Chapter 1

INTRODUCTION

1.1 BACKGROUND

The majority of power transformers in operation today are filled with mineral oil. The primary function of the oil is to provide a high dielectric strength and to act as an efficient coolant. The effectiveness of the oil as an insulating material is reduced as the moisture level increases, while cooling is reduced as the oil oxidizes. Paper insulation will also absorb moisture from the oil, thus increasing power factor.

Oxidation of transformer oil begins when the transformer is energized and loaded. A chemical reaction occurs when the oil is exposed to a combination of heat, oxygen, core and coil components. As the process of oxidation progresses, acids and polar compounds are formed and in turn become sludge. This sludge form a coating on the heat transfer surfaces of the core/coil and the tank/radiators. This reduces the heat transfer capacity of the system. The operational temperatures are increased, thus accelerating the degradation of the oil.

Corrosive sulphur in mineral oils may occur in elemental form or be part of certain molecular structures of hydrocarbons: thiophenes, disulfides and polysulfides, thioesters, Mercaptans and elemental sulphur. Disulfides are the most commonly occurring corrosive compounds and in particular, dibenzyl-disulfide (DBDS) is frequently detected in transformers. There also are other molecules naturally which are present in transformer oil that contain elements such as oxygen, nitrogen and sulphur,
some of which are useful for maintaining oil oxidation stability. There are five main classes of sulphur compounds found in crude oil but not all types are considered to be corrosive or reactive [1]. Elemental sulphur and sulphur compounds in concentrations up to 20% [2] are present in the crude oil which is used for manufacturing of transformer oil. Details of sulphur and sulphur compounds generally found in transformer oil are listed in table 1.1. The table also furnishes details of the reactivity and chemical formula of the sulphur compounds.

**Table 1.1 Sulphur and Sulphur Compounds Found in Crude Oil**

<table>
<thead>
<tr>
<th>Group</th>
<th>Reactivity</th>
<th>Chemical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elemental (Free) Sulphur</td>
<td>Very reactive</td>
<td>S</td>
</tr>
<tr>
<td>Mercaptans (thiols)</td>
<td>Very reactive</td>
<td>R-SH</td>
</tr>
<tr>
<td>Sulfides (thio-ethers)</td>
<td>Reactive</td>
<td>R-S-R1</td>
</tr>
<tr>
<td>Disulfides</td>
<td>Reactive/stable</td>
<td>R-S•S-R</td>
</tr>
<tr>
<td>Thiophenes</td>
<td>Very stable</td>
<td>Five-member ring containing sulphur</td>
</tr>
</tbody>
</table>

Most reactive sulphur compounds are removed from the oil during refining, but some of them are allowed to remain in the finished product to maintain oxidation stability, something that is also of very great importance to prevent corrosion. Certain sulphur compounds present in the insulating liquids exhibit antioxidant and metal deactivating properties without being corrosive, whereas some sulphur compounds have been known to react with metal surfaces. Specifically, sulphur compounds such as mercaptans are very corrosive to metallic components used electrical equipment like copper, silver etc. Presence of these corrosive sulphur species has been linked to total failure of electrical equipment used in generation, transmission, distribution of electrical Power for several decades. A review of the literature [3] indicates that DBDS is the frequently occurring sulphur compound in concentrations ranging from 100 to 1000 mg/kg (ppm) in certain lubricating oils. With its successful use in laboratory oils, DBDS is added to mineral oils to protect against wear, reduce friction and increase oxidation stability as in lubricants.

In the last decade [4] a number of failures of power transformers and reactors have taken place due to sulphur in oil causing corrosion of copper conductor resulting in formation of copper sulfide on conductors and insulating materials. A number of
transformers have been affected by corrosive sulphur mainly due to the presence of Dibenzyl-disulfide (DBDS) [5-7]. The conductive copper sulfide reduces the electrical strength of the insulation system. Therefore the problem of copper corrosion due to sulphur is of significance and there is a need to control corrosion and understand the chemistry of copper sulphide formation and develop methods for its detection. In the majority of cases, the identified mechanism for failure was arcing between adjacent disks of conductors of winding due to formation of deposits of copper-containing material on the cellulosic insulating paper. Copper corrosion in oil is a highly complex issue which is not yet fully understood [8]. It has been suggested that the certain organic sulphur compounds in oil cause this corrosion.

