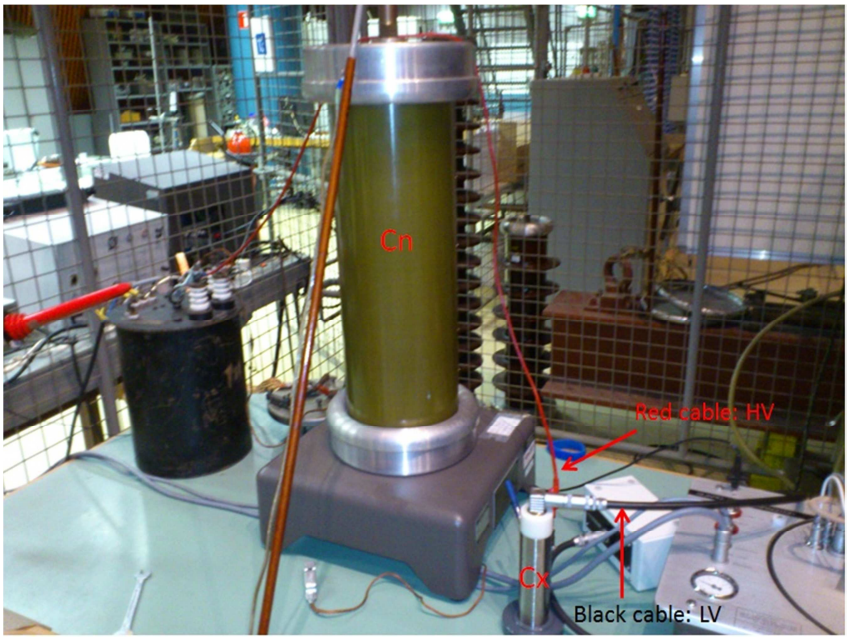


Figure 3.13 Test cell connections to HV-LV side. Before touching each instrument, an earthing stick must be placed on the top of the capacitor C_N to remove possible residual charge.

The arrangement of detector Tettex C & tan δ 2811, Tettex C,L & tan δ 2840 and the voltage regulator is shown in Figure 3.14. Both Tettex detectors are able to measure tan δ of a dielectric material, but the newer Tettex 2840 has a higher sensitivity and accuracy than the older Tettex 2811. Therefore, to protect the newer detector from possible damage during an unforeseen breakdown of oil, indicative measurements were firstly performed with the older detector. After applying 350 V and no breakdown in the cell, the newer Tettex 2840 was then used to measure the tan δ of the oil.



Figure 3.14 The arrangement of balance detector (a) Tettex C & tan δ 2811, (b) Tettex C,L & tan δ 2840 and (c) voltage regulator.

3.2.2.2 Test procedure

Before measuring tan δ , the first step is cleaning the cell. The cleaning procedure is as follows:

1. Fill the cell with Nebol and insert the LV electrode, move the LV electrode up and down several time, then dry the HV and LV electrode. This step must be performed twice before continuing.
2. Fill the cell with benzene and insert the LV electrode, move the LV electrode up and down several time, then dry the HV and LV electrode. This step must be performed twice before moving forward.

The following step is preconditioning the oil sample, which is the exactly the same as in accelerated aging test.

Following is the measurement of tan δ using Tettex 2840. The operating window of the software is shown in Figure 3.15.

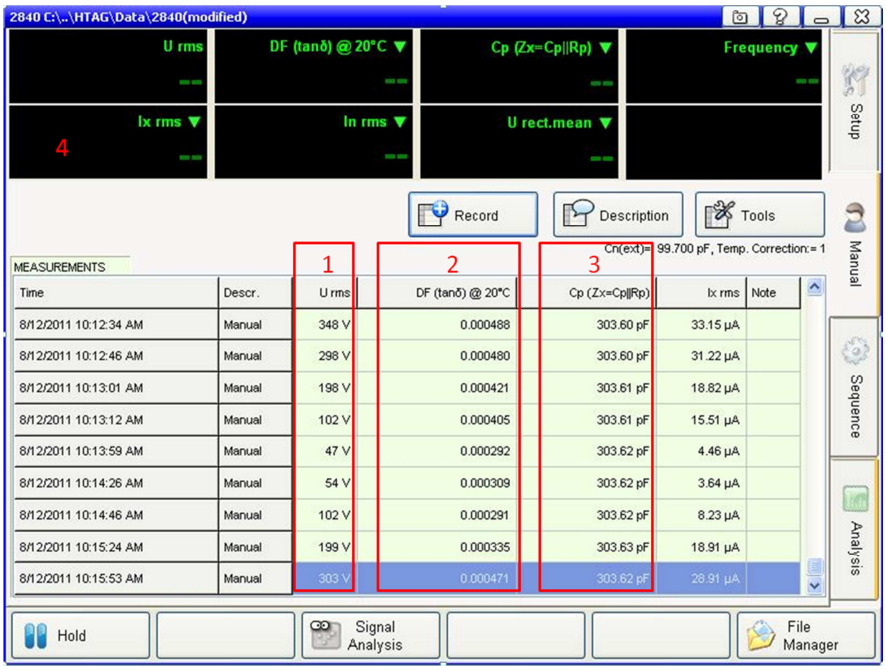


Figure 3.15 Operating window of Tettex 2840, from which (1) applied voltage, (2) tan δ and (3) capacitance can be read and recorded when (4) the values in the screen is in highlighted green as e.g. in this figure.

The test cell and oil samples are measured at ambient temperature. The test cell should be rinsed three times with a portion of oil sample. The filling process of oil samples is carefully done to minimize the entrapment of air bubbles.

The test starts from 55V and will performed at 100V, 200V, 300V and 350V. Tan δ and capacitance of the oil samples under these voltages will be recorded.

3.2.3 Acidity test

The Total Acid Number (TAN) is the amount of potassium hydroxide in milligrams that is needed to neutralize the acids in one gram of oil. It is an important quality measurement of crude oil. The TAN value indicates to the crude oil refinery the potential of corrosion problems. The TAN value can be determined by a couple of methods, e.g. by potentiometric titration or by color indicator titration:

- Potentiometric titration: The sample is normally dissolved in toluene and propanol with a small amount of water and titrated with alcoholic potassium hydroxide. A glass electrode and reference electrode is immersed in the sample and connected to a voltmeter/potentiometer. The meter reading (in millivolts) is plotted against the volume of titrant. The end point is taken at the distinct inflection of the resulting titration curve corresponding to the basic buffer solution.
- Color indicating titration: An appropriate pH color indicator e.g. phenolphthalein, is used. Titrant is added to the sample by means of a burette. The volume of titrant used to cause a permanent color change in the sample is recorded and used to calculate the TAN value.

The acidity test was performed at SMIT transformer using the color indicating titration method according to IEC standard 62021-1.

3.2.4 Humidity test

In this series of test, a humidity tester (Vaisala MM170) will be used to measure the moisture of the oil sample. The tester contains two parts which are shown as Figure 3.16.

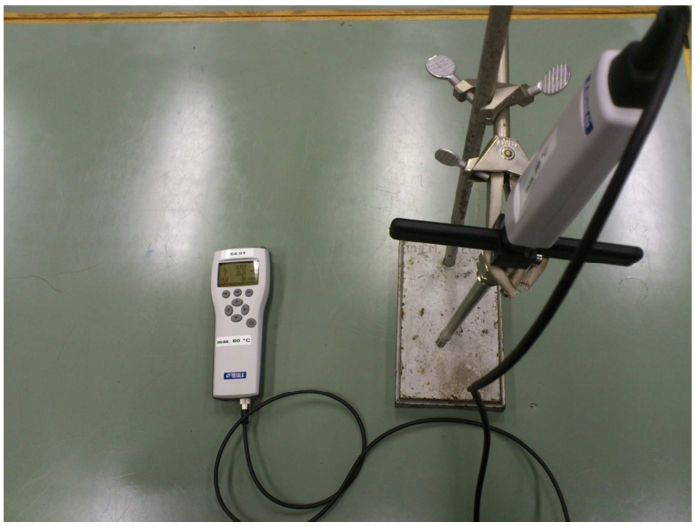


Figure 3.16 Vaisala MM170. An electric probe on the right side is connected to a processor showing test result on the left side.

The humidity tester should be turned on before placing the humidity probe inside the oil. The result is shown after several minutes, until it reaches a steady value in ppm. This humidity tester has an operating temperature range of −40 ℃ to 60 ℃ and sensitivity of 1 ppm.

To clean the probe after a measurement, two types of cleaning solvent (Nebol and Benzene) are used. The humidity tester can be used again at least 30 minutes after cleaning to get rid of any traces of the cleaning solvent.

3.2.5 Breakdown test

Breakdown test is performed according to standard IEC 60156 at 50 Hz. The voltage varies from 0 to 40 kV. Each breakdown test will be repeated 6 times on each oil sample.

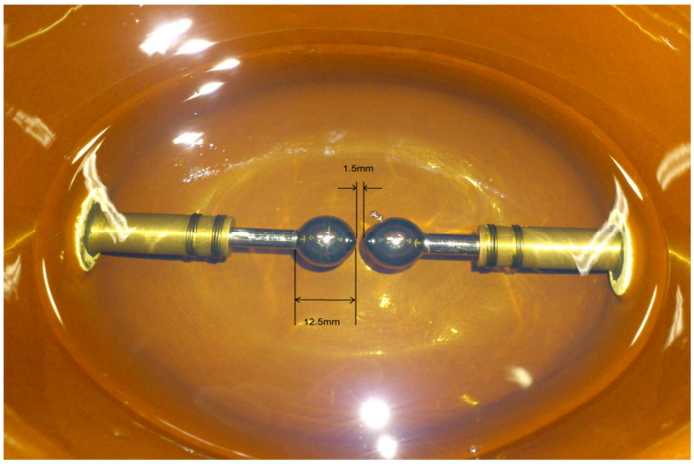
3.2.5.1 Test setup

The breakdown test setup of oil samples is shown in Figure 3.17(a). The electrodes are polished and spherical (12.5 mm diameter). The axis of the electrode system should be horizontal and at least 40 mm below the surface of the test liquid in the cell. No part of the electrode should be closer than 12 mm to the cell wall. According to IEC standard 60156, the gap between the electrodes is originally set to 2.5 mm ± 0.05 mm. Due to limitation of output voltage of the test setup, the gap is adjusted to 1.5 mm because when the distance of gap is set to 2.5 mm, no breakdown can be observed and applied

voltage cannot be increased anymore. According to previous research [16], the BDV of mineral oil is proportional to the gap distance. Therefore, the adjustment of gap distance is acceptable and the results are still valid of comparing the BDV of oil with varying properties. The dimension of the electrode is shown in Figure 3.17(b).



(a) Test cell placed in the testing instrument.



(b) Dimensions of the electrodes and the distance between the two electrodes.

Figure 3.17 Breakdown test cell.

3.2.5.2 Test procedure

The breakdown test is performed as follows:

1. Keep pouring oil sample into the tank until the surface of oil reaches 5cm to the top of the tank. During testing, temperature of the oil is equal to ambient temperature.
2. Voltage application is started 5 minutes after completion of the filling. There should be no air bubbles visible in the electrode gap.

3. The applied voltage is uniformly increased from zero at the rate of 2 kV/s ± 0.2 kV/s manually until breakdown occurs.
4. The measurements are performed until 6 breakdowns on the same cell filling have occurred.
5. The final result is determined by averaging the 6 measured breakdowns voltages.

3.2.6 Condensing test

3.2.6.1 Preparation

Before starting condensing test, following steps are performed to make sure that the oil has a high value of initial humidity:

1. Fill a beaker with 500 ml of oil and put it inside an oven.
2. Fill a beaker with 1000 ml water and put it inside the oven where the oil is placed.
3. Set the temperature of oven to 60℃.
4. Heat the oil and water for 48 hours.

3.2.6.2 Test set up

The test instruments include: a beaker, a plate and a humidity tester. The schematic drawing is shown in Figure 3.18.

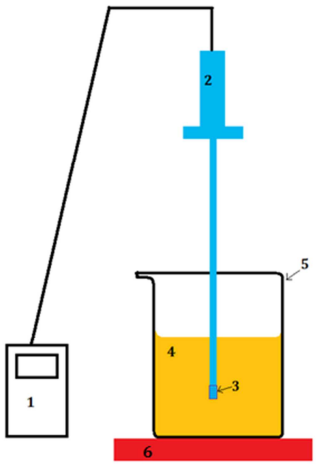


Figure 3.18. In this figure: 1. is the indicator of humidity tester； 2 is the testing stick；3. is the probe which measures the humidity of oil；4 is oil; 5 is the beaker; 6. is the plate.

The time interval between each measurement of humidity of oil is set to 1 minute. The accuracy of the tester is 1 ppm. The total time of the whole measurement is 14 hours.

3.3 Conclusions

In this chapter, test design and setup were provided. Preparation steps were first provided before building test setup and performing tests. These steps are sampling and preconditioning of oil. New oil and naturally aged oil are sampled according to the procedures mentioned in section 3.1.

After these steps, 6 tests have been designed. These tests are accelerated aging test, tan δ test, acidity test, humidity test, breakdown test and condensing test. The test setup and procedures of each test are introduced and explained in section 3.2.

Accelerated aging test is performed on new oil. Oil samples are placed with and without copper in glass bottles. Thus, the influence of copper on chemical aging process and BDV of oil can be determined by comparing the data from samples with copper and samples without copper.
Tan δ test and acidity test are performed both on oil after accelerated aging test and naturally aged oil from switchgear. Tan δ is used to indicate the aging level of oil.

Humidity test is performed before breakdown test. The humidity of oil will be adjusted by keep the oil samples exposed to the open air after being dried in the vacuum oven.

Condensing test is performed to see the decreasing humidity of oil when the oil cools down. Oil with 3 different TAN will be included in the test.

All the measurements have been collected after performing these 6 tests and will be analyzed and discussed in the next chapter.

Chapter 4 Test results and interpretation

After performing the tests mentioned in chapter 4, data was recorded. In this chapter, data analysis is performed to quantify the relationship between the following parameters:

1. tan δ vs. aging time
2. tan δ vs. copper
3. tan δ vs. Breakdown voltage(BDV)
4. acidity vs. aging time
5. acidity vs. copper
6. acidity vs. BDV
7. BDV vs. copper
8. BDV vs. humidity
9. humidity vs. acidity

In section 4.1, the various types of oil involved in this thesis are listed and named for clarity. In section 4.2, visual inspection of color of oil after accelerated aging test will be shown and explained.

In section 4.3, data and interpretation of tan δ vs. aging time will firstly be provided. Tan δ of oil with and without copper will be compared with aging time separately. After this, the difference of tan δ between oil samples with and without copper after the same accelerated aging time will be provided. This section ends with comparing tan δ of accelerated aged oil and service aged oil from switchgear.

In section 4.4, data and interpretation of total acidity number (TAN) vs. aging time will firstly be provided. TAN of oil with and without copper will be compared with aging time separately.

In section 4.5, data and interpretation of tan δ vs. BDV, copper vs. BDV, BDV vs. acidity and BDV vs. humidity will be provided.

The results of condensing process of oil will be explained in section 4.6. This section ends with the data analysis of humidity of oil vs. relative humidity of air.

Finally, section 4.7 gives conclusions of this chapter and provides suggestions to Stedin on which factors should be paid attention to. These suggestions can be helpful to improve the inspection and maintenance strategy and further reduce the risk of breakdown of oil in COQ.

4.1 Introduction

4.1.1 Definition

In this chapter, two types of oil are analyzed. One type is taken directly from the switchgear of Stedin and is named ‘service aged oil’. The other type of oil is new when taken and then has been artificially aged by means of an accelerated aging test in the high voltage lab at Delft University of Technology. This oil is named ‘accelerated aged oil’.

4.1.2 Timescale of accelerated aging test

The new oil samples are being kept in the oven at 130 ℃ following the schedule as in Table 4.1. After a period of time, the oil is taken out. Half of the oil samples are heated with copper in the oil and the other half of the samples are heated without copper.

Table 4.1 Time schedule of taking oil samples out of the oven.

