Power transformers: Influence of moisture in pressboard insulation on standing time

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Power transformers: Influence of moisture in pressboard insulation on standing time

By

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ABSTRACT

A large power transformer, is often, a custom designed equipment that entails a complex and capital intensive manufacturing process. It is an integral part of the power system and the cost of failure during service can be significant. Due to its importance in the power system, transformers should perform reliably under the conditions for which it has been designed while keeping the manufacturing costs to a minimum. Therefore, it is important to optimize the production process.

Standing time, or hold time, is the period between the end of tank filling with mineral oil and factory acceptance tests (FAT). During this period, the newly completed transformer is left undisturbed for several days, depending on its design. It is necessary in order to improve insulating properties of the cellulosic insulation, thereby preventing partial discharges (PD) and failure during FAT.

Moisture is disadvantageous to any insulation design and is particularly true in the case of cellulosic insulation (widely used in transformer construction). Cellulosic insulation is highly hygroscopic and moisture ingress in small concentrations during the final clamping procedure is inevitable. Based on the research at TU Delft, moisture in cellulosic insulation was found to be the major factor leading to PD and can also have an influence on standing time.

This thesis focusses on the moisture ingress into **pressboard insulation** when dried insulation is exposed to ambient air during manufacture. The aim of the thesis is to investigate the effects of moisture on partial discharges in pressboard insulation and its influence on standing time. The results of this thesis could help optimize the production of transformers.

This thesis discusses the results of experiments investigating the effects of moisture in pressboard samples with respect to standing time. 3 different configurations of pressboard samples are subjected to various conditions in a climate chamber (to simulate moisture ingress during clamping) and impregnated with dry mineral oil. PD tests on samples are carried out one by one over 9 days of standing time. The effect of standing time on partial discharge inception voltage and discharge magnitudes on samples with different moisture contents are observed.

Additionally, during the course of the thesis, several tests were carried out to study the effect of oil temperature during FAT and the effects of moisture transients in oil. Furthermore, moisture ingress and egress to and from the samples are also analysed.

Based on the results of the experiments it can be concluded that the standing time can be reduced considerably. Furthermore, the presence of a temperature gradient along with moisture content greater than 2 % in pressboard can produce discharges which can lead to failure during FAT. A moisture estimation tool is also developed which can be used to vary the vacuum cycle duration in order to control moisture content in pressboard.

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ABBREVIATIONS

1. CC - Climate chamber
2. EMF- Electromotive force
3. FAT - Factory acceptance tests
4. HV - High voltage
5. HVDC - High Voltage Direct Current
6. IEC - International Electrotechnical Commission
7. IEEE - Institute of Electrical and Electronics Engineers
8. IVPD – Induced voltage partial discharge
9. kV - kilo Volt
10. LV - Low voltage
11. PB - Pressboard
12. PD - Partial discharges
13. PDIV - Partial discharge inception voltage
14. PRPD - Phase resolved Partial discharge
15. RH - Relative humidity

ACKNOWLEDGEMENT

The satisfaction and elation that accompany the successful completion of any task would be incomplete without the mention of the people who made it a possibility. It is my great privilege to express my gratitude and respect to all those who have guided me and inspired me during the course of the thesis work.

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Apart from those mentioned above, it would be incomplete without the mention of my parents and sister who have been a continuous source of support throughout my life.

Research is a gamble. But the only risk greater than doing research is not doing it.

-F. H. Kreuger, High Voltage Engineer

Electricity and water do not form a happy partnership, do they?

- Electrical Engineering Portal

CHAPTER 1

INTRODUCTION

1.1 GENERAL WORDS

A transformer is a static device that transfers electrical energy from one circuit to another by electromagnetic induction without a change in frequency. Transformers are essential devices used in conventional power systems for transmission, distribution and utilization of AC electrical energy. SGB-SMIT Group is the leading medium and large-sized transformer manufacturer in Europe and has been involved in the manufacture of transformers for over 60 years [1]. Transformer manufacturing is a labour and capital intensive process. Furthermore, it is one of the most expensive assets in a power system and the cost associated with a failure during service can be significant. Therefore, it is important for the manufacturer to optimise the production process without compromising on quality.

In order to make sure that all the newly manufactured transformers meet the prescribed standards (IEC, IEEE, etc.), all the transformers are subjected to testing before they are dispatched to the customers. The tests give an indication of the mechanical, electrical and thermal performance of the transformer. Cellulosic insulation is widely used in insulation of transformers and one of the most important parameter to be checked is the dielectric property of insulation. Literature [2] and previous research at TU Delft [3] show that the dielectric strength of cellulosic insulation depends on the moisture content in the insulation material. In this thesis, the effect of moisture on partial discharges in pressboard insulation is studied which could help optimise the transformer production process.

1.2 ROLE OF A TRANSFORMER

The world that we know today is unimaginable without electricity. The supply is possible due to the extensive electricity grid that extends across the borders of a nation. Transformers help in regulating the voltage at different levels of the transmission process thereby reducing losses and make transmission of electricity highly efficient.

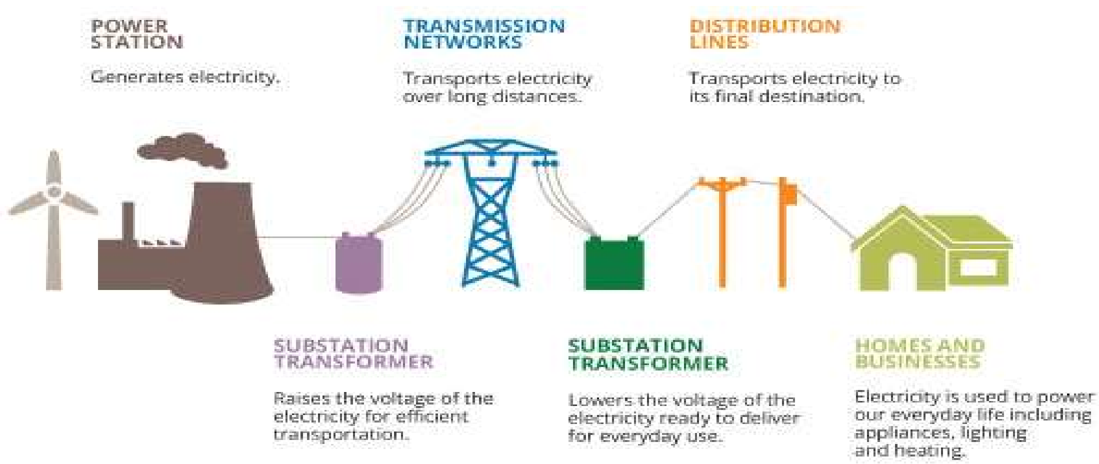


Figure 1-1: Power supply chain [4]

The principle of operation of a transformer is based on Faraday's law of electromagnetic induction, where the EMF produced at the secondary winding is proportional to the number of turns of the winding and the rate of change of magnetic flux. Figure 1-1 shows the traditional power system where power is generated in the power station, voltage is stepped up and transported long distances to the load centres. On reaching the substation near the load centre, the voltage is stepped down where it can be supplied to industrial centres and is further stepped down for domestic supply. For example, at the power stations, the power is produced at voltages usually between 2.3 kV and 30 kV, depending on the size of the unit. Then, the voltage is stepped up by a transformer to 380 /220/110 kV which is the transmission and sub-transmission grid voltage in The Netherlands. The distribution network voltages are usually in the range of 3.3 to 25 kV and the voltage is finally stepped down to 230-400 V for retail customers and small enterprises. Therefore, a transformer is used each and every time the voltage has to be changed and it plays a very important role in the power system.

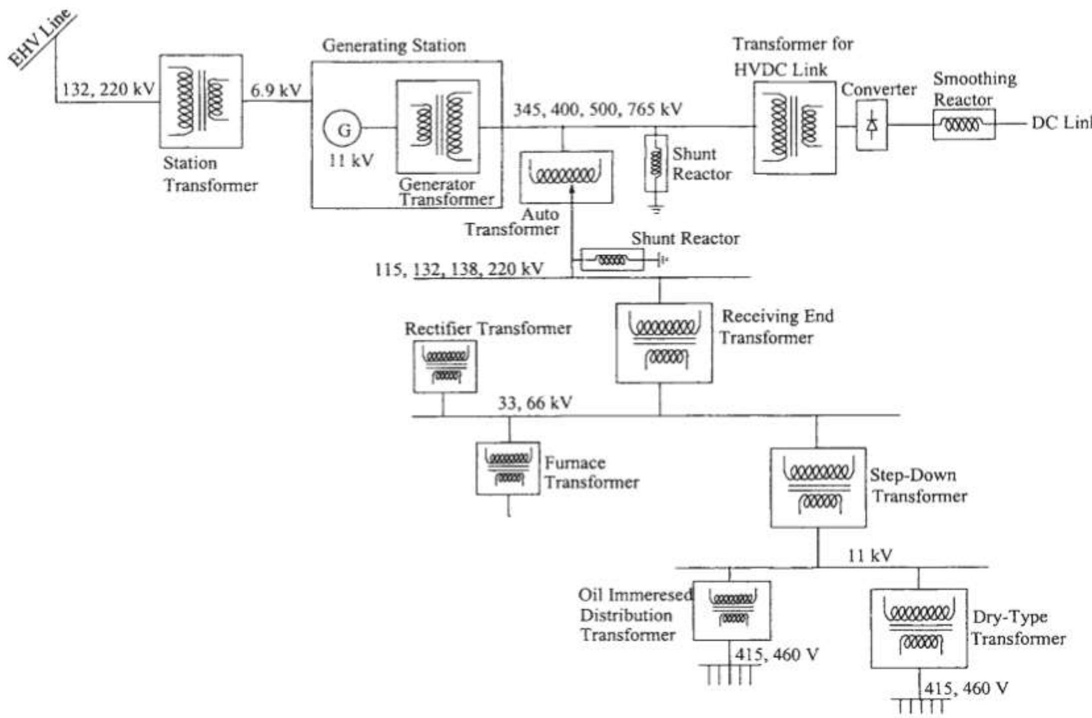


Figure 1-2: Types of transformers in a typical power system [5]

Figure 1-2 shows the different types of transformers used in a grid, the various types of transformers are generator transformer, auto transformer, dry type transformer, transformers for HVDC links etc. These transformers have various sizes and shapes, from pole mounted distribution to large power transformers. SMIT transformers, Nijmegen, which is a part of the SGB-SMIT group is specialized in the manufacture of large power transformers up to 800 kV [1].

The large power transformers built by SMIT (as shown in Figure 1-3) serve many functions in the transmission of electricity. Some of them are: step up transformers near the generating stations, phase shifting transformers and grid transformers which interconnect grids operating at different voltages. These high power transformers manufactured by SMIT are oil filled transformers and have advantages over dry type transformers. These transformers are normally more efficient than the latter, they also have better insulation and thermal capabilities [6, 7]. However, they require some additional steps and care during the construction process which is described in the following section.

Figure 1-3: One of the large transformers manufactured by SMIT transformers, Nijmegen [1]

1.3 TRANSFORMER MANUFACTURING PROCESS

Transformer manufacturing is a highly capital intensive business and the prices of these large transformers can be in the order of a few million Euros [8].

Except for accessories like tap changers and bushing, transformers cannot be repaired during their lifespan. Considering that the desired lifespan of a transformer is 30 years or more [9], it is important to make sure that the quality of the transformer construction is maintained at the highest standards.

The overview of transformer manufacturing process at SMIT transformers is described below and a step by step procedure is depicted in Figure 1-4

- The core and the windings are the main parts of any transformer. First, both the low and high voltage windings are built. One of the most critical components of any electrical device is its insulation. The solid insulators consist of cellulosic insulation i.e.- paper and pressboard. Paper insulation is used mainly around the conductors and pressboard insulation is used in the manufacture of many parts of the transformer like angle rings and transformerboard cylinders.

- Simultaneously, the core of the transformer is also constructed manually by stacking thin sheets of insulated silicon steel to prevent Eddy currents.

- Once the windings and core are ready, they are put together along with components like tap changer etc. to form the active part of the transformer.

- Since the cellulosic insulation is hygroscopic, it absorbs moisture from the atmosphere. Moisture has ill effects on the transformer and will shorten its life. Therefore, the moisture is removed by drying the assembly in a vapour phase oven at 125 °C.

- Due to loss of moisture while drying, some parts of the transformer shrink. Tightening of these components is necessary to maintain required clamping force to ensure mechanical stability during short circuit.

- This tightening process is done at ambient atmospheric conditions which takes a number of hours depending on the size of the unit. During this process, there will be re-absorption of moisture from the ambient.

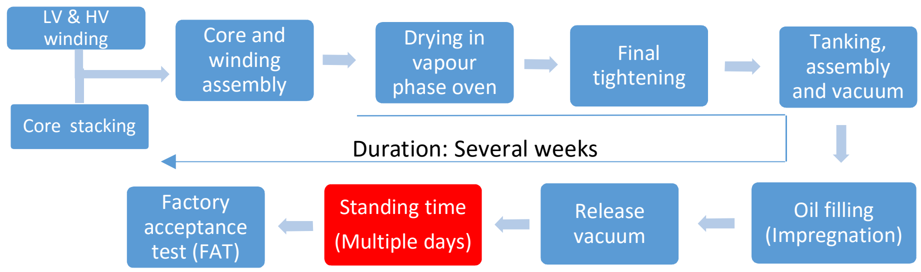


Figure 1-4: Transformer manufacturing process

- Then the active part of the transformer is placed in the tank and sealed. Final assembling process is initiated where fans, pumps, radiators etc. are installed.

- It is followed by evacuating air from the tank to make vacuum of a desired level, which is held for a minimum of 24 hours. Then, oil filling is commenced where dry and purified mineral oil is let into the tank which flows due to the pressure difference.

- Once the tank is filled, vacuum is released and the transformer is left undisturbed for a few days. This period is known as ***standing time***. This is done to ensure that the cellulosic insulation is properly impregnated and the quality of insulation is improved, thereby, reducing the possibility of failure during testing. The duration of standing time can span multiple days depending on the design of the transformer.

- Finally, the transformer is subjected to several tests at the factory to ensure its integrity and is later shipped to the customer.

This construction process altogether from drying in the oven to factory acceptance tests takes multiple weeks. In the following chapter the insulation materials and its design will be explained in detail.

1.4 The issue: Moisture Ingress

Once the transformer is removed from the vapour phase oven, the tightening or clamping activity can take a few hours based on logistical constraints. During this period the hygroscopic cellulosic insulation can adsorb moisture as depicted in Figure 1-5. Ideally, new transformers have a moisture content of less than 1% moisture [10]. The focus of this research is to estimate the quantity of moisture that can be absorbed by the insulation during this period and if it has significant effects on standing time employed during construction.

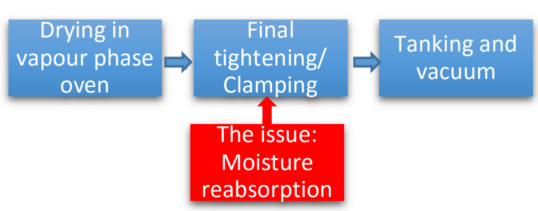


Figure 1-5: Stage where moisture ingress occurs during manufacture

Furthermore, the effects of moisture on partial discharge (PD) activity during the factory acceptance tests (FAT) is also investigated.

1.5 Standing time

The focus of this thesis is on the "standing time" of a transformer in the factory. Standing time uses up a considerable amount of resources. A longer than necessary standing time may lead to a less than optimum manufacturing process. Large power transformers not only occupy a significant area of the limited floor space available at the factory, they can cause logistical bottlenecks leading to a reduction in the production efficiency.

It is generally accepted that the minimum standing time shall be long enough to prevent any disturbances during the dielectric tests (i.e. prevent partial discharge (PD) occurrence when applying AC test voltage in the factory acceptance test).

The aim of this thesis is to find the minimum standing time and optimize the transformer production process.

1.6 Literature and previous work

In order to investigate the effects of impregnation process on standing time and optimize the impregnation process of cellulosic materials with mineral oil, substantial work has been carried out previously in the High Voltage Laboratory at TU Delft. Some of the important conclusions are stated below [3]:

1. Impregnation process of high-density cellulosic materials is faster than generally assumed and therefore the standing time can be optimized.
2. Completely dried pressboard material will not generate any partial discharges (PD) when the electric stress in the sample is comparable to that of transformers during factory tests.
3. Incompletely dried material will generate PD when impregnated with hot oil (60 to 70 °C) on testing directly after impregnation. Performing the same test tests on samples impregnated with cold oil did not reveal any PD activity
4. The samples with residual moisture content when impregnated with hot oil, produced partial discharges when tested directly after impregnation. Leaving the same samples for a period of 7 days (standing time) resulted in no discharges up to the stress level comparable to those occurring during 1-hour factory tests.

From the results of the previous research, it can be stated that the long standing time employed is not related to the speed of the impregnation of the cellulosic insulation as it was previously assumed. Furthermore, the results point toward the moisture content present in the insulation of the transformer as a cause of partial discharges (PD).

Although a lot of research work [2, 11-14] has been carried out to understand the effects and ways of estimating moisture in pressboard, most of it focussed on life and condition assessment. Very limited work has been carried out on improving the production process where few papers [15, 16] investigate the effects on moisture ingress by oiling the insulation before the final tightening.

As mentioned above partial discharges were not observed in samples containing moisture with a standing time of 7 days. Therefore, the main aim of this thesis is to optimize the production process by investigating the effects of moisture on standing time. Furthermore, the interplay of moisture and temperature of oil while testing is also investigated. The detailed objectives are described in the following section.

1.7 Objectives of the thesis

This project focusses on the effects moisture has on the properties of ***pressboard insulation*** material.

The following statements provide the objectives of this thesis:

1. Effects of moisture on pressboard material – do they produce partial discharges when exposed to moisture? If so, what is the critical moisture level?
2. Does standing time have an effect on pressboard insulation? If yes, estimate the optimum standing time for transformer
3. Effect of oil temperature on partial discharge (PD) tests. Does hot oil have an adverse effect on PD test outcome?
4. Study the moisture dynamics between pressboard and oil, can this phenomenon be used to control moisture in transformer?
5. Build a model to estimate the moisture content during the production process

Since the main aim of the project is to investigate effect of standing time on the partial discharges during factory tests, the following procedure is used to investigate the effect of standing time

- Samples of various pressboard configurations used in the manufacture of transformers are exposed to a climate chamber. This is done in order to enable controlled moisture ingress into the sample which simulates the moisture absorption during manufacture.
- The samples are subjected to vacuum cycle and impregnated with hot oil.
- Samples are tested one by one over a period of 9 days to study the effect of standing time on partial discharges.

Other cellulosic insulation materials like paper and transformer wood are not considered in this research and the reasons are mentioned in chapter 2.

1.8 Outline of the thesis

In chapter 1, the transformer manufacturing process, problem statement and the research objectives are briefly discussed.

Chapter 2 deals with the background theory which forms the foundation for the rest of the thesis. In this chapter, theory regarding transformer construction, insulation materials and partial discharges are discussed.

In Chapter 3, the experimental setup and procedure which were employed for various tests are explained in detail.

Chapter 4 is mainly divided into four parts, where the results of the various experiments conducted to investigate the questions raised in the objectives are analysed in detail.

In the final chapter (Chapter 5) the conclusions based on the results of various experiments are presented and discussed. Furthermore, it also contains some recommendations on moisture levels and standing time to be employed during the construction process.

"Materials do not exist". -F.H. Kreuger

What it means is that we should not focus on the (insulating) material, but on the complete technical construction with all its interfaces and flaws.

CHAPTER 2

BACKGROUND THEORY OF TRANSFORMER INSULATION

2.1 TRANSFORMER CONSTRUCTION

Although a large power transformer is often custom built, all the transformers have a common basic structure. Most of the large power transformers in use are oil filled transformers [17]. A transformer construction is illustrated in Figure 2-1.

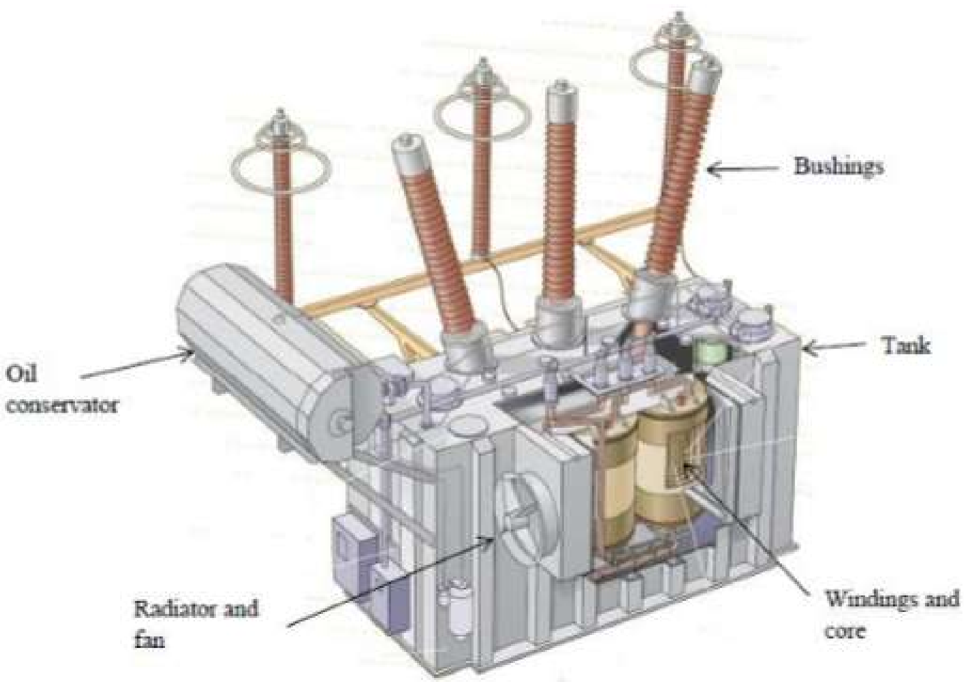


Figure 2-1: Parts of an oil filled transformer [8]

A transformer consists of the active part, tank and transformer accessories like bushings, radiators/ fans, protection devices etc. The different parts of the transformers are briefly explained below.

Active part : The main working part of the transformer is called the active part which consists of the core and windings, pressed parts, tap changer and connecting cables[18].

Core: It is the magnetic circuit which is designed to provide a low reluctance path for the magnetic flux linking the low voltage and high voltage windings. The core is built by manually stacking thin laminated sheets of electrical grade steel to prevent eddy current losses.

Windings: The voltage transformation is a function of the turns ratio. Therefore, at least two windings (Low voltage and High voltage) are present in a transformer. In a HV power transformer continuously transposed conductors (CTC) are used in the windings which have a rectangular cross-section and are made of copper. This arrangement helps reduce losses.

Tank: Another main component in the construction is the tank which is a closed structure made of steel plates. Apart from the protection it provides to the active part of the transformer, it acts as a vessel to hold the transformer oil and also as a structure attach the transformer accessories.

Transformer accessories

There are many accessories used in a transformer, however, two important accessories are mentioned below:

Bushings: It is an insulated device that allows an electrical conductor to pass safely through an earthed conducting barrier such as the wall of a transformer.

Cooling devices: There exist various methods to keep the transformer at optimum temperatures such as oil natural air forced (ONAF), oil natural water forced (ONAN) etc. Most of these require a radiator and cooling fan which constitute cooling devices.

There are many other accessories which are not mentioned here as they are not important for this thesis.

2.2 Insulation Design

In high voltage transformers, insulation is probably the most important aspect of transformer design. The margin between the withstand levels and operating stress is reducing, due to increase in voltage ratings of transformers. With the ever increasing capacity and voltage rating of a transformer, manufacturers have to find the right balance between the weight of the transformer, use of environment-friendly materials, maintaining electrical isolation for the desired time while keeping the costs to a minimum.

2.3 Transformer insulation materials

The insulation of a power transformer consists of both solid and liquid dielectrics. Cellulosic materials like pressboard come under the former and the latter include oils like mineral oil or synthetic oils. This section starts with the evolution of transformer insulation materials and then continues to describe briefly the properties of both mineral oil and cellulosic insulation, which are the preferred insulation materials nowadays.

2.3.1 Evolution of transformer insulation materials

Insulating materials are used in transformers to provide electrical isolation (separation) between various parts of a transformer. Along with the insulating properties, they also help in the mechanical properties and cooling of a transformer. Some examples of insulating materials used are glass, wood, porcelain, oil, air etc.

The earliest transformers were designed in the latter half of the 1800's by a team of Austrian- Hungarian Engineers, in the same period other companies such as GE and Westinghouse also started to improve on the transformer design. In the early years, transformers were insulated using asbestos and low-grade pressboard. In the 20th century, shellac impregnated paper was used, which was superior to its predecessor. However, as the transformers of higher rating were produced, shellac impregnated paper was no longer suitable due to its low thermal and mechanical strength.

With the development of phenol-formaldehyde resin began the manufacture of resin impregnated Kraft paper. The paper and pressboard used for electrical insulation were known as Kraft paper since the paper was manufactured using a method known as Kraft chemical process – Kraft in German stands for strong. Although the resin impregnated paper was a good insulation material, the manufacture of the special moulds for different diameters were found to be difficult and not economically viable.

In the late 1920's Weidmann Ltd. was involved in the development of a high-grade pressboard which later came to be known as transformerboard [19]. It was made of high-grade sulphate cellulose. It can be dried, degassed under vacuum and oil impregnated to provide high dielectric strength.

Cellulosic insulation is primarily used as insulation in transformers of various sizes. It is used in small distribution transformers to large substation units that can have several tons of cellulosic insulation (paper and pressboard) immersed in 40,000 to 100,000 Litres of oil. These cellulosic insulations are used in the main core and also as spacers, in LV & HV bushing etc. They are usually not manufactured by transformer manufacturers but, procured from companies specialized in its manufacturing insulating materials.

Nowadays, kraft paper (pressboard is a thicker version of paper during manufacture) is still widely used in manufacture of transformers and is chosen due to the following reasons [17]:

1. It has high dielectric strength
2. Low dielectric losses
3. Dielectric constant closest to oil

The dielectric constant of transformer mineral oil is about 2.2 and that of Kraft paper is approximately 4.4. [17]

It is important to take into account the dielectric constants of the insulation material because the electric field stress distribution is inversely proportional to the dielectric constant. In case of a transformer which operates on AC, the electric field stress is concentrated in the oil. By having a solid insulation with a dielectric constant near to that of oil helps in the distribution of stress between the insulation.