Generally it is believed that the main contaminant in unused and used mineral insulating oils is an antioxidant additive namely dibenzyl disulfide (DBDS). Experimental results have revealed that DBDS enhances the oxidation stability of oils but it also makes it corrosive thereby attacking copper to form copper sulfide.

The primary effect of the corrosive sulphur species in mineral oil is the formation of copper sulfide on the surface of copper conductors and its subsequent migration through many layers of insulating paper, both of which lead to electrical faults. The former may produce conductive particles of copper sulfide detached from the conductor surface, which becomes the focal point for electrical discharge and gas generation. The latter causes the progressive degradation of the dielectric properties of the insulating paper, leading to short circuit failures.

In order to understand the problems of corrosive sulphur, its mitigation techniques and the methods of analysis, it is essential to understand basics of transformers, its components and properties of its components which may be impacted by the problem of copper corrosion.

1.2 TRANSFORMER

An iron-core transformer having a primary winding that is connected to an alternating-current power line and one or more secondary windings that provide different alternating voltage values.
Insulation is one of the most important constituent of a transformer. The long term performance and reliability of transformer depend upon the proper utilization of insulating materials in it. Two very important insulating materials used in transformers are

1. Transformer oil
2. Kraft insulating paper

In addition, press boards, press paper, cork sheet and gaskets are also used in transformers and are sources of sulphur. However, the impact of copper corrosion is mainly observed on paper and mineral oil and hence understanding the basic properties of kraft insulating paper and mineral oil are important.

1.2.1 Transformer oil

Mineral transformer oil or insulating oil is usually highly-refined oil that is stable at high temperatures and has excellent electrical insulating properties. It is used in oil-filled transformers. The expected functions of mineral transformer oil are to insulate, suppress corona and arcing, and to serve as a coolant by efficient transfer of heat.

Transformer uses hydrocarbon mineral oil which is a mixture of aromatics, paraffins, naphthenes and olefines.

Performance of transformer oil is better when aromatic, paraffinic, naphthenic and olefins concentration are present in right proportions. Reliable performance of mineral oil in an insulation system depends on the following basic characteristics:

- Higher electric strength to withstand the stresses in service.
- Higher resistivity so that oil provides better insulation between windings.
- Sufficiently low viscosity so that its ability to circulate and transfer heat is not impaired.
- Adequately good electrical and thermal performance at temperature extremes in a given ambient condition.
- Proper oxidation resistance to ensure long life during service.
- Good resistance to emulsion to prevent holding of water in suspension.
- Low volume loss due to evaporation.
- Free from nitrogen acid, alkali and corrosive sulphur which cause corrosion of metal parts leading to insulation failures and to prevent acceleration of sludge formation.
- Free from sludge under normal working conditions.
- High flash/fire point.
- Low water content.
- Low pour point.

A transformer is affected by its operating conditions. Various laboratory tests like electrical, physical, chemical tests, ageing etc. which are performance tests carried out on oil and the results are used to establish preventive maintenance procedures by Power utilities to avoid premature equipment failures and also to extend the service life.

1.2.2 Kraft Insulating Paper

In large power transformers, rectangular paper wrapped conductors are used as windings. The paper is prepared from wood pulp and contains 90% cellulose. Cellulose is a good isolator and is also polar, having a dielectric constant of 3 or higher. Cellulose is an organic compound with the formula \( (C_6H_{10}O_5)_n \), a polysaccharide consisting of a linear chain of several hundred to many thousands of \( \beta (1\rightarrow4) \) linked D-glucose units. The degree of polymerization of the molecular unit is indicated by the letter \( n \). It varies widely from one manufacturing plant to another. The value of \( n \) can go up to 2500 or more for cotton fibers and up to 1200 or more for wood pulp. Various other materials, e.g. lignin, hemi cellulose, mineral matter and resins are associated with the cellulose in the fibers. These contaminants are removed by sulphate process treatment of wood pulp which is followed by careful water washing.