Type of oil	Aging time (hours)				
New oil with and without copper	24	48	96	168	240

4.2 Visual inspection

The color of an oil sample is related to the deterioration of the sample. New oil has a pale white color. With increasing time of heating in the oven, the oil becomes darker. Lightly aged oil has a yellow color and the heavily aged oil has a dark brown color. The changing color of oil is shown in Figure 4.1.



Figure 4.1 New mineral oil is pale. With the aging time went longer, the color became darker.

New mineral oil is essentially colorless, however, as the sample ages over time or is subjected to severe conditions such as local hot sports or arcing, the sample will become darker in color. The clarity of a fresh sample of oil should be sparkling with no indication of cloudiness, sludge, or particulate matter. The color of an oil sample is used mainly as a guide to the degree of refinement of the oil when it is new. It should be pointed out that the color of the oil by itself should never be used to indicate the dielectric quality of the oil [30]. However, it can be used to determine whether more definitive tests should be performed to determine specific characteristics of the sample that are more related to the performance of the oil. With these results, evidence of certain aging, overheating or increased chemical reactor process can be looked for.

4.3 Tan δ vs. aging time regarding the influence of copper

The tan δ of oil with and without copper is measured at fixed applied voltages (55V, 100V, 200V, 300V and 350V. The results are shown in Table 4.2 and Table 4.3. The electrical stress range for this measurement can be calculated by dividing the applied voltage by the distance between two electrodes. The range is 0.0375-0.233 kV/mm.

The electrical stress (0.0375-0.233 kV/mm) of the tan δ test is in the range of the standard electrical stress for tan δ measurement in oil (0.03-1 kV/mm) according to IEC 60247 standard.

4.3.1 Tan δ vs. applied voltage

Table 4.2 Tan δ results of oil without copper. Tan δ of oil with different aging time have different behaviors with increasing applied voltage. At each applied voltage, tan δ increases with longer aging time.

Aging time (hour)	Tan δ results ($\times 10^{-4}$)				
	55 V	100 V	200 V	300 V	350 V
0	0.34	0.36	0.34	0.35	0.38
24	0.60	0.62	0.60	0.62	0.67
48	0.68	0.69	0.72	0.73	0.87
96	0.80	0.80	0.81	0.85	0.88
168	1.44	1.42	1.43	1.51	1.68
240	1.52	1.43	1.56	1.65	1.69

In Table 4.2, it can be seen that, with increasing applied voltage, the rate of increase of the tan δ are different with each type of oil. These different rates of tan δ have been plotted in Figure 4.2:

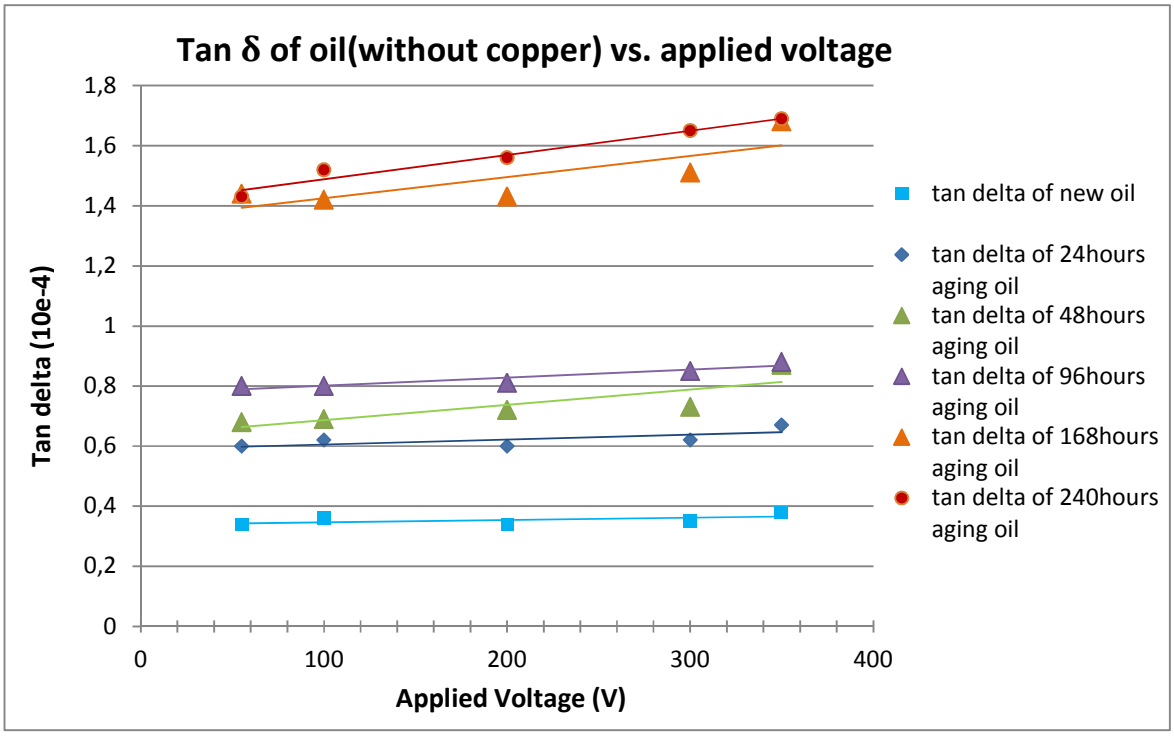


Figure 4.2 Comparison of varying tan δ of oil (without copper) with different aging time versus applied voltage.

Figure 4.2 shows a comparison of tan δ variation of oil with different aging time at increasing applied voltage. For the shorter accelerated aged oil, especially with new oil, tan δ changes little with increasing applied voltage. However, for the longer accelerated aged oil, tan δ becomes higher with

increasing applied voltage. Rather than a flat trend line of the tan δ versus voltage of the new oil, the slope of the trend line of the longer accelerated aged oil is steeper as shown in Figure 4.2.

Table 4.3 Tan δ results of oil with copper. Tan δ of oil with different aging time have different behaviors with increasing applied voltage. At each applied voltage, tan δ increases with longer aging time.

Aging time (hour)	Tan δ results ($\times 10^{-4}$)				
	55 V	100 V	200 V	300 V	350 V
0	0.34	0.36	0.34	0.35	0.38
24	0.76	0.76	0.77	0.80	0.84
48	0.95	0.95	0.96	0.99	1.02
96	1.32	1.32	1.36	1.44	1.51
168	2.10	2.01	2.21	2.29	2.52
240	2.78	2.77	2.81	3.00	3.24

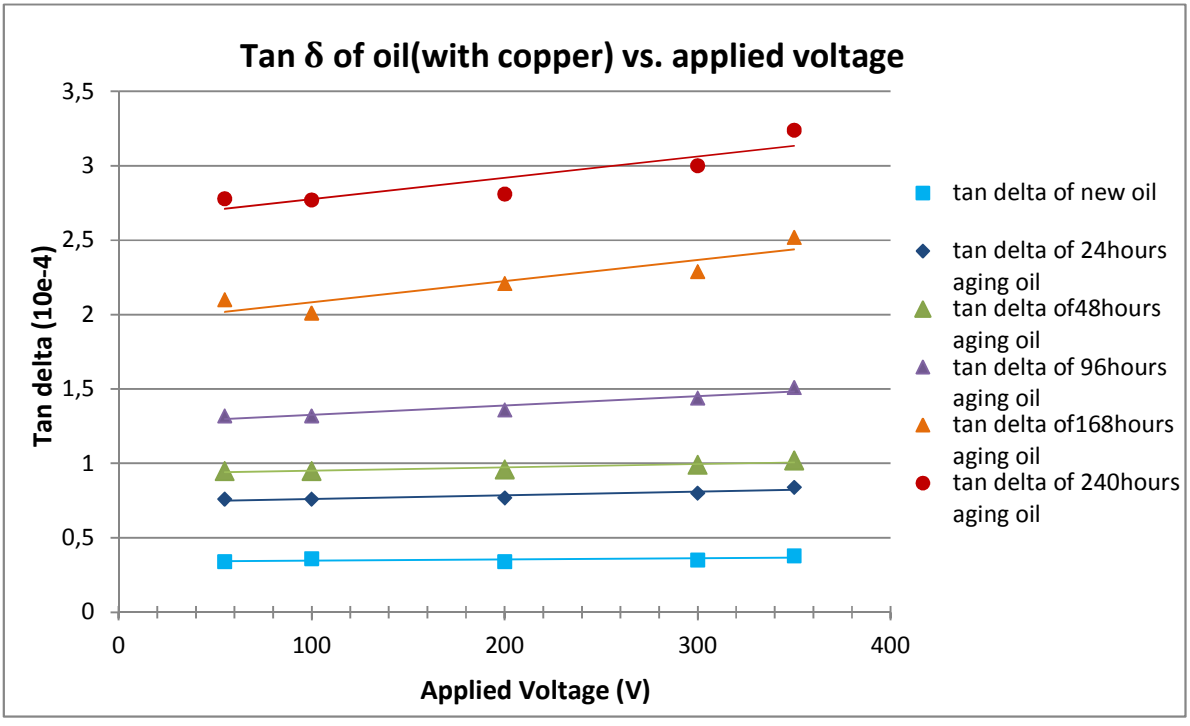


Figure 4.3 Comparison of varying tan δ of oil (with copper) with different aging time versus applied voltage.

Compared to oil without copper, oil with copper inside shows a higher rate of increase of tan δ for oil with increasing aging time. Similar to the result from oil without copper inside, for shorter accelerated aged oil (especially with new oil), tan δ will only marginally increase as the applied voltage is increased. For longer accelerated aged oil, tan δ is higher at higher voltages. Rather than a flat trend

line of the tan δ versus voltage of the new oil, the slope of the trend line of the longer accelerated aged oil is steeper as shown in Figure 4.3.

4.3.2 Tan δ vs. aging time & copper

Figure 4.4 to 4.8 plots the value of tan δ at test voltage of 55V, 100 V, 200 V, 300 V and 350 V respectively.

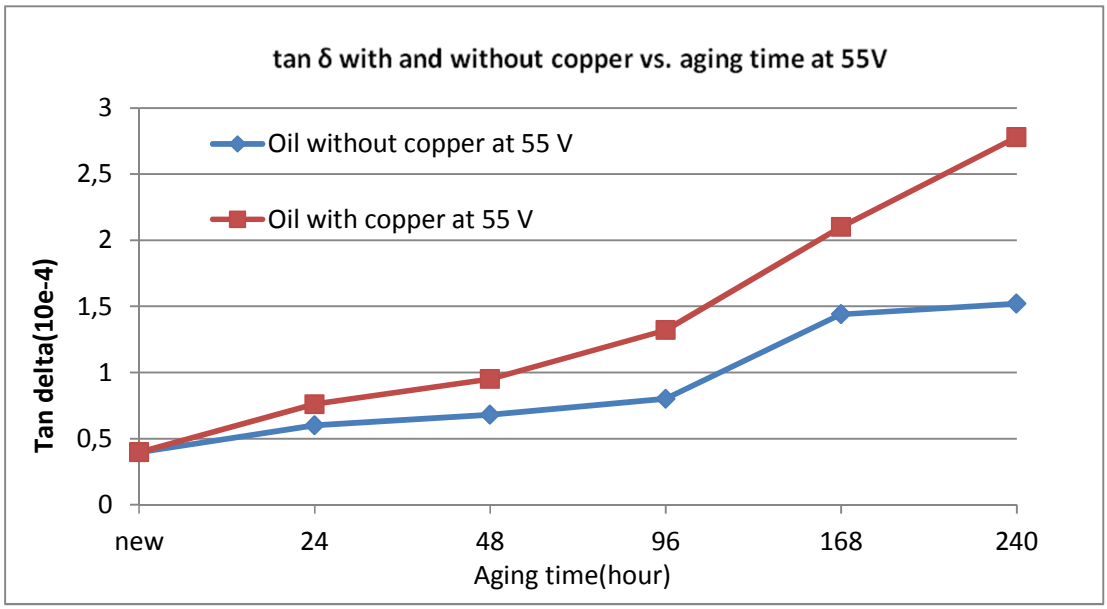


Figure 4.4 Tan δ vs. aging time regarding the influence of copper at 55 V applied voltage. Tan δ increases with longer aging time and copper accelerate the aging process of oil samples.

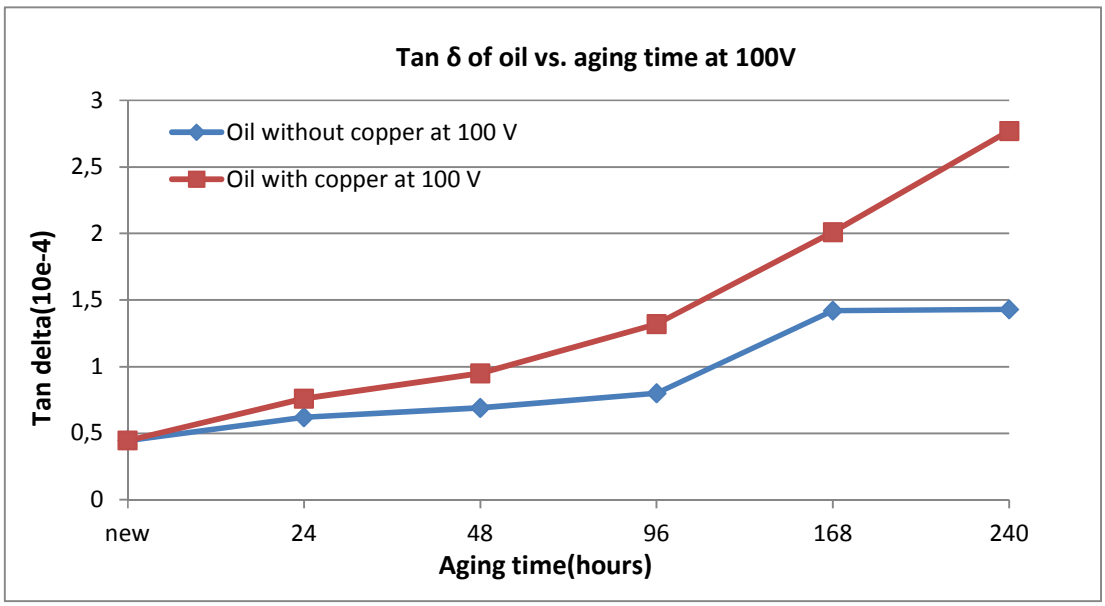


Figure 4.5 Tan δ vs. aging time regarding the influence of copper at 100 V applied voltage. Tan δ increases with longer aging time and copper accelerate the aging process of oil samples.

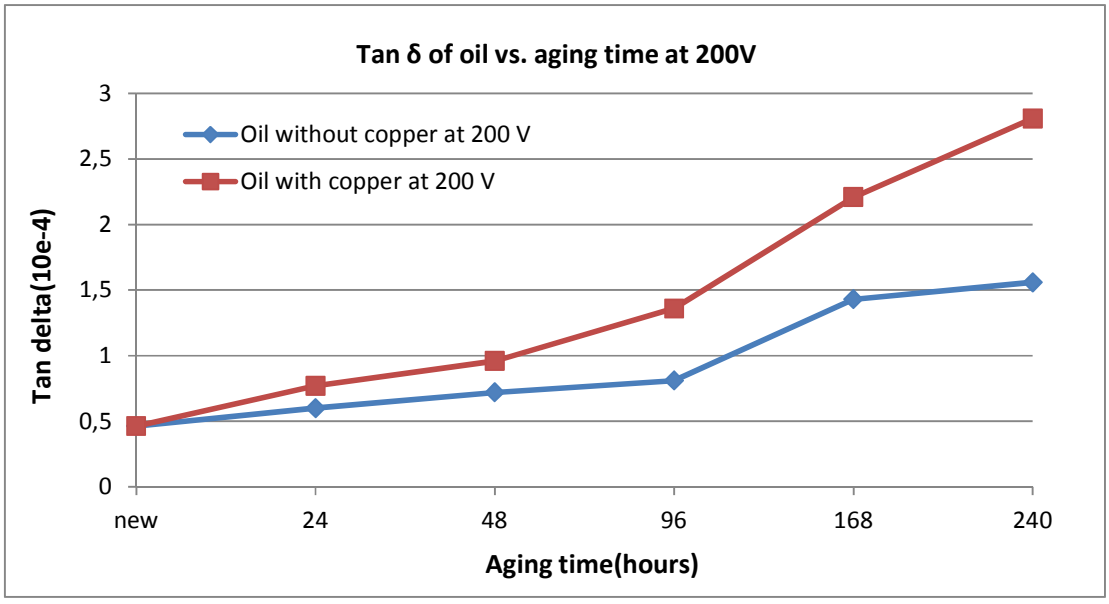


Figure 4.6 Tan δ vs. aging time regarding the influence of copper at 200 V applied voltage. Tan δ increases with longer aging time and copper accelerate the aging process of oil samples.