2.3.2 Cellulosic insulation

Cellulosic insulation was chosen as the insulation of choice due to its abundant availability. Cellulose is a high-polymer carbohydrate chain consisting of glucose units with a polymerisation level of 1200 (Figure 2-2).

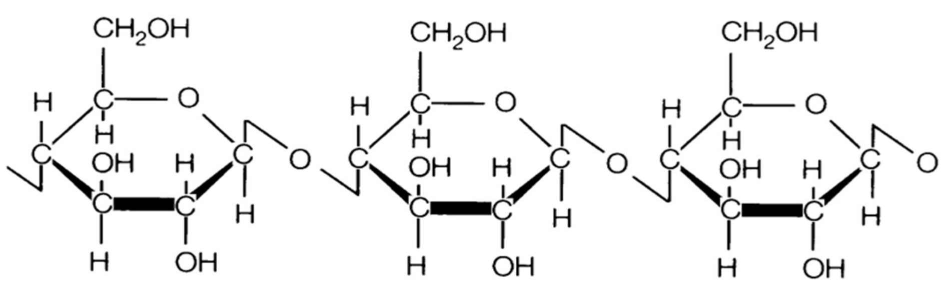


Figure 2-2: Structure of cellulose molecules

A transformer's solid insulation is classified into two, namely minor and major insulation.

Minor insulation is the insulation on the windings.

Major insulation consists of insulation between windings and limb/yoke, high voltage leads and ground. e.g. barriers, spacers, clamps etc.

Cellulosic insulation is also classified based on their thickness: If the thickness is less than 0.0381 mm then it is classified as paper and if the thickness is greater than 0.508 mm [20] , then it is considered as pressboard. One of the layers of pressboard when viewed under a microscope looks as depicted in Figure 2-3.

Cellulosic insulation can be classified as follows:

1. **Paper**: There exist different types of electrical grade paper such as crepe paper, thermally upgraded paper etc. They are mainly as insulators used on the windings and forms a part of minor insulation. Although, paper and pressboard have some similarities, they usually encounter higher stress and also the rate of moisture ingress and egress are different. Therefore, a separate research is undertaken and paper insulation is not a part of this research.

2. **Pressboard:** It is made of high-grade sulphate cellulose. Pressboard is called by different names such as transformer board, PSP, PB etc. Transformerboard is not to be considered as another insulation material and it is the brand name of pressboard manufactured by Weidmann. Pressboard is manufactured in such way that it has no gas inclusions which are present in resin impregnated paper and also have a 25% lower dielectric constant. Pressboard is used extensively in the manufacture of transformers and is manufactured in different shapes and sizes – i.e. sheets. Rolls, angle rings etc. Also, there is also no thermally upgraded pressboard.

Pressboard is used due to the following advantages:

- Easy drying and impregnation
- Low dielectric constant
- Good mechanical properties
- Lower manufacturing costs compared to resin impregnated paper
- Has high PD inception voltage and high arc resistance in case partial discharges occur

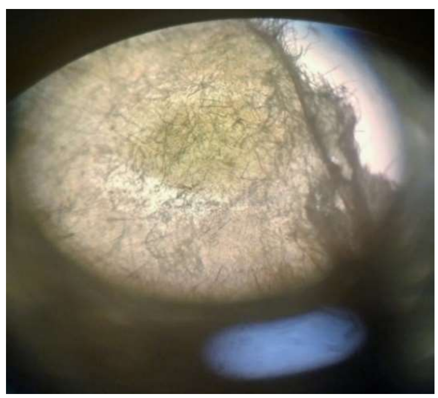


Figure 2-3: Cellulose fibres in pressboard when viewed under a microscope

3. **Transformer wood**: Paper and pressboard form the greatest part of the insulation materials used in transformers. However, transformer wood is also one of the important insulation materials used in transformers, albeit in smaller quantities when compared to pressboard and paper. The wood however, is not a part of this research as it is often used in support structures and is far away from the conductors and experiences electrical stress well below 4 kV/mm. In the previous research [3] it was observed that wood was not susceptible to partial discharges up to 4 kV/mm.

There have been some modification attempts to the insulation by having a mixture of synthetic materials with cellulosic materials in order to improve the properties of insulation. One example is Nomex, a material manufactured by DuPont. When used in the manufacture of pressboard, it increases its thermal capability at the same time reducing its hygroscopic nature. However, this material is not used very often due to economic reasons and some practical difficulties [19]. Therefore, synthetic materials are also not the focus of this research.

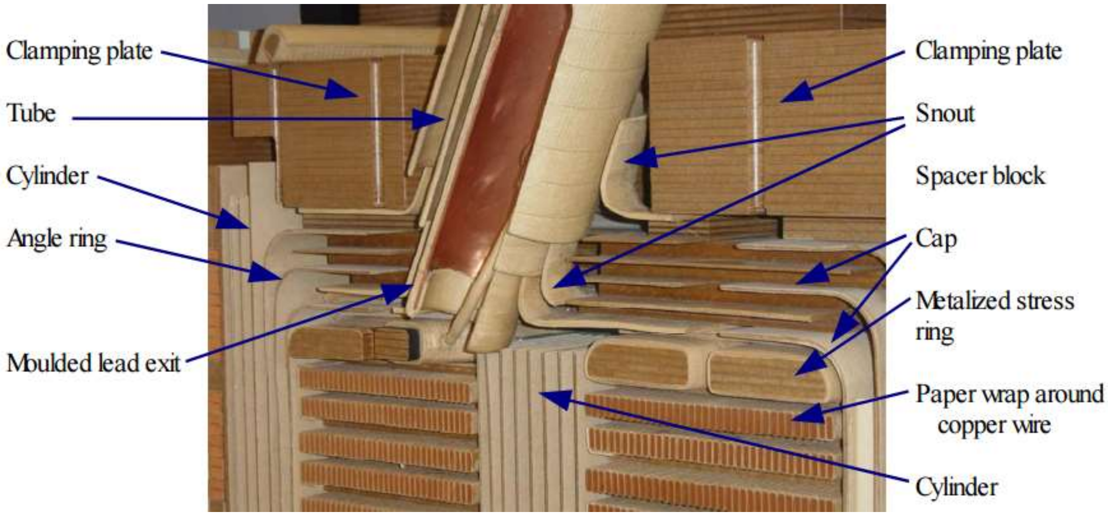


Figure 2-4: Cross-sectional view of a 400 kV transformer end insulation [21]

Figure 2-4 is cross-sectional view of a 400 kV transformer end insulation which shows the usage of cellulosic insulation in a transformer construction. This image is taken from the internet [21] and not the design used at SMIT, however, it helps visualize the use of cellulosic insulation in a transformer. Cellulosic insulation is ubiquitous in a transformer. The thin cylinders and angle rings are made of pressboard material. These cylinders form barriers which prevent impurities in the oil from forming chains leading to the breakdown of oil [22]. The clamping plate is made of laminated transformer wood and is distant from the conductors and thereby experiences less electrical stress. Paper insulation is mainly used wrapped around conductors and also around metalized stress ring. The metalized stress ring, however, has the paper coated with metal and is connected to the top most winding and helps distribute the field lines.

Figure 2-5 is the top view of a winding under construction which depicts the use of paper and pressboard insulation.

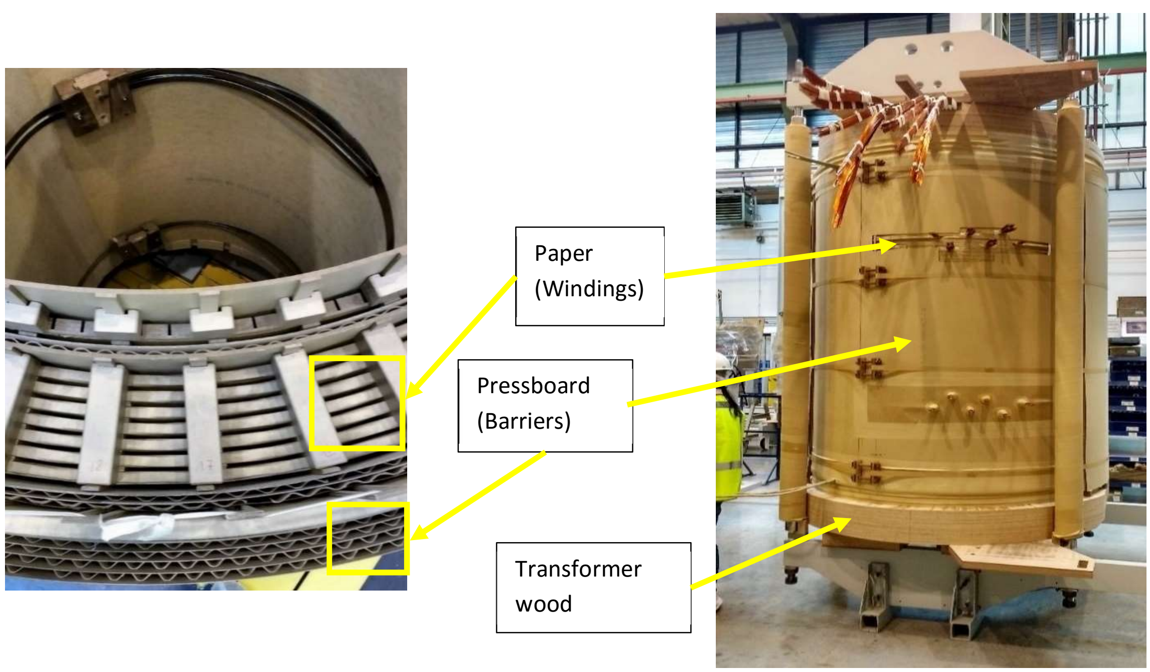


Figure 2-5: Windings with paper, pressboard and wood insulation

2.3.3 LIQUID INSULATION

The commonly used liquid insulation in a transformer is mineral oil. It is also used in many high voltage devices like cables and HV capacitors. Its functions are to insulate, suppress corona and arcing, and to serve as a coolant.

Mineral oil is obtained from crude petroleum and is essentially a by-product obtained during the fractional distillation of crude oil. Crude oil is a complex mixture of molecules mainly consisting of hydrocarbons. These hydrocarbons can be classified into four main groups namely - paraffins, napthenes, olefins and aromatics. Mineral oil is mainly extracted from napthenic crudes [17] and is also known as napthenic oil.

The most important properties of insulating mineral oil [17]

- High electrical strength: Since Oil takes the higher stress as compared to cellulosic insulation, it is important to have a high breakdown strength
- Low viscosity: It is required for fast impregnation during potting and to ensure an effective heat transfer which occurs due to convection.
- Low pour point: In order to allow use of oil in cold environments
- High flash point: One of the disadvantages of mineral oil in its combustible nature, hence, it is important to have a high flash point in order to ensure safety even during faults or operation under high temperatures or loads.
- Excellent chemical stability: Should be resistant to electrical discharges and in case of localised discharges, the decomposition should not lead to further faults.

Electrical strength of transformer oil

Transformer oil in its pure form has a very high breakdown strength (70 kV/2.5 mm). However, this strength is greatly reduced in the presence of impurities like dust or moisture content where the breakdown strength can reduce to 30 kV/2.5 mm or lower.

The oil used in the experiments conducted is Nynas Nytro Taurus oil and the breakdown values mentioned are from the datasheet.

2.3.4 DESIGN STRENGTH CALCULATION FOR TESTING

When the electric field moves from one medium to another it does not remain constant. The stress in oil can be simulated and the stress in pressboard is calculated as follows:

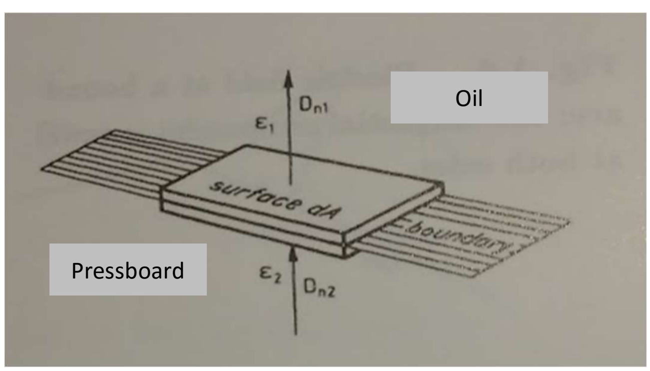


Figure 2-6: Electric field at a boundary [22]

Let us consider two materials forming an interface, let us assume material 1 to be oil and 2 as pressboard.

From the integral form of Gauss Law, we know that;

$$\oiint \overrightarrow{D}.\ \overrightarrow{dS} = Q \tag{1}$$

Let us consider a pillbox at the boundary as shown in Figure 2-6, whose thickness is infinitesimally small, with thickness Δh → 0. Hence, the field lines enter and exit through the top and bottom surfaces and there is no field entering or exiting laterally. Hence, the equation 1 can be expressed as:

$$\oiint \overrightarrow{D}.\ \overrightarrow{dS} = \iint \overrightarrow{D_{\text{n1}}}.\ \overrightarrow{dS} + \iint \overrightarrow{D_{\text{n2}}}.\ \overrightarrow{dS} \tag{2}$$

Since there is no charge accumulation on the surface (no space charges are present in a perfect insulator), then the equation 1 can be written as

$$\oiint \overrightarrow{D}\ .\overrightarrow{dS} = 0 \tag{3}$$

Substituting (3) into the L.H.S of (2), we get

$$\overrightarrow{D_{n1}}\ .\overrightarrow{dS} - \overrightarrow{D_{n2}}\ .\overrightarrow{dS} = 0 \tag{4}$$

We know that,

$$\overrightarrow{D} = \varepsilon\overrightarrow{E} \tag{5}$$

Substituting (5) in (4) equation we get,

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{\boldsymbol{E}_2}{\boldsymbol{E}_1}$$

In case of the interface between oil a pressboard, the equation can be written as follows,

$$\frac{\varepsilon_{oil}}{\varepsilon_{pb}} = \frac{\boldsymbol{E}_{pb}}{\boldsymbol{E}_{oil}}$$

We know the three parameters the permittivity of oil, pressboard and the electric field in from simulations shown in Figure 2-7 (The maximum field stress is in the simulation (8 kV/mm) is used for the calculation).

$$\varepsilon_{oil} = 2.2;\ \varepsilon_{pb} = 4.4$$

$$\boldsymbol{E}_{oil} = 8\ kv/mm$$

By substituting these values back into the equation we can calculate the electric field experienced by the pressboard.

$$\boldsymbol{E}_{pb} = \frac{2.2}{4.4} * 8$$

$$\boldsymbol{E}_{pb} = 4\ kv/mm$$

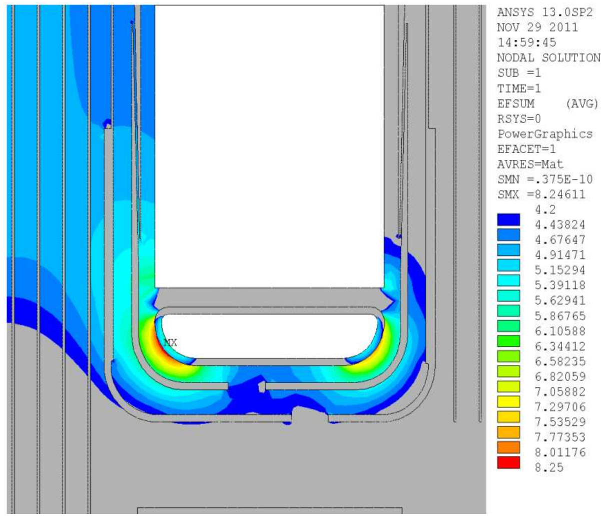


Figure 2-7: Electric field distribution in a transformer [23]

Therefore, the electric field stress employed for all tests in this thesis is **4 kV/mm**.

2.4 MOISTURE IN INSULATION

Cellulosic insulation has excellent electrical and mechanical properties when dry, however, it has a few drawbacks, namely:

1. It is hydrophilic in nature, i.e. tends to absorb moisture.
   The cellulose fibres consist of a large number of hydroxyl-groups. These polar groups attract and bind water molecules (H_2O), which makes it hygroscopic. When moisture content increases beyond specified limits; it leads to reduced dielectric strength i.e. increased propensity for discharges
2. Acceleration of aging in the presence of moisture: Moisture increases dielectric losses and leads to ageing. This ageing of cellulosic insulation produces water molecules as by-products and this causes a feedback mechanism which accelerates this process.
3. Bubbling: There is increased risk of bubbling under high load [21].

Moisture in oil can also be critical and can lead to severe consequences.

Water condensation during cooldown: When the load suddenly decreases, the transformer can cool down and cause the water in the oil to condense and turn into free water. This water can cause corrosion or also reduce the dielectric strength of oil appreciably causing discharges/ flashover or in worst cases, a catastrophic explosion [24].

The IEEE standard 62 classifies transformer based on its moisture content (Table 2-1). Here, the moisture content is measured in the oil and equivalent moisture content is calculated in the paper assuming thermal equilibrium.

Transformer condition	Moisture content (%)
Dry	0-2
Wet	2-4
Very Wet	4.5 % +

Table 2-1: Transformer condition based on moisture content [25] [21]

2.4.1 Sources of moisture in transformer

There are three sources of moisture contamination in transformer insulation as shown in Figure 2-8 [26]:

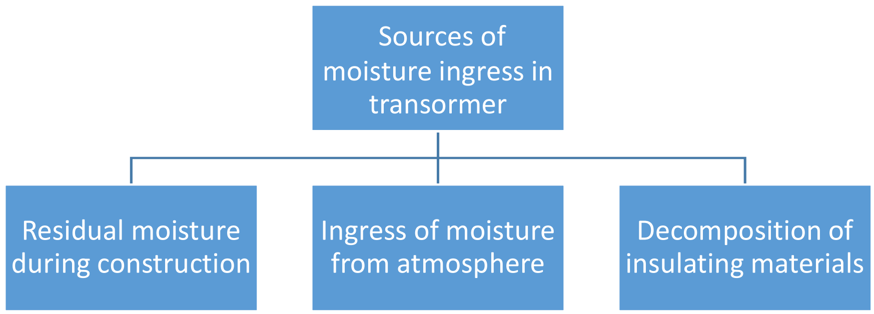


Figure 2-8: Sources of moisture ingress into transformer

The different sources of moisture are explained below in detail:

1. **Residual moisture during construction**: Although, utmost care is taken to make the transformer assembly as dry as possible, it is impossible to manufacture a transformer which is completely dry. A new transformer is considered to be dry if the moisture content is kept less than 1%. Certain thick elements, which are used in the construction of transformers, take longer to dry as compared to pressboard [26]. During the normal operation of transformers, this water diffuses into the oil and later be reabsorbed into the cellulosic insulation, thus increasing the moisture content in cellulosic insulation. This process, however, occurs over the life of the transformer as the movement of moisture takes time and can occur only after a number of heat cycles.

2. **Ingress of atmospheric moisture**: Ingress of moisture from atmosphere can involve three mechanisms.
   - Adsorption of water during direct exposure of insulation to air (can occur during manufacture, installation, repair works)
   - Ingress of moisture into tank due to the difference in water concentration between atmosphere and oil
   - Viscous flow of water filled air into transformer tank through poor sealing.

   Of the three mentioned mechanisms, water during installation and viscous flow of air with high humidity through poor sealing is the main cause for moisture absorption. In this thesis, the focus is only on the moisture ingress during the construction of the transformer.

3. **Decomposition of cellulosic insulation**: There is a phenomenon where the by-products of decomposition of cellulosic insulation release water molecules. Hence, normal ageing process by itself can lead to an increase in moisture content in the transformer. Although ironical, normal ageing of transformer accelerates the ageing process and leads to a reduction in lifetime.

In this thesis, the focus is on moisture ingress into a transformer during construction and its effects on factory acceptance test. Therefore, only adsorption of water during direct exposure during manufacture is considered.

2.5 Transformer Testing

A transformer is an expensive asset and can be designed to last up to 30 years or longer. In order to ensure the quality of workmanship and design, a set of tests are performed once the transformer is completed.

Prediction of insulation failure is very difficult as it is a complex interplay of electrical, thermal and mechanical properties. Hence three types of tests are performed to ensure the quality of the product. These tests can be classified as:

1. Tests to ensure the workmanship of the product
2. Tests to ensure that the transformer losses are under prescribed limits
3. To ensure the lifespan of the product

In order to check the design and make sure it can last for such long periods in field conditions, various tests are performed as follows:

1. Type test
2. Routine Tests
3. On-site testing
4. Sample tests

Type tests and sample tests are destructive tests, where the samples are tested to their limits in order to find the time to breakdown or maximum voltage withstand level.

In this thesis, we are concerned with the routine tests performed on every product before the transformer is delivered to the customer (i.e. routine tests). The tests performed are according to the standards mentioned in IEC 600076-3.

Different tests performed on a power transformer are [27]:

1. Transformer winding resistance measurement
2. Transformer ratio test
3. Transformer vector group test
4. Measurement of impedance voltage/short circuit impedance (principal tap) and load loss (Short circuit test)
5. Measurement of no load loss and current (Open circuit test)
6. Measurement of insulation resistance
7. Dielectric tests of transformer (consists of – (IVPD) induced voltage with partial discharge measurement)
8. Tests on on-load tap-changer
9. Oil pressure test on transformer to check against leakages past joints and gaskets

Only the dielectric tests (IVPD) is under consideration as the aim of the thesis is to observe the behavior of PD vs. standing time.

2.6 Partial discharge and their effects on insulation systems

Partial discharges are defined as breakdown phenomena that do not completely bridge the distance between the electrodes [28]. They are quite harmful to the insulation and can cause the insulation to age, due to various degradation mechanisms.

In general, partial discharges occur when the electric field intensity at a certain location in the insulation or on the surface of the insulation exceeds the dielectric strength of the insulation as a consequence of local electric field concentration [29]. PD activity, which is produced by incipient faults in insulation system, is widely regarded as one of the best indicators of insulation degradation and provides an ‘early warning’ against insulation faults which allows taking corrective action before catastrophic failure occurs.

Hence, PD testing is one of the important tests performed before the transformer is shipped out of the factory.

The standards state that the Level of PD must not exceed 100 pC before being delivered to the customer. It is very important to note that PD do not particularly help in deciding the lifetime of an asset but is an important tool to assess the quality of the insulation.

Partial discharges can be broadly classified into three types as follows:

1. **Internal discharges**: These occur due to the presence of cavities in the insulation material. These can occur from bad manufacturing or ageing. A cavity which can lead to internal discharges is shown in Figure 2-9

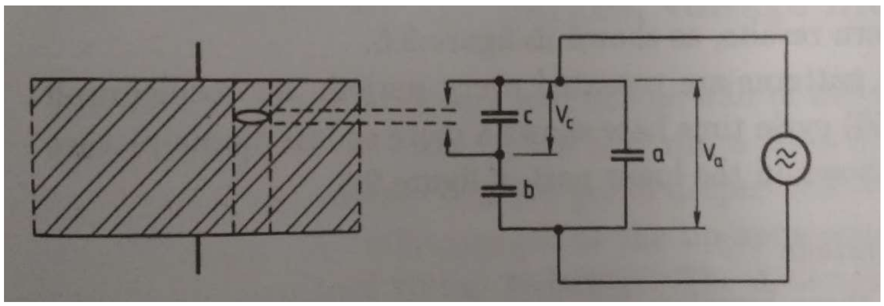


Figure 2-9: A sample with internal cavity represented alongside the classic ABC circuit [22]

2. **Surface discharges**: These occur along the surface of a solid insulation which forms an interface with liquid or gas insulation. These occur in areas where a substantial tangential field is present. For example, in transformers, they may occur at in pressboard insulation where the barriers are not perpendicular to the field lines as shown in Figure 2-10.

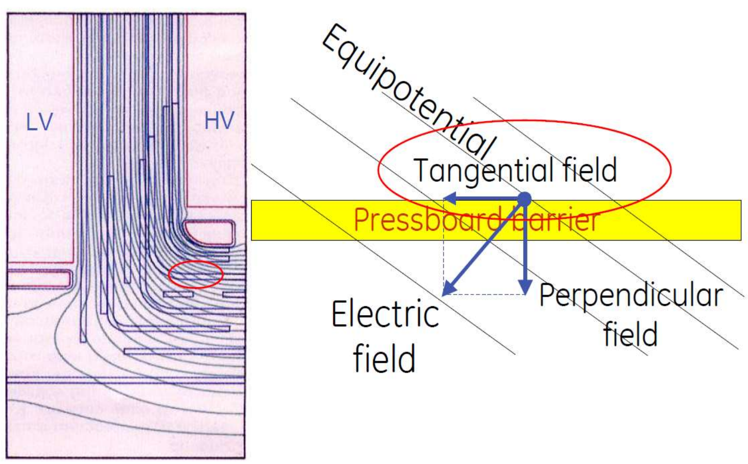
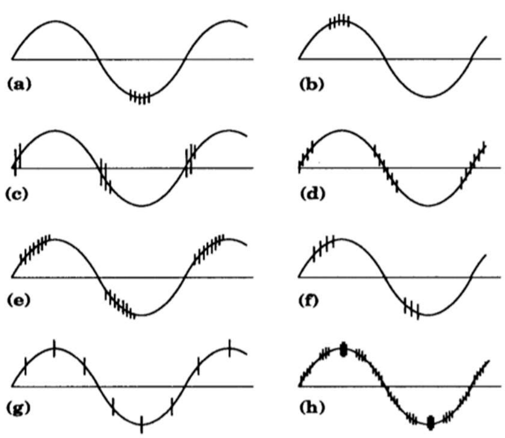


Figure 2-10: Surface discharge occurs due to the presence of tangential field stress [21]

3. **Corona discharges**: These discharges occur around when sharp points are present in the construction leading to a localized breakdown.

Using a partial discharge detector which is mentioned in chapter 3, these partial discharges can be measured and compared with the standard patterns as shown in Figure 2-11 and analysed to find the type of defect.



a) Corona discharge on a high voltage electrode

b) Corona discharge on a grounded point

c) Unearthed conductive object near test object

d) Noise due to bad contact*

e) PD in oil-paper insulation or gas bubbles

f) Surface (creeping) discharges in oil

g) Interference due to thyristor pulses

h) Interference due to modulated periodic signal

* Pattern can also occur in some types of internal discharges

Figure 2-11: Typical Phase-resolved partial discharge pattern [30]

CHAPTER 3

EXPERIMENTAL SETUP AND TEST PROCEDURE

3.1 EXPERIMENTAL SETUP

As mentioned in chapter 1, the main aim of this thesis is to investigate the effects of moisture in pressboard on partial discharges. Moisture absorption into the pressboard material is inevitable during production and this process is simulated on pressboard samples at the HV lab, TU Delft using a climate chamber. In Figure 3-1, the construction process used in SMIT factory is compared to the process used in the lab.