Reliable performance of kraft paper in an insulation system depends on the following basic characteristics which can be classified into Physical properties, Mechanical properties, Electrical and chemical properties.

a) Physical Properties:
   i) Substance (grammage)
   ii) Density
   iii) Moisture content
iv) Oil and water absorption  

v) Air permeability  

b) **Mechanical properties:**  
i) Tensile strength and elongation  
ii) Internal tearing resistance  
iii) Bursting Strength  
iv) Heat stability  

c) **Electrical Properties:**  
i) Electrical Strength  
ii) Dissipation factor  
iii) Freedom from conducting paths  

d) **Chemical Properties:**  
i) Conductivity of aqueous extract  
ii) Conductivity of organic extract and pH  
iii) Mineral ash and solid residue  

Transformer conductor windings are insulated by paper and then impregnated with insulating oil. The paper oil insulation is expected to last for a minimum of 25 years.  

**1.3 FAILURES OF TRANSFORMERS**  

Power transformers are very important assets of Power generation/transmission companies. Any adverse effect on transformer causes huge economic losses along with inconvenience to the society. Hence extending the life of transformers beyond their normal life is very important to the Power utilities. Repairing or replacing the transformer matters both in terms of cost and time. Hence great care is exercised in maintaining the health of transformer insulation [9]. Paper-oil insulation is the heart of transformers and there are many factors which affect the life of insulation. These include oxidation, moisture, ageing due to thermal and electrical stresses etc., in addition to formation of copper sulphide due to corrosive sulphur compounds in oil.  

Data on worldwide failure of transformers, as early as 2001 for transformers of 25 MVA rating and above was obtained by CIGRE [10]. Table lists the causes and number of cases for each cause. The results of table 1.2 are not very different each after a decade
and half after publication of CIGRE report. Hence study of transformer insulation is very important for proper functioning and maintenance of transformers.

**Table 1.2 Failure of transformers**

<table>
<thead>
<tr>
<th>Causes</th>
<th>No. of transformers failed</th>
<th>Percentage of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation Failure</td>
<td>24</td>
<td>52 %</td>
</tr>
<tr>
<td>Design/Material/Workmanship</td>
<td>22</td>
<td>23 %</td>
</tr>
<tr>
<td>Unknown</td>
<td>15</td>
<td>10 %</td>
</tr>
<tr>
<td>Oil Contamination</td>
<td>4</td>
<td>4 %</td>
</tr>
<tr>
<td>Overloading</td>
<td>5</td>
<td>3 %</td>
</tr>
<tr>
<td>Fire/Explosion</td>
<td>3</td>
<td>3 %</td>
</tr>
<tr>
<td>Improper Maintenance/Operation</td>
<td>5</td>
<td>1 %</td>
</tr>
<tr>
<td>Flood</td>
<td>2</td>
<td>1 %</td>
</tr>
<tr>
<td>Loose Connection</td>
<td>6</td>
<td>1 %</td>
</tr>
<tr>
<td>Line Surge</td>
<td>4</td>
<td>2 %</td>
</tr>
<tr>
<td>Lighting</td>
<td>3</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>Moisture</td>
<td>1</td>
<td>&lt;1 %</td>
</tr>
</tbody>
</table>

Insulation failure is the leading cause of failures of transformers. This category excludes failure due to lightening or a line surges. There are actually four factors which are responsible for deterioration of insulation. These are oxidation, pyrolysis, moisture and acidity in oil which also affects the properties of paper. But moisture is reported separately. The average age of the transformers that failed due to deterioration of insulation is about 18 years.

Design/manufacturing defects includes condition such as loose or unsupported leads, poor brazing, loose blocking, inadequate core insulation, interior short circuit strength and foreign object left in the tank. In addition to the types of failures listed in table 1.1, in the last decade, transformers have failed all over the world due to corrosion of copper conductors due to sulphur in mineral oil.