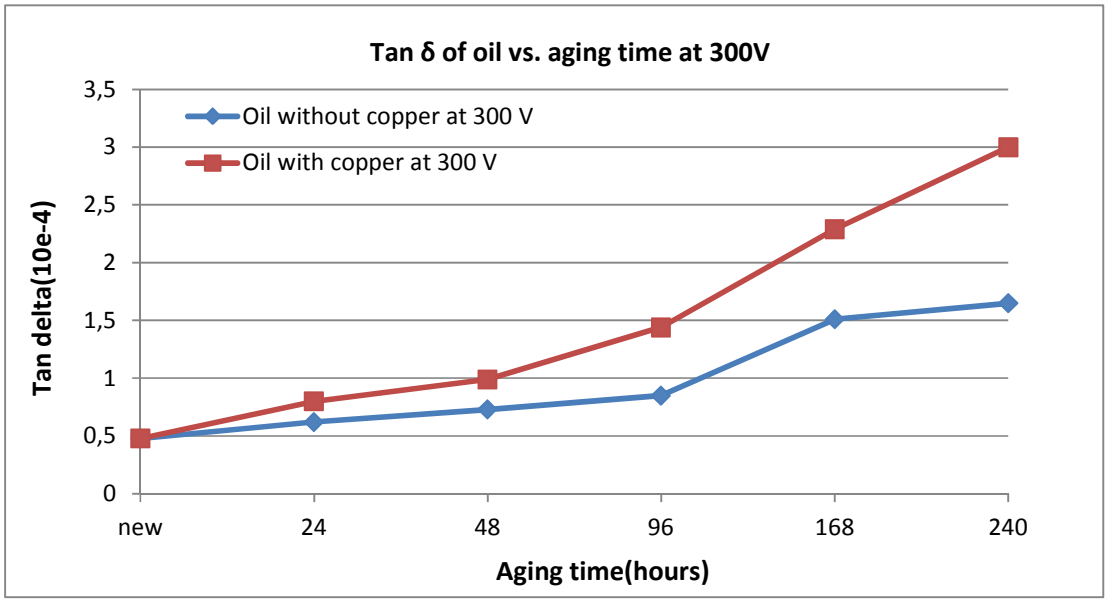


Figure 4.7 Tan δ vs. aging time regarding the influence of copper at 300 V applied voltage. Tan δ increases with longer aging time and copper accelerate the aging process of oil samples.

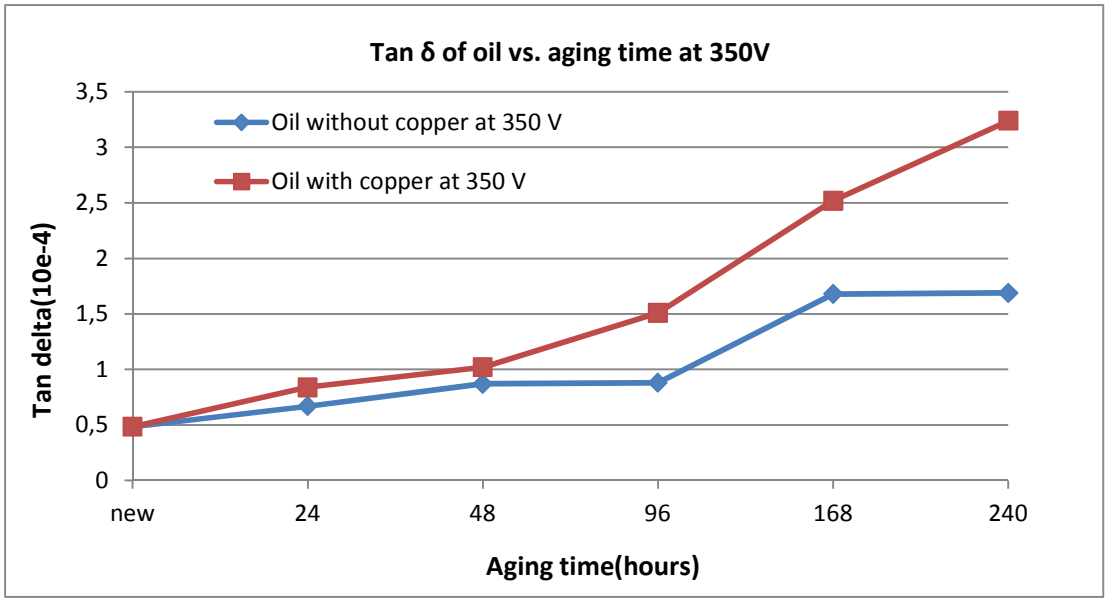


Figure 4.8 Tan δ vs. aging time regarding the influence of copper at 350 V applied voltage. Tan δ increases with longer aging time and copper accelerate the aging process of oil samples.

After comparing Figure 4.4 through 4.8, it is found that the value of tan δ increases with aging time. For the oil without copper, the mean value of tan δ of new oil at all applied voltages is 0.45. After 240 hours of accelerated aging, the mean value of tan δ of oil is 1.57 and increases of approximately 2.5

times the initial value. Similar trends have been discovered by Perrier and Beroual [22] in which the tan δ increased with increasing aging time.

For the oil with copper, after 240 hours of accelerated aging, the mean value of tan δ of oil at all applied voltages is 2.92 and increases of approximately 5.5 times the initial value.

After 240 hours of accelerated aging, the value of tan δ of oil with copper is 86% larger that the value of oil without copper. Therefore, the presence of copper in the oil accelerates the aging process of oil.

The principal charge carriers in mineral oil are ions, which are associated with either the structure of the dielectric liquids themselves or impurity ions introduced into the oil. Exposure of the oils to air can result in oxidation of the liquid dielectric, thereby augmenting further the supply of hydrogen ions, since the end of the oxidation product results in an acid. Results of acidity of oil with increasing aged time will be interpreted in section 4.4.

4.3.3 Time scale of accelerated aging test

From a practical point of view, it is necessary to compare tan δ results from new oil after accelerated aging test with service aged oil from switchgear. The reason for performing the comparison is to check whether the accelerated aging test is sufficiently long to simulate the real life aging of oil in the switchgear.

As part of the research, the tan δ of service aged oil from switchgear was also measured. The values are shown in Table 4.4.

Table 4.4 Tan δ results of service aged oil from switchgear. In both cases, tan δ becomes higher with increasing applied voltage. At a fixed applied voltage, tan δ seems to increase with longer aging time.

Oil type	Tan δ results ($\times 10^{-4}$)				
	55V	100V	200V	300V	350V
aged 0.5 year	0.40	0.45	0.46	0.48	0.49
aged 5 years	0.51	0.52	0.53	0.55	0.55

From Table 4.4, similar to the accelerated aged oil, it can be seen that the tan δ of the service aged oil increases with service time. Tan δ of oil increases from 0.49 to 0.55 at 350 V with the age of oil increase from 0.5 year to 5years.

After checking the data of tan δ from the previous accelerated aging test, we find increasing values of tan δ along the accelerated aging process. Together with the data from service aged oil, we can conclude that the tan δ increases with aging in the time range as defined in Table 4.1.

However, whether the time range as defined in Table 4.1 is sufficient enough to cover the life time of oil in switchgear is not known. To check whether this time range covers the life time of oil in switchgear, we compare the data of oil without copper from the aging test and the oil from switchgear together.

Table 4.5 merges (1) the tan δ values from oil with copper from accelerated aging test, which have been listed in Table 4.3 and, (2) values from service aged oil from switchgear, which have been listed in Table 4.4. Graphs plotting tan δ at the various applied voltages can be found in Appendix A.

Table 4.5 Comparison of tan δ of oil (with copper) from the accelerated aging tests and oil from switchgear. We can see that tan δ of oil from switchgear (0.5year and 5 year) are larger than of new oil and smaller than of 24 hours. This means the timescale of accelerated aging test is sufficient to cover the whole service life of oil in COQ.

Oil type	Tan δ results ($\times 10^{-4}$)				
	55 V	100 V	200 V	300 V	350 V
new	0.34	0.36	0.34	0.35	0.38
aged 0.5 year	0.40	0.45	0.46	0.48	0.49
aged 5 years	0.51	0.52	0.53	0.55	0.55
24 hours	0.76	0.76	0.77	0.80	0.84
48 hours	0.95	0.95	0.96	0.99	1.02
96 hours	1.32	1.32	1.36	1.44	1.51
168 hours	2.10	2.01	2.21	2.29	2.52
240 hours	2.78	2.77	2.81	3.00	3.24

From Table 4.5, we can see that tan δ of the two service aged oil samples are both smaller than the value of tan δ of oil with aging time of 24 hours and larger than that of new oil. The length of the whole aging process is ten periods of 24 hours. Tan δ of 5-year aged oil is smaller than that of 24-hour accelerated aged oil. Therefore, based on the similarity of the aging process, the tan δ of 50 year-aged oil is assumed to be smaller than that of 240-hour accelerated aged oil.

We can therefore draw the conclusion that the time length designed for the accelerated aging test is sufficient to cover the real life time of oil in switchgear. Moreover, the tan δ of oil in switchgear increases with longer service time in switchgear. Thus, the accelerated aging test in this thesis is able to simulate the real service life of oil.

From section 4.2.1 through 4.2.3, the following conclusions are obtained:

1. When increasing the applied voltage, the tan δ shows a clearer increase with longer aged oil than with shorter aged oil.
2. During the accelerating test, with or without copper inside oil, tan δ increases with increasing aging time.
3. The presence of copper accelerates the aging of oil compared to oil with copper under similar remaining conditions.

In section 4.6, test results of tan δ from accelerated aging test will be linked with BDV of oil. The relationship of BDV with service aged time will be quantified afterwards.

4.4 Acidity vs. aging time

In this research, the acidity of oil is obtained by measuring the total acidity number (TAN) of each sample of oil. The unit of TAN is mg KOH/g, i.e. the amount of KOH in milligrams per gram of oil.

4.4.1 Acidity of oil from switchgear

From Table 4.6, it can be observed that TAN of service aged oil increases with longer serving time of the switchgear oil. The TAN of new oil is 0.006 and increases to 0.007 after 0.5 year. The TAN of 5-year-service aged oil is 0.008. This trend of TAN of service aged oil has been plotted in Figure 4.9.

Table 4.6 TAN of oil from switchgear.

Type of oil	TAN (mg KOH/g)
New oil	0,006
Aged 0.5 year	0,007
Aged 5 years	0,008

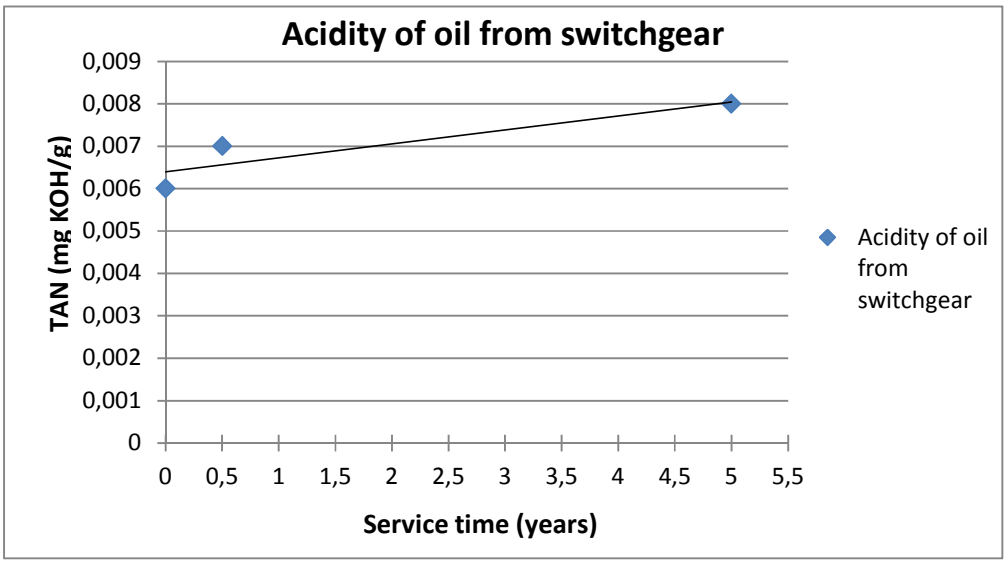


Figure 4.9 TAN of oil from switchgear versus serving years.

Only two service aged oil samples (0.5 year and 5 years) were analyzed in this thesis. Therefore, caution must be taken to draw definite conclusions on the behavior of TAN of oil.

To obtain a reliable behavior of TAN with increasing aging time, TAN of oil samples (not from switchgear), that have been aged using the accelerated aging test, need to be also measured and included in the analysis. This will be done in the next section.

4.4.2 Acidity of oil from aging test without copper

In Table 4.7, it can be observed that apart from the oil aged 240 hours, the TAN of accelerated aged oil increases with longer aging time. The TAN of new oil is 0.006 and increases to 0.011 after l68 aging hours. This has been plotted in Figure 4.10.

Table 4.7 TAN of oil (without copper) from aging test.

Type of oil	Acidity number
New	0,006
48h	0,006
96h	0,01
168h	0,011
240h	0,01

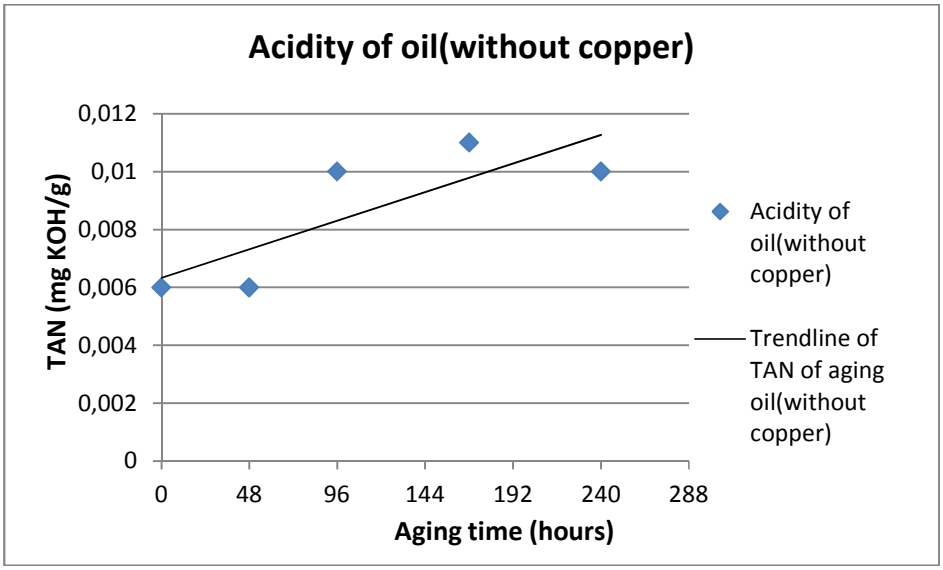


Figure 4.10 TAN of oil without copper from accelerated aging test versus aging time.

In chapter 2, factors that lead to the aging of oil in OIS were indicated. These factors are oxygen and water dissolved in the oil and copper. Without the presence of copper in oil, factors that cause the TAN of oil to increase are oxygen and water dissolved in the oil. The largest value of TAN of accelerated aged oil is obtained at the end of aging test and the TAN follows an increasing trend versus aging time. Oil showing an acid number of 0.15 or larger can be expected to show accelerated acid formation and leads to the form of sludge. Sludge will decrease the BDV of oil in switchgear. The largest value of TAN of oil from accelerated aging test is 0.011 which is acceptable since it is lower than 0.15.