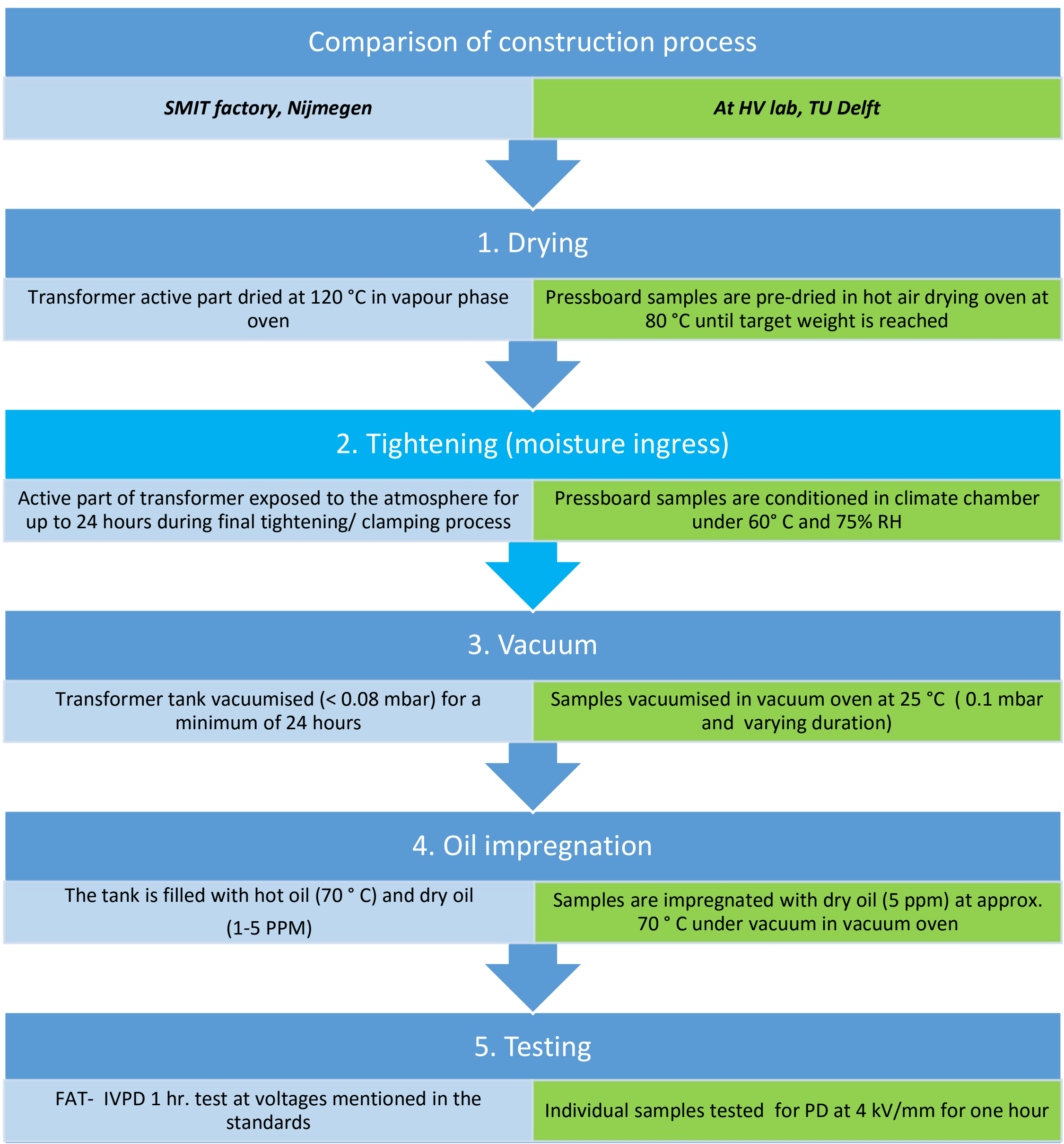


Figure 3-1: Transformer construction process at factory vs. sample conditioning at HV lab, Delft

3.2 Parameters for sample conditioning in climate chamber

As mentioned in the earlier chapters, it is almost impossible to keep the cellulosic insulation free from moisture and the insulation will be exposed to the ambient conditions very briefly. This ambient weather conditions in the hall where the tightening activities are undertaken vary throughout the year.

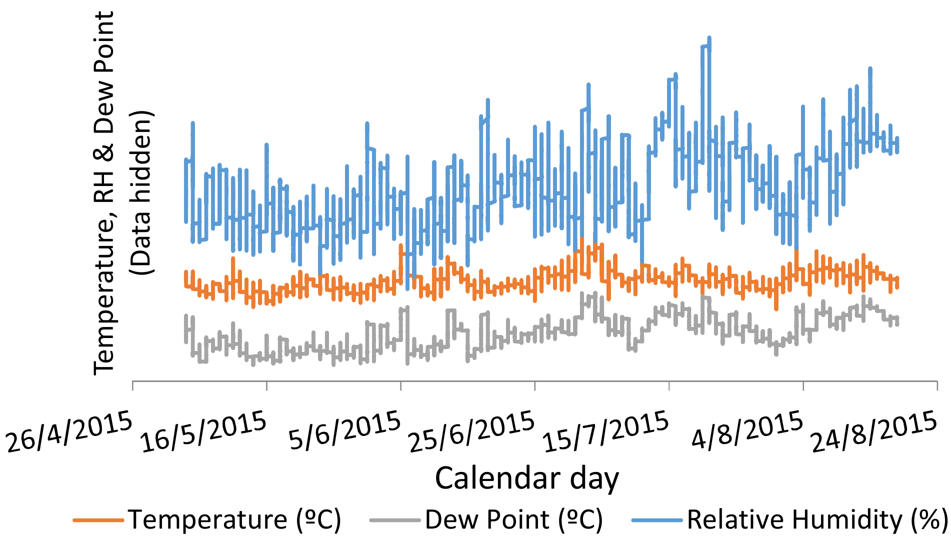


Figure 3-2: Temperature, relative humidity and dew point in the vicinity of the oven in the months from May till August.

A long-term measurement of temperature, relative humidity and dew point were carried out by the engineers at SMIT in the hall where the tightening is carried out. The results are plotted in Figure 3-2. As it can be observed the relative humidity of reaches a maximum in the month of July. Even though it is just a spike, the high relative humidity lasts for a couple of days. 75% relative humidity is considered as the worst case scenario.

Once the winding assembly is removed from the vapour phase oven, it is dispatched for tightening. When exposed to the ambient, the transformer assembly cools. The rate of cooling is uneven and top of the transformer cools faster than the bottom. The temperature inside the oven is around 120 °C, however, when the active part exposed to the atmosphere takes a long time to cool since it has a very high mass. Even after a couple of hours the temperature of the transformer is still around 60 °C. Therefore, temperature chosen for exposing the samples is 60 °C in a climate chamber.

It is also important to take into account that the relative humidity is temperature dependent. As the temperature increases, the ability of the air to carry moisture also increases. The amount of moisture that can be held by air at a particular temperature is given by psychrometric chart.

The conditions chosen for the climate chamber are 60 °C and 75 % RH. If we test for the worst case scenario, the transformer will be able to survive all the conditions. In the tests performed, samples of pressboard are exposed to different durations in the climate chamber. During the tightening process, the active part is exposed to the ambient environment for 3 to 24 hours.

The vacuum stage is very important to evacuate the pores/ capillaries present in the pressboard in order to encourage proper impregnation. Two cases are considered in order to observe the effects of different tightening and vacuum durations.

The two extreme cases of sample conditioning employed are mentioned in Table 3-1.

Sample conditioning			**Temperature: 60 °C**	**Relative Humidity: 75 %**
S.no	**Climate chamber**	**Vacuum Chamber**	**Comments**	
1	24 hours	4 hours	24 hours is the longest time the transformer is permitted to be exposed to the ambient conditions. 4 hours of vacuum was the chosen to observe the effects of short vacuum cycle. This condition simulates the worst case scenario and helps us observe the effects of higher moisture and lower vacuum.	
2	3 hours	24 hours	3 hours is the shortest time taken for tightening process in the factory. 24 hours is the duration of vacuum cycle used in the factory. This represents the best case scenario, i.e. least moisture	

Table 3-1: Sample conditioning duration

3.3 Sample conditioning

In this section, the various configurations of pressboard used for the tests are described. Furthermore, the conditioning process employed before the partial discharge tests is also mentioned in detail.

3.3.1 Samples used

Pressboard of different thickness and types are used in a transformer. Pressboard can be classified into laminated and non-laminated pressboard. In laminated pressboard many layers of pressboard are joined together with casein glue to form a thicker sample. In Table 3-2 four configurations of pressboard are mentioned which were conditioned as mentioned in section 3.3.2 and were checked for partial discharges.

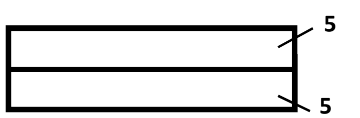
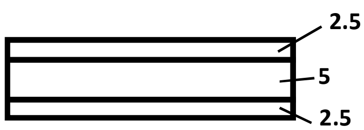
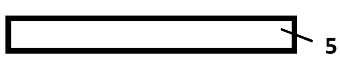
Sample configuration	**Cross section**	**Dimensions (L*B*H) mm**	**Description**
A		150*150*10	Two layered, laminated pressboard
B		150*150*10	Three layered, laminated pressboard
C		150*150*5	Single layered, non-laminated pressboard
D		150*150*4	Single layered, non-laminated pressboard

Table 3-2: Sample configurations used for measurements

3.3.2 SAMPLE PREPARATION FOR PARTIAL DISCHARGE TEST

The sample conditioning procedure is depicted in Figure 3-3 and explained below.

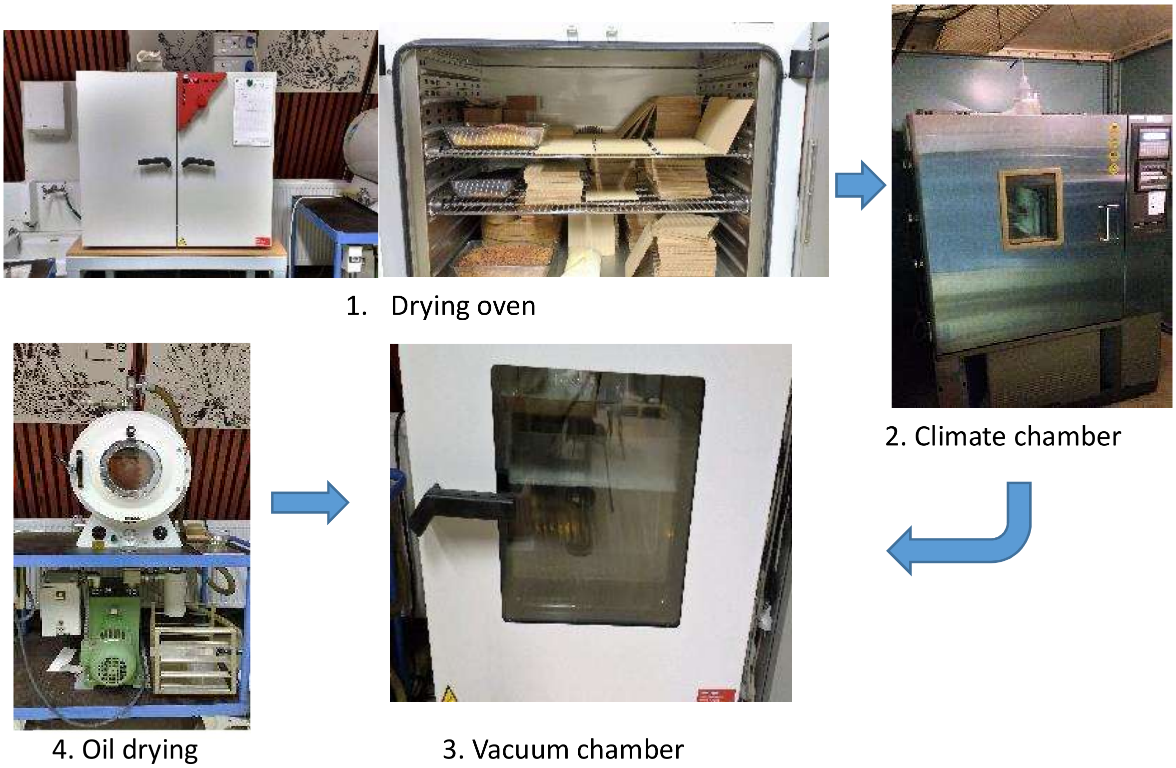


Figure 3-3: Sample preparation process

As mentioned in the previous section, two parameters are used for the sample preparation namely, 3 h in climate chamber followed by 24-hour vacuum and 24 h exposure followed by 4 h vacuum. The former case is explained step by step in this section and a similar process is used for the latter case and is depicted in Figure 3-6.

Preparation: While performing these tests about fourteen samples each configuration is conditioned, prepared and tested as shown in Figure 3-4.

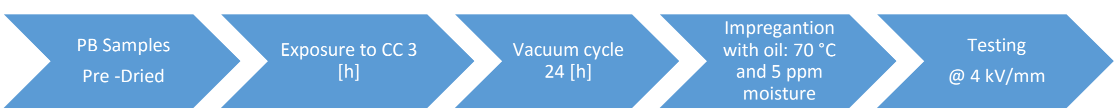


Figure 3-4: Sample preparation flowchart

- **Drying Pressboard samples:** These samples were pre-dried in the oven at 80 °C and are completely dry. This can be confirmed by weighing them and checking if they are dried to the desired value. To ensure that they are completely dry, all the samples are arranged in such a way that all the sides of the sample are exposed to the hot air in the oven to ensure even drying on all sides.

- **Climate chamber exposure:** The samples are weighed and exposed to the climate chamber for a duration of 3 hours, where the temperature and humidity are set to 60 °C and 75% RH, respectively. Once removed from the climate chamber the samples are weighed once again to measure the moisture absorbed by the sample.

- **Vacuum:** After the climate chamber exposure the samples are subjected to a vacuum cycle of 24 hours at 25°C in the vacuum chamber. The samples are arranged in an aquarium in such a way that the surfaces of the samples are free for moisture extraction.

- **Oil impregnation:** At the end of the vacuum cycle, the samples are impregnated with oil which has been purified, dried to 5 ppm and heated to 70 °C in a separate vacuum oven for oil (Refer Figure 3-3). The oil is then let into the oven containing pressboard samples using a special valve. The oil flows due to the pressure difference which exists between the atmosphere and vacuum chamber. After impregnation is completed vacuum is still applied for a few minutes after impregnation in order to remove the bubbles that occur while impregnating the samples as shown in Figure 3-5.

- Once the rate of bubbling reduces vacuum is released and the container is covered with a plastic lid with silica gel to prevent moisture ingress from the atmosphere.

- **PD Testing:** In order to observe the effect of standing time, the samples are tested one by one for a standing time of 9 days. In the first week, 3 samples are tested every day at an interval of 3 hours. In the following week, one sample is tested every day until a standing time of 9 days.

Figure 3-5: Bubbling during impregnation

The process for testing the samples exposed to 24 hours in climate chamber followed by a 4-hour vacuum cycle is same except for the exposure times and the process is depicted in Figure 3-6.

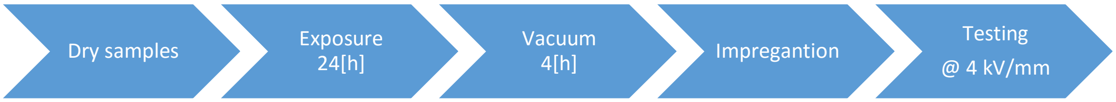


Figure 3-6: Sample preparation flowchart for 24 hrs. climate chamber and 24-hour vacuum cycle

For all the tests conducted in the following section each sample is tested only once unless mentioned otherwise.

3.4 PD TEST SETUP

The purpose of the study is to observe how the behaviour of partial discharges changes with standing time. Therefore, electrical PD detection circuit is employed in this research to observe the partial discharges. Figure 3-7 is the schematic of the straight PD measurement circuit.

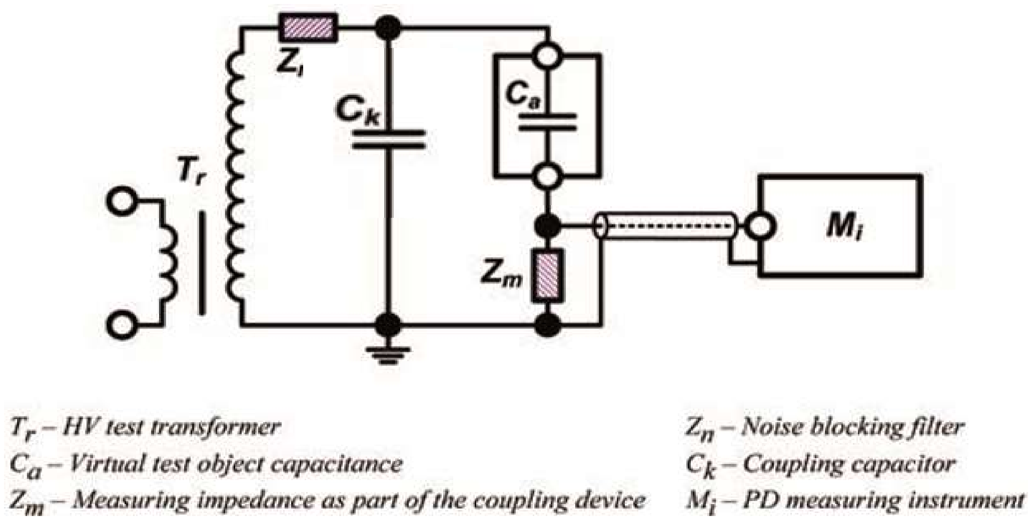


Figure 3-7: Schematic of PD detection circuit

The setup consists of a Power supply, PD free HV transformer, coupling capacitor, test object, detection impedance and a PD acquisition device. Figure: 3-9 shows the HV side of the setup used for experiments.

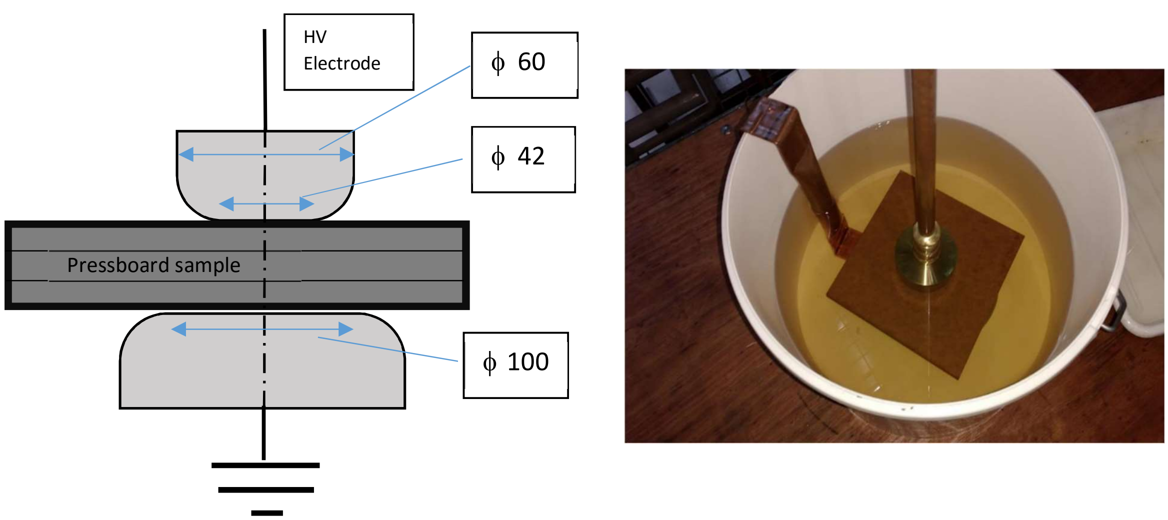


Figure 3-8: Electrode arrangement used in this study – (left) schematic and (right) photo of test chamber

The transformer is connected to a 1200 pF coupling capacitor which is much higher than the test capacitance (< 22 pF). The coupling capacitor is connected in parallel to the test chamber. The test object is a sample of pressboard which is placed in between the electrodes and is tested under oil as shown in Figure 3-8 (right). The test arrangement along with electrode dimensions are mentioned in Figure 3-8 (left).

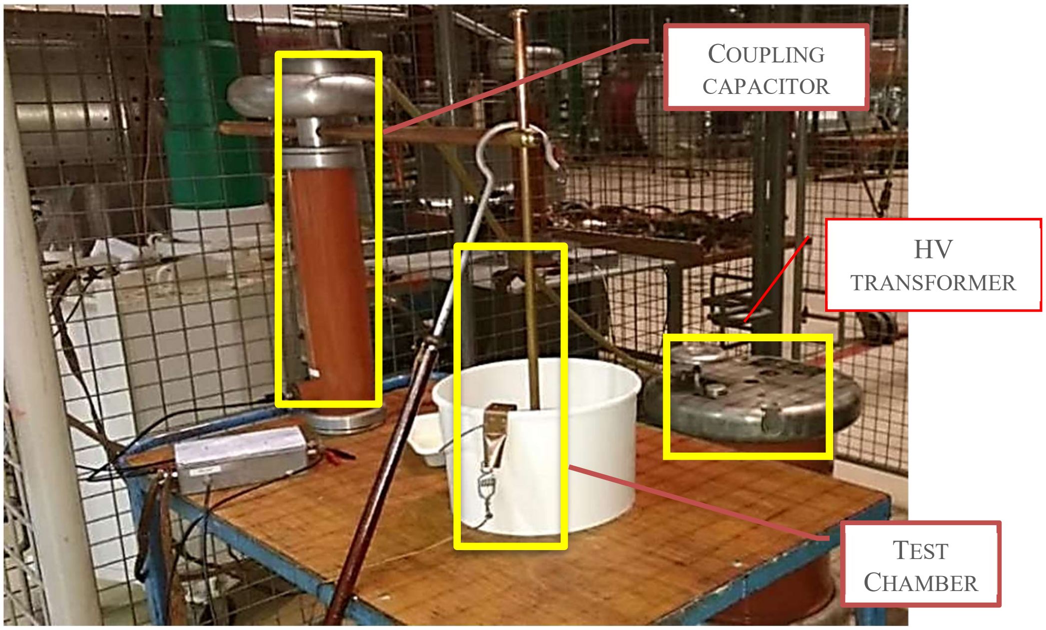


Figure: 3-9: Test setup (High voltage side)

Across the measuring impedance, the signals are acquired through Techimp PD Base II PD acquisition device. The setup is calibrated before the start of every test. PD Base II comes with a software where the PRPD pattern is plotted and it is also equipped with a detection algorithm which was used to verify the source of the discharge.

Figure 3-10: Test setup (Operator side)

3.5 PD TEST PROCEDURE

Firstly, it has to be ensured that a proper test setup is used with an acceptable noise level. An appropriate trigger level has to be set to differentiate the noise from the actual partial discharge.

It is even more critical to choose a proper test method. In literature, various test methods are used. For example, one of the commonly used voltage profile was a step increase in the applied voltage, where, the voltage is uniformly increased step by step every minute until PD is observed or breakdown occurs [2]. Although, this method may be useful for determining the breakdown level of the sample, this thesis is focussed on the transformer factory acceptance tests and the sample being tested must have the PD level below the acceptance level for the entire duration of the test as mentioned in the standard (IEC 60076).

Therefore, the exact test procedure used in the factory test is replicated. The one-hour testing followed consists of various stages, where first the voltage is switched on and the noise level is noted down. Then the voltage is raised to an intermediate voltage for 1 minute and then the voltage is raised to the test voltage for a period of 5 minutes. This is followed by 60 seconds of enhancement voltage, which is the specified time for transformers rated up to 400 kV.

Following the enhancement voltage, the one-hour test starts. The samples are subjected to an electric stress of 4 kV/mm for one hour and then decreased to an intermediate voltage and then switched off. The voltage steps are mentioned in Figure 3-11.

One hour tests will have better accuracy than uniform voltage increase until breakdown, since, these tests are longer and also replicate the conditions while testing. IEC 60076 specifies the insulation requirements and the corresponding insulation tests.

General Terms as defined in IEC 60076-3:

Rated insulation level: Set of rated withstand voltages which characterise the dielectric strength of the insulation

Rated voltage of a winding (Ur): Voltage assigned to be applied, or developed at no-load, between the terminals of an untapped winding, or a tapped winding connected on the principal tapping, for a three-phase winding it is the voltage between line terminals

U_m: Maximum voltage that the transformer may be subjected for an arbitrary long period

U_0: Rated voltage between conductor and earth, for line voltages $U_0 = \frac{Ur}{\sqrt{3}}$; This is an important parameter as the test voltages are defined as a multiple of this voltage.

The method described in the IEC codes are for a transformer and may not be exactly applicable for testing a small sample. For example, the rated insulation level for a class of transformer is specified in volts, in this case depending on the thickness of the sample being tested the voltage can vary. Therefore, keeping the design stress of the transformer construction in mind the one-hour test voltage for the samples is calculated based on the sample thickness.

Calculation of test voltage levels:

Let us take an example of a 4 mm sample, the design stress of the pressboard material in the transformer insulation is 4 kV/mm. therefore, the one-hour test voltage is 16 kV. From this, the Ur can be calculated.