**1.4 AGEING OF PAPER – OIL INSULATION**

Ageing of the paper-oil insulation system of power transformer is influenced by thermal, electrical, mechanical and environmental factors.
1.4.1 Thermal ageing: Thermal ageing involves the process of physical and chemical changes as a consequence of chemical degradation reactions, polymerization and depolarization, diffusion etc. It also involves the thermomechanical effects caused by the forces due to thermal expansion or contraction. The rate of thermal ageing is very much influenced by the operating temperature of transformers.

1.4.2 Electrical ageing: Electrical ageing is caused by the following:
- Partial discharges
- Effects of tracking on press boards
- Effects of treeing on press boards
- Effects of electrolysis in mineral oil

1.4.3 Mechanical Ageing: This is a very important property which involves the following
- Fatigue failure of insulation components due to low-level stress cycles
- Thermo mechanical effects caused by thermal expansion and/or contraction
- Rupture of insulation by higher of mechanical stresses
- Abrasion wear caused by relative motion between components of Power equipment.

1.4.4 Environmental ageing: Environmental factors like presence of moisture, oxygen and dust lead to gradual loss of stability of oil. The ageing mechanisms of oil are complicated. In general, oxygen reacts with certain hydrocarbons by a free radical process generating hydro peroxides which are not stable and decompose to form ketones and water. Ketones can be oxidized further to form carboxylic acids and the presence of hydroxyl groups will result in production of alcohols and phenols. Most oxidation products will have a negative effect on the electrical properties of oil. The carboxylic acids that are produced will either dissolve in the oil or volatilize into the headspace. Dissolved acids may cause damage to the paper and copper windings, while volatile acids corrode the top of the unit. This leads to the degradation of oil and hence the transformer. Moisture and oxygen are extremely hazardous to transformer insulation and cause degradation of oil and paper insulation at a much faster rate.
Chapter 1

Introduction

The ageing of oil is assessed by monitoring the properties such as flash point, viscosity, specific gravity, total acid number, oxidation stability, breakdown voltage, dissipation factor, moisture content, volume resistivity, dielectric constant, etc.

Following are the important dielectric properties of paper-oil insulation system of transformer which require monitoring during thermal ageing under service conditions:

- Polarization and Depolarization current.
- Maximum recovery voltage.
- Water content in paper/oil.
- Breakdown voltage of paper/oil.
- Acid number of oil.
- Mechanical strength of paper.
- Dissipation factor of paper-oil insulation.
- Variations in capacitance of the insulation of the Power apparatus.

1.5 LIFE EXTENSION OF TRANSFORMER INSULATION

Transformer life management is an essential part of a modern power system operation. This is carried out through management of oil chemistry. Oil filled transformer technology has been used for more than 100 years. The principle of operation has not changed over many decades. In fact many transformers that were built and installed in post-world war still remain in service. A properly maintained power transformer can function for 50 to 75 years. However, the maintenance of the insulation system largely determines the extent of a transformer’s life. Future transformers will no doubt have increased capacity and size and their design may require the use of new materials. Transformers may operate at higher temperatures and in turn demand transformer oils of greater stability and improved thermal/electrical and chemical properties.

1.6 ADDITIVES

An additive is a suitable chemical substance, which is added to a mineral insulating oil to improve certain characteristics. Additives are the inhibitors added to the transformer oils to extend their life. These are antioxidants and passivators. Additives are used to increase thermal stability and to retard degradation of insulation system.
1.6.1 Antioxidants

Chemical Substances added to the transformer oil to improve the oxidation stability of insulating oil present in transformer are antioxidants. Different types of antioxidants are as follows.

a) 2,6-di-tert-butyl-p-cresol (DBPC) / Butylated hydroxytoluene (BHT)

DBPC is used as antioxidant for extending the life of transformer oils. DBPC is phenolic type synthetic inhibitors. It is also known as Butylated hydroxytoluene (BHT). By addition of only 0.1% to 0.3% of DBPC, the life of new oils has been extended by five to fifteen folds. The same results are also evident in case of reclaimed transformer oil. DBPC also inhibits peroxides formation which is responsible for disintegration of insulation. Hence, the use of DBPC extends service life of transformer. The addition of DBPC to transformer oil also reduces sludge formation. Structure of DBPC is shown in Figure 1.1.