As mentioned in previous chapters, copper can negatively influence the oxidation process of oil. In the following section, the TAN of oil with copper will be interpreted.

4.4.3 Acidity of oil from aging test with copper

In Table 4.8, it can be observed that the TAN of accelerated aged oil increases with longer aging time. The TAN of new oil is 0.006 and increases to 0.013 after 240 aging hours. This has been plotted in Figure 4.11.

Table 4.8 TAN of oil (with copper) from aging test.

Type of oil	Acidity number
New	0,006
48h	0,007
96h	0,008
168h	0,013
240h	0,013

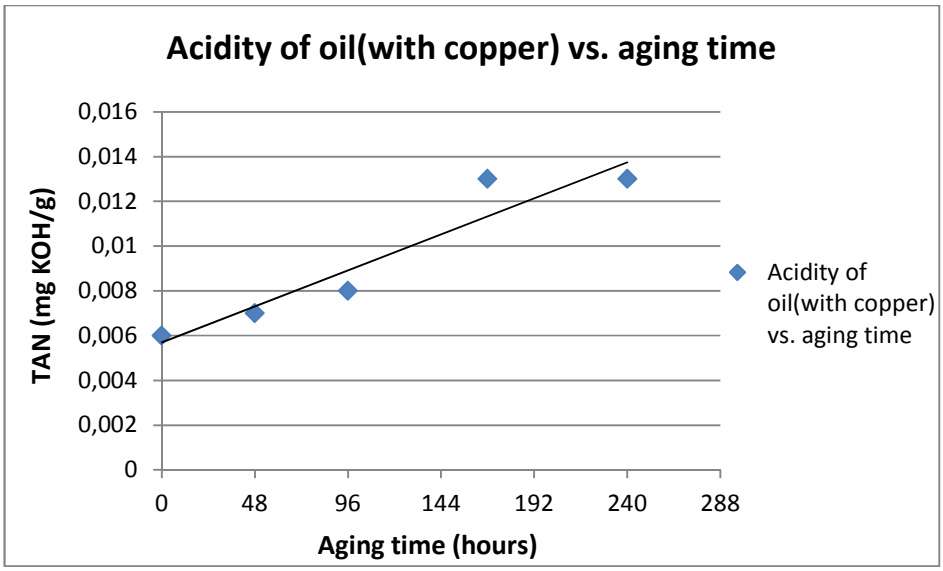


Figure 4.11 TAN of oil with copper from aging test.

With copper, the factors that cause the TAN of oil to increase are oxygen and water dissolved in the oil and the copper in the oil. The largest value of TAN of accelerated aged oil is obtained at the end of aging test and the TAN follows an increasing trend versus aging time. The largest value of TAN is 0.013 which is acceptable since it is lower than 0.15.

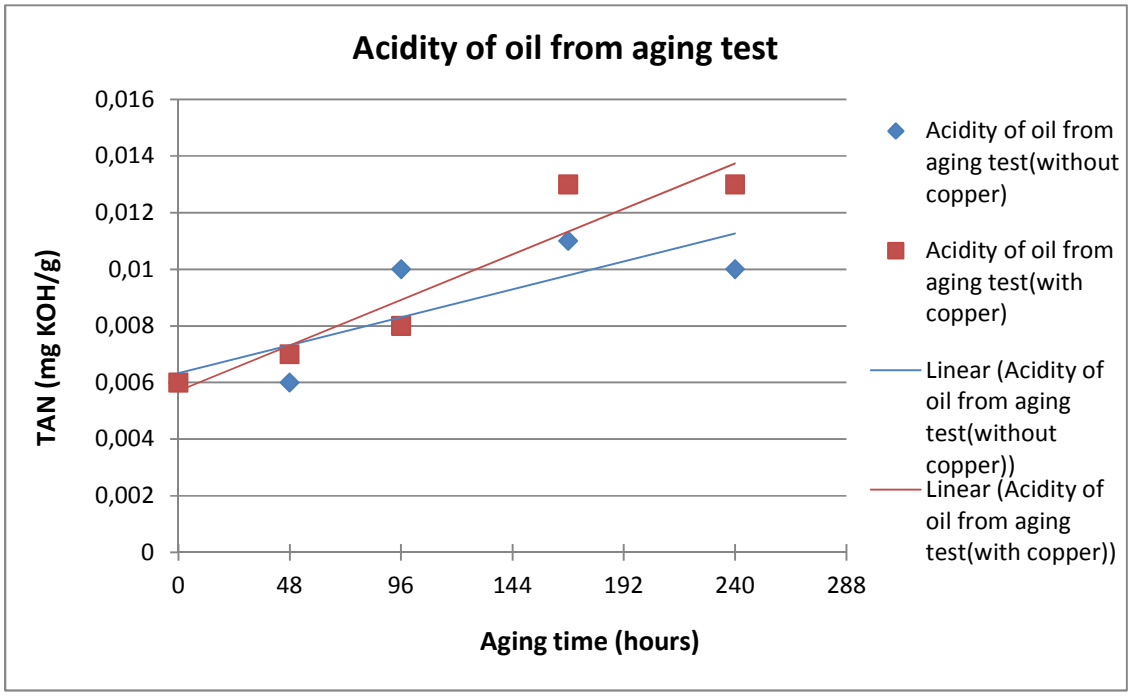


Figure 4.12 Comparison of TAN between oil with and without copper.

The TAN of oil without copper and oil with copper are compared in Figure 4.12. In Figure 4.12, it can be seen that the increasing rate of the trend line of TAN of oil with copper is steeper than that of oil without copper. From this, we conclude that copper accelerates the chemical aging process.

It is recommended that an upper limit of 0.2 be used to determine when oil should be replaced. From the TAN results in this section, it can be concluded that the TAN of both service aged oil and accelerated aging test oil (with and without copper) are significantly lower than 0.15.

In the timescale of accelerated aging test, the chemical aging process will increase the TAN of oil but it will not cause the formation of sludge in the oil. However, the increasing acidity number of oil may have an influence on other processes. One of these processes is condensing process of oil. Therefore, it is still necessary to consider acidity of oil and this will be introduced further in section 4.6.

4.5 Breakdown voltage of oil

4.5.1 BDV vs. tan δ

The results of breakdown voltage (BDV) measurements for oils without copper are listed in Table 4.9.

Table 4.9 BDV of oil without copper. We can see with similar humidity, the BDV of oil with different aging times does not differ significantly.

Aging time	humidity(ppm)	BDV (kV)		
		max	min	mean
new	32	28	22	26.8
24	32	28	20	26.3
48	32	31	23	27.0
96	34	27	20	23.7
168	33	27	20	24.8
240	32	33	20	26.3

From Table 4.9, it can be seen that a longer aging time does not influence the BDV of oil without copper. However, from the results of previous section, a longer aging time does influence tan δ and TAN of oil. Thus, without copper, the aging process does not significantly influence the BDV of oil during the time of accelerated aging test when the humidity of oil is constant. The data has been plotted in Figure 4.13.

To obtain an accurate analysis of the data from Table 4.9, we use confidence intervals for the mean value to analyze the BDV value at different aging times.

Given a set of 6 BDV measurements, the standard error of estimation of the mean σ_m can be calculated by:

$$\sigma_m = \frac{\sigma}{\sqrt{N}}$$

$$\sigma = \frac{1}{N}\sum_{i-1}^{N} (x_i - \mu)^2$$

where N is the number of data recorded, σ is variance and μ is the mean value of the data.

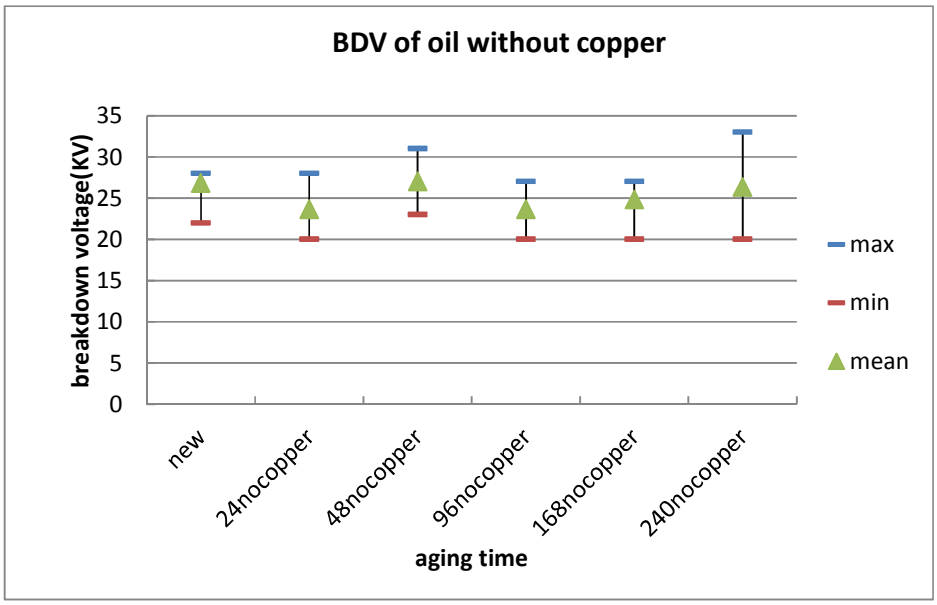


Figure 4.13 BDV of oil without copper. We can see with similar humidity, the BDV of oil with different aging time does not differ significantly.

Then we can get lower limit and upper limit of BDV value of accelerated aged oil samples and the results are shown in Table 4.10.

Table 4.10 Confidence interval of BDV data of accelerated aged oil samples.

	new	24nocopper	48nocopper	96nocopper	168nocopper	240nocopper
Lower limit	22.1	19.8	21.7	17.8	19.1	20.2
Upper limit	31.5	32.8	32.3	29.6	30.5	32.4

We can see that the confidence interval of different aging overlaps with each other, and we can conclude that the BDV of these oil samples does not significantly differ with each other.

4.5.2 BDV comparison: oil with copper vs. oil without copper

Without copper in the oil, the aging process does not influence the BDV of oil under the condition that the humidity of oil remains constant. Next, the influence of the presence of copper in the oil on the BDV is analyzed.

Table 4.11 Comparison of BDV of oil with copper and oil without copper. We can see that copper does not significantly influence the BDV of oil with similar humidity.

Oil type	humidity(ppm)	BDV(kV)				
		max	min	mean	Lower limit	Upper limit
24copper	36	26	20	22.8	18.096	27.504
24nocopper	35	28	20	23.7	17.232	30.168
96copper	38	21	16	18	12.708	23.292
96nocopper	38	26	15	18.7	12.82	24.58
168copper	36	27	18	22.2	16.516	27.884
168nocopper	36	27	20	24.8	18.724	30.876
240copper	36	24	21	22.7	17.212	28.188
240nocopper	36	26	17	21	15.708	26.292

In Table 4.11, a similar trend of the BDV of oil with longer aging time can be seen. Longer aging time does not influence the BDV of oil with copper. However, a longer aging time indeed influences tan δ of oil, as was discussed in the previous section.

In Table 4.11, a similar trend of the BDV of oil with longer aging time can be seen. A longer aging time does not influence the BDV of oil with copper. However, a longer aging time still influences tan δ of oil, as was discussed in the previous section.

Thus, with copper in the oil, the aging process does not influence the BDV of oil when the humidity of oil is constant. We draw this conclusion from Figure 4.14. In Figure 4.14 we can see the mean value of BDV of oil samples (without copper) with longer aging time remains almost constant.

After analyzing the influence of increasing tan δ on BDV of oil in this section, we can conclude that the aging process does not significantly influences the BDV of the oil when oil samples have similar humidity under ambient temperature (normally 20℃ in the lab).

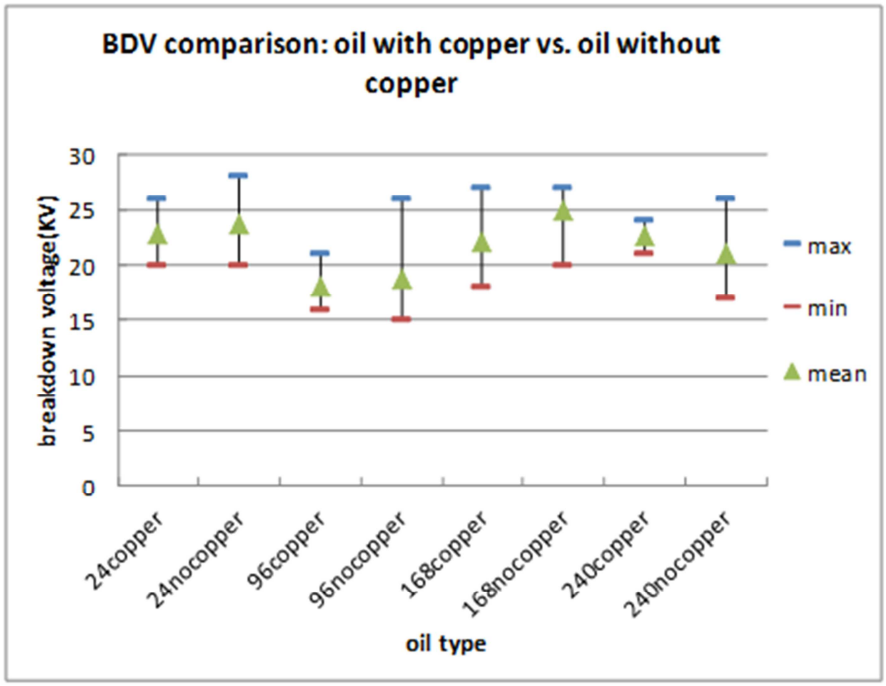


Figure 4.14 Comparison of the BDV of oil with copper and oil without copper. We can see that copper does not significantly influences the BDV of oil under similar humidity.

4.5.3 BDV vs. acidity of oil

From previous sections, it was noticed that the TAN and tan δ of oil both increase during the aging process and increasing tan δ does not influence the BDV of oil when the humidity of oil is constant. Therefore, increasing acidity of oil does not influence the BDV of oil significantly when the humidity of oil is constant.

T501 is an anti-oxidant which reacts with oxygen free radicals. It can thus slow down the oxidation rate of oil. Previous research shows that the copper can make consumption of the antioxidant T501 in oil accelerated than without the presence of copper in the oil; as a result, the oxidation stability of oil is decreased, thereby accelerating the aging process of oil [8]. The acidity value of oil in the presence of copper is higher than that in the absence of copper, and the content of copper in oil increases because that the acid and other aging products can corrode the copper, so the catalytic action of copper on oil is strengthened. Some copper will precipitate with oil sludge in later stage of the aging process. Thus, the content of copper in oil decreases.

When the copper content in oil is higher than a certain critical level in the later stage of the aging process, together with the fact that copper will precipitate with oil sludge, the dielectric strength of oil

insulation will be decreased. Thus, the BDV will decrease at a high rate which is undesirable. However, in the early stage of aging process of oil, the copper content in oil is still low and there will be no oil sludge.

The fact that the data shows that there is almost no influence of copper on the BDV can be explained by the difference in working principle between of OIS and transformers. Transformer oil is operating at a higher temperature and higher electric stress, resulting in a more rapid aging process of oil in transformers compared to OIS. This can be seen from the length of accelerated aging tests of oil used for transformers [8]. The length can be up to 2400 hours which is ten times the length of the aging tests in this research.

After comparing the tan δ of service aged oil with the data from accelerated aging test, the length of this test is proved to be sufficient to cover the life time of switchgear oil. Therefore, the conclusion that copper barely influences the BDV of oil in switchgear seems reasonable. The complete aging process of oil insulation in switchgear exists in the early stage of the aging process of oil in transformers. In this initial period, the content of copper in the oil does not reach the level where it can affect the BDV of oil.

4.5.4 BDV vs. humidity

In this section, the effect of varying humidity of oil on the BDV of oil is investigated.

The data of BDV from new oil with varying humidity is analyzed. The new oil was taken from a sealed off tank next to switchgear for back up use and immediately put inside an air tight aluminum bottle.