It is stated in the standard that The one-hour test level should be measured at $\frac{(1.58*Ur)}{\sqrt{3}}$. The test voltage measurement is already phase to neutral voltage hence there is no need to account for line to phase voltage conversion, which implies U_0=U_r. Therefore, the U_r is calculated as:

$$1.58 * U_0 = 16\ kV$$

$$U_0 = 10.12\ kV$$

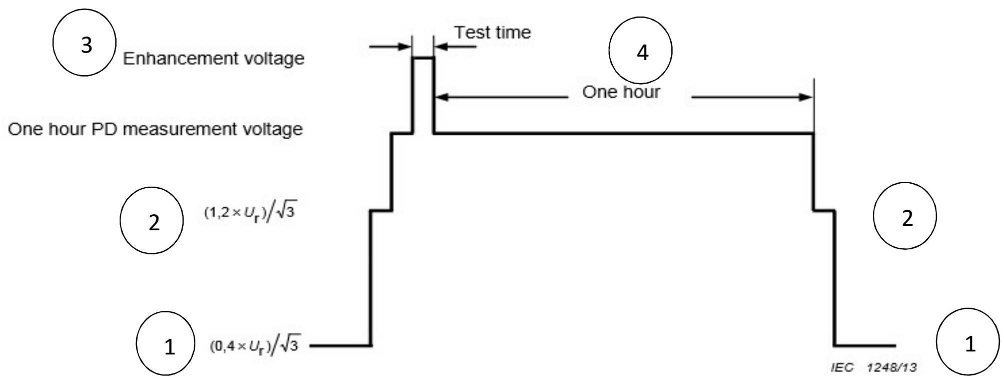


Figure 3-11: One-hour PD testing as mentioned in the IEC 60076-3 transformer testing standard

S.no	Voltage steps	Voltage (kV)
1	Starting voltage	< 4
2	Intermediate voltage	12.15
3	Enhancement voltage (60 seconds)	18.25
4	One-hour PD measurement voltage	16

Table 3-3: Voltages employed for testing Type D samples (4 mm)

Test sequence

1. The voltage is switched on not higher than 4 kV
2. The voltage shall be raised to 10 kV and the background PD measurement was measured in order to set appropriate trigger level.
3. The voltage shall be raised to 12 kV and held for a period of 1 min and then the PD level and repetition to be required.
4. The voltage is raised to the one-hour PD measurement and held for a period of 5 min
5. The PD level shall be measured and recorded
6. Enhancement: the voltage is raised to enhancement voltage and held for a period of 60 seconds. 60 seconds is the prescribed enhancement testing time for transformers rated less than 800 kV.
7. The voltage is reduced to the one-hour PD measurement voltage and the PD level is measured and recorded.
8. The PD level shall be measured and recorded for every 5 minutes during the one-hour period
9. After the last PD measurement in the one-hour period, the voltage shall be reduced to 12 kV and held for a duration of 1 min and then the PD measurement is measured and recorded.
10. The voltage shall be reduced to 4 kV and the background noise level is recorded.
11. The voltage is reduced to the minimum and the supply is turned off.

PD Noise and PD level

The PD test setup used in the lab was of sufficient sensitivity and had a very low level of background noise level. Although the noise level could vary slightly from one day to another, it stayed in the region of 0.17- 0.4 pC throughout the period where the experiments were conducted.

For all the experiments once the noise level was noted, the trigger level was set to 0.5 pC in order to eliminate the effects of noise. If the noise level was higher or lower, the trigger level was adjusted accordingly to eliminate unnecessary discharges.

3.6 OTHER APPARATUS USED

While preparing the samples for the partial discharge tests, the samples are exposed to climate chamber and vacuum and these lead to variation in moisture content of the pressboard samples. In order to measure the moisture content in the samples a weighing scale is used as shown in Figure 3-12.

Figure 3-12: Weighing scale used to measure moisture ingress

There are other methods which exist to measure the moisture content such as Karl- Fischer titration. However, it is not used since it is a destructive testing process and it can lead to inconsistent results as it depends on the location of the specimen used for testing (Center/ surface of the pressboard).

Moisture level in oil was also monitored using Vaisala HUMICAP® Hand-held moisture meter for oil (MM70) which is shown in Figure 3-13.

Figure 3-13: Vaisala handheld moisture meter

CHAPTER 4

EXPERIMENTAL RESULTS & ANALYSIS

With the problem statement, test setup and procedure described in the previous chapters the next step is to perform the experiments. In this chapter the results of various tests performed are discussed and analysed. It is divided into 4 sections as follows:

1. **Effect of standing time**: How does standing time affect partial discharges on pressboard samples?
2. **Effect of oil temperature:** Can temperature of oil influence results of FAT?
3. **Moisture in oil:** What is pressboard-oil moisture dynamics and can this be used to control moisture in a transformer?
4. **Influence of vacuum on moisture extraction**: Can a longer vacuum cycle during manufacturing be used to control moisture content? if so, what is the optimum vacuum time?

The first two experiments (effects of standing time and oil temperature) are partial discharge tests, where the effect of various sample configurations and conditioning are investigated. An overview of the test program used is mentioned in Table 4-1

<table>
<tr><th colspan="3">Partial discharge test program</th></tr>
<tr><td colspan="3">Experiment 1: Effect of standing time</td></tr>
<tr><td colspan="3">Test procedure: one-hour partial discharge tests
Description: For each test, 12-14 samples subjected to climate chamber exposure, vacuum cycle and impregnated with hot and dry oil. Sample tested one by one for PD over standing time of 9 days</td></tr>
<tr><td>Sample</td><td>PD tests on:</td><td>Test program</td></tr>
<tr><td>Type A</td><td>1. Samples conditioned to 3-hour climate chamber & 24-hour vacuum cycle
2. Samples conditioned to 24-hour climate chamber & 4-hour vacuum cycle</td><td rowspan="3">Duration: 9 days
Day 0: 1 sample
Day 1-3:
3 samples/day
Day 4-5: 0 tests
Day 6-9:
1 sample/ day</td></tr>
<tr><td>Type B</td><td>1. Samples conditioned to 3-hour climate chamber & 24-hour vacuum cycle
2. Samples conditioned to 24-hour climate chamber & 4-hour vacuum cycle</td></tr>
<tr><td>Type D</td><td>1. Samples conditioned to 3-hour climate chamber & 24-hour vacuum cycle
2. Samples conditioned to 24-hour climate chamber & 4-hour vacuum cycle
3. Completely dry samples</td></tr>
<tr><td colspan="3">Experiment 2: Effect of oil temperature</td></tr>
<tr><td colspan="3">Test procedure: one-hour partial discharge tests</td></tr>
<tr><td>Sample</td><td colspan="2">Test cases</td></tr>
<tr><td>Type B</td><td colspan="2">1. Wet and unconditioned sample investigated in cold oil
2. Wet sample impregnated and investigated in hot oil
3. Semi dry sample impregnated and investigated in hot oil</td></tr>
</table>

Table 4-1: Partial discharge test program

4.1 Effect of standing time - partial discharge tests

In this section the results of partial discharge (PD) tests performed on various configurations of pressboard material with varying moisture content are presented, discussed and inferences are drawn. The PD test is performed on different samples and configurations (mentioned in chapter 3) over a period of **9 days** in order to observe the effect of standing time on PD magnitude and PDIV. These results will help decide if there is an advantage of employing a long standing time during the manufacturing process. Since partial discharge measurement can be destructive (for a void/cavity), a new sample is used for every test during the investigation. This is envisaged as the best setup to observe the effect of standing time on partial discharge levels/PDIV and also obtain statistical data.

In the following sections the results of PD vs standing time is presented and analysed for each of the sample type (A, B & D – refer chapter 3) and conclusions are drawn. partial discharge tests on type C are not performed since its construction is similar to that of type D. All these tests are performed when the oil in the test chamber is at room temperature.

Each test series conducted, lasts for 9 days and 12-14 pressboard samples are prepared. On day 1, 1 sample is investigated for PD. Similarly, during day 1-3, 3 samples are investigated per day and from day 6-9, 1 test is performed per day. No tests are performed on day 4 & 5. In high voltage engineering, the largest PD measured during a test is considered as the discharge magnitude. In the graph, the biggest discharge per day is plotted and the lowest PD inception voltage of the discharges tested during the day is considered. In most samples, the sample which produces the highest discharges usually has the lowest PDIV. For example, if three samples were tested on a particular day and two of them produced PD, the biggest discharge of the two is then plotted as the discharge magnitude.

4.1.1 PD test on type-A samples

In this section, the test results obtained for 10 mm thick, 2 layered laminated Type- “A” samples which were prepared as per the procedure explained in chapter 3 are presented and analysed.

The thickness of the samples is 10 mm on an average and for the required electrical stress of 4 kV/mm, 40 kV test voltage is used. As per the testing procedure defined in chapter 3 the voltages at intermediate stages are mentioned in Table 4-2.

Voltage steps	**Voltage (kV)**
Starting voltage (noise level- recorded)	10
1.2* U_r	30.35
One-hour PD measurement voltage	40
Enhancement voltage (60 seconds)	45.5

Table 4-2: Voltage steps employed for testing Type- A & B

Enhancement voltage: Once the one-hour test was completed, the voltage was slowly raised step by step in order to check if discharges occur when the samples are exposed to higher than designed stress of about 5 kV/mm

The procedure is given below:

1. Once the final reading is made at 10 kV (at the end of one-hour test), the voltage is smoothly raised to 40 kV and held just to ensure a stable PD measurement.
2. The voltage is raised to 45 kV (4.5 kV/mm) and held for a minute the voltage to stabilize.
3. The voltage is ramped up slowly and smoothly to 50 kV in about a minute and held at 50 for 5 min and look for sustained PD.

4. If they can be observed, they are noted down and the voltage is reduced, else the voltage is slowly increased until discharges are observed.

The PD tests on type A samples have been divided into 2 sections, namely, (1) samples conditioned to 3 hours in a climate chamber and (2) samples conditioned to 24 hours in a climate chamber.

4.1.1.1 SAMPLES CONDITIONED TO 3-HOUR CLIMATE CHAMBER & 24-HOUR VACUUM CYCLE

The important parameters for analysis of results are shown in Table 4-3

Sample configuration	Two layers, 10 mm thick
Conditioning	3 h exposure to climate chamber (60°C & 75% RH) followed by 24 hours in vacuum (25 °C)
One-hour test voltage	40 kV (4 kV/mm)
Final moisture content (% weight)	0.95

Table 4-4: Important parameters for Type A samples conditioned to 3 h climate chamber and 24 h vacuum

Preparation: While performing these tests, fourteen samples of 2 layered, 10mm thick ‘A’ configuration were used. After exposure to climate chamber for 3 hours, the samples are weighed to measure moisture ingress. Moisture ingress of the 14 samples on an average is 1.31%. When followed by a vacuum cycle of 24 hours, it can be estimated (based on separate experiments) that the final moisture content after application of vacuum would be approximately 0.95% by weight. The samples are impregnated and tested one by one over a period of 9 days.

Test results and discussion

It takes about 1.5 days to prepare the sample for testing. Since the first sample tested immediately after impregnation does not have any standing time it is denoted as day 0. The important discharges during the standing time are mentioned below.

Day 0 (No standing time)

One sample was tested on the day the samples were impregnated (day 0), which produced 1 pC discharges with a pattern as depicted in Figure 4-1. These discharge patterns are not clear and could not be identified. They have a low magnitude last only during the ramp up period and therefore not considered as partial discharges. The sample was PD free up to 5 kV/mm (50 kV).

On increasing the voltage beyond 50 kV discharges were being produced which had a magnitude of 44 pC. However, they were later identified to caused due to corona discharges in the setup

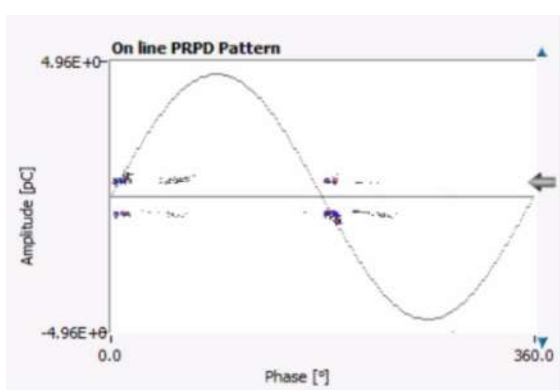


Figure 4-1: Discharges at 40 kV

Day 1 (20-28 hours standing time)

On day 1, two samples were tested and no PD were observed during the one-hour test. Both the samples were PD free up to 5 kV/mm.

Day 2 (44 to 52 hours of standing time)

On day-2 after impregnation 4 samples were tested. The first sample tested did not produce any PD during the one-hour test. However, there were 1 pC discharges (Refer Figure 4-2) when the voltage was increased to the enhancement voltage (5 kV/mm) after the test.

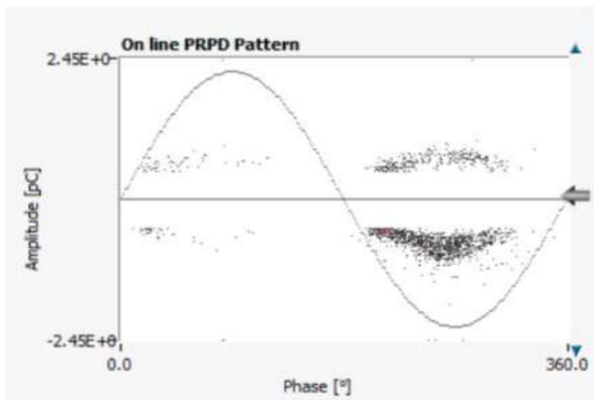


Figure 4-2: 1 pC discharge during enhancement voltage (5 kV/mm)

The second sample tested on day 2 was PD free. Samples 3 & 4 tested on day 2 produced discharges which are identified as a combination of internal and surface discharges. The discharge produced by both samples 3 and 4 had a discharge magnitude of 5 pC. The discharge pattern produced by sample 3 is plotted in Figure 4-3, the figure on the left was during the ramp up period and these discharges continue into the one-hour test, although decreasing in magnitude to 1 pC as shown in Figure 4-3 (right).

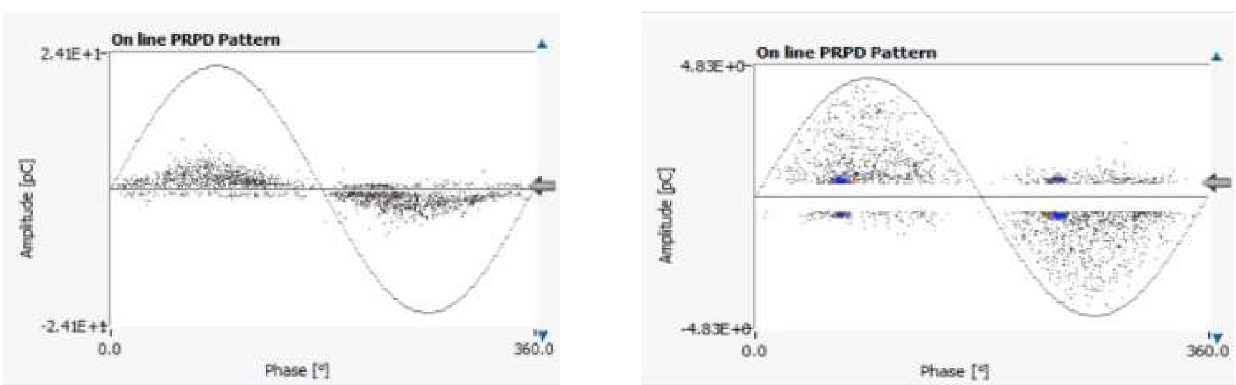


Figure 4-3: Discharges produced on day 2 -sample 3

Similar to the case described above, sample 4 on day 2 produced discharges of 5 pC (Refer Figure 4-4) during the ramp-up period and are extinguished before the one-hour test starts. The patterns produced by both the samples 3 and 4 tested on day 2 are a combination of surface and internal discharges.

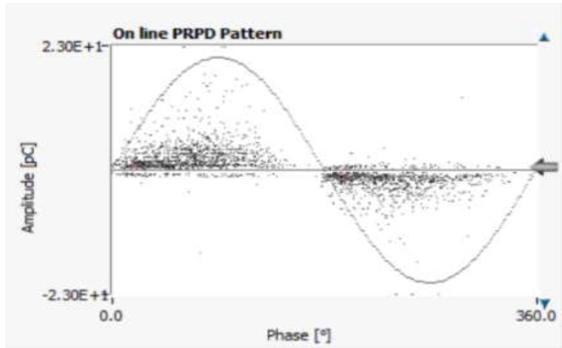


Figure 4-4: Discharge produced on day 2 -sample 4

Day 3 and onwards (standing time >72 hours)

On day-3, one of the 3 samples tested produced internal PD of 1 pC magnitude during the ramp up before the one-hour testing as shown in Figure 4-5. They incept at 29 kV last for about 5 minutes and are extinct before the one-hour test begins. The discharges begin as internal discharges (Figure 4-5 (left)) and later develop into a combination of internal and surface discharges (Figure 4-5 (right)). The other 2 samples were discharge free up to a stress of 5 kV/mm.

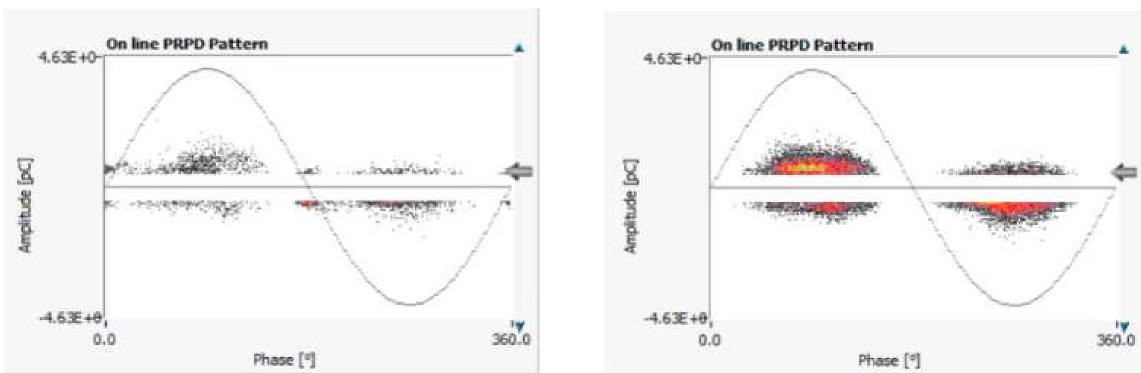


Figure 4-5: Discharges on day 3

Four more samples are tested with a standing time of 6 to 9 days. All the samples were PD free up to 5 kV/mm.

The discharges were observed only up to 3 days of standing time. Even in these cases, the maximum discharge magnitude was 5 pC which is much lower than the level specified in the standards (100 pC). Also, these samples are free of discharges at an elevated stress of 5 kV/mm.

4.1.1.2 SAMPLES CONDITIONED TO 24-HOUR CLIMATE CHAMBER & 4-HOUR VACUUM

A similar procedure to the one mentioned in the previous task was followed except for the time of exposure to climate chamber and vacuum.

Sample configuration	Two layers, 10 mm thick
Conditioning	24 h exposure to climate chamber (60 °C & 75% RH) followed by 4 hours in vacuum
One-hour test voltage	40 kV (4 kV/mm)
Final moisture content (% weight)	3.37

Table 4-5: Important parameters for Type A samples subjected to 24 hours in climate chamber and 4 hours of vacuum

Preparation: While performing these tests, fourteen samples of 2 layered, 10 mm thick 'A' configuration were used. After the climate chamber, the moisture ingress is 3.67 % on an average. It can also be estimated that after the vacuum cycle the moisture content would be around 3.37 %.

Test results and discussion

Day 0 (No standing time)

The sample tested immediately after impregnation (day 0) did not produce any partial discharges. There were, however, some discharges as depicted in Figure 4-6. These discharges are noise attributed to the operation of other equipment in the lab and are not taken into consideration. Although random discharges of high magnitude can occur while testing these can be attributed to the effects of switching equipment or other disturbances. Since the standards state that only sustained discharges should be considered as partial discharges, in this thesis random discharges are neglected.

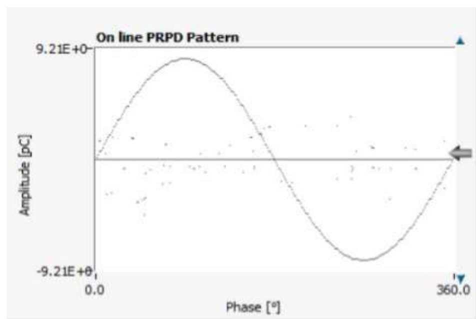


Figure 4-6: Discharges due to the operation of crane

Day 1 (20-28 hours standing time)

On Day 1) three samples are tested which are completely PD free even up to 5 kV/mm. However, when going beyond 5 kV/mm discharges as shown in Figure 4-7 appear. These discharges were the ones mentioned even in the previous section 4.1.1.1. From the figure the discharge magnitude found to be around 1.5 nC and based on the pattern, it was identified as corona on the high voltage side. Since stress beyond 5 kV/mm would not occur in a transformer under normal dielectric tests, it was decided to continue using the setup and 50 kV was the maximum attainable voltage.

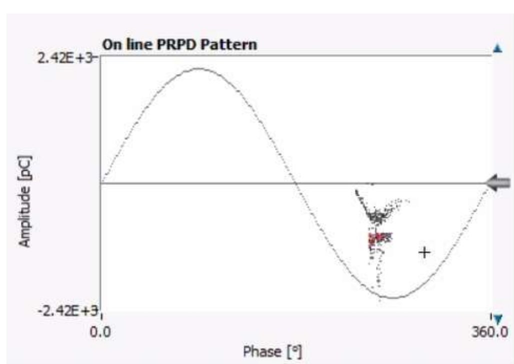


Figure 4-7: Discharge when applied electric stress >5 kV/mm

Day 2 onwards

Similar tests were performed on samples up to six days of standing time and none of the 9 samples tested produced discharges.

4.1.1.3 Summary for type A samples

Figure 4-8 summarizes the results of PD vs standing time test performed on type A sample conditioned to 3 hours in climate chamber.

The primary Y (left) axis denotes the PD magnitude (pC) and the Secondary Y (right) axis corresponds to voltage (kV). The dotted yellow line displays the one-hour testing voltage of 40 kV (4 kV/mm). With a moisture content of 0.95 %, the samples conditioned to 3 hours in the climate chamber are quite resilient to discharges as no discharges were observed after 3 days of standing time. The discharge magnitude of day 4 and 5 are not mentioned as no tests were performed on these days.

The maximum discharge magnitude observed was 5 pC which is much lower than the level specified in the standards (100 pC) and therefore not a cause of concern for factory acceptance tests.

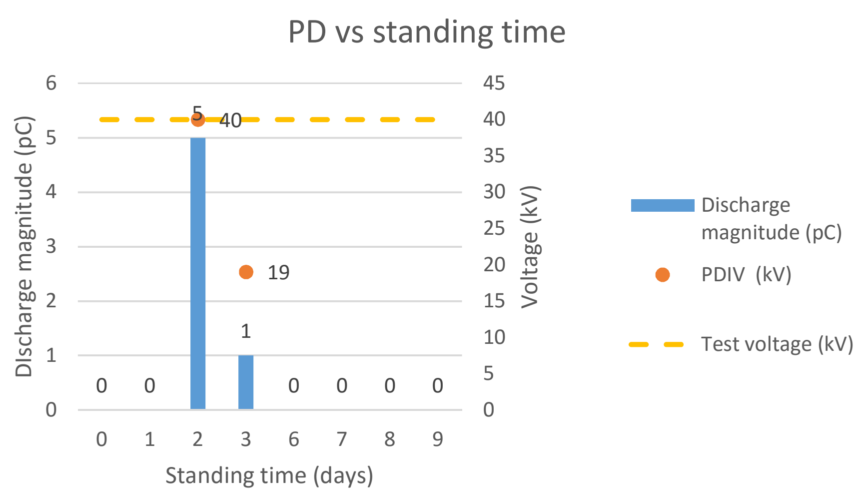


Figure 4-8: PD vs standing time : A (3/24)

The samples conditioned to 24 hours in the climate chamber have a moisture content of over 3 %. Although these sample samples contain more moisture as compared to the former case, it was observed that the samples did not produce PD for the entire standing time.

This can be attributed to the fact that occurrence of partial discharge is a stochastic process which relies on many factors such as availability of starting electron, size of cavities, feedback mechanism etc. Furthermore, literature [2] suggests that although moisture reduces dielectric strength greatly, discharges may not be present at a stress level of 4 kV/mm.

It can be concluded that both the cases of conditioning of Type-A samples (moisture up to 3.3 %), will not cause failure during the 1-hour factory tests.

4.1.2 PD TEST ON TYPE-B SAMPLES

In this section, the results of partial discharge tests on Type-B (10 mm thick, laminated- three-layer) samples are presented and analysed. The same test voltages which were used for Type- A samples are employed (Refer Table 4-2) as they have the same thickness.

The PD tests have been divided into 2 sections, namely, (1) samples conditioned to a 3-hour climate chamber exposure and (2) samples conditioned for 24-hours in a climate chamber.

4.1.2.1 SAMPLES CONDITIONED TO 3-HOUR CLIMATE CHAMBER & 24-HOUR VACUUM

Preparation: While performing these tests, thirteen samples of 'B' configuration are used. After exposure to climate chamber, the samples absorb a moisture of 1.40 %. Following the vacuum cycle, the resultant moisture was about 1%. Some important parameters are mentioned in Table 4-6.

Sample configuration	Three layers, 10 mm thick
Conditioning	3 h exposure to climate chamber (60 °C and 75 % RH) followed by 24 hours in vacuum (25 °C)
One-hour test voltage	40 kV (4 kV/mm)
Final moisture content (% weight)	1%

Table 4-6: Important parameters of Type B samples subjected to 3 hrs. in climate chamber and 24 hrs. of vacuum

Test results and discussion

Day 0 (No standing time):

Three samples were tested on the day of impregnation (day -0) and all of them were discharge free.

Day 1 (20-28 hours of standing time):

On day 1, one of the three samples tested produced PD as shown in Figure 4-9. These discharges are internal discharges and have a magnitude of 2 pC and occur during the ramp up period and extinguish during the one-hour tests.

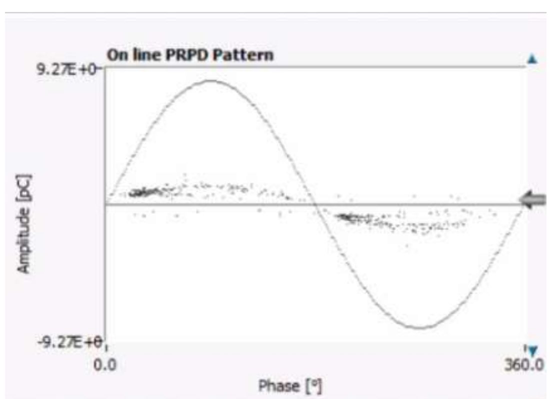


Figure 4-9: Internal discharge on Day 1

Day 2 (44-52 hours of standing time):

48 hours after impregnation (day 2), three samples were tested which were all discharge free.