![Figure 1.1 Structure of Butylated hydroxytoluene](image)

b) Dibenzyl disulfide (DBDS)

Dibenzyl Disulfide (DBDS) is one of several sulphur compounds known to cause copper corrosion in transformers under certain circumstances. DBDS was once selected to boost oil performance and its transition as “corrosion agent” was propagated by the increase in copper temperatures which has resulted due to certain changes in of design criteria during the year 1980. Thus it is difficult to find copper corrosion problem in transformer older than 1980’s. DBDS at low temperature is an active antioxidant, at medium temperatures, it is sludge forming and at higher temperatures it turns corrosive. A relatively large percentage of commercially available mineral insulating oils have been observed to contain DBDS. It is present as an undeclared artificial antioxidant additive [11]. Remedial processes such as adsorbents, absorbents, and oil change-out have been known to reduce the concentration of DBDS in oil. However, if not destroyed or removed
below several mg/kg (ppm), breakdown of the DBDS to benzyl mercaptan or a DBDS-
copper complex can still cause corrosion of copper and the formation of copper sulfide.
The chemical structure of DBDS is shown in Figure 1.2.

![Structure of dibenzyl disulphide](image)

**Figure 1.2** Structure of dibenzyl disulphide

### 1.6.1.1 Mechanism of degradation of DBDS

Different authors have suggested different mechanisms for the degradation of
DBDS and the formation of copper sulphide.

According to Lance Lewand [11], DBDS in oil were cleaved into corresponding
mercaptides and other six ring products as temperature of the oil increases. These
mercaptides react with copper forming copper sulphide and ethyl benzene.

\[
(C_6H_5CH_2)S_2 + 2H^+ \rightarrow 2C_6H_5CH_2SH + 4Cu^+ \rightarrow 2Cu_2S + 2C_6H_5CH_2CH_3 \quad (1.1)
\]

Some authors of [12] have suggested that dissolution of copper takes place by the
formation of DBDS-Cu complex. Formation of copper sulphide on insulating paper
occurs at low temperature via DBDS-Cu complex. Copper sulphide and the radical
intermediates are generated by the decomposition of Cu-DBDS complex. These radical
intermediates form bibenzyl (BiBZ) and dibenzyl sulphide (DBS).

Reaction mechanism for the formation of copper sulphide is as follows.

**Step 1:** Formation of DBDS-Cu complex

\[
2Cu + (C_6H_5CH_2)_2S_2 \rightarrow (C_6H_5CH_2)_2S_2 - Cu_2 \quad (1.2)
\]

**Step 2:** Formation of copper sulphide and by-products

**Step 2.1:** Formation of copper sulphide

\[
(C_6H_5CH_2)_2S_2 - Cu_2 \rightarrow Cu_2S + C_6H_5CH_2 \ast + C_6H_5CH_2S \ast \quad (*\ radical) \quad (1.3)
\]

**Step 2.2:** Formation of by-products
Equations (1.2) and (1.4) can be combined to give equation (1.5).

\[ 8Cu + 3 (C_6H_5CH_2)_2S_2 \rightarrow 4Cu_2S + C_6H_5CH_2CH_2C_6H_5 + 2 (C_6H_5CH_2)_2S \]  
(1.5)

Further, dibenzyl sulphide formed in equation (1.5) reacts with copper to give equation (1.6)

\[ 4Cu+(C_6H_5CH_2)_2S \rightarrow 2Cu_2S + C_6H_5CH_2CH_2C_6H_5 \]  
(1.6)

Then equations (1.5) and (1.6) can be combined to give equation (1.7)

\[ 4Cu + (C_6H_5CH_2)_2S_2 \rightarrow 2Cu_2S + C_6H_5CH_2CH_2C_6H_5 \]  
(1.7)

### 1.6.2 Passivators

Passivators are the chemical compounds which upon addition to oil suppress the corrosive sulphur attack on copper thereby prevent copper corrosion and ultimate formation of copper sulphide formation.