After transport to the laboratory, the humidity of oil and BDV were both measured immediately. The oil was kept in the tank and only exposed to the open air of the breakdown tester for 3 days and the humidity of oil increased from 21 ppm to 30 ppm and the mean BDV decreased from 32.3 kV to 26.8 kV. The decrease of BDV is 17% of initial value. The humidity value and BDV of oil are shown in Table 4.12 and Figure 4.15 and the mean values of the BDV are calculated and given as well as the minimum and maximum BDV in the test series.

Table 4.12 BDV of new oil with different humidity value. When the new oil is dry with humidity of 21ppm, the mean BDV is 32.3 kV, when the humidity increases to 30ppm, the mean BDV drops to 26.8 kV. Therefore, we can see that humidity highly affects the BDV of the oil.

Oil type	humidity(ppm)	BDV(kV)		
		max	min	mean
new	16	>40	>40	>40
	21	36	29	32.3
	30	28	22	26.8

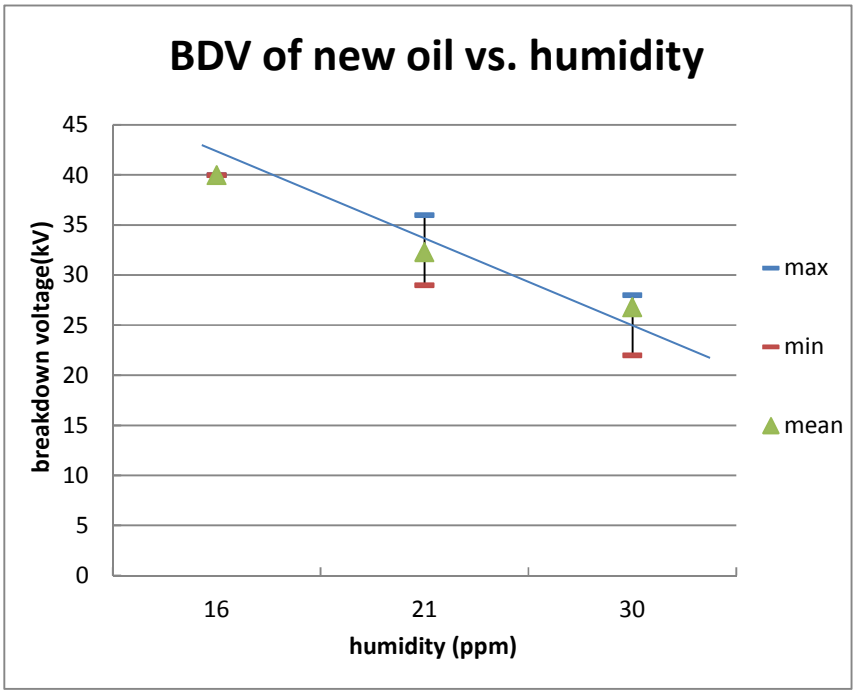


Figure 4.15 BDV of new oil with different humidity value. When the new oil is dry with humidity 21ppm, the mean BDV is 32 kV, when the humidity increases to 30ppm, the mean BDV drops to 26.8 kV. We can see humidity highly affect the BDV of the oil.

Next, the data of BDV from service aged oil with varying humidity is analyzed. After the oil is placed in the switchgear and used for five years, the humidity of the oil is higher than the oil just taken from the sealed off tank next to switchgear for back up use. Using a vacuum oven, the humidity of aged oil can be adjusted and the results also show that humidity highly affects the BDV of the aged oil similar to new oil.

In Table 4.13, the mean BDV are calculated and the minimum and maximum BDV in the test series are listed. From Figure 4.16, we can see that the BDV of 5-year aged oil drops significantly with increasing humidity of oil. When the humidity of oil is below 17 ppm, no breakdowns were observed, even after increasing the voltage to 40 kV. When the humidity of oil increases from 17 ppm to 28 ppm, the mean BDV drops from over 40 kV to 23.8 kV. The BDV of the oil with humidity of 28 ppm decreases by 17.4% from BDV of the oil with humidity of 23 ppm. From Figure 4.16 we can see an almost linear relationship between BDV and the humidity of the oil.

Table 4.13 BDV of 5-year aged with different humidity value. The BDV of 5-year aged oil drops significantly with increasing humidity of oil. When the humidity of oil is below 17ppm, no breakdowns are observed.

Oil type	humidity(ppm)	BDV(kV)		
		max	min	mean
Aged 5 years	17	>40	>40	>40
	23	33	25	28.8
	25	28	22	25.8
	28	30	20	23.8

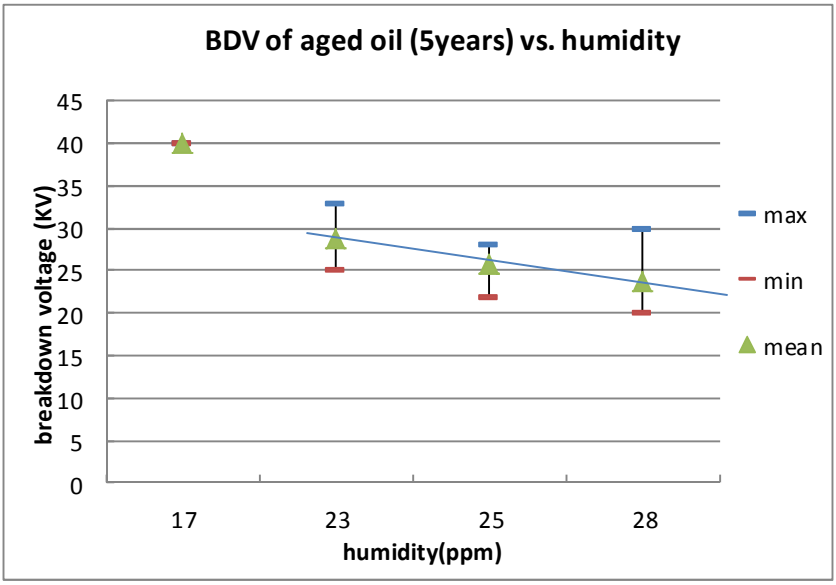


Figure 4.16 BDV of 5-year aged with different humidity value. The BDV of 5-year aged oil drops significantly with increasing humidity of oil. When the humidity of oil is below 17ppm, no breakdowns are observed.

According to [15], an almost linear relationship between the BDV and the relative water content in the oil is suggested and can be seen in Figure 4.17. This relationship fits the experiment result from

this study when the water content is less than 60% (60000 ppm) since the BDV of oil has an almost linear relationship with the humidity of oil.

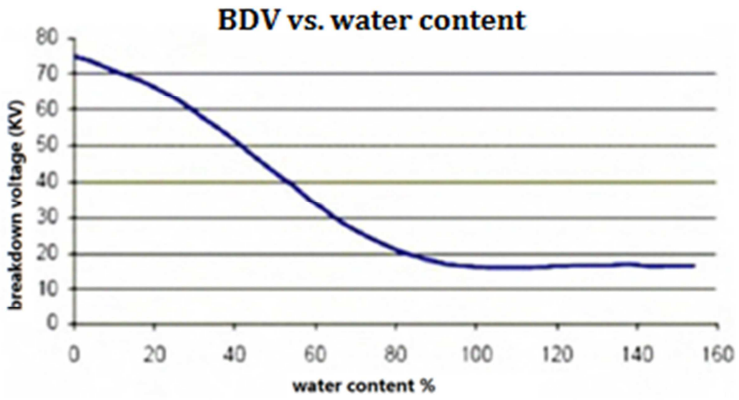


Figure 4.17 Relation of water content and BDV. We can see an almost linear relationship between BDV and the relative water content in the oil [15].

Increasing humidity of oil also leads to a decrease in the BDV of service aged oil (0.5 year). In Table 4.14, the mean BDV are calculated and the minimum and maximum BDV in the test series are listed. From Figure 4.18, we can see the BDV of 0.5-year service aged oil decreases significantly with increasing humidity of oil. When the humidity of oil is below 16ppm no breakdowns are observed while the voltage is increased up until 40 kV. The humidity of oil increases from 16 ppm to 34 ppm and the mean BDV decreases from over 40 kV to 23.8 kV. The BDV of the oil with humidity of 34 ppm decreases of 29.5% from BDV of the oil with humidity of 23 ppm. From Figure 4.18, we can see an almost linear relationship between BDV and the humidity of the oil.

Table 4.14 BDV of aged oil (0.5year) with different humidity value. The BDV of aged (0.5 year) oil drops significantly with increasing humidity of oil. When the humidity of oil is 16ppm, the BDV of oil cannot be measured since there was not breakdown occurring between the electrodes in the oil.

Oil type	humidity(ppm)	BDV(kV)		
		max	min	mean
aged 0.5 year	16	>40	>40	>40
	23	35	25	29.5
	34	27	15	20.8

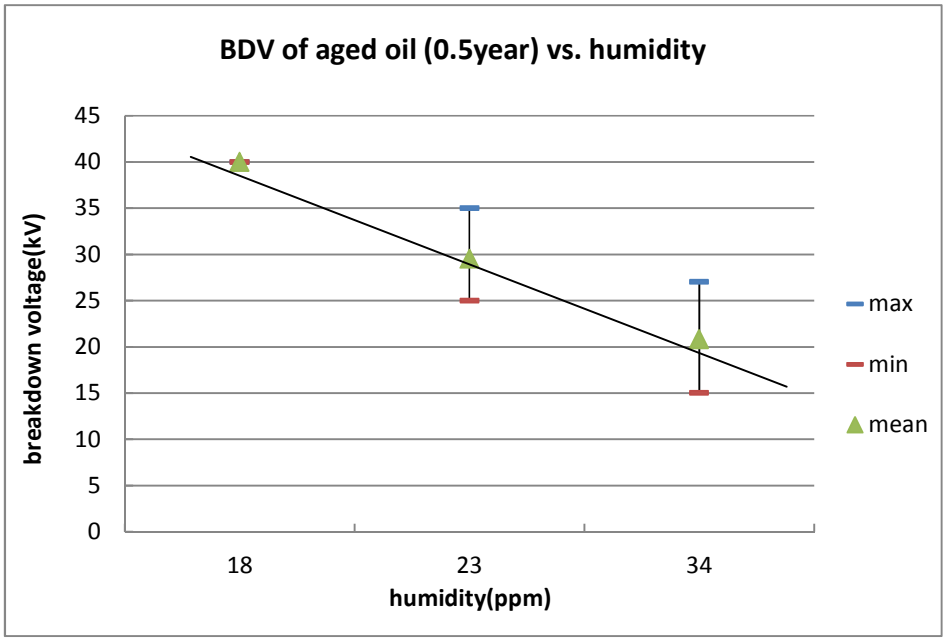


Figure 4.18 BDV of aged oil (0.5year) with different humidity values. The BDV of aged (0.5 year) oil decreases significantly with increasing humidity of oil. When the humidity of oil is 16ppm, the BDV of oil cannot be measured, since no breakdowns occurred between the electrodes in the oil.

4.6 Condensing test

This test simulates the situation that after high load, the temperature of oil will decrease and water will come out of oil.

4.6.1 Condensing process of new oil

The condensing process of new oil is shown in Figure 4.19. The humidity starts to decrease from 67 ppm. We can see that the temperature is also decreasing since the ambient temperature is 20 ℃ while the temperature of the oil is more than 45 ℃. During this period, the relative humidity of air in the lab is constant (60%). After 150 minutes, the temperature and humidity of oil reach stable values at the same time. The temperature of oil remains at 21 ℃ and the humidity of oil remains at 27 ppm.

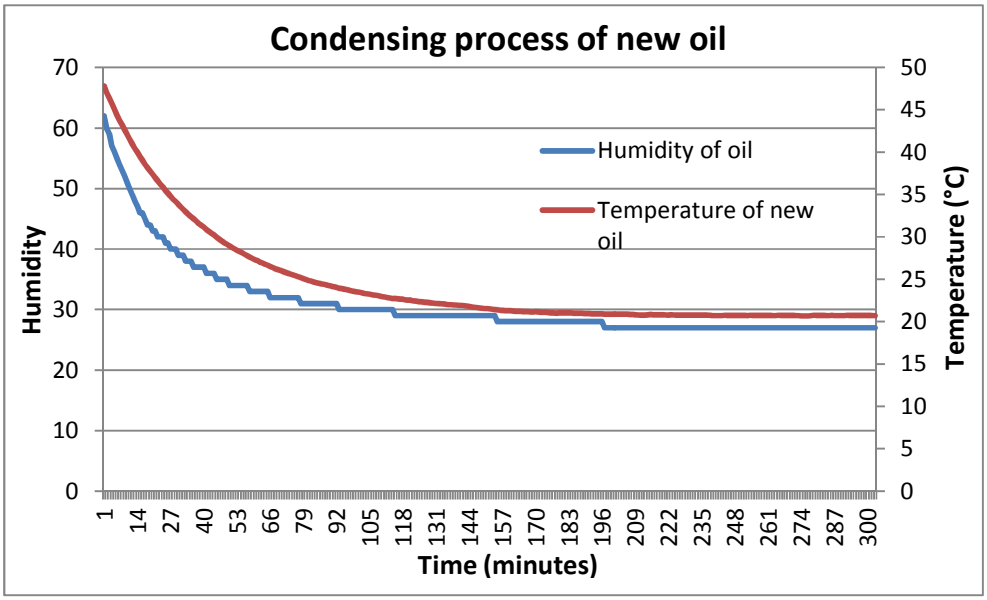


Figure 4.19 Condensing process of new oil.

4.6.2 Condensing process of service aged oil

The condensing process of service aged oil is shown in Figure 4.20. The humidity starts to decrease from 71 ppm. We can see that the temperature is also decreasing since the ambient temperature is 20 ℃ while the temperature of the oil is more than 45 ℃. During this period the relative humidity of air in the lab is constant (60%). After about 150 minutes the temperature and humidity of oil reach stable values at the same time. The temperature of oil stays at 21 ℃ and the humidity of oil stays at 27 ppm.

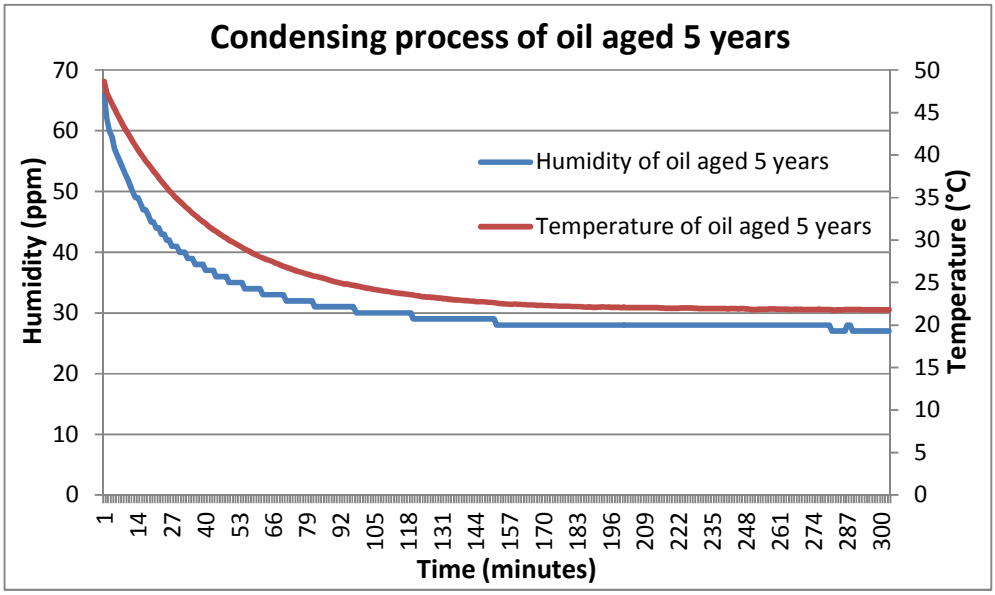


Figure 4.20 Condensing process of oil aged 5 years.

4.6.3 Condensing of accelerated aged oil

The condensing process of accelerated aged oil is shown in Figure 4.21. The humidity starts to decrease from 80 ppm. We can see that the temperature is also decreasing since the ambient temperature is 20 ℃ while the temperature of the oil is more than 45 ℃. During this period the relative humidity of air in the lab is constant (60%). After about 150 minutes the temperature and humidity of oil reach stable values at the same time. The temperature of oil stays at 21 ℃ and the humidity of oil stays at 27 ppm.