Day 3 and onwards:

One of the samples produced discharges of 2 pC as shown in Figure 4-10. Although these discharges did not produce the distinctive discharge pattern, as it was developing the arc like discharges could be observed and were also confirmed by the software as a combination of internal and surface discharges. Hence, they are considered for as partial discharges.

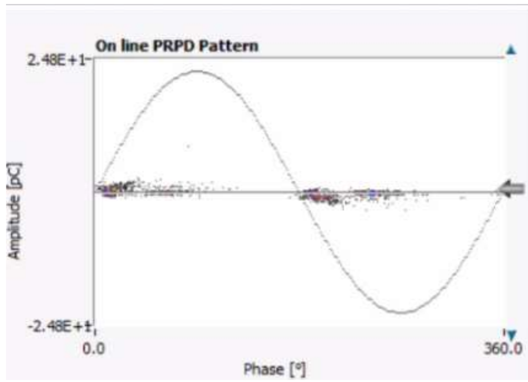


Figure 4-10: Discharge pattern observed on day 3 of standing time

No further discharges were observed for the rest of the standing time.

4.1.2.2 Samples conditioned to 24-hour climate chamber & 4-hour vacuum

Preparation: While performing these tests, thirteen samples of 'B' configuration are used. Some important parameters are mentioned in Table 4-7

Sample configuration	Three layers, 10 mm thick
Conditioning	24 h exposure to climate chamber (60 °C and 75 % RH) followed by 4 hours in vacuum (25 °C)
One-hour test voltage	40 kV (4 kV/mm)
Final moisture content (% weight)	3.43

Table 4-7: Important parameters of Type B samples subjected to 24 H in climate chamber and 4 h of vacuum

The samples were prepared and impregnated as mentioned in chapter 3. In this case although enough oil was used to cover the samples, within half an hour after impregnation the first sample was removed from the tank for PD test. Following volume replacement, removal of a sample can cause the level of the oil to dip. Furthermore, the bottom of the tank has a curvature and is not completely flat. While removing a sample the stand which holds the samples was displaced slightly causing the samples to have a higher elevation leading to a few sample edges to slightly protrude above the surface of oil. As shown in Figure 4-11, 4^{th} sample and the last sample edges from the left are exposed to air. This opportunity was used to test the effects of improper impregnation.

Two samples were protruding overnight (day 0), after which one sample was tested (on day 1) and the other sample was positioned in such a way that the edge was still exposed to air in order to test when the partial discharges subside.

Figure 4-11: Two samples which are protruding 4th and last sample

While testing the sample which was improperly impregnated, the edge of the sample which was exposed to air was tested with the test configuration as shown in Figure 4-12.

Figure 4-12: Test configuration: Improperly impregnated edge

Test results and discussion

Day 0 (No standing time)

On the day of impregnation, the center of one sample was tested and it was discharge free.

Day 1 (20-28 hours of standing time)

On day 1, two samples were tested. The first sample was discharge free. The second sample was tested on its edge as shown in Figure 4-12 as it was marginally exposed to the air overnight. The PRPD discharge pattern was as shown in Figure 4-13 (left) and later develops into a pattern shown in Figure 4-13 (right). They were a combination of internal and surface discharges and had a magnitude of 8 pC during the enhancement voltage which reduced to 4 pC during the one hour test. Internal discharge is dominating with multiple cavities and a pattern resembling a “rabbit ear” . These discharges continued for about 40 minutes into the test at a constant magnitude of 3 pC.

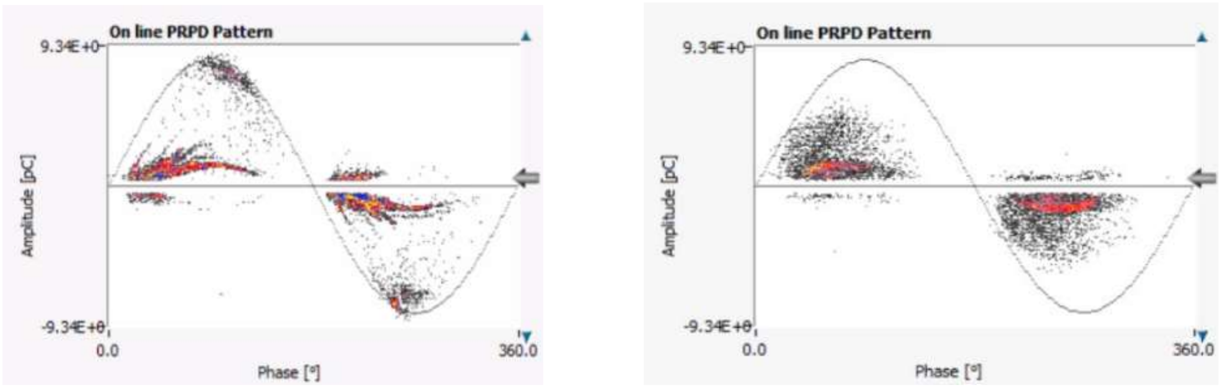


Figure 4-13: PRPD pattern when testing improperly impregnated part (Day-1)

This test was repeated on the center of the same sample and no PD were observed and therefore the cause of PD can be attributed to improper impregnation. Hence, the presence of PD can be explained due to improper impregnation.

Day 2 (44-52 hour standing time)

On Day 2, three samples are tested. The other sample whose edge was exposed to air was discharge free (Figure 4-11). This observation can be attributed to the fact that the voids were filled through capillary action [3]. The third sample tested on day 2 produced discharges of 1 pC magnitude (Figure 4-14) and was identified using software as internal discharges.

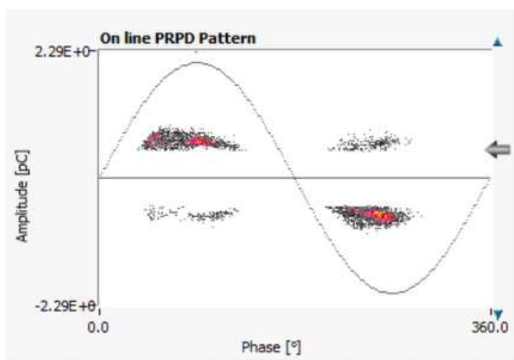


Figure 4-14: Discharge pattern on day 2

Day 3 and onwards (standing time > 72 hours)

From day 3 onwards, 7 more samples were tested until day 9 after impregnation and none of them produced PD during the one hour test.

On the 8^{th} day after impregnation, a sample was being tested on its edge for enhancement voltage after the one-hour test for a stress of 5kV/mm. It is interesting to note that a flashover occurred right next to the interface through the oil as represented in Figure 4-15. Black residue was observed in the oil at the interface and also on the LV electrode indicating a breakdown in oil. There was no evidence of breakdown in the pressboard sample.

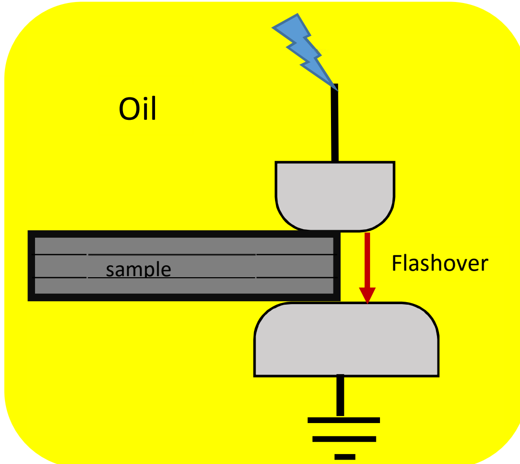


Figure 4-15: Flashover at 5 kV/mm

4.1.2.3 SUMMARY FOR TYPE B SAMPLES

Figure 4-16 summarizes the results of the PD test versus standing time for samples exposed to 24 hours in climate chamber. As it can be observed discharges exist only up to day 2 and from day 3 onwards the samples are discharge free.

The PD on day 1 has a magnitude of 8 pC, which is significant because it was due to the improper impregnation of the edge. In a real transformer, there could be an air bubble pressing against the insulation which can slow down the speed of impregnation and cause PD.

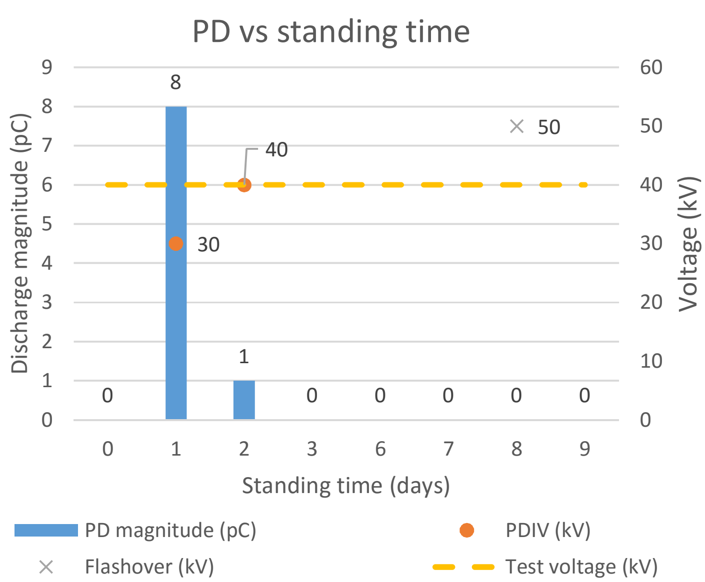


Figure 4-16: PD magnitude vs standing time for type B samples exposed to 24 hours and 4 hours CC & vacuum, respectively

However, the PD due to improper impregnation disappear after day 2. It is possible that due to capillary action, impregnation of the protruding portion takes place within two days and the sample becomes PD free. Usually, air bubbles occur immediately after filling the transformer which is still under vacuum. These bubbles disappear once the vacuum is released and is under atmospheric pressure. From the above experiment, it is advisable to allow a standing time of 2 days which will ensure that the pressboard insulation is completely impregnated.

The results of PD tests where samples were exposed to 3 hrs. in climate chamber are summarised in Figure 4-17. It can be observed that the PD magnitude is restricted to a maximum of 2 pC and the magnitude is very low to cause any problem during the FAT. Also, the PD observed lasted for a very short while a hence are not a cause for concern.

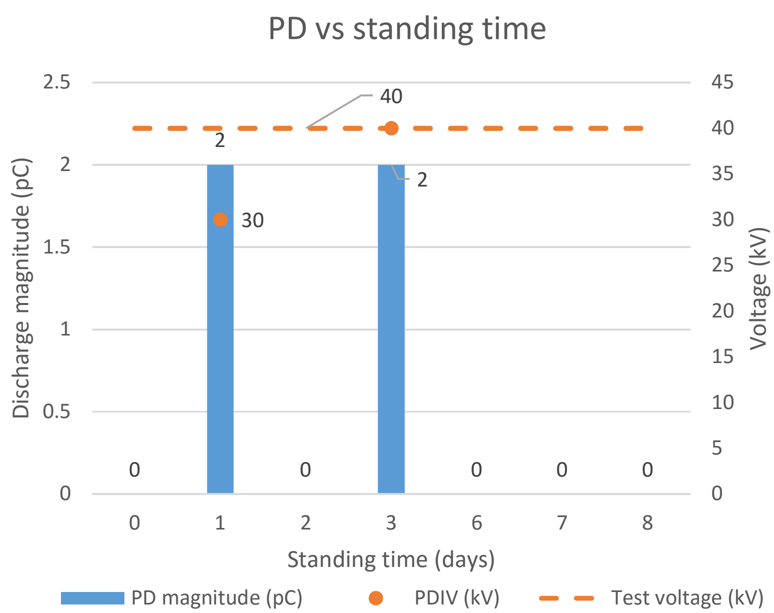


Figure 4-17: PD magnitude vs standing time for type B samples exposed to 3 hours and 24 hours in CC & vacuum, respectively

The flashover takes place at an electric stress greater than 5 kV/mm. It is well known that the interface is the weakest link in the insulation design [31]. However, the stress applied is greater than the design parameter. Moreover, it is likely that the flashover may have been due to field enhancement caused due to an impurity (for e.g. small cellulose particle) in the oil since many other samples were tested in a similar setup without flashover.

Therefore, to conclude the results of test on type -B samples even moisture of 3.4% does not have an effect on partial discharges as the discharge magnitude is not high enough to endanger the factory tests. However, standing time of 2 days will definitely help in preventing discharges arising due to improper impregnation.

4.1.3 PD TEST ON TYPE-D SAMPLES

In this section the test results of single layer 4 mm thick Type- D samples which were prepared as per the procedure explained in chapter 3 are presented and analysed. The voltage steps used for the testing process is mentioned in Table 3-3

4.1.3.1 SAMPLES CONDITIONED FOR 3 HOURS IN THE CLIMATE CHAMBER

Preparation: For these tests, 13 samples of the 4 mm samples (Type -D) are conditioned with a 3-hour exposure to climate chamber in which there is an average moisture ingress of 3.65% in the samples. After a 24-hour vacuum cycle, the final moisture in the samples can be estimated to be 2.12 % (based on separate experiments). The samples were tested at 16 kV (4 kV/mm).

Sample configuration	Single layer, 4 mm thick
Conditioning	3 h exposure to climate chamber (60 °C & 75 % RH) followed by 24 hours in vacuum (25 °C)
One-hour test voltage	16 kV (4 kV/mm)
Final moisture content (% weight)	2.12

Table 4-8: Important parameters for Type D samples conditioned to 3 h climate chamber and 24 h vacuum

The overview of test parameters is mentioned in Table 4-8.

Day 0 (No standing time)

On the day of impregnation (day 0), one sample is tested which produces PD (as shown in Figure 4-18) soon after the test begins and has a magnitude of 3 pC. The PD incept when the stress is 2 kV/mm and last for about ten minutes into the one-hour test.

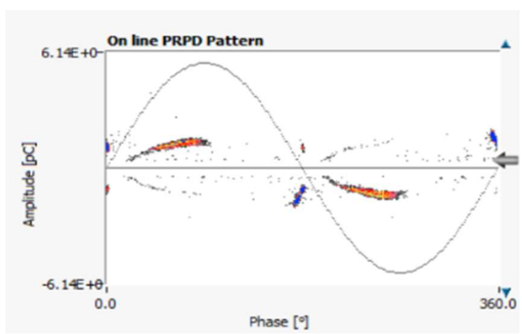


Figure 4-18: Discharges on the day of impregnation

Day 1 (20-28 hours of standing time)

On day-1 (standing time of 24 hours), three samples are tested. The 1st sample produces discharges incepting at less than 2 kV/mm with a magnitude of 2 pC. Sample 2 did not produce any discharges. However, sample 3 produces a discharge of 5 pC.

Day 2 (44-52 hours of standing time) and onwards

From day-2 after impregnation, 9 more samples are tested. No tests were conducted on day 4 & 5. All samples tested on day 2,3 & 6 were discharge free. The sample tested on day- 7 produced some discharges which were classified as noise. Hence, the discharges were not taken into account for the PD vs standing time.

The last sample on day-9 produced 33 pC discharges as shown in Figure 4-19 . These were internal discharges of high magnitude and the setup was calibrated once again to confirm the level of discharge. The PD incept at 4kV/mm and continue for the entire duration of the test. The test is repeated at the same location after about 2 hours and the PD are no longer present for the entire one-hour test.

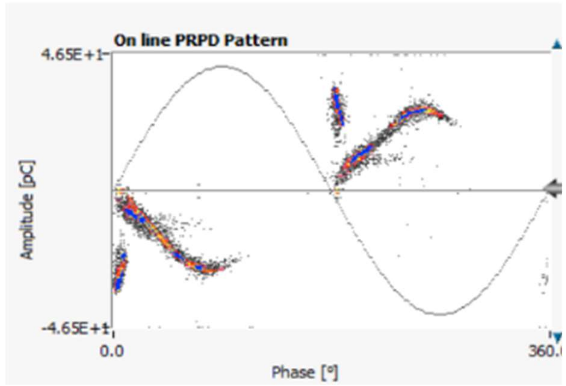


Figure 4-19: 33 pC discharges observed on 9th day

Test at enhancement voltage

In order to test the stress level at which PD of higher magnitude start to appear, five samples were exposed to enhancement voltages after the one-hour test was completed. The tests were performed on samples which did not produce PD and had a standing time of 3 to 7 days. Once, the one-hour test is completed the voltage was increased to 25 kV (6.5 kV/mm) held for 5 minutes, then it was slowly increased to 30 kV (7.5 kV/mm) and maintained 5 minutes and so on until discharges were observed.

The surface discharge inception stress for different samples tested at elevated voltages are plotted in Figure 4-20. These surface discharges have a high magnitude discharge in the range of 30- 100 pC. The first sample which was tested at enhancement voltages was on day 3, which was PD free up to 6 kV/mm, the first discharges occur at 37 kV (9.25 kV/mm), which are internal discharges (Figure 4-21) which proceed to surface discharges at 10 kV/mm.

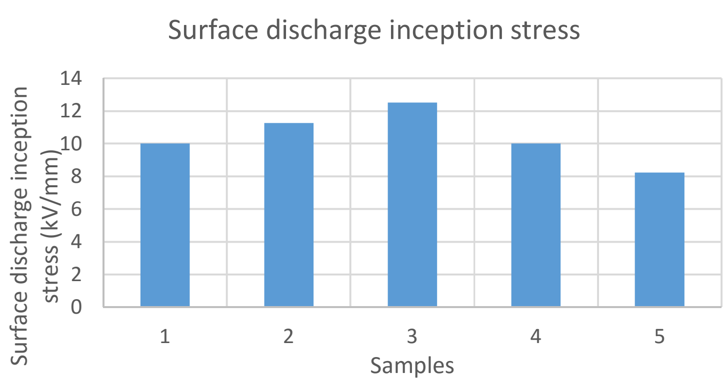


Figure 4-20: Surface discharge inception stress

Other samples at enhancement voltages did not produce internal discharges and directly proceeded to surface discharges. From the results the tests on samples conditioned to 3 h in climate chamber, it can be concluded that type D samples with 2.1% moisture do not produce discharges of magnitude greater than 100 pC at enhancement voltage up to 8 kV/mm.

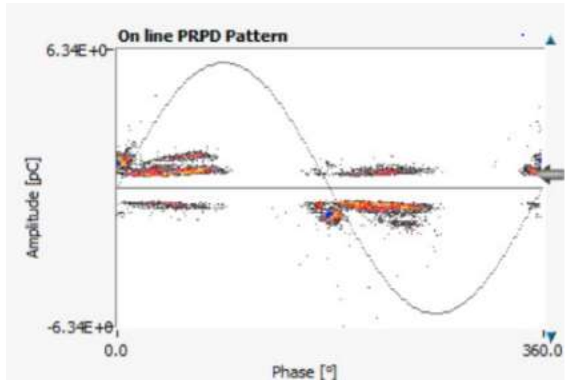


Figure 4-21: Internal discharges at enhancement voltage (sample 1, stress: 9.25 kV/mm)

4.1.3.2 Samples conditioned for 24 hours in the climate chamber

The important parameters for analysis of the results are shown in Table 4-9.

Sample configuration	Single layer, 4 mm thick
Conditioning	24 h exposure to climate chamber (60 °C & 75 % RH) followed by 4 hours in vacuum (25 °C)
One-hour test voltage	16 kV (4 kV/mm)
Final moisture content (% weight)	6.4

Table 4-9: Important parameters for Type D samples

Preparation: For this experiment 12 samples were prepared by conditioning the samples in climate chamber for 24 hours and the samples gain 7.61 % moisture on an average. When it is followed by 4 hours of vacuum, the final moisture content can be estimated (Based on separate experiments) to be 6.4 %. There would be an effect of impregnation on moisture in the sample, as there would be some moisture migrating into the oil. However, its effects are negligible as most of the moisture would remain in the pressboard (Refer Section 4.3.2).

Test results and discussion

Day 0: (No standing time)

The first sample is tested immediately after impregnation and produces discharges of 2 pC with an inception voltage of 8.9 kV (2.2 kV/mm). The discharges last continuously for the entire one-hour test and the PD magnitude decreases to 1 pC after 5 minutes into the one-hour test and maintains the level throughout the test. The discharge pattern at 12 kV (3 kV/mm) is depicted in Figure 4-22.

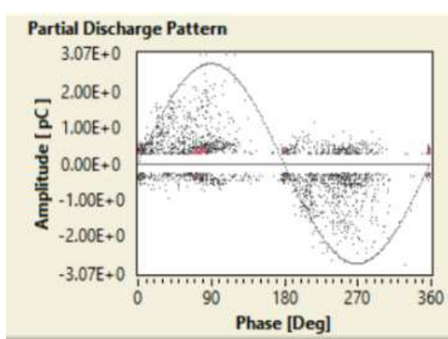


Figure 4-22: Discharge pattern in sample tested immediately after impregnation (day 0)

Day 1: (20-28 hours of standing time)

On the day 1 after impregnation only 2 samples were tested. The first sample tested on day 1 was discharge free. The 2nd test on day 1 was repeated on the sample tested on day 0 (No standing time). It was performed to check if the PD still occur. No discharges were observed for the entire test duration.

Day 2 (44-52 hours of standing time) and onwards:

On day-2, two samples were tested which produce PD incepting at 12 kV with a magnitude of 2 pC. The next test was performed on day-5 of standing time. The first sample produced discharges (Figure 4-23), however, it was discovered that it occurred due to bypassing of the noise blocking filter and is not considered as partial discharges.

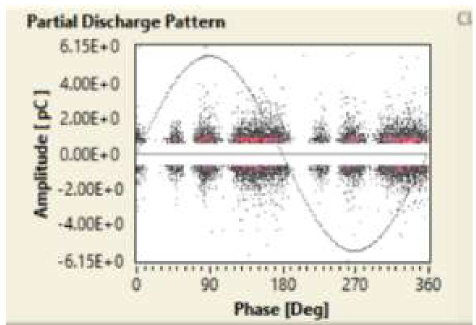


Figure 4-23: Pattern arising due to bypassing of filter

Two more samples are tested on day 5 which are discharge free. The samples tested on 6th, 8th and 9th day produce PD with a discharge magnitude less than 4 pC. The PD inception voltage is still less than 16 kV even after 9 days of standing time. The discharge magnitude is in the range of 2-4 pC which is still considerably lower than 100 pC which is specified in the standards, but it does not decrease with standing time with 6.4 % moisture content.

Test at enhancement voltage

Six samples were tested at enhanced voltages after the completion of the one-hour test to check the effects of higher stress. All the samples produced surface discharges incepting at 18-23 kV (4.5-5.75) kV/mm. The discharge patterns are shown in Figure 4-24 and have a magnitude ranging from tens of pC to nC. These discharge inception stress is very close to the test stress of 4 kV/mm and can be catastrophic during FAT or operation of the transformer under certain conditions. Therefore, 24-hour exposure to ambient should be prevented.

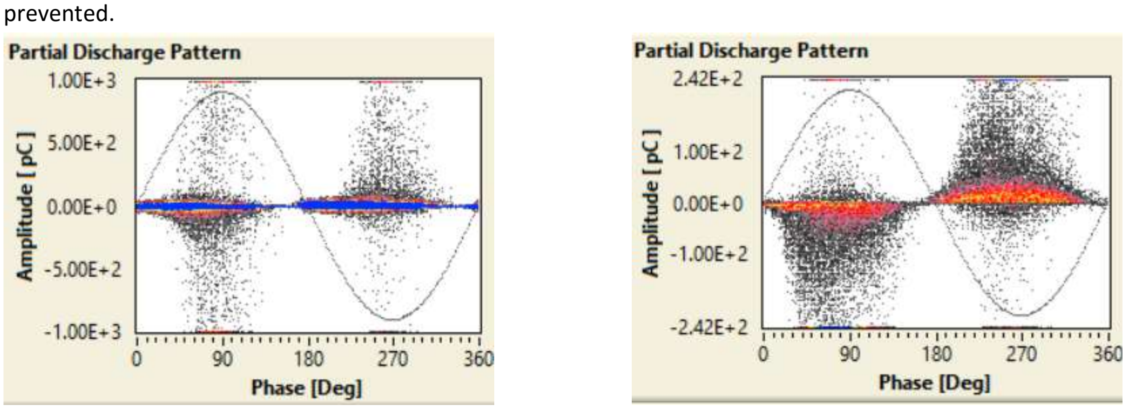


Figure 4-24: Surface discharges at enhancement voltages

4.1.3.3 *COMPLETELY DRY SAMPLES*

One of the results of the previous research work [3] was that that dry samples do not produce PD. In order to confirm this observation, one-hour PD tests are repeated on dry samples. This will also help confirm if the discharges observed were indeed due to moisture.

Preparation: 13 samples of 4 mm pressboard (type -D) were dried, impregnated and tested for a standing time of 8 days.

Test results and discussion:

The same one-hour test procedure was followed as mentioned in the chapter 3. 13 samples tested were completely discharge free for the entire standing time of 8 days at the designed stress levels.

Once the one-hour test was completed, the voltage was smoothly ramped to 30 kV (about a min to reach 30 kV) and held for 1 min and then again slowly ramped up to 40 kV and held for 5 min. These test voltages were used, since the first few samples tested did not give rise to PD when the voltages were increased to 40 kV (10 kV/mm).

The samples are completely free of partial discharges even at 40 kV (10 kV/mm) which is above acceptable design stress levels. Some samples were even raised to 45 kV (~ 11 kV/mm), However, there were some discharges on the surface. Even those discharges were pulses (not sustained – Hence, cannot be considered as PD)

Therefore, dry samples are completely free of PD even at higher stress levels even above 10 kV/mm.

4.1.3.4 *SUMMARY FOR TYPE D SAMPLES*

On analysing the results of three cases of type D samples it can be concluded that completely dry samples are PD free for stress levels up to 10 kV/mm, which is higher than the designed stress levels of 4 kV/mm.