Different types of passivators which are available are as follows:

1. **Nitrogen based passivators**
   - Benzotriazole (BTA)
   - Irgamet 30 and 39
   - Cobratec 122 and 911 S
   - Certain amines
   - Benzimidazole

2. **Sulphur based passivators**
   - Cuvan 484 and 826
   - Vanlube 601 and 691
   - 2, 5-dimercapto-1,3,4-thiadiazole
   - Amoco-150 [13]

Sulphur based passivators are mainly used in lubrication industry. BTA and its derivatives are most commonly used in transformers. BTA is granular solid at room temperature and hence it requires heating and mixing to dissolve in oil. Hence, it is less desirable than its derivatives. BTA derivatives are liquid at room temperatures and readily mix with transformer oil. Irgamet 39 is one such compound which has gained
popularity for its use in suppressing copper sulphide formation [14]. Structure of BTA and Irgamet 39 are shown in figure 1.3.

Action of BTA and Irgamet 39 on copper can be explained either any one or all of the following mechanisms.

1. Bonding between BTA or Irgamet 39 and copper through lone pair orbitals on nitrogen.
2. Passivators form hydrogen bond with copper oxide film on copper surface.
3. Passivators forms Cu-Passivator polymer through strong charge transformer interactions between passivator molecules.

![BTA and Irgamet 39](image)

**Figure 1.3** Structure of BTA and Irgamet 39

Formation of copper sulphide and action of passivators on conductors are schematically represented by figure 1.4 to 1.6. Figure 1.4 shows the attack of sulphur compounds over copper surface as well as copper ions detached from conductor surface. Figure 1.5 shows the formation of copper sulphide. Figure 1.6 shows the action of passivator. Figure shows the formation of passivator layer over the copper surface thereby preventing the attack of sulphur on copper conductor.

**1.6.2.1 Limitations of Passivators**

Bonding of passivators is 90 to 99% effective only on clean copper surfaces in oil and bonding does not takes place over copper sites which are already occupied by sulphur species as the bonding between sulphur and copper is very strong.
**Figure 1.4** Action of sulphur compounds on copper

**Figure 1.5** Formation of copper sulphide

**Figure 1.6** Action of passivators on copper
Long term effectiveness of the passivators is not well understood. Hence Power utilities must be prepared to add passivators several times over the life of transformers.

Possibility of stray gassing and high oil power factors are observed in few cases upon adding passivators to oil. Hence performance of passivators over long service life of Power apparatus needs useful investigation.

1.7 SOLVENT EXTRACTION

Solvent extraction is a process whereby two immiscible liquids in a container are vigorously subjected to churning in an attempt to disperse one in the other so that solutes can migrate from one solvent to the other.

Different polar solvents like methanol, acetonitrile, monomethyl formamide, dimethyl formamide, N-methyl-pyrrolidone (NMP), furfural, dimethyl sulfoxide and propylene glycol are used in extraction of sulphur. Extraction with pyrrolidone followed by hydro treatment reduces the sulphur content to 0.01 mass % [15]

1.8 NEED FOR THE STUDY ON COPPER CORROSION

It is observed that paper oil insulation of transformers is a complex dielectric system whose performance can be influenced by a number of parameters in addition to temperature and humidity. In recent years, because of higher transmission voltages and large requirements of power, there have been some changes in design of higher rated transformers. In addition, increase in connected load to transformers and higher electrical and thermal stresses have resulted in a situation where it is not easy to understand the performance of insulation system. The changes in design parameters of transformers have no doubt led to compact design and higher operating stresses have led to the use of many new additives. This has resulted in some new and serious dielectric problems. Corrosion of copper conductor is one such new problem which has resulted in several complex thermal and electrochemical problems.

Study of literature reveals the fact that presence of corrosive sulphur compounds, mainly DBDS, is responsible for copper corrosion in transformers. Origin of DBDS in transformer oil, its detection, and its behavior in presence of thermal and electrical stresses have gained importance due to its corrosive action. It is also observed that thermal ageing of DBDS leads to the formation of thiols, which is again a corrosive compound. Though there are many published reports on study of DBDS in transformer
oil, its behavior in presence of passivators, understanding of kinetics of degradation of DBDS in transformer oil, its degradation in presence of thiols are very crucial to the understanding of the mechanisms involved.