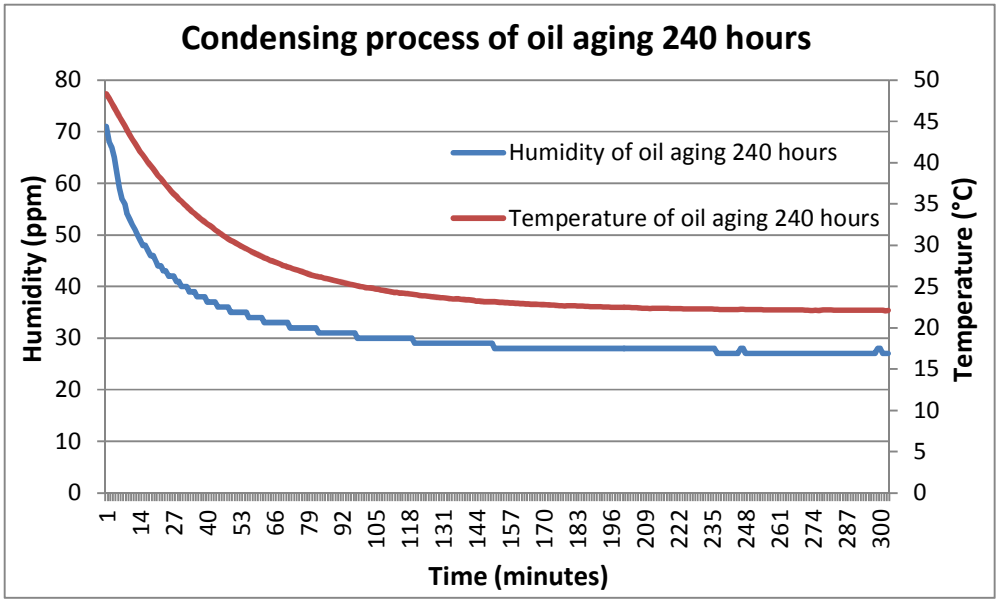


Figure 4.21 Condensing of oil aging 240 hours.

From all three results, we can see that the humidity of oil is decreasing simultaneously with the decreasing temperature of oil. Finally, they reach stable values almost simultaneously. In the following section, the decreasing humidity of the three oil samples will be analyzed to determine whether the aging of oil has an influence on the condensing process of oil.

4.6.4 The influence of acidity on condensing process of oil

In Figure 4.22, we can see that the three lines of humidity of oil almost overlap. The most obvious differences appear in the period from the starting point to 30 minutes. This part of condensing process is paid special attention to. The condensing process of oil from the beginning to 30 minutes is shown in Figure 4.23.

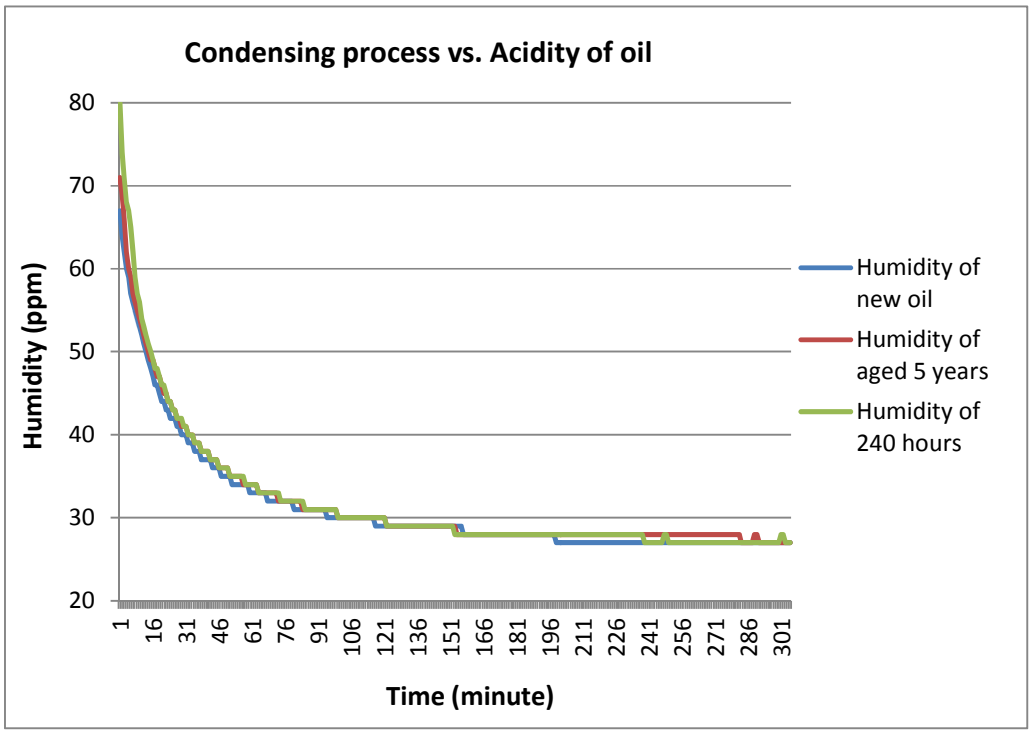


Figure 4.22 The complete condensing process vs. acidity of oil.

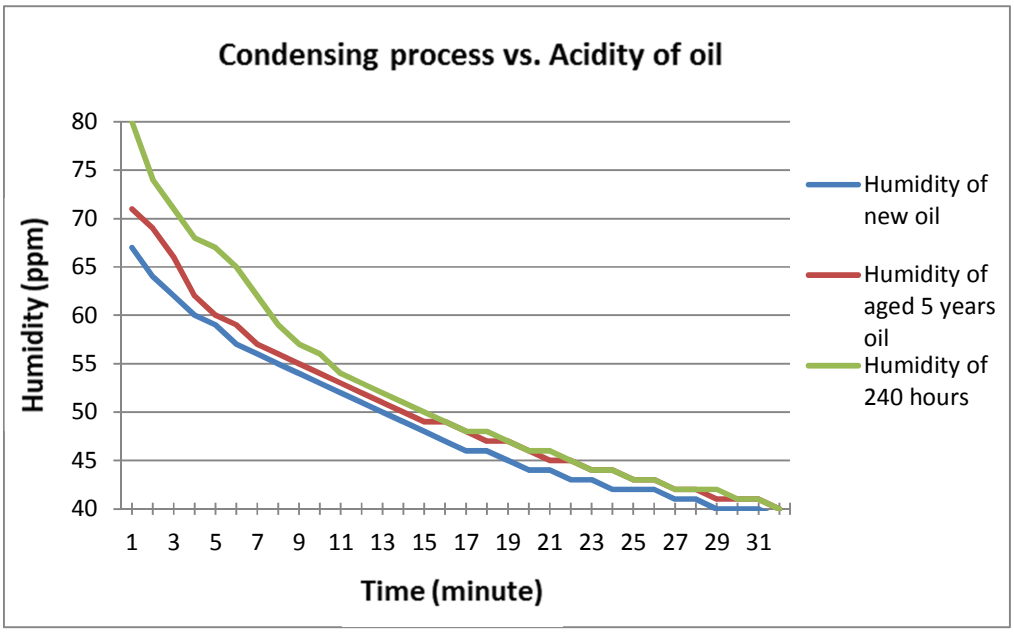


Figure 4.23 The condensing process from 0 to 30 minutes vs. acidity of oil.

Before starting the condensing test, all three oil samples have been preconditioned in a vacuum oven and their humidity are set to 21 ppm. Afterwards, the samples were placed in a normal oven together with water for 48 hours as described in Chapter 3. The relative humidity of air inside the oven is 99%.

The first main difference after this wetting process is the resulting humidity value of the three testing oil. The humidity of the oil becomes 67 ppm (new oil), 71 ppm (oil aged 5 years) and 80 ppm (oil aging 240 hours). The original humidity of the three oil samples increases with increasing acidity of oil. This means when being placed in the same environment with same temperature and humidity of air, the oil with higher acidity absorbs more water than oil with lower acidity.

Another clear difference is the different decreasing rates of the humidity among the three oil samples. From Figure 4.22, we notice that the final value of the humidity of the three oil samples is the same and remains constant at 27 ppm. Thus, the decreasing speed of humidity of the three samples is different. From Figure 4.23, we can see that the difference of decreasing rate of humidity of three oil samples mainly exist in the period of 1 to 10 minutes. After 10 minutes, the decreasing rate is almost similar for the three oil samples. As introduced in Chapter 3, the dissolved water in the oil can precipitate out of oil and become free water and accumulate in the bottom of the oil tank.

Therefore, when being placed in the same environment, at high temperature (above 50℃), the oil with higher acidity absorb more water than the oil with low acidity. However, at low temperature (20℃), the humidity of oil is the same. When the condensing process repeats, more water will accumulate in the bottom of the oil with higher acidity value.

Based on the results in this section, we conclude that when the oil ages, the rate of the condensing process of oil increases and oil will also absorb more water than shorter aged oil. Thus, after a long time in service, the humidity of oil and free water in the bottom of the oil tank should be given extra consideration.

4.6.5 Humidity of oil vs. humidity of ambient air at fixed temperature

The new oil and service aged oil are placed in the ambient air after condensing test. The plots of humidity of oil together with the relative humidity of ambient air are shown in Figure 4.24.

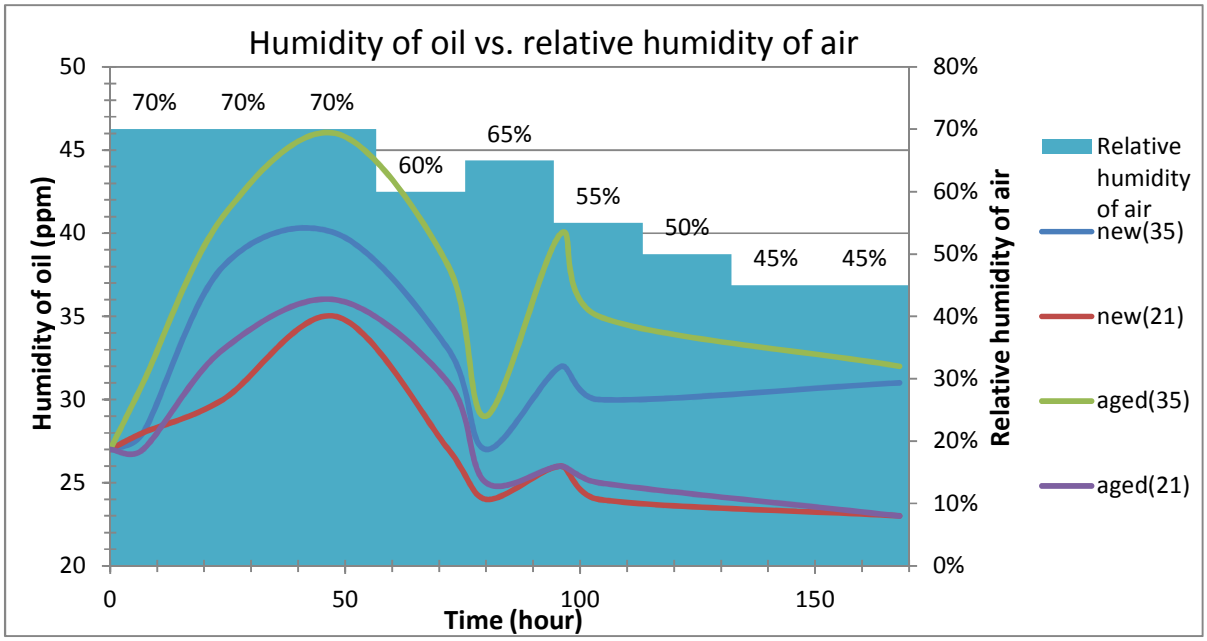


Figure 4.24 Humidity of oil vs. relative humidity of air.

In Figure 4.24, new (35) means new oil with the temperature of 35 ℃. From figure 4.24, it can be seen that:

1. Oil will absorb more water before saturation when the temperature of oil increases when the humidity of air is constant.
2. The humidity of oil is highly related to the humidity of ambient air. When the relative humidity of air increases, oil will absorb more water. In the opposite case, the humidity of oil will drop.
3. Oil with higher TAN absorbs more water than oil with lower TAN when the relative humidity of ambient air is constant when the temperature of oil is high (35℃).

As introduced in Chapter 2, the oil in OIS is directly exposed to the ambient air. In section 4.5, we have the conclusion that BDV of oil is highly influenced by the humidity of oil. In section 4.6, the humidity of oil is highly affected by the ambient air and oil with higher acidity absorb more water and condense faster than the oil with lower acidity number.

Therefore, we can now draw the conclusion that humidity of oil in switchgear must be paid attention to and when the oil ages, the humidity of oil will be more sensitive to the ambient air and will raise the risk of breakdown in OIS.

4.7 Conclusions

In section 4.2, visual inspection of the color of oil is given. With increasing time heated in the oven, the oil becomes darker. Lightly accelerated aged oil has a yellow color and the heavily accelerated aged oil has a dark brown color. . The color of the oil can be used to determine whether more definitive tests should be done to determine specific characteristics of the oil.

In section 4.3, following conclusions are obtained after interpreting the results:

1. For the slightly accelerated aged oil, especially with new oil, tan δ changes little with increasing applied voltage. However, for the heavily accelerated aged oil, tan δ becomes higher with increasing applied voltage. Rather than a flat curve for the tan δ versus voltage of the new oil, the curve of the heavily accelerated aged oil is nonlinear.
2. After 240 hours of accelerated aging:
    a. The mean value of tan δ of oil without copper increases of about 2.5 times the initial value.
    b. The mean value of tan δ of oil with copper increases by about 5.5 times the initial value.
    c. The value of tan δ of oil with copper is 86% larger that the value of oil without copper. The presence of copper in the oil accelerates the aging process of oil.
3. The time length designed in this thesis is sufficient enough to cover the life time of oil in switchgear

In section 4.4, The acidity of oil is obtained in this thesis by measuring the total acidity number (TAN) of each oil. The TAN of new oil is 0.006 and increases to 0.007 after 0.5 serving year. The TAN of 5-year-service aged oil is 0.008.

With and without copper in the oil, the largest value of TAN of accelerated aged oil is obtained at the end of aging test and the TAN follows an increasing trend versus aging time. The increasing rate of the trend line of TAN of oil with copper is steeper than that of oil without copper and this means that copper accelerates the chemical aging process. Oil showing an acid number of 0.15 or larger can be expected to show accelerated acid formation and leads to the form of sludge. From the TAN results in this section, it can be concluded that the TAN of both service aged oil and accelerated aging test oil (with and without copper) are far lower than 0.15. Thus, it is not compulsory to consider the influence of chemical aging process on the form of sludge in the oil during service period of oil. However, it is still necessary to consider the influence of increasing acidity of oil on the condensing process.

In section 4.5, data interpretation is provided to quantify the relationship between:

1. tan δ vs. BDV
2. acidity vs. BDV
3. BDV vs. copper
4. BDV vs. humidity

We can conclude that acidity and tan δ of oil do not influence the BDV of oil significantly when the humidity of oil is constant. BDV of oil is highly influence by the humidity of oil from following results:

1. For new oil, the mean BDV decreases from 32.3 kV to 26.8 kV when the humidity of oil increases from 21 ppm to 30 ppm. The decrease of BDV is 17% of initial value.
2. For 5 year-service aged oil, the mean BDV decreases from 28.8 kV to 23.8 kV when the humidity of oil increases from 23 ppm to 28 ppm. The decrease of BDV is 17% of initial value.
3. For 0.5 year-service aged oil, the mean BDV decreases from 29.5 kV to 20.8 kV when the humidity of oil increases from 23 ppm to 34 ppm. The decrease of BDV is 29% of initial value.

Therefore, humidity of oil must be paid close attention to. The humidity of oil must be monitored during the inspection and maintenance of OIS.