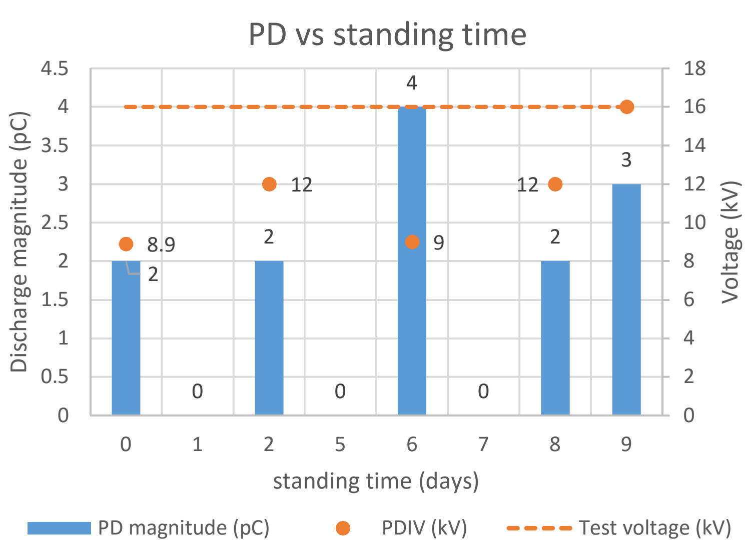


Figure 4-25: PD vs standing time : D (24/4)

The samples exposed to 24 hours of climate chamber followed by 4 hours of vacuum contain 6.4 % moisture by weight and produced discharges for nine days of standing time Figure 4-25 summarizes the results of the tests performed. It displays the PD magnitude in the primary (left) Y axis. The PD inception voltage is plotted on the secondary (right) axis. The dotted yellow line represents the test voltage, in this case it is 16 kV which corresponds to the design field stress of 4 kV/mm.

There is no appreciable trend in the PD inception voltage and the PD magnitude is below 4 pC for the 9 days of testing. However, it is clear that long exposure to moisture (24 hrs.) makes pressboard material susceptible to PD.

Furthermore, the inception voltage of surface discharges (PDIV) is inversely proportional to the moisture content of the samples. In the samples that contain 6 % moisture, surface discharges appear at a stress of 4.5 kV/mm and the margin between the voltage at which surface discharges arise and the design stress is close. This moisture content is dangerous as it can result in failure during FAT.

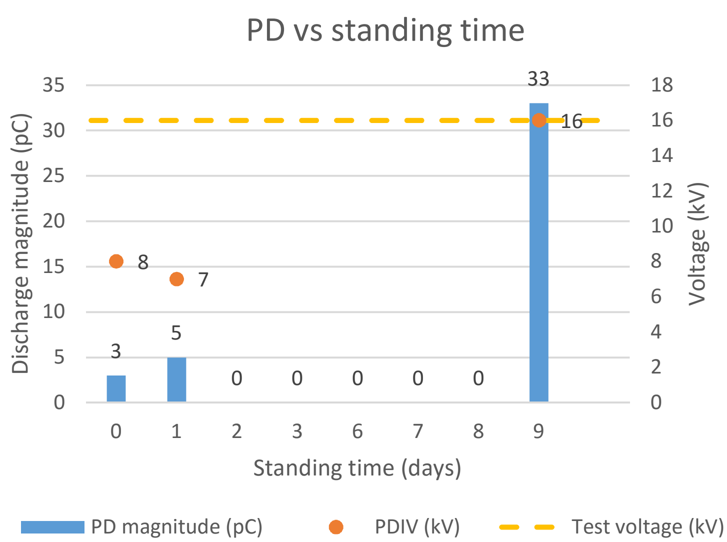


Figure 4-26: PD vs standing time : D (3/24)

For the samples conditioned 3 hours in climate chamber the summarized results are plotted in Figure 4-26 and explained below. Although the samples did not produce discharges from day 2-9, the high magnitude discharge on the 9th day suggests that they are still prone to PD. It is possible that the sample was faulty and contained cavities, even then the results suggest that 2% moisture encourages discharges.

The 33 pC discharges are below the 100pC specified in the standards and will not lead to failure during FAT, but it may be advantageous to keep the moisture content below 2%. More importantly, this demonstrates that a longer standing time does not lead to a decrease in the PD magnitude produced by the pressboard.

4.1.4 Conclusions on effect of standing time-partial discharge tests

The important observations based on the results of the seven tests conducted are stated below:

- ***No appreciable correlation observed between PDIV/ magnitude and standing time for all sample configurations***.
- Dry samples are PD free up to 10 kV/mm; much higher than the design stress.
- Surface discharge inception voltage is inversely proportional to moisture content of sample.
- Samples with over 2% moisture are susceptible to PD (Refer section 4.1.3.4).
- Improper impregnation in samples with moisture can lead to partial discharges.

With over 13 hours of tests conducted on dry samples, there is enough statistics to conclude that dry pressboard insulation is PD free at designed stress and even higher stresses.

Figure 4-27 shows the surface discharge inception stress (on type D samples). It can be observed that higher the moisture content lower is the inception voltage for discharges on the surface of the sample. There is some scatter in the PD inception voltages, for the graph the lowest stress at which discharges were observed are used. The sample with 0% moisture may contain a very small amount of residual moisture which is why an asterisk is marked in Figure 4-27.

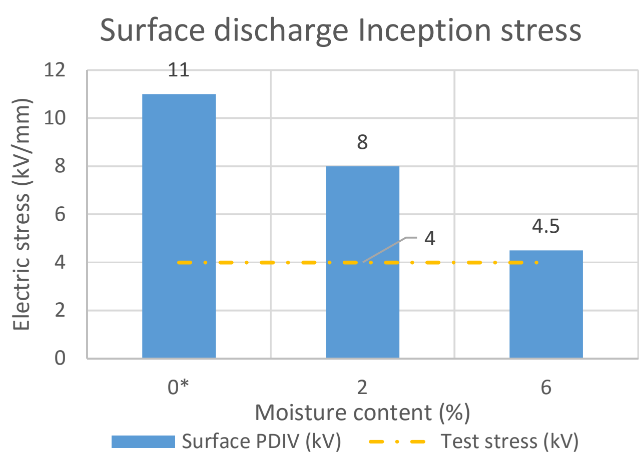


Figure 4-27: Surface discharge inception stress vs. moisture content in sample

These surface discharges can have a magnitude from tens of pC to nC and can cause failure during FAT.

- A moisture content up to 6% does not produce discharges which will lead to failure during FAT.
- However, moisture beyond 2 % seems to promote discharges.
- Based on the experiments single layer thin samples are more susceptible as compared to thick & laminated pressboard as they absorb more moisture as a percentage of their mass. While testing at designed stress the largest PD observed had a magnitude of 33 pC, however, most of the samples had discharge magnitude less than 5 pC.

This level is much lower than the 100 pC mentioned in the standards and indicates that standing time can be reduced. Except for the type D sample which produced discharges on the 9th day, in all other samples, PD could not be observed from the 4th day of standing time onwards (These discharges are small and will not cause failure during FAT). This also correlates with literature [2] that partial discharges/ breakdown can occur at the design field strength (4 kV/mm) only when the moisture content is greater than 5%.

There is a possibility that there may be a bubble of air pressing against the pressboard material leading to a slower/improper impregnation, which can lead to partial discharges. Even in this case, due to capillary action complete impregnation takes place within 48 hours.

Therefore, with these results it can be concluded that:

- Even improper impregnation is completed within 48 hours.
- 48 hours of standing time is sufficient because the discharges after 2 days of standing time are small and will not affect the outcome of FAT.
- Ambient exposure time while tightening should be limited to decrease the risk of failure during factory tests.

4.2 EFFECT OF OIL TEMPERATURE AND MOISTURE

In the previous research at TU Delft [3], one of the observations was that the samples impregnated with hot oil produced discharges at a lower voltage when compared to similar samples impregnated with oil at room temperature. Hence, the effect of oil temperature during test process is investigated and the results are presented in the section below.

In order to analyse the effect of temperature on partial discharges, three experiments were conducted as follows:

1. Wet and unconditioned sample investigated in cold oil
2. Wet sample impregnated and investigated in hot oil
3. Semi-dry sample impregnated and investigated in hot oil

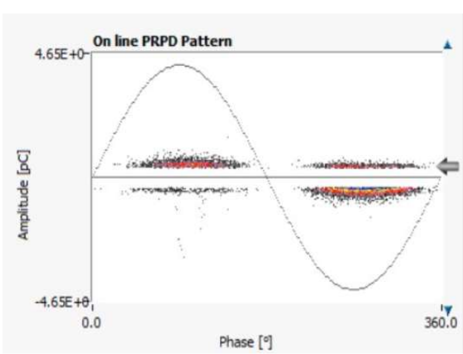
For these tests only type B (10 mm, 3 layered) pressboard samples are used because the PD inception stress can be more accurately calculated when compared to thinner samples.

4.2.1 PD TEST- WET AND UNCONDITIONED SAMPLE (COLD OIL)

In order to observe the effects of improper impregnation on discharge behaviour, a sample of type B is chosen with a moisture content of about 3.8 % by weight. It is positioned into the test tank in oil at room temperature (~ 20 °C) without conditioning in climate or vacuum chamber. One-hour PD test process is employed which is same as that used in the previous tests. The results give a good picture of the effects of improper impregnation and moisture removal.

The discharges start during the ramp up at 37 kV (3.7 kV/mm) with a 1 pC discharge magnitude (Figure 4-28 (left)). These discharges are present during the entire 1 hour of testing. In the first 10 minutes, the PD repetition is slow and it picks up towards the end of the test and becomes repetitive. The level of the discharges does not change throughout the experiment and maintains a constant 1 pC. At the end of the test the extinction voltage was found to be 31 kV and 2^{nd} PD inception is at 35 kV. The lower extinction voltage compared to inception voltage suggests it was internal discharges. Also, the discharge pattern was classified as a combination of surface and internal discharges.

Then in order to understand the effects of higher stress, the voltage was slowly raised over a minute to 50 kV (stress level of 5 kV/mm) and which is also the corona level of the setup. At 49 kV (4.9 kV/mm) surface discharges of high magnitude (8 nC) start. Before the discharges start the magnitude of the discharge remains the same, however, the repetition rate of discharges increases. The discharges develop as in Figure 4-28 (right), notice the discharge showing saturation.



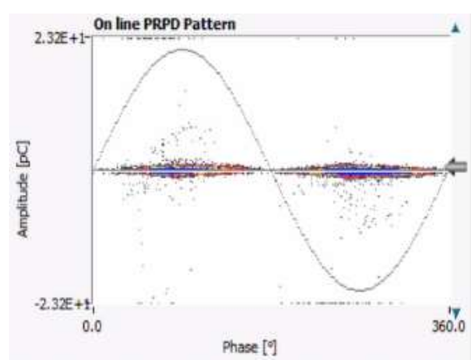


Figure 4-28: 1 pC discharges at 4 kV/mm (left) & saturated discharges at 5 kV/mm (right)

These discharges had a high magnitude of over 8 nC (refer Figure 4-29 (left)). This was the maximum the PD detector could measure at the calibration settings used.

The discharge extinction voltage is 42 kV (refer Figure 4-29 (right)). Based on the discharge pattern and characteristics these discharges are identified as surface discharges. The discharge magnitude cannot be accurately measured since the waveform was saturated. Therefore, the test was repeated after about 1 hour.

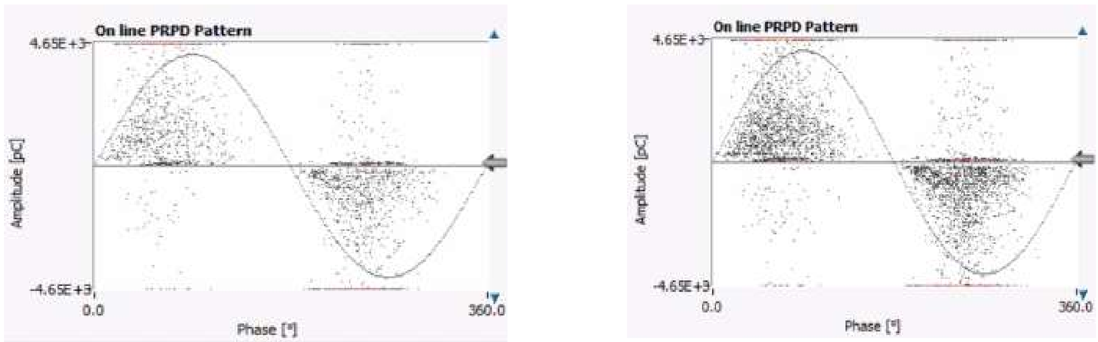


Figure 4-29: Surface discharges (left - inception) (right - extinction)

The surface discharge incepts at 46 kV and the extinguish at 37 kV. The was still waveform was still saturated and was the discharge magnitude was greater than 30 nC (Figure 4-30). These high magnitude discharges leave behind a black ring on the high voltage side of the sample as shown in Figure 4-31 (left).

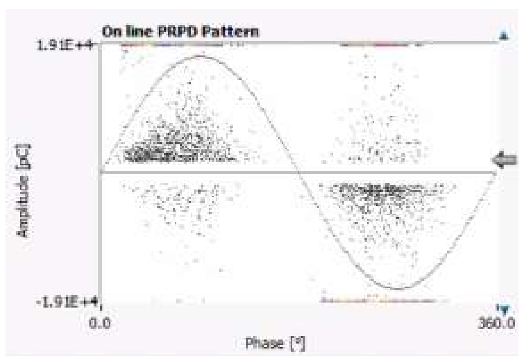


Figure 4-30: 30 nC surface discharges

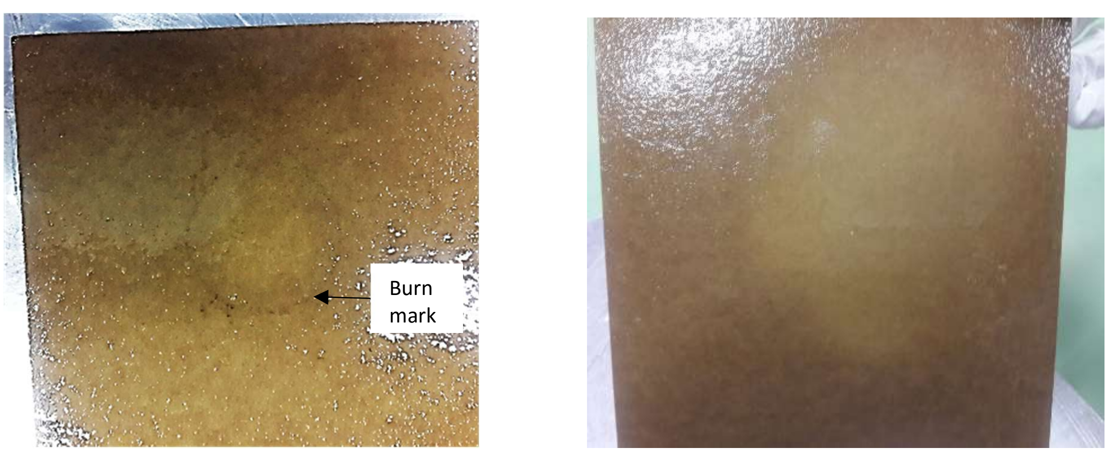


Figure 4-31: (Left) HV side and (right) LV side of the sample under test; observe the black ring indicating surface discharges

Since the discharges of high magnitude start around 4.5kV/mm, which is near the enhancement stress during the one-hour test. Hence, the effect of not impregnating and vacuuming is very relevant and can not only cause failure during FAT but also harm the insulation at a stress of 4 kV/mm.

4.2.2 IMPREGNATION -PD TEST (HOT OIL)

4.2.2.1 WET SAMPLE IN HOT OIL

This test was performed to study the effect of hot oil on pressboard insulation with a similar moisture content as the sample mentioned in section 4.2.1. The sample was taken from the storage and vacuumed for 3 hours and then impregnated with pure hot oil and the test was repeated. It was vacuumed in order to impregnate the sample with hot oil.

The sample weighs around 275 g, which is similar to the weight of the sample after 24 hours of exposure to climate chamber and has a moisture content of about 3.8 %.

The test setup is modified slightly; the test bucket is replaced with a glass container in which the sample was impregnated.

The first test is conducted when the sample temperature was 45 °C. Although the sample was impregnated with oil at 70 °C, it rapidly cools down to 45 °C by the time the test begins. When testing the sample according to the one-hour test profile, the sample produced a few intermittent discharges but not PD at 30 kV. Anticipating discharges, the voltage was slowly raised. At 34 kV (3.4 kV/mm) the sample produced surface discharges with a magnitude of over 2 nC (Refer Figure 4-32). The voltage was reduced and switched off after recording the pattern in to reduce damage to the surface and the experiment was repeated after an hour with lower temperature.

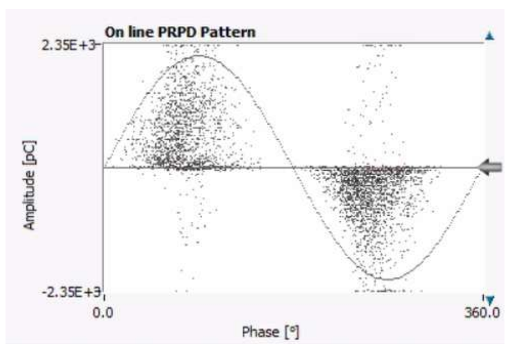


Figure 4-32: PD at 34 kV with magnitude over 2 nC (oil temp: 45 °C)

After 1 hour the temperature was about 36 °C (gradient 9 °C/ hour) and the test is repeated. The PDIV had increased to 38 kV with a discharge magnitude of 3 nC (Figure 4-33)

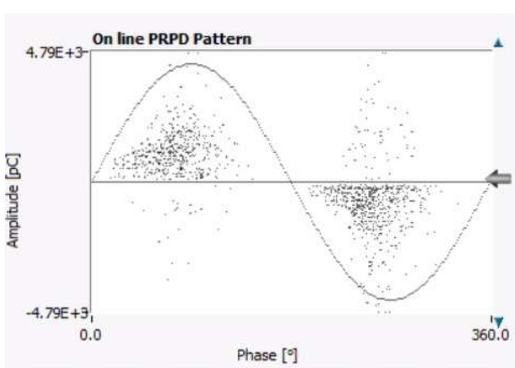


Figure 4-33: PD at 38 kV (oil temp. 35 °C)

To make sure this is not due the effect of the previous defect being carbonized, the sample is flipped and a PD measurement is made again. Now, the PD started again with over 4.6 nC at about 39 kV discharges as shown in Figure 4-34.

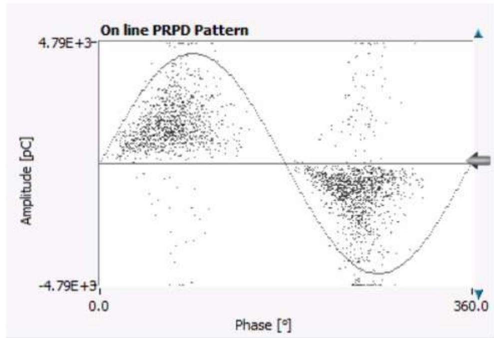


Figure 4-34: PD on flipped sample

4.2.2.2 PARTIALLY DRY SAMPLE IN HOT OIL

The sample used in this section was dried for 2 days in the oven at 80 °C and the final moisture content is about 1.9 %, half of that was present in the sample mentioned in section 4.2.2.1. The sample is conditioned to 3 hours of vacuum and impregnated with hot and purified oil, similar to the previous conditioning and the effect of moisture reduction is studied. The temperature of the oil is 50 ° C at the start of the test and decreases to about 45 degrees at the end of the test.

Since in the previous experiments, surface discharges were observed at 3.4 kV/mm the voltage was increased to 40 kV slowly in around a minute and no discharges were observed. When the voltage is raised to 45 kV (4.5 kV/mm) an indication of surface discharge is observed, however, it is not sustained even after one minute at 4.5 kV/mm. Since, 45kV is our test voltage at enhancement voltage, it is an indication that this value is the critical value of moisture content.

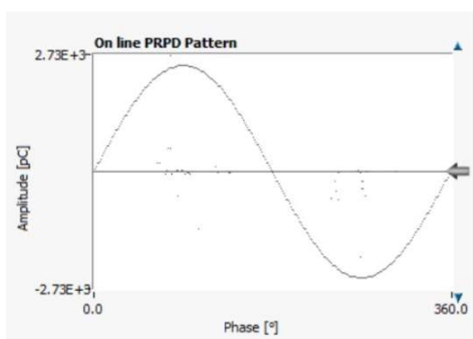


Figure 4-35: Few pulses of 2 nC – no pattern produced

Observe in Figure 4-35, that a 2 nC discharge is registered, however, there is no repetition unlike the previous cases. According to one-hour test procedure the voltage is reduced to the test voltage of 40 kV for another 45 minutes and no partial discharges are observed. Due to time constraints the test had to be stopped.

Before quitting the test, the voltage on the sample was increased slowly up to 50 kV and no discharges were produced. The voltage was held at 50 kV for over 5 min and there were few pulses similar to the one shown in Figure 4-35, however, they were not sustained.

4.2.3 Results and analysis of the effect of temperature during testing

In order to analyse the effect of testing under hot oil, three experiments were conducted in sections 4.2.1, 4.2.2.1, 4.2.2.2. The results for analysis are plotted in Figure 4-36.

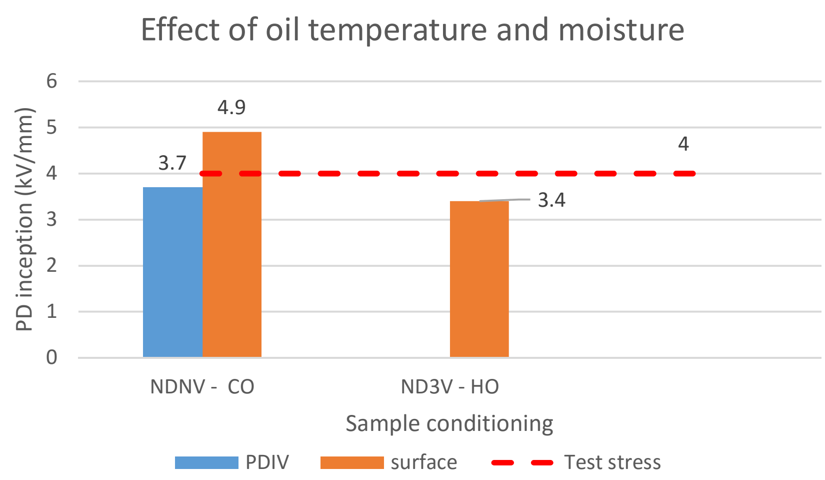


Figure 4-36: Effect of oil temperature on partial discharge inception stress

The three cases analysed are abbreviated as follows:

NDNV- CO: Sample Not Dried (3.8 % moisture), No Vacuum – test in Cold Oil (Section 4.2.1)

ND3V-HO – Sample Not Dried (3.8 % moisture), 3-hour Vacuum – Hot Oil (Section 4.2.2.1)

D3V- HO (not in graph) – Sample Dried (1.9 % moisture), 3-hour Vacuum –Hot Oil (Section 4.2.2.2)

In case of the completely unconditioned sample (NDNV) when tested in cold oil, discharges (1 pC magnitude) incept at 37 pC (3.7 kV/mm) and the surface discharges (nC range) occur at 49 kV (4.9 kV/mm). The 2nd case (ND3V- HO) which was tested under hot oil, produced surface discharges at 34 kV (3.4 kV/mm) onwards. On comparing the results of the cases mentioned above, the lower discharge inception voltage under hot oil points to a situation where pressboard is more susceptible to PD under hot oil, which was one of the hypotheses put forth at the end of the earlier research [3].

A similar experiment as NDNV-HO was repeated with a sample with about half the moisture content (D3V-HO) and it did not produce any sustained surface discharges up to 50 kV, hence it is not mentioned in the graph (Figure 4-36). Therefore, from the results, we can infer that there exists a relationship between the initial moisture content in pressboard.

It is interesting to note that none of the 10 mm samples with similar moisture contents produced surface discharges below 4.5 kV/mm when the samples are in thermal equilibrium (Refer Section 4.1) Therefore, it is inferred that temperature of oil does have an effect on partial discharges.

From literature [32], the mechanism for the breakdown characteristics depends on 3 parameters (stated below) which can be used to explain the observed phenomenon.

- Moisture content of pressboard
- Temperature gradient (positive or negative)
- Disturbance of moisture equilibrium

A higher temperature may initially provide higher thermal excitation to the starting electron facilitating discharges. However, the influence of moisture seems to be greater because the tests on samples with different moisture contents impregnated and tested with hot oil (at same temperature) show stark differences in PDIV.

The effect of high initial moisture in pressboard when combined with a temperature gradient will lead to discharges which can be harmful to the insulation. In the experiments mentioned in section 4.2.2 there was a negative temperature gradient (the test setup- hot oil and pressboard were cooling due to exposure to ambient conditions). During this cooling process moisture migrates from the oil to pressboard (and vice versa) leading to a higher moisture content at the interface. The build-up of moisture at the interface between pressboard and oil leads to a reduction in the dielectric strength, thus producing discharges.

The moisture migration between two media is complex because first, the oil absorbs moisture from pressboard up to a critical value. Then, as the setup cools the moisture migrates back into the pressboard. This process is mentioned in detail in section 4.3.1. and the moisture migration would follow a similar pattern as depicted in Figure 4-39. Furthermore, the sensitivity of dielectric strength to negative temperature gradient is greater than that of positive gradient [32].

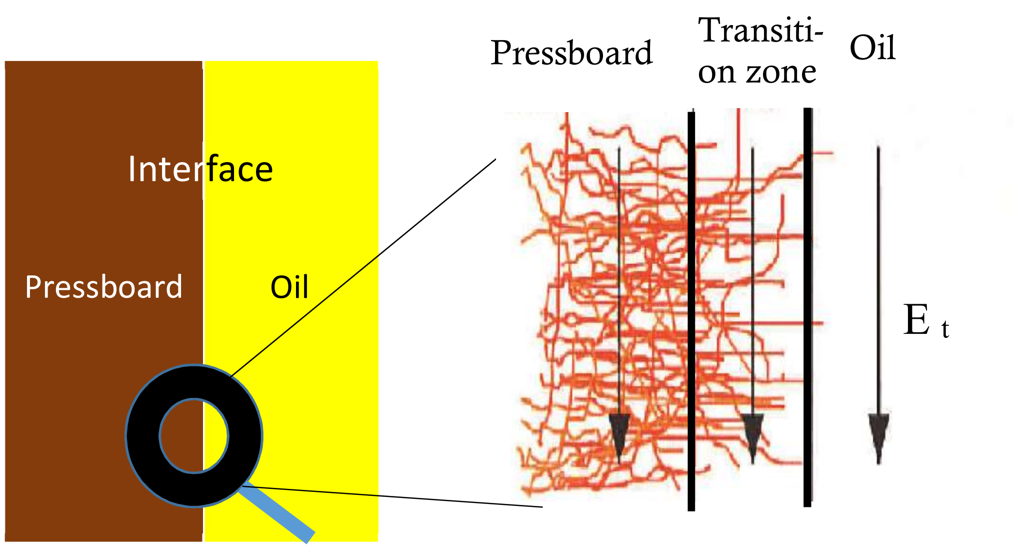


Figure 4-37: Pressboard - oil interface

Figure 4-37 shows the pressboard-oil interface which much more complex than a simple solid (pressboard)-liquid (oil) interface. At the interface of the two media, a transition zone exists which consists of pressboard fibres and oil. At times of moisture migration, there is an increased moisture content in the transition layer. The discharge physics is not clear, however, it can be said for certain that the effect of moisture combined with a thermal gradient can lead to a reduced dielectric strength at the interface.