Mitigation techniques like passivation using Irgamet 39 and BTA have become complex due to unpredictable thermal degradation of DBDS. Therefore there is a need to study the behavior of passivators in presence of sulphur compounds.

Though literature reveals different aspects of copper corrosion, there are many complex processes which are poorly understood. Hence this study was taken up for a better understanding of the phenomenon of copper corrosion and its effects on the dielectric performance of paper oil insulation.

1.9 OBJECTIVES AND SCOPE OF THE PRESENT STUDY

The important objective of the study was to understand the mechanism of formation of copper sulphide in presence of sulphur compounds like DBDS and 2MBT and to evolve mitigation techniques using metal passivators. The main objective has been achieved by carrying out the following laboratory experimental investigations and analysis of mineral oil samples drawn from in-service transformers:

A. Laboratory investigations undertaken:

1. Studies on the mechanism of action of sulphur compounds like dibenzyl disulphide and mercaptan sulphur on copper corrosion and to quantify the same in terms of their thermal degradation over a temperature range of 100 to 150 °C.

2. Understand the effect of initial concentrations of sulphur compounds the implications of duration of thermal ageing and the influence of the surrounding environment like air and sealed conditions during thermal ageing.

3. Investigate the effects of DBDS and mercaptan sulphur on quantifiable terms on the dielectric and chemical properties of oil.

4. Study, analyze and understand the mechanism of action of metal passivators or metal deactivators namely Irgamet 39 and BTA and estimate their thermal depletion over a range of temperatures. It is also intended to understand the
depletion rate in presence of sulphur compounds like DBDS and 2MBT, against which they are expected to protect copper conductors.

5. To compare the performance, advantages, disadvantages and implications of the long term use of BTA metal deactivator and Irgamet 39 metal passivator under thermal ageing.

6. Explore the use of solvent extraction as a possible mitigation technique for copper corrosion, as a viable alternative to the use of metal deactivators or passivators.

7. Study and understand moisture dynamics in paper oil insulation in presence of MS and DBDS, moisture is an important cellulose ageing parameter and its accumulation will be a serious threat to the life of insulation.

8. Understand the effects of sulphur compounds and metal passivators/deactivators on oil parameters like acidity, Interfacial tension etc., which are very crucial to the effective performance of mineral oil primarily as an insulator in addition to being a coolant.

**B. Analyze mineral oil from in-service transformers**

To understand the state of mineral oil during their service life in transformers, it is intended to draw mineral oil samples from transformers of different voltage and power ratings and based on the service life of transformers, arrive at bench mark properties of mineral oil as reference so that the results of laboratory experiments can be compared and evaluated. This work was mainly confined to estimation of total sulphur, mercaptan sulphur, DBDS content and dissolved copper content.

### 1.10 ORGANIZATION OF THE THESIS

The thesis is presented in eleven different chapters. A discussion on literature on the problems of corrosive sulphur in mineral insulating oil, its mitigation techniques, and dielectric measurements discussed in chapter 2. The experimental methods and plan of research studies are presented and discussed in chapter 3. The study of thermal degradation of DBDS in transformer oil is discussed in chapter 4 to highlight the problems of degradation of DBDS.
Kinetics of thermal degradation of DBDS is discussed under chapter 5. The effect and depletion of Irgamet 39 and BTA are studied and discussed in chapter 6.

Method and analysis of solvent extraction and its efficiency are explained under chapter 7. Various analytical techniques which were used to understand the copper sulphide formation and mitigation are discussed in chapter 8. This chapter also discusses the results of TGA, DSC, AAS and UV-Visible spectroscopy to explain the phenomenon of copper sulphide formation.

Dielectric studies of the paper oil insulation under different experimental conditions are discussed in chapter 9. In chapter 10, the results of field studies based on transformer oils drawn from different transformers are analyzed for sulphur compounds. This is an important chapter and the results are correlated to results of laboratory investigations.

Important conclusions, summery of work and major recommendations for work Power utilities in transformer oil diagnostics and scope for future work are discussed in chapter 11.

REFERENCES


18
Chapter 1

Introduction


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