In section 4.6, the condensing process of oil is analyzed. The most obvious differences between the three oil samples (new, 0.5 year and 5 years-service aged) appear from the starting point to 30 minutes of this test. This period of condensing was analyzed in further detail. The following results were obtained:

1. After the ‘wetting’ process, the resulting humidity of the oil becomes 67 ppm (new oil), 71 ppm (oil aged 5 years) and 80 ppm (oil aging 240 hours). The original humidity of the three oil samples increases with increasing acidity of oil.
2. The final values of humidity of the three oil samples are similar and remain constant at 27 ppm under ambient temperature (20 ℃) and relative humidity of the ambient air of 60%.
3. The decreasing rate of humidity of the three oil samples is different. The difference between the decreasing rates of humidity of three oil samples mainly exists between 0 to 10 minutes. After 10 minutes, the decreasing rate is almost similar for the three oil samples.

Therefore, when being placed in a same environment, at high temperature(above 50℃), the oil with higher acidity absorb more water than the oil with low acidity. However, at low temperature (20℃), the humidity of oil is the same. The dissolved water in the oil can precipitate out of oil, become free water and accumulate in the bottom of the oil tank. When the condensing process repeats, more water will accumulate in the bottom of the oil with higher acidity value.

After condensing test, the oil samples are placed in the ambient air at different temperatures and the, following conclusions are obtained:

1. Oil will absorb more water before saturation when the temperature of oil increases when the humidity of air is constant.
2. The humidity of oil is highly related to the humidity of ambient air. When the relative humidity of air increases, oil will absorb more water. In the opposite case, the humidity of oil will drop.
3. Oil with higher TAN absorbs water than oil with lower TAN when the relative humidity of ambient air is constant when the temperature of oil is high (35℃).

The structure of OIS has been introduced in Chapter 2 and the oil in OIS is directly exposed to the ambient air. The results in this section approve that the humidity of oil is highly affected by the ambient air and humidity highly influence the BDV of oil.

Thus, the humidity of oil in switchgear must be paid close attention to and when the oil gets older, the humidity of oil will be more sensitive to the ambient air and will raise the risk of breakdown in OIS. When the oil gets older, the condensing process of oil becomes faster and oil will also absorb more water than younger oil. Thus, after long time in service, the humidity of oil and free water in the bottom of the oil tank should be paid more attention to.

Chapter 5 Conclusions and recommendations

5.1 Conclusions

In Chapter 1, following questions are proposed:

1. Which factors influence the dielectric strength of oil insulation?
2. What is the influence of humidity on the BDV of oil insulation?
3. What is the influence of chemical and electrical aging processes on the BDV of oil insulation?
4. What is the influence of copper on the chemical and electrical aging processes of oil insulation?
5. What is the influence of copper on the BDV of oil insulation?
6. What is the influence of acidity on the steepness of condensing curve of insulating oil?

The dielectric properties of switchgear oil insulation are mainly determined by environmental factors such as oxygen, electrical stress and humidity. Chemical aging process of oil of switchgear is caused by reaction among moisture, oxygen, copper and oil. Among these factors, the humidity of oil highly influences the BDV of oil.

The tan δ of oil without copper increases from 0.38 to 1.69 at 20℃ at an applied voltage of 350 V, and tan δ of oil with copper increase from 0.38 to 3.24 at 20℃ at applied voltage of 350 V. Tan δ increases continuously with the aging of oil performed accelerated aging test with and without copper, so it can be used as the indicator of aging level of oil in this thesis.

Copper increases the tan δ of oil during accelerated aging test, which implies that it accelerates the aging process. But existence of copper in the oil sample during the accelerated aging process does not influence the BDV of oil significantly.

With and without copper in the oil, the largest value of TAN of accelerated aged oil is obtained at the end of aging test and the TAN follows an increasing trend versus aging time. The increasing rate of the trend line of TAN of oil with copper is steeper than that of oil without copper and this means that copper accelerates the chemical aging process.

Aging level does not affect the BDV of oil insulation when the humidity of oil is constant.

Humidity highly affects the BDV of oil. Test result shows:

1. For new oil, the mean BDV decreases from 32.3 kV to 26.8 kV when the humidity of oil increases from 21 ppm to 30 ppm. The decrease of BDV is 18% of initial value.
2. For 5 year-service aged oil, the mean BDV decreases from 28.8 kV to 23.8 kV when the humidity of oil increases from 23 ppm to 28 ppm. The decrease of BDV is 17% of initial value.
3. For 0.5 year-service aged oil, the mean BDV decreases from 29.5 kV to 20.8 kV when the humidity of oil increases from 23 ppm to 34 ppm. The decrease of BDV is 29% of initial value.

The humidity of oil is highly influenced by the relative humidity of air , the temperature of oil and the acidity of oil.

During the condensing process:

1. After the 'wetting' process, the resulting humidity of the oil becomes 67 ppm (new oil), 71 ppm (oil aged 5 years) and 80 ppm (oil aging 240 hours). The original humidity of the three oil samples increases with increasing acidity of oil.
2. The final values of humidity of the three oil samples are equal and remain constant at 27 ppm under ambient temperature (20℃).
3. The decreasing rates of humidity of the three oil samples are different. The difference of decreasing rate of humidity of three oil samples mainly exists between 0 to 10 minutes. After 10 minutes, the decreasing rate is almost similar for the three oil samples.

After condensing test, the oil are placed in the ambient air at different temperature, following conclusions are obtained:

1. Oil will absorb more water before saturation when the temperature of oil increases when the humidity of air is constant.
2. The humidity of oil is highly related to the humidity of ambient air. When the relative humidity of air increases, oil will absorb more water. In the opposite case, the humidity of oil will drop.
3. Oil with a higher TAN absorbs water than oil with a lower TAN when the relative humidity of ambient air is constant and the temperature of oil is high (35℃).

5.2 Recommendations

Successful asset management heavily relies on the use of information and data to facilitate the decision making process. However, for the case of OIS COQ, up until now, the data recorded with relation to acidity, humidity and breakdown voltage of oil has been sporadic. Therefore, to reduce the risk of breakdown in COQ oil, the following recommendations are provided.

Adequate storage of oil samples at different time intervals

The first recommendation is on the storage of oil samples. As mentioned in the beginning of the thesis, oil samples from only two service ages (0.5 and 5 years) are involved in this project. Since oil can only be taken when the COQ is switched off from the network, it is important to take the samples immediately when there is maintenance of switchgear. When taking the oil samples, strictly following the standard is very important to assure the results of the tests on these samples accurate and reliable. When taking samples, the IEC standard 60475 should be followed as described in Chapter 3 of this thesis.

Following tests are recommended to be performed in the further research:

1. Breakdown tests under different temperature whilst measuring humidity of oil is are recommended to be performed.
2. After repeating condensing test for certain times, measure the free water formed in the bottom of oil bottles.

Inspection

The second recommendation is about inspection. For optimal condition assessment, it is recommended to perform all the following tests on the oil from the COQ installations:

1. Visual inspection
2. Humidity test
3. Acidity test
4. Breakdown test
5. Tan δ

However, in practical operation, it may be not possible to perform all these tests during each inspection of COQ. We want to reduce the risk of breakdown of oil in OIS by monitoring the factors

that are most highly influencing the BDV of oil in switchgear. Therefore, according to the results in this thesis, environmental factors that can influence the humidity and acidity of oil are used to help narrow the inspection methods down. The related factors are:

- **Relative humidity of air**

If the relative humidity of a certain area where the COQ is located is low (below 60%), the humidity of oil may remain at a low value (in the order of 27 ppm) and inspection of the oil is required to be performed once every six months with:

1. Visual inspection
2. Humidity test

If the relative humidity of a certain area where the COQ is located is high (over 60%), humidity of oil may remain at or reach a high value, which can harm the dielectric strength of oil, therefore, inspection of the oil is recommended to be performed monthly with:

1. Visual inspection
2. Humidity test
3. Breakdown test

- **Temperature of ambient environment**

Saturation water content of oil increases with higher temperature of oil. The temperature of oil is influenced by the temperature of ambient environment. Therefore, in the area where the temperature is high, it is recommended to monitor the humidity of oil and perform following tests:

1. Visual inspection
2. Humidity test
3. Breakdown test

Above mentioned factors are environmental factors. These factors can highly influence the breakdown voltage of oil in COQ. Therefore, it is recommended to record the climate condition where breakdown in COQ has already occurred.

In the area where temperature and relative humidity of air are both high, it is highly recommended to perform inspection of the COQ oil monthly using the tests:

1. Visual inspection
2. Humidity test
3. Breakdown test

- **Overload frequency**

Temperature of oil can also be influenced by an overload, leading to an increase in temperature of oil. After the overload has passed, the temperature of oil will decrease. The condensing tests in this thesis simulate this process and shows that water content may precipitate from oil and form free water which will increase the risk of breakdown of oil. Therefore, if overloads are frequent and/or expected, the humidity of oil is recommended to be monitored. The following tests should be performed:

1. Visual inspection
2. Humidity test
3. Acidity test
4. Breakdown test
5. Tan δ

30 ppm of humidity is recommended to be used as a reference value. When the humidity of oil reaches a value above 30 ppm, free water is possibly produced after condensing process. Free water should be removed from the tank when discovered. Therefore, it is recommended that Stedin should find a solution of detecting and removing free water.

- **Service year**

The service year of COQ oil shows a correlation with the acidity of oil. As mentioned in previous chapters, oil with a higher acidity can absorb more water from ambient air. During the condensing process, this may lead to more free water accumulation. Therefore, with the COQ oil having served for more than 5 years since last replacement of the oil, it is recommended to measure the humidity of oil every half year and also check the free water in the bottom of the tank.

Following tests are recommended to perform with long service aged oil since last replacement:

1. Visual inspection
2. Humidity test
3. Acidity test
4. Breakdown test
5. Tan δ

The same recommendation can be followed as those given with respect to the overload frequency.

- **Color of oil**

The color of an oil sample is recommended to be used mainly as a guide to determine whether more definitive tests should be performed. These tests can determine specific characteristics of the particular sample that are indicative for the performance of the oil from which the sample was taken.

It should be pointed out that the color of the oil by itself should never be used to indicate the dielectric quality of the oil. However, when the color of oil is uncommonly dark, which is a rare situation, following tests must be performed and a possible replacement of the oil may be required if necessary:

1. Humidity test
2. Acidity test
3. Breakdown test
4. Tan δ

Finally, it must be noted that, all these recommendations are provided based on the results in this thesis which are all obtained in the lab and oil from only two different switchgear locations were analyzed. In order to make the results more reliable and more broadly applicable, more samples should be involved to repeat the tests designed in this thesis to adjust the recommended values which could help define a more reliable and better strategy of inspection and maintenance.