In the experiments, when the moisture content was 1.9 % (D3-HO) no sustained discharges were observed. This observation is in line with that of standard which states that moisture content greater than 2 % is considered aged and can lead to a significant reduction in dielectric strength.

The transformer would have a much lower thermal gradient due to higher mass when compared to the test setup used in the lab. However, it is advisable to keep the transformer at a constant temperature and restrict the moisture content in pressboard to less than 2 %. Furthermore, the transformer is subjected to heating cycles during FAT and it is recommended that thermal equilibrium is maintained during the dielectric tests.

4.3 MOISTURE IN OIL

Transformer manufacturers and utilities are concerned with the moisture content in a transformer, which is mainly the moisture in solid insulation. It is destructive and impractical to measure moisture directly in the solid insulation. Therefore, in a transformer moisture content is measured in oil which is compared with known equilibrium curves to estimate the moisture content in solid insulation [14].

Therefore, in this thesis along with the measurement of partial discharges on pressboard, the moisture content in oil was measured while preparing the samples and the observations are discussed in this section.

4.3.1 PRESSBOARD-OIL MOISTURE DYNAMICS

While preparing the samples for the PD tests, pressboard samples were conditioned in the climate chamber. After impregnation, the moisture content of the oil was measured daily in the aquarium tank containing samples (12- 14 samples) using a capacitive moisture measurement probe Vaisala- MM70.

The measurement device measures three parameters, namely water activity (A_w), temperature (T) and moisture content in PPM.

Description of different parameters:

Water activity (A_w): Water activity is the amount of water in a substance relative to the total amount of water it can hold. It is defined as [33]:

$$A\_w = \frac{p}{p0}$$

Where, p = the partial pressure of water in a substance above the material

p0 = the saturated vapour pressure of pure water at the same temperature.

In simpler terms it gives the relative saturation: the actual amount of water measured in the oil in relation to the solubility level at that temperature.

Temperature: The temperature of the oil is measured in degree Celsius.

Moisture content (PPM): It is the traditional method of measuring the quantity of water in oil when the moisture content is very low, where the number of water molecules per million parts of oil.

$$By\ volume: 1\ ppm\ water = 1\ ml\ of\ water\ /\ 1\ m3\ of\ oil \qquad (6)$$

Or

$$By\ mass: 1\ ppm\ water = 1\ g\ of\ water\ /\ 1000\ kg\ of\ oil$$ [33]

4.3.2 RESULTS AND ANALYSIS

When the oil is ready for impregnation process, it is dried to a level where the moisture content is about 5 ppm. Then the pressboard samples are impregnated with hot oil at 70 °C. Since, the moisture measurement probe cannot be used at temperatures above 60 °C, the oil is allowed to cool and the measurements were taken a couple of hours after impregnation. The moisture content is also measured at regular intervals throughout the standing time.

Figure 4-38 shows variation of moisture content in oil with standing time. Each line is named using the following convention: (sample configuration – Climate chamber exposure time/ vacuum time). For example, in A-24/4, the letter A stands for the sample configuration followed by 24 hours of climate chamber and 4 hours of vacuum.

It can be observed that on the day of impregnation (day 0) the moisture level in oil shoots up and later settles to a stable value from 2nd day after impregnation. First, let us consider type D samples which were exposed to 24-hours in climate chamber followed by 4-hour vacuum cycle. Within a few hours after impregnation, the moisture level in the oil shoots to over 40 ppm from an initial 5 ppm. Furthermore, when the oil had reached room temperature the moisture level was down to 23 ppm, which is maintained as long as the temperature remains constant.

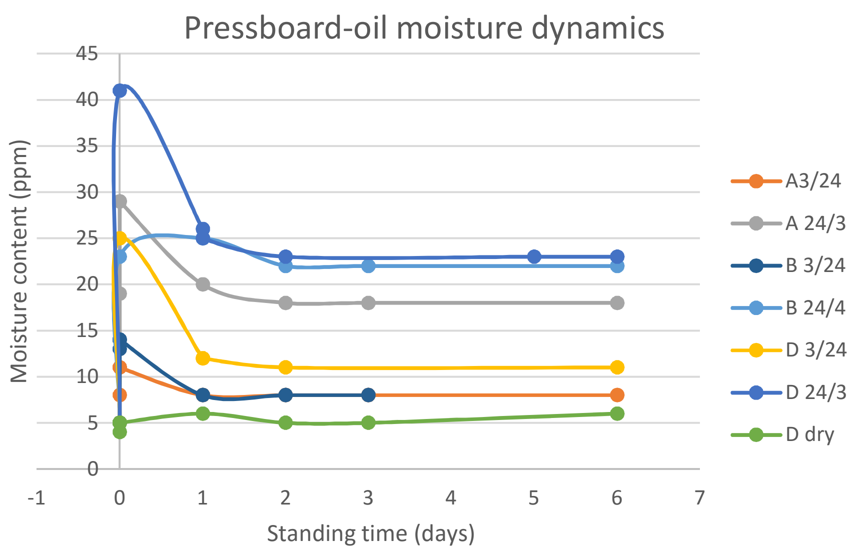


Figure 4-38: Moisture in oil vs. standing time

Similarly, on considering the 3-hour exposure of type D to climate chamber, it is observed that the graph follows a similar trend as the 24-hour exposure. However, it is interesting to note that the moisture level graph is shifted down for the samples exposed to 3 hours is the climate chamber. A similar trend can be observed for sample configurations A and B.

The increase in moisture level immediately after impregnation is an interesting observation as it would deal with moisture dynamics in pressboard-oil interface. However, caution must be exercised when measuring moisture at varied temperature, since, the observation could be an effect of temperature on the measuring instrument. In order to confirm this, a separate set of experiments was carried out only with oil and is mentioned in Appendix A. On heat cycling oil without pressboard it is confirmed that this observation is indeed due to pressboard-oil dynamics.

Pressboard-oil dynamics is the movement of moisture content from oil to pressboard and vice versa which occurs due to temperature variation. The change of moisture in oil is vs temperature is plotted in Figure 4-39. It can be observed that the amount of moisture migrating to and from pressboard is directly proportional to the moisture content in the pressboard sample (Refer section 4.4.1 for sample moisture content) and also on the construction of pressboard.

For example, in Figure 4-39: Type-D samples exposed to 3 hours in climate chamber has lower moisture content than that of 24-hour exposure. The participation of the former is lower is than the latter in pressboard-oil dynamics due to its lower moisture content.

Furthermore, on comparing sample type A which was exposed to 24 hours in climate chamber to type D samples conditioned in similar conditions it can be observed that participation of type A is much lower although it contains more absolute moisture (Refer section 4.4.1). This is because of the construction of the sample, the higher the thickness of pressboard the longer it takes to reach equilibrium conditions which is denoted by the following equation [34].

$$\tau = \frac{d^2}{\pi^2 * D}$$

Where τ is the diffusion time; d is the sample thickness and D is the diffusion time coefficient. The coefficient is dependent on several factors such as temperature, type of pressboard.

This is important regarding the results on partial discharge testing under non-equilibrium conditions (Section 4.2). Thin samples have a higher moisture migration and may be more dispositioned to discharges of high magnitude at the interface. Also, the moisture in oil is highest when temperature is between 40 and 30 °C and may have the lowest dielectric strength at these temperatures.

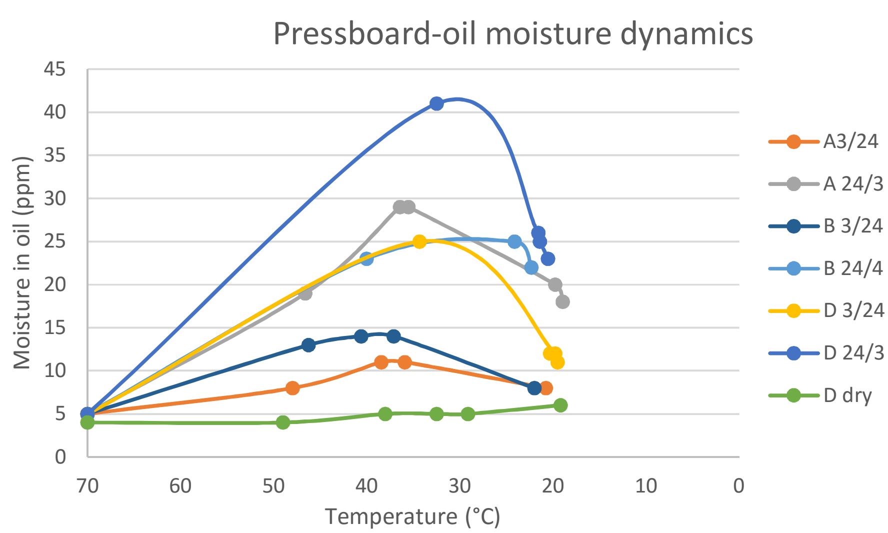


Figure 4-39: Moisture content in oil Vs. temperature

Why does this spike of moisture in oil occur?

As the temperature of the oil increases, the solubility of moisture in oil also increases as is given by the equation:

$Log\ S = \ (-1567/K) + 7.0895$ [35], where S is the solubility and K is the temperature in Kelvin.

This solubility limits of moisture in oil with temperature isn't linear and it is plotted in Figure 4-40 and increases exponentially with increase in temperature.

When the moist pressboard is impregnated with hot and dried oil, the oil is at 70°C and has a moisture content of 5 ppm. Due to the high solubility of water in oil at 70 °C, the oil now absorbs moisture mainly from the pressboard which contains most of the moisture and the moisture starts diffusing from the pressboard to oil.

This diffusion process takes a bit longer than the change in temperature [32]. Simultaneously, the oil is cooling down due to the temperature gradient between the hot oil (with samples) and the ambient which is around 20 °C and its ability to absorb and hold moisture decreases. Therefore, the moisture in oil starts to decrease until a thermal equilibrium sets in and the moisture content remains constant thereon.

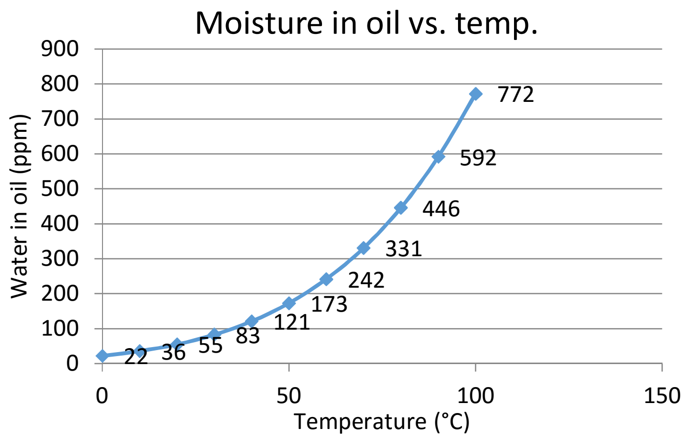


Figure 4-40: Solubility limits for oil at various temperatures [32]

The final moisture in oil at thermal equilibrium is directly proportional to the moisture content in pressboard and can be observed in Figure B-1 - Appendix B. In the cooling down phase the diffusion process is fast and in line with the change in temperature [32]. To sum up; when the samples are impregnated with hot oil there is a movement of moisture from pressboard to oil. Since the oil is also cooling at the same time due to the temperature gradient, the moisture is starts reducing in oil and moves back to the pressboard. Hence we obtain a spike in the oil moisture content.

Can moisture migration be used to remove moisture from the cellulosic insulation?

Since there is a substantial increase in the moisture content in oil shortly after impregnation, there was an idea to check if the moisture could be removed from the oil. The oil drying can be performed when the transformer is cooling after impregnation and the moisture content is highest (when the temperature of oil is between 30 & 40 °C- Refer Figure 4-39).

The calculation is as follows:

$$Weight\ of\ oil\ per\ litre\ = 783.86\ g$$

The measurement is made at room temperature (20 °C) and atmospheric pressure

Let us assume there are 10 litres of oil in the impregnation tank when performing the PD tests, so the weight of oil is 7.84 kg.

From the relation mentioned in (76), we can calculate that

$$1\ ppm\ of\ water\ in\ oil\ in\ 10\ litres\ corresponds\ to\ 7.84\ mg\ of\ water \qquad (7)$$

Let us consider the case of type D sample exposed to 24 hours in climate chamber which produces the maximum amount of moisture migration in oil (5 to 41 ppm) (Refer Figure 4-39).

Based on measurements made before the samples were impregnated the moisture in the samples we know that:

$When\ 12\ samples\ are\ exposed\ to\ 24\ h\ in\ climate\ chamber, there\ is\ a\ moisture\ ingress\ of\ 96\ g;$

$81\ g\ of\ moisture\ remains\ after\ vacuum\ cycle\ of\ 4\ hours\ (estimate\ based\ on\ separate\ experiment).$

When the moisture content is maximum in the oil, the moisture content is 41 ppm (refer Figure 4-39). The oil before impregnation had a moisture content of 5 ppm.

Therefore, increase in moisture content due to moisture migration is $41 - 5 = 36\ ppm$

From equation (7) 36 ppm corresponds to 0.282 g of moisture; (36 ppm in 10 L of oil => 36* 7.84 mg = 0.282 g)

Hence, drying the oil to 5 ppm would only remove only 0.282 g of moisture out of 81 g which was initially present in the pressboard and is less than 0.4 %. After one drying cycle, the moisture removed would be less than 0.4 % of the total moisture content and is negligible.

4.3.3 SUMMARY

It can be inferred from the analysis that:

- Moisture migrates to and from the pressboard after impregnation due to change in temperature.
- Thin samples have higher participation in pressboard oil dynamics due to their lower diffusion time constant.
- The moisture content in pressboard reflects in the moisture in oil.
- Moisture content in oil is very low (< 0.4 %) as compared to the moisture content in pressboard.
- Moisture content that will be removed by drying oil after impregnation would be very low and not feasible even when the moisture content is highest in oil.

4.4 INFLUENCE OF VACUUM ON MOISTURE EXTRACTION

In this section, the effect of vacuum cycle on moisture extraction is analysed. The section is divided into two as follows:

1. Measuring moisture ingress into the sample and effect of vacuum
2. Moisture estimation tool: A model has been developed to estimate the moisture content in pressboard during the production process

4.4.1 MEASURING MOISTURE INGRESS INTO PRESSBOARD AND EFFECT OF VACUUM CYCLE

In this section, the amount of moisture ingress into the pressboard material during exposure to the climate chamber is measured. Along with the rate of absorption of moisture into the sample during climate chamber exposure, the effect of vacuum cycle is analysed and presented.

Procedure

3 different dried samples of each configuration (A, B, C & D) were chosen. The samples are dried in the oven for over 4 weeks and hence are considered to be completely dry. The samples were weighed before exposing them to the specified conditions (60 °C & 75 % RH) in a climate chamber. The samples were weighed at regular intervals in order to measure the moisture ingress with time. The samples were then transferred to the vacuum oven and kept in vacuum at 25 °C to observe the effects of vacuum on moisture removal. This process is described in the flowchart below (refer Figure 4-41)

Figure 4-41: Procedure employed for observing moisture ingress and egress

The weight used for calculation of percentage weight increase is the average weight of 3 samples of each configuration. The weight of completely dried samples is considered for the base of percentages. Furthermore, the moisture ingress is the average moisture content in the sample as the moisture is not evenly distributed.

Moisture ingress in the sample is calculated as follows:

$$\%\ moisture\ (by\ weight) = \frac{(W - W0) * 100}{W0}$$

Where:
W is the weight of the sample
W0 is the weight of the sample when it is completely dry

The main aim of the experiment is to estimate the amount of moisture that can be expected in the insulation under the different scenarios. This will help optimise the exposure time. The moisture ingress section is divided into 2 sections as follows:

1. Effects of 3-hour exposure to climate chamber
2. Effects of 24-hour exposure to climate chamber

Furthermore, in the following section, the effect of vacuum on moisture removal is also analysed.

4.4.1.1 EFFECTS OF 3 HOUR EXPOSURE TO CLIMATE CHAMBER

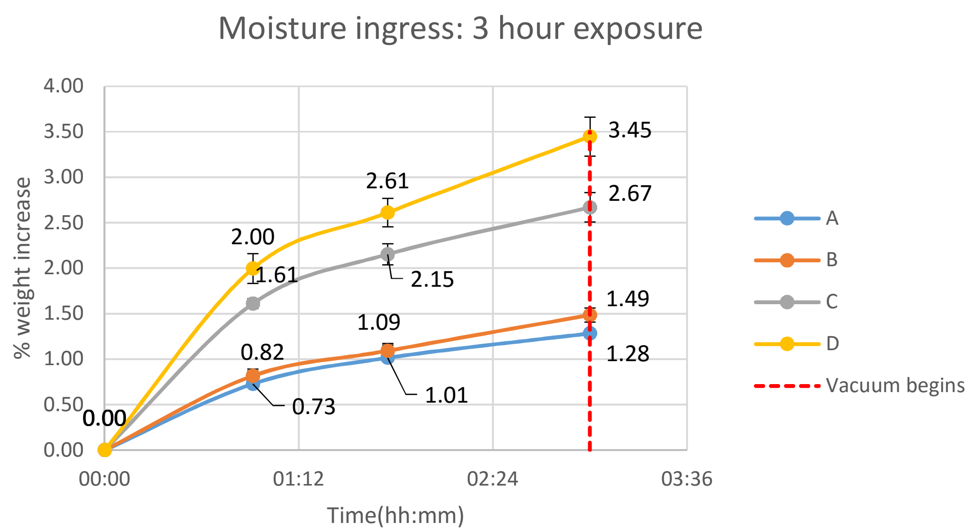


Figure 4-42: Moisture ingress (% weight) when exposed to climate chamber for 3 hours

Figure 4-42 shows the moisture ingress into various samples types when exposed to the climate chamber for 3 hours. First, let us consider the A & B configurations which are 10 mm thick samples. Both the configurations almost follow a similar trend for moisture ingress and weight increase is about 1.3 and 1.5%, respectively. This moisture ingress is still below the critical 2%, which is considered to be wet.

The ‘C’ configuration however, absorbs considerably higher moisture corresponding to its weight and at the end of 3 hours it has a moisture content of roughly 2.7% by weight. D configuration which is the thinnest at 4mm has a moisture content slightly less than 3.5% which is wet.

Vacuum Cycle

Vacuum is mainly used during the production to empty the voids in the insulation and ensure proper impregnation of the insulation. However, Vacuum may increase the evaporation rate by reducing the boiling point of water and thereby could have drying effects on the transformer.

After exposure to Climate chamber, the samples are subjected to vacuum cycle at 25 °C. After the vacuum cycle, the samples were weighed and tabulated. The percentage weight change is as depicted in Figure 4-43

It is clear from Figure 4-43, that vacuum cycle leads to weight reduction in all the samples. However, the weight loss can be due to loss of moisture or clearing of small air pockets inside the pressboard material. In order to confirm this, a number of completely dry samples were exposed to the vacuum chamber for 24 hours and found out to have no weight loss. Therefore, the weight loss must be due to the removal of moisture.

The moisture removed due to the vacuum of 24 hours varies between 25-40 %. The maximum moisture removed in in sample D which loses 40% of the moisture. A configuration loses about 27% percent and both B & C lose about 32 % moisture by weight.

Similar experiment was repeated with 24-hour exposure to climate chamber

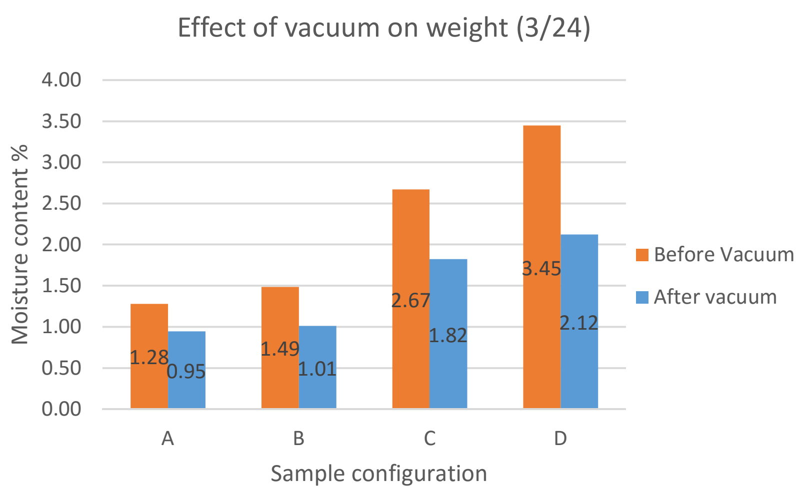


Figure 4-43: Effect of vacuum on weight

4.4.1.2 EFFECTS OF 24-HOUR EXPOSURE TO CLIMATE CHAMBER

The effects of exposing pressboard to climate chamber for 24 hours is depicted in Figure 4-44. It follows a similar trend to that of 3-hour exposure. With A and B configurations absorbing slightly less than 4% moisture at the end of 24 hours. C and D configurations have 7 and 7.6 % moisture. The error for all the samples is less than 0.2 % and is not plotted on the graph to help with clarity. All the samples are very wet according to the standards. After the exposure, the amount of moisture is almost equal to the moisture content that can be found in a sample which has been stored in ambient conditions in the lab at about 20 °C and 30-50 % RH. Hence, such a long exposure must be avoided.

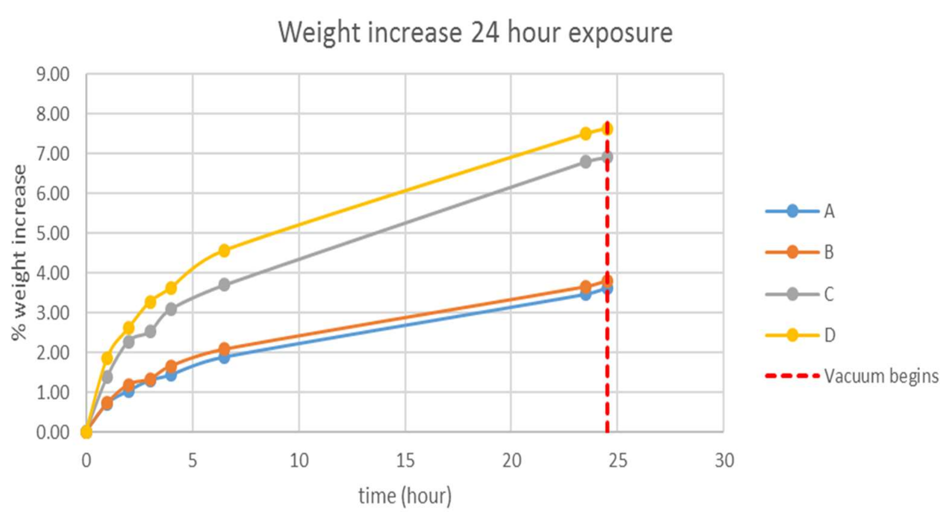


Figure 4-44: Weight increase with 24-hour exposure to climate chamber

Although, moisture content in terms of percentage weight increase gives a good picture of the rate of moisture ingress, the weights of different configurations vary by a considerable amount. Therefore, to study the absolute moisture content in different samples it is plotted in Figure 4-45.

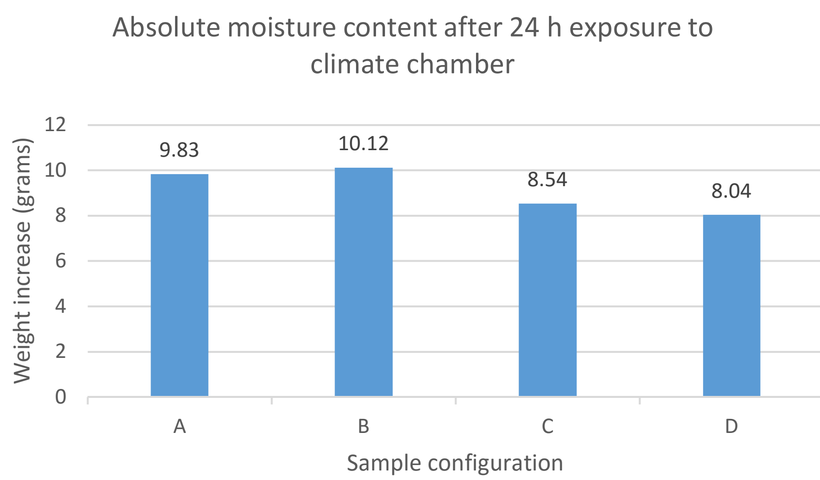


Figure 4-45: Absolute moisture content (g) when exposed to climate chamber for 24 hours

After 24 h exposure to climate chamber each sample of configuration A & B absorb moisture around 10 g. The highest moisture absorption is by configuration B. Samples C & D absorb around 8 g. Therefore, after a long exposure, thicker samples have a higher absolute moisture content.

Although the 10 mm samples have a higher moisture content, the moisture increase in percentage is lower than that of thinner samples (C & D) due to the different initial weights of the samples.

Vacuum Cycle

In order to observe the effects of vacuum cycle, two measurements were made, one after 4 hours and another after 24 hours and the results are plotted in the graph (refer Figure 4-46). After the samples were weighed following the 4-hour vacuum, the samples were put back into the vacuum chamber and exposed to another 24 hours in vacuum. In both cases, the moisture removal is clearly evident and confirms the effect of vacuum on moisture removal. Although a longer vacuum time helps, the amount of moisture remaining due to 24 h climate chamber exposure is high, Type B sample has 2.77% moisture and Type D has over 4 %.