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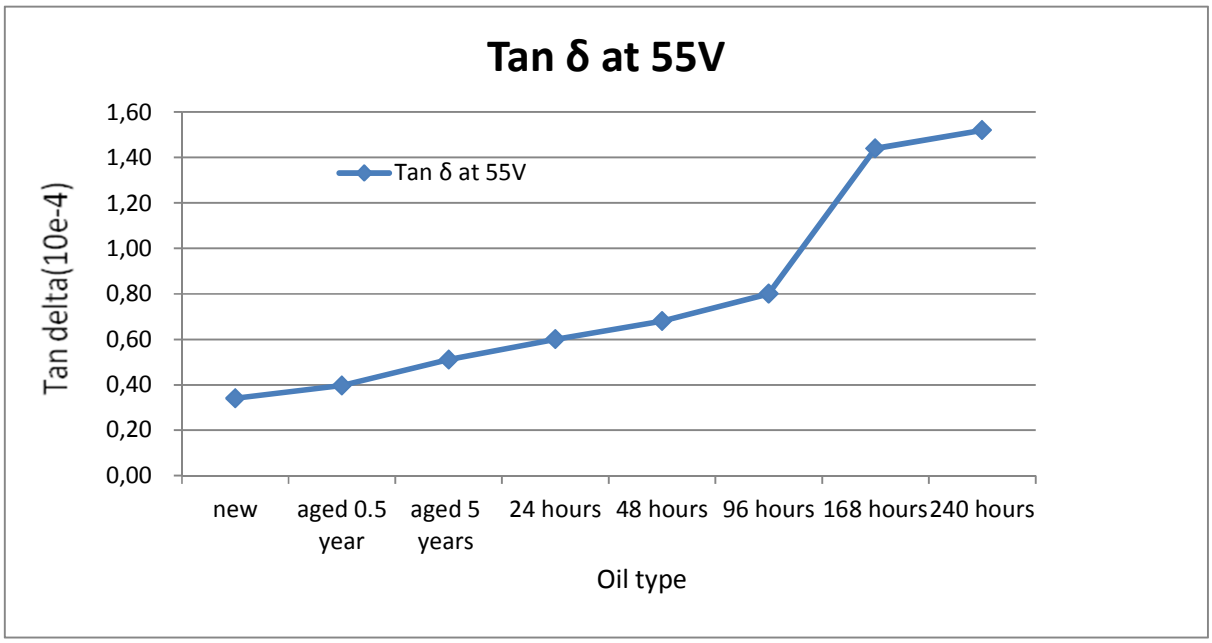
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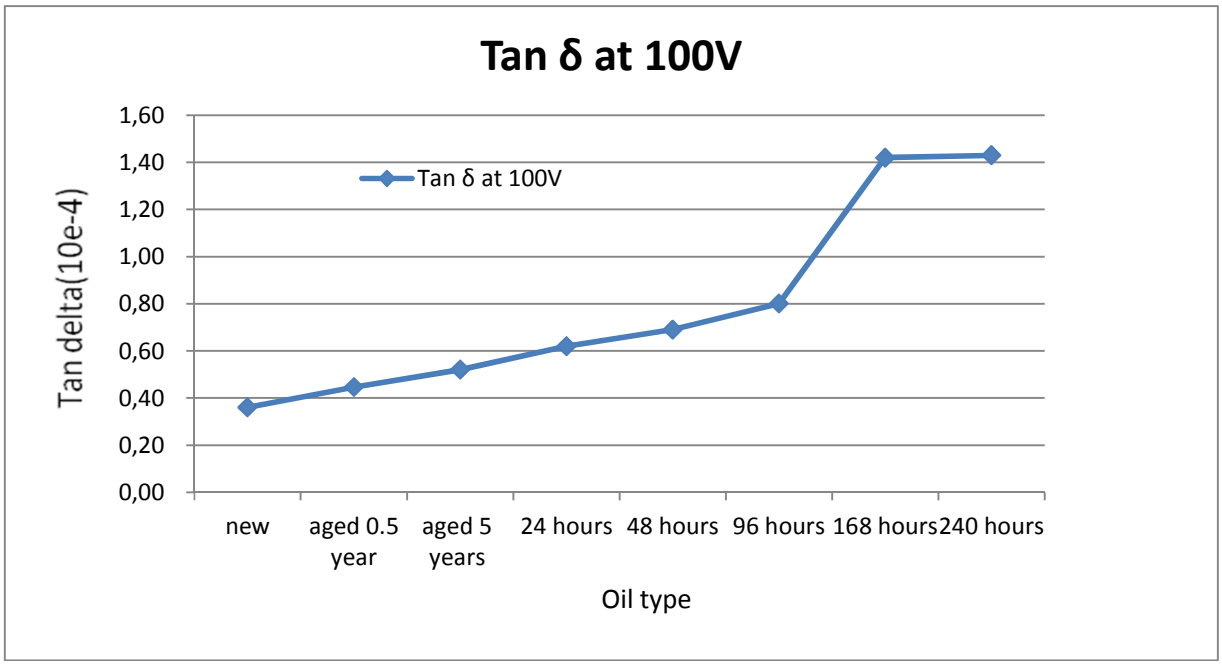
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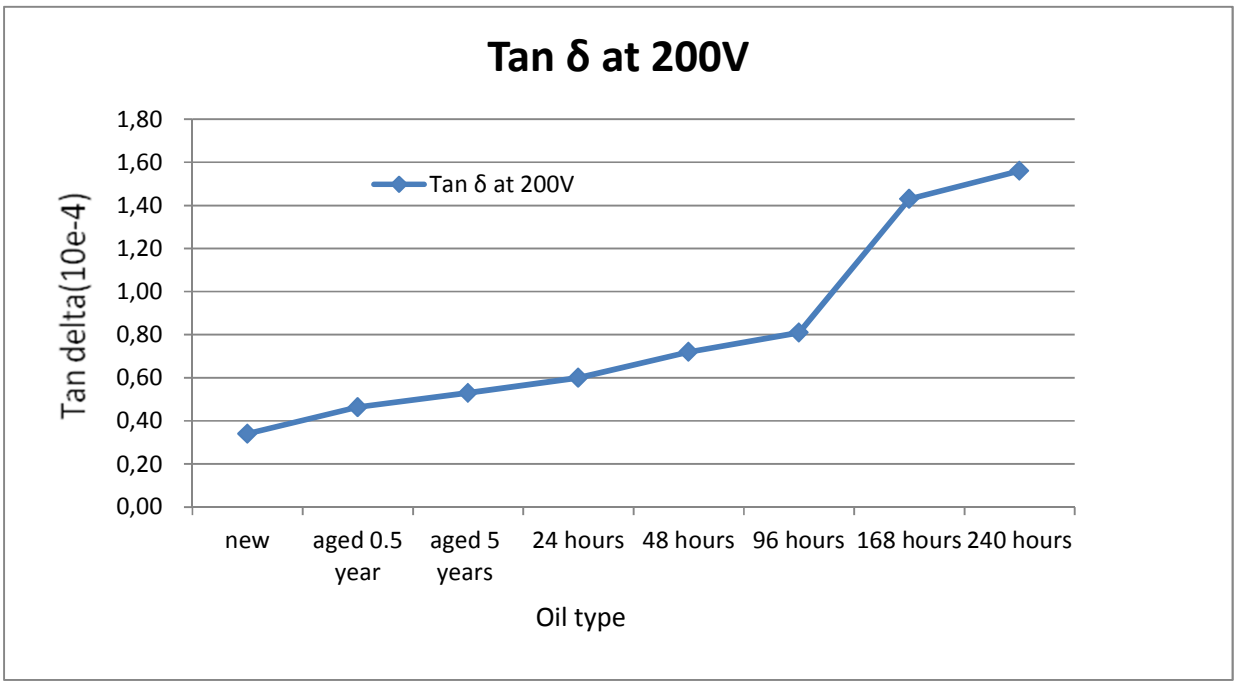
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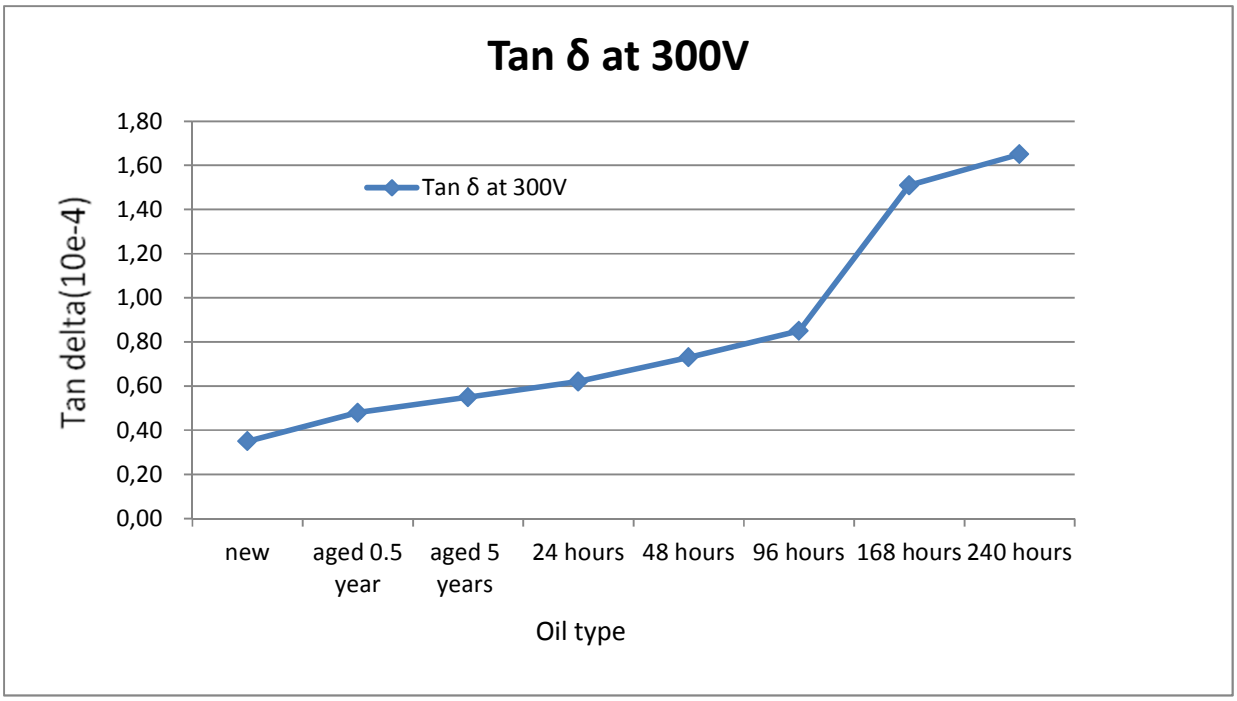
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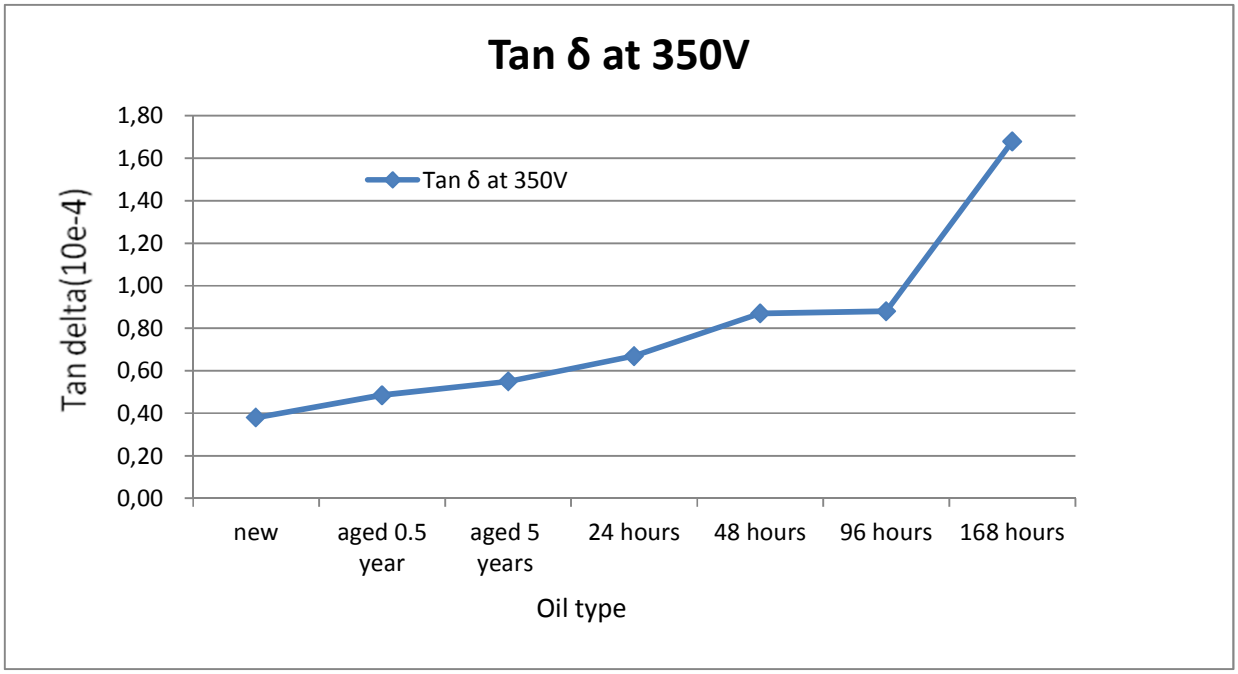
Appendix A


Tan δ at 55V
Tan delta(10e-4)
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Tan δ at 55V
new
aged 0.5 year
aged 5 years
24 hours
48 hours
96 hours
168 hours
240 hours
Oil type


Tan δ at 100V
Tan delta(10e-4)
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Tan δ at 100V
new
aged 0.5 year
aged 5 years
24 hours
48 hours
96 hours
168 hours
240 hours
Oil type


Tan δ at 200V
Tan delta(10e-4)
1,80
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Tan δ at 200V
new
aged 0.5 year
aged 5 years
24 hours
48 hours
96 hours
168 hours
240 hours
Oil type


Tan δ at 300V
Tan delta(10e-4)
1,80
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Tan δ at 300V
new
aged 0.5 year
aged 5 years
24 hours
48 hours
96 hours
168 hours
240 hours
Oil type


Tan δ at 350V
1,80
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Tan delta(10e-4)
Tan δ at 350V
new
aged 0.5 year
aged 5 years
24 hours
48 hours
96 hours
168 hours
Oil type

Appendix B

When current flows through a circuit breaker and the contacts of the breaker part, driven by the mechanism, the magnetic energy stored in the inductances of the power system forces the current to flow. Just before contact separation, the breaker contacts touch each other at a very small surface area and the resulting high current density causes the contact material to melt. The melting contact material explodes and this leads to a gas discharge in the surrounding medium either air, oil, or SF6 [9].

When the molecular kinetic energy exceeds the combination energy, matter changes from a solid state into a liquid state. When more energy is added by an increase in temperature and the Van der Waals forces are overcome, matter changes from a liquid state into a gaseous state. A further increase in temperature gives the individual molecules so much energy that they dissociate into separate atoms, and if the energy level is increased even further, orbital electrons of the atoms dissociate into free moving electrons, leaving positive ions. This is called the *plasma state*. Because of the free electrons and the heavier positive ions in the high temperature plasma channel, the plasma channel is highly conducting and the current continues to flow after contact separation [9].

For higher temperatures, the conductivity increases rapidly. The thermal ionisation, as a result of the high temperatures in the electric arc, is caused by collisions between the fast-moving electrons and photons, the slower-moving positively charged ions and the neutral atoms. At the same time, there is also a recombination process when electrons and positively charged ions recombine to a neutral atom. When there is a thermal equilibrium, the rate of ionisation is in balance with the rate of recombination.

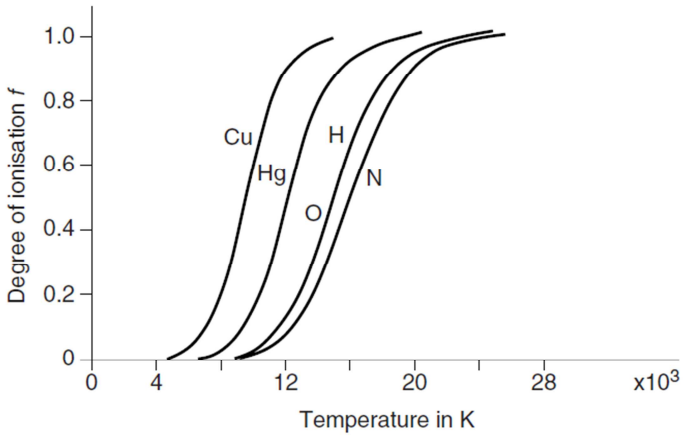


Figure B.1 Degree of thermal ionisation for some metal vapours and atomic gases

The graph of Figure B.1 shows that thermal ionisation can be used to switch between a conducting state (f = 1) and an isolating state (f = 0). Because of the rather steep slope of the function between the temperature and the degree of ionisation, reduction of the average kinetic energy level of the moving particles by cooling with cold gas is a very good way to bring the arc channel from a conducting to a nonconducting state [9].

Appendix C

PROPERTY	UNIT	TEST METHOD IEC	GUARANTEED DATA MIN	MAX	TYPICAL DATA
Physical					
Appearance		IEC 60296	Clear, free from sediment		complies
Density, 20°C	kg/dm^3	ISO 12185		0,895	0,879
Viscosity, 40°C	mm^2/s	ISO 3104		12,0	9,4
Viscosity, -30°C	mm^2/s	ISO 3104		1800	1100
Pour point	°C	ISO 3016		-40	-53
Chemical					
Acidity	mg KOH/g	IEC 62021		0,01	<0,01
Corrosive sulphur		DIN 51353	non-corrosive		non-corrosive
Corrosive sulphur		ASTM D 1275 B	non-corrosive		non-corrosive
Corrosive sulphur		IEC 62535	non-corrosive		non-corrosive
Aromatic content	%	IEC 60590			10
Antioxidant, phenols	Wt %	IEC 60666	not detectable		not detectable
Water content	mg/kg	IEC 60814		30	<20
Furfural content	mg/kg	IEC 61198		0,1	<0,1
Electrical					
Dielectric dissipation factor (DDF) at 90°C		IEC 60247		0,005	<0,001
Interfacial tension	mN/m	ISO 6295	40		48
Breakdown voltage					
- Before treatment	kV	IEC 60156	30		40-60
- After treatment	kV		70		>70
Oxidation stability					
At 120°C, 164 h		IEC 61125 C			
Total acidity	mg KOH/g			1,2	0,50
Sludge	Wt %			0,8	0,15
DDF/90°C				0,500	0,080
Health, safety and environment					
Flash point, PM	°C	ISO 2719	135		148
DMSO extractable compounds	Wt %	IP 346		3	<3
PCB		IEC 61619	not detectable		not detectable

Nytro Libra is an uninhibited insulating oil, meeting IEC 60296 (03) General specifications.

Severely Hydrotreated Insulating Oil
Issuing date: 2010-03-24

Appendix D

The top part of LV electrode is made of epoxy as an insulator and equipped with a guard which is put inside it as shown in Figure D.1. The guard has a function to minimize the effect of any leakage current in the measurement.



Figure D.1 The guard(the copper ring) put inside LV electrode

The principle of such a guard is illustrated in Figure D.2. When a voltage is applied over the dielectric material, a leakage current through the dielectric material can occur. The tan **δ** is measured to determine this leakage current. However, there will also be a leakage current from the dotted loop, which will affect the accuracy of the measurement results. To remove these unwanted leakage currents, a guard is placed next to the LV electrode. The unwanted leakage current goes to the earth and will not add to the results of the leakage current for tan **δ** measurement.

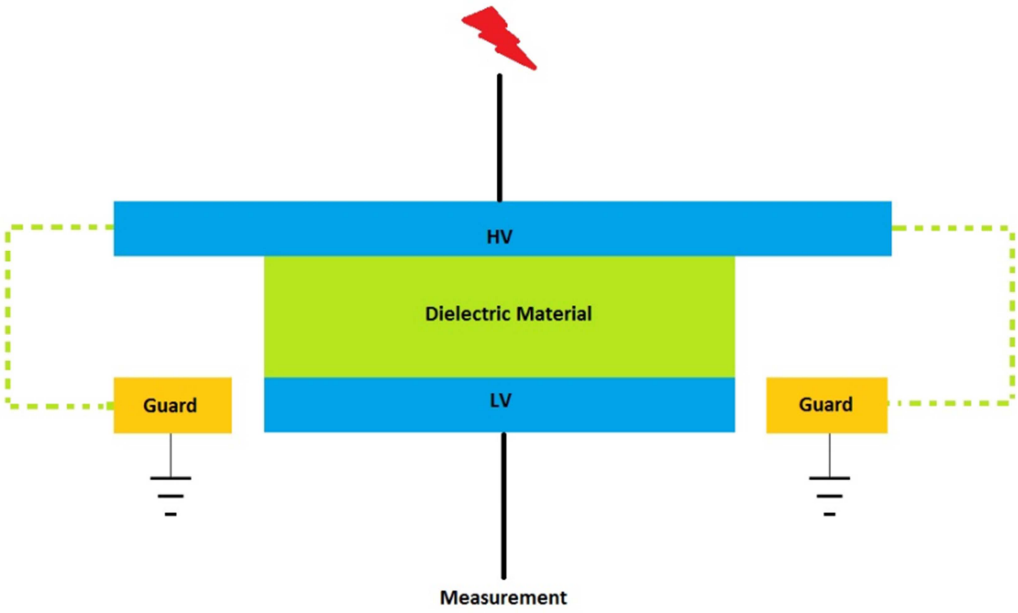


Figure D.2 Principle of the guard