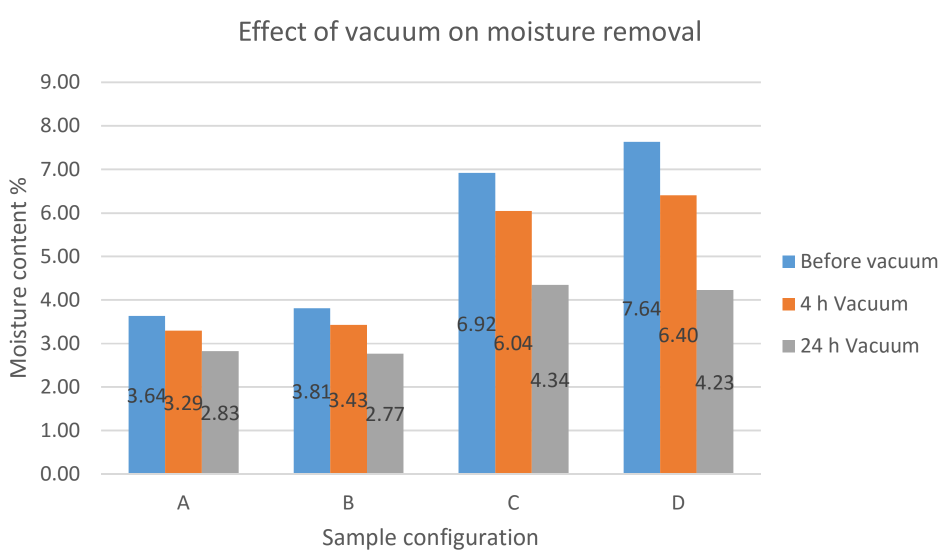


Figure 4-46: Effect of vacuum on moisture

Therefore, it can be concluded that vacuum cycle reduces moisture content in pressboard.

4.4.1.3 OPTIMUM VACUUM TIME TO CONTROL MOISTURE

From the section on PD testing under non-equilibrium conditions (Section 4.2), it was summarised that the PD level can be high and would pose a major threat in factory acceptance tests (FAT). Hence, in order to produce a transformer of acceptable quality and ensure that it can function reliably for the designed period, the moisture level is to be restricted below a certain level. Vacuum has an effect on moisture removal and it can be used to control the moisture level. Hence, in this section, the results of the experiments to find the optimum vacuum time to be used during the manufacturing are discussed.

With new regulations at SMIT factory, the tightening process has been restricted to a maximum of 7 hours during the production process. In order to find the optimum vacuum time two scenarios are considered. First, when the transformer is exposed for 7 h to the atmosphere and the effects of expediting the tightening process to 5 hours.

Therefore, two sets of samples are exposed to the climate chamber for the respective time periods to 60 °C and 75 % RH. Each set of samples consists of 4 configurations (A, B, C, D) and 3 samples of each configuration were used.

After exposure to climate chamber, the samples are exposed vacuum for an extended period at 25 °C. This temperature is to simulate the worst case scenario as higher temperatures would dry the transformer faster. A period of around 60 hours of vacuum is chosen as it would be ideal during manufacturing. It would be the approximate time the vacuum cycle can be extended without losing productivity. The idea was to bring the moisture content in all samples to less than 2% by weight

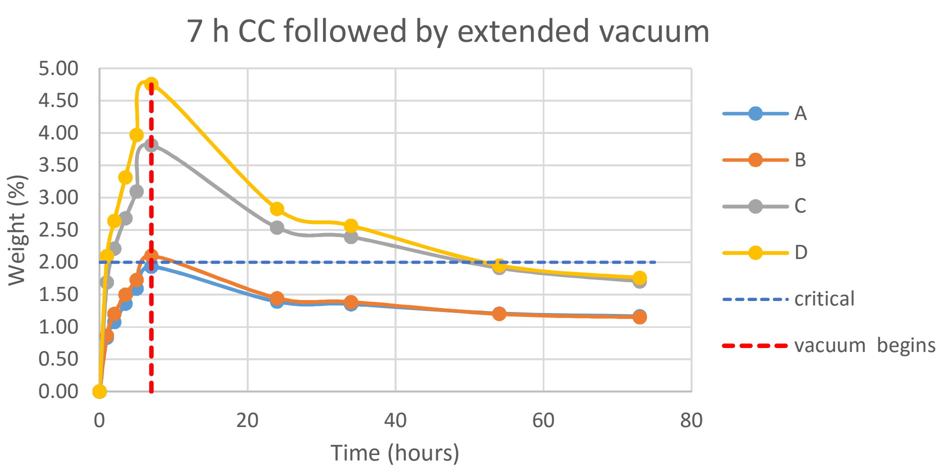


Figure 4-47: Moisture ingress and egress with 7 h climate chamber & 66 h vacuum cycle

Figure 4-47 depicts the moisture ingress and egress during 7 h climate chamber & 66 h vacuum cycle. The laminated sample A and B absorb around 2% moisture at the end of 7 hours in climate chamber. However, samples C & D absorb around 4 and 4.8 %, respectively.

If all the sample configurations are maintained under 2% moisture; the whole transformer can be safe. The vacuum cycle currently used is 24 hours and in this case, the C & D samples would contain 2.5 - 3 % moisture. It takes just short of 48 hours of vacuum to get samples under 2 % moisture.

In Figure 4-48, the samples were exposed to 5 hrs. in climate chamber before the vacuum cycle. A & B type samples absorb moisture and increase in weight by 1.67 & 1.76 % (average), respectively. Similarly, C & D type samples absorb moisture and increase in weight by 3.2 & 3.8 %, respectively. Under vacuum the configurations A & B lose moisture quickly in the first few hours and then the rate decreases, although still losing weight. Similarly, in C & D configuration, the samples lose considerable weight and reach 2 % around the 40-hour mark, however still maintaining the downward trend at the end of 68 hours. Therefore, a shorter exposure could lead to a shorter vacuum time.

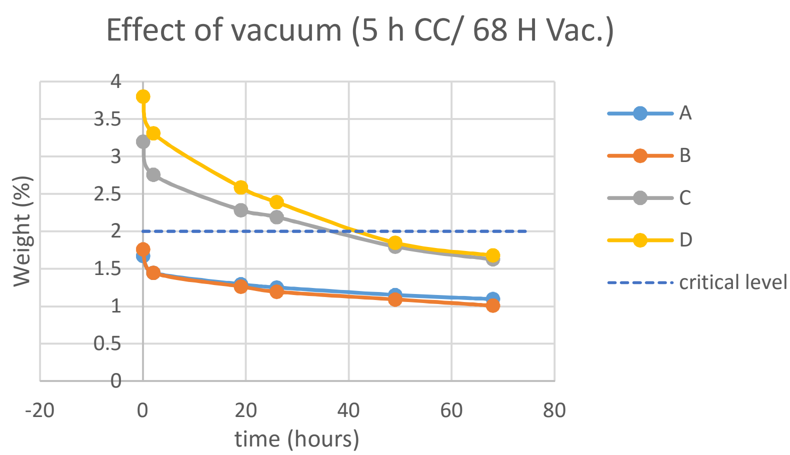


Figure 4-48: Effect of vacuum on samples exposed to 5h in CC

Testing

It was necessary to confirm that the samples are free of PD after the extended vacuum. Based on previous PD tests it was decided to test sample configuration of B & D since they produced more PD. 12 samples (6 samples of each type B&D) were impregnated with hot oil at the end of vacuum cycle and were tested for PD occurrence.

The first sample chosen for testing was of type D, which had ***no*** standing time and was tested barely 10 minutes after impregnation. The PD of 3 pC magnitude started during the ramp up to enhancement voltage of 18 kV (as shown in Figure 4-49) and persisted for 10 min into the tests and became extinct for the entire duration of the test. Since the sample is moist a longer time has to be given for proper impregnation.

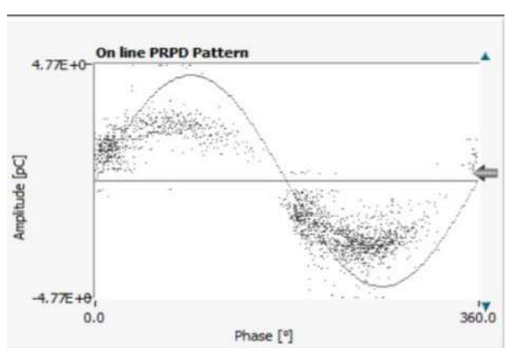


Figure 4-49: Internal discharges in sample with no standing time

Similarly, other samples were tested at regular intervals up to a standing time of 5 days and none of them produced PD. Even at enhanced stress, the D-type samples were PD free up to 45 kV (10.75 kV/mm) and B-type were free up to 50 kV (5 kV/mm).

4.4.1.4 SUMMARY

On analysing the results of the experiments it can be concluded that:

- Vacuum cycle reduces moisture
- If tightening process restricted to 7 hrs., vacuum cycle of 48 hrs. will ensure moisture content is below 2 %.
- If tightening process restricted to 2 h, extended vacuum time will not be necessary
- Samples with moisture content less than 2 % do not produce PD after 24 hours of standing time.

4.4.2 MOISTURE ESTIMATION TOOL

In this section, a tool is made to estimate the moisture content during the manufacturing process and help decide the vacuum time to restrict the moisture under 2% in 4mm thick pressboard. For this tool only the thinnest samples (4 mm type D) have been utilized because they are the limiting factor for vacuum time.

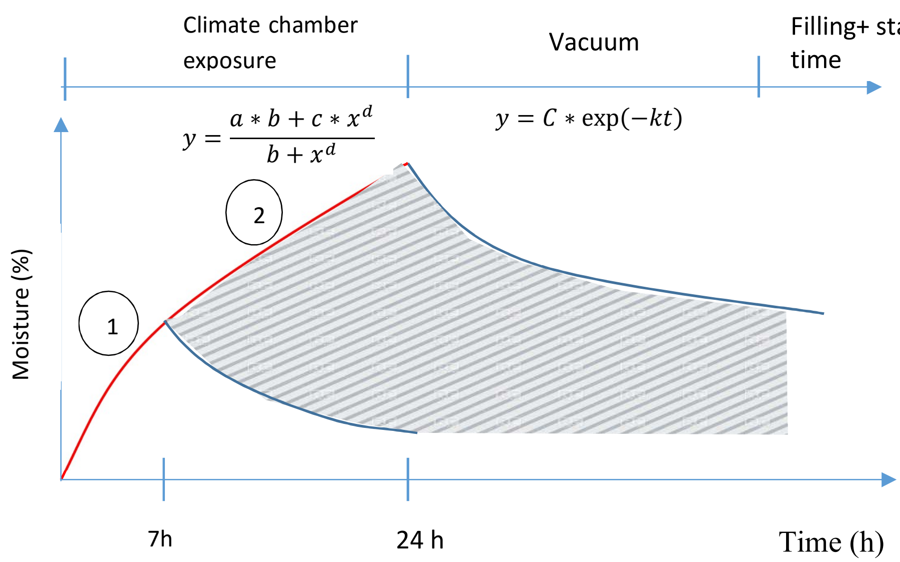


Figure 4-50: Moisture to be estimated in the shaded region

In Figure 4-50 the curves represent the moisture ingress and egress during the climate chamber and vacuum cycles. The curves 1 and 2 stand for short and long exposure, respectively and have been obtained experimentally. However, using this tool, the moisture can also be estimated in the intermediate stage (i.e. the shaded region).

S.no	Phase	Equations	Values
1.	Growth phase (Tightening)	$y = a * (1 - \exp(-kx))$	a=7.584 k=0.173 x= time
2.	Growth phase equation 2	$y = \frac{a * b + c * x^d}{b + x^d}$	a = -1.54E-04 b = 9.27E+00 c = 1.91E+01 d = 5.69E-01
3.	Decay phase equation (vacuum)	$y = C * \exp(-kt)$	C= final moisture content after climate chamber k= 0.01778 decay constant

Table 4-10: Equations used for moisture estimation tool

A model has been developed in Microsoft Excel (refer Appendix C) which can give the moisture remaining and the estimated vacuum time remaining for target moisture just using an input of 3 values; i.e. tightening time, vacuum time & target moisture. This simple tool can easily be used by the designers to estimate the required vacuum time.

During the tightening phase the moisture ingress can be represented using an exponential decay (increasing form) as represented in equation 1 in Table 4-10. However, using a curve fitting software - CurveExpert a very good fit (correlation coefficient: 0.999) was obtained and mentioned in growth phase equation 2, which has been used in the model to achieve better accuracy.

While measuring the moisture ingress the errors that occur can be due to the following:

$$\delta W\ (error)\ = \delta_{scale\ resolution} + \delta_{statistical} + \delta_{time\ of\ measurement}$$

Scale resolution is accurate down to 10 mg. The statistical error is 0.260 and corresponds to the standard deviation of the population investigated. Also, another source of error is due to the slight difference in time in weighing different samples ($\delta_{time\ of\ measurement}$), however it is negligible as all the samples are weighed within a couple of minutes and its impact is very low. Since ($\delta_{scale\ resolution}$, $\delta_{time\ of\ measurement}$) $\ll \delta_{statistical}$, the error during moisture ingress is limited to 0.26 %

During the vacuum phase, the moisture egress is represented using an exponential decay function whose equations and parameters are mentioned in equation 3. The decay rate is obtained using curve fitting when the samples are exposed to 7 hours in climate chamber. The model assumes a similar decay rate for all the initial moisture contents in the samples. The sample is verified with samples exposed to 5 and 7 hours and gives a very good fit with an R-square value of 0.9459 and 0.9046, respectively. However, since this model assumes similar decay rate some error may be present when extrapolating to samples which were exposed to the atmosphere for very long period say 24 hours. Since, the tightening process is restricted between 3- 8 hours this model will provide a very good insight on the moisture content in the pressboard insulation.

The model does not display the average moisture content in the transformer but that of 4 mm pressboard. The average content would be lower than this value.

A sample of the model developed is attached in Appendix C

4.5 OTHER POSSIBLE SOURCES OF PARTIAL DISCHARGES

There are several reasons why partial discharges can occur in oil-impregnated transformers. Some of the most probable causes of PD are :

- Insufficient drying of the insulant
- Imperfect degasifying of the insulant
- Imperfect degasifying of the oil
- Presence of dirt or other foreign matter
- Ageing of oil during operation
- Field concentration which cause local breakdown
- Others

Insufficient drying of the insulant (pressboard) is the main research of this research and keeping moisture content below the specified limits is very critical. By regulating the exposure during tightening and increasing the vacuuming time as stated in the earlier sections moisture content can be kept under the limits and a long standing time is not warranted in this case.

SMIT transformers, Nijmegen follows the prescribed standards regarding degasifying, filtering and drying of oil during manufacture and is not considered to be a factor for standing time. Furthermore, we are considering new and properly designed transformers, hence, ageing and field concentration do not affect standing time.

Another mechanism which was considered was of development of static charge during oil filling which could lead to PD due to space charge formation. However, this is also considered by SMIT while designing transformers and not a cause for concern for standing time.

With the most probable causes of partial discharges taken into account, the conclusions and recommendations on standing time to be employed are mentioned in the following chapter.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the results of all individual tests discussed in chapter 4 are taken into account to answer the problems defined in the introduction unit. The main research objectives which were mentioned were:

1. Effects of moisture on pressboard material – do they produce partial discharges when exposed to moisture? If so, what is the critical moisture level?
2. Does standing time have an effect on pressboard insulation? If yes, estimate the optimum standing time for a transformer during construction.
3. Effect of oil temperature on partial discharge (PD) tests. Does hot oil have an adverse effect on PD test outcome?

5.1 CONCLUSIONS

Based on the experiments conducted to study the effects of standing time, it can be concluded that:

1. Dry samples are PD free up to 10 kV/mm, which is higher than the design stress.
2. Moisture content greater than 2% makes pressboard susceptible to partial discharges.
3. However, none of the samples tested (even those with 6% moisture) produced discharges which would jeopardise the factory acceptance tests when tested at thermal equilibrium and a stress of 4 kV/mm.
4. 24- hour exposure to climate chamber can lead to an average moisture ingress of 6 % in 4 mm thick samples. These samples can produce surface discharges incepting at 4.5 kV/mm. These discharges can be of very high magnitude (nC) and hence such exposure to ambient during tightening must be avoided.
5. Even in case of improper impregnation partial discharge activity is not observed after 48 hrs. of standing time.
6. No appreciable correlation is observed between PD inception voltage/ magnitude and standing time for all pressboard sample configurations. No partial discharge activity is observed after 48 hours which can cause failure during FAT. Therefore, standing time can be optimized to 48-72 hours (Refer recommendations).

Based on the experiments to study the effect of oil temperature while testing, it can be concluded that samples with moisture content above 2% can lead to discharges of high magnitude (nC) under non-thermal equilibrium conditions, therefore, moisture must be kept under 2 %.

It was found out that the oil moisture content increases immediately after impregnation due to moisture migration. Drying the oil during this period will lead to removal of < 0.4 % of the moisture present in the transformer. Hence, this phenomenon cannot be used to control the moisture present in transformer.

With the latest regulations at SMIT limiting tightening time to 7 hrs., a 48-hour vacuum cycle will ensure 4 mm thick samples will have less than 2% moisture. Thick samples (10 mm) will have less moisture content (percentage) compared to 4 mm thick samples (due to their higher initial mass). Therefore, the transformer moisture content would be less than 2% even under worst case scenario (60 °C and 75 % RH).

Furthermore, a model is developed to estimate moisture ingress into the transformer depending on the duration of tightening. It can be used to adjust vacuum time to control moisture during production.

Based on the above statements, recommendations to optimize standing time are mentioned below:

1. Based on the experiments on pressboard insulation, standing time can be reduced to 48 hours in order to reduce the effects of bubbles which can cause partial discharges by slowing down impregnation.

2. Caution must be exercised while extrapolating the results of test on pressboard samples to that of a full transformer construction. However, based on internal discussions it is believed that in a transformer construction, discharges measured will be smaller in magnitude due to signal attenuation and the effects of stray capacitance.

3. With considerations on partial discharges arising from insulating paper and how discharges from samples would reflect in a transformer construction, SMIT transformers can optimize the standing time to 48-72 hours. One of the books on transformer design [5] suggests a 72 hour holding/standing time for transformers rated at 400 kV. This may also include a safety margin as it states that this can be reduced based on manufacturers experience.

4. It is advisable to keep the temperature of transformer constant as much as possible during partial discharge tests in order to reduce the effects of moisture migration. The discharges arising due to moisture migration (when moisture > 2%) can otherwise lead to failure during FAT.

5.2 Recommendations for future work

With clear conclusions on the influence of moisture in pressboard insulation on standing time obtained, a few suggestions for future development of this project are mentioned below:

1. More tests can be conducted to obtain statistical data especially on thin samples (4 mm thick) regarding discharges when samples are under non-thermal equilibrium (to study the effects of moisture migration on partial discharges).

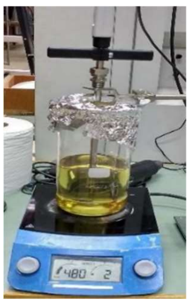
2. The moisture estimation tool can be expanded to help decide vacuum time based on real-time climatic conditions and not just the worst case scenario.

Appendix A. Moisture in oil – without pressboard

This test was performed in order to study the change in moisture content of oil after impregnation. The aim of the experiment was to observe if the absolute moisture content (ppm) in oil varies with change in temperature. Since the test sample is only oil, the influence of pressboard-oil dynamics is eliminated. Using these results, it can be verified if the spike in moisture content occurs due to pressboard-oil dynamics or is the effect of temperature on the measuring device.

Two sets of experiments were conducted:

1. Wet oil – heat cycling
2. Dry oil: heat cycling



Setup: For both the experiments, 1.5 L of mineral oil at room temperature was taken in a glass jar. The Vaisala probe is positioned in such a way that the sensor is always below the oil level. The moisture content was continuously measured while kept on a hot plate. In order to reduce the effects of atmospheric conditions, the glass jar was covered with aluminium foil. Although the jar was covered, the setup was not airtight. The sensor is works on measuring the change in capacitance of the sample. Therefore, a magnetic stirrer was used to stir the oil continuously to prevent formation of an oil layer which may lead to erroneous results. The measurement setup is shown in Figure A-1.

Figure A-1: Test setup for Measuring moisture in oil

Results

Moist oil – heat cycling

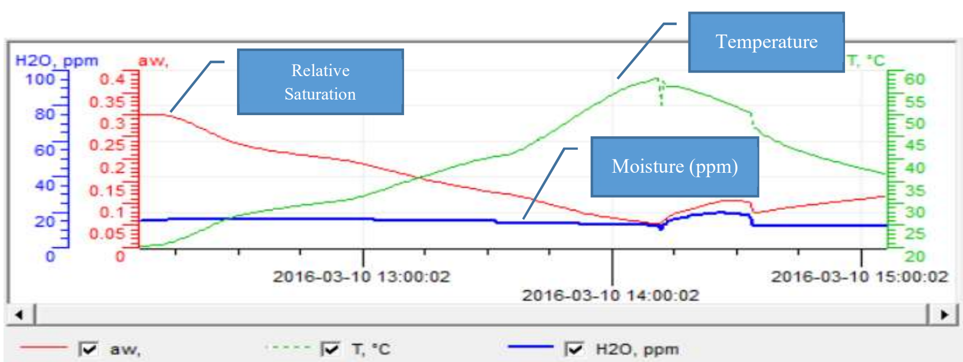


Figure A-2: Heat cycling of wet oil

The first experiment was on moist oil, the moisture content is 16 ppm and is considered as wet. First, the sample is at room temperature and the oil is slowly heated in about 2 hours to 58°C. The three parameters temperature, water activity and moisture absolute ppm are measured by the sensor and the measurements are stored in the handheld device connected to the sensor and was plotted on the computer as shown in Figure A-2. Then, the effect of cooling is investigated. In the graph during the cooling down an increase in moisture ppm level is observed. This is due to the effect of turning off the stirrer along with the heater which led to erroneous results. Once the stirrer is turned on the meter once again records the correct value.

Dry oil: heat cycling

A similar experiment as above is conducted with dry oil (5 ppm). In this case the oil is first cooled and then it is heated. The result of heat cycling is plotted in Figure A-3

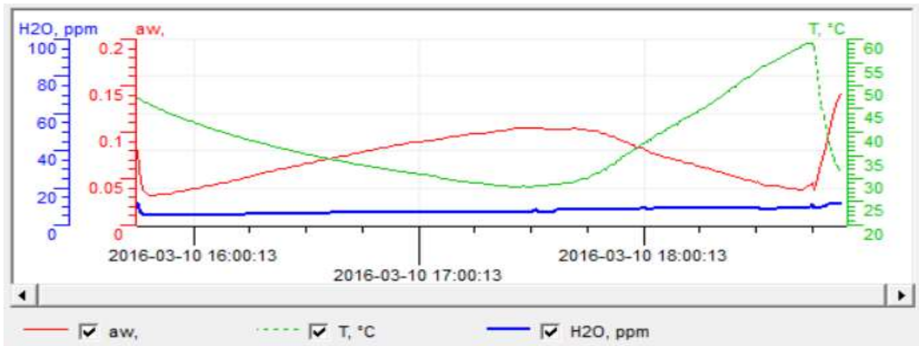


Figure A-3: Heat cycling of dry oil

Observation:

As it can be observed in the graphs, the moisture content (ppm) does not vary much with temperature.

It can be observed that the moisture (ppm) level in both experiments are constant throughout the period of measurement, irrespective of the temperature. It can thus be concluded that the spike in the moisture level is due to the dynamics of pressboard-oil insulation.

Result:

Moisture content (ppm) is not a function of temperature and the observed moisture fluctuation were due to pressboard-oil dynamics.

Appendix B. Moisture in oil after equilibrium

In the series of PD tests that were conducted on various pressboard samples, the moisture level in oil was monitored for the entire standing time. Soon after impregnation there was a period of non-equilibrium (Refer Section 4.3.1) where the moisture levels vary. Once the moisture in oil is at equilibrium the moisture is recorded and plotted as shown in Figure B-1.

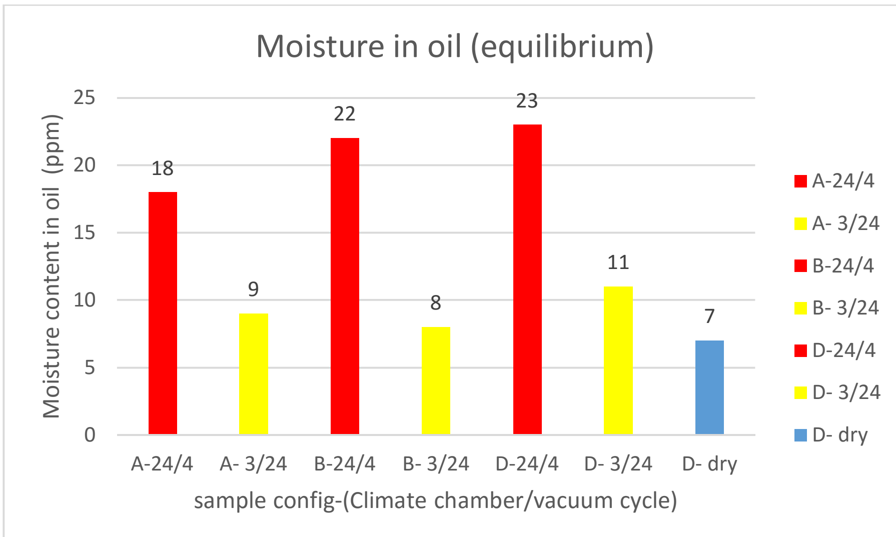


Figure B-1: Moisture level (ppm) in oil after equilibrium is reached

In Figure B-1, each bar represents the moisture level measured in oil. Each bar is named using the following convention: (sample configuration – Climate chamber exposure time/ vacuum time). For example, in A-24/4, the letter A stands for the sample configuration followed by 24 hours of climate chamber and 4 hours of vacuum.

The red bars in the figure represent the samples that were exposed to the climate chamber at 60 °C and 75 % RH for 24 hours. Similarly, the yellow bars stand for 3 hours of climate chamber exposure and 24 hours vacuum time. The Blue bar represents the tests carried out on completely dry samples.

Observations

At first glance, a clear trend can be observed, the moisture content in the samples that were exposed to 24 hours to climate chamber are much higher than the samples with an exposure time of 3 hours. Dry samples have the least moisture content in oil. Hence, the moisture content in oil indicates the moisture contained in pressboard. This fact is well documented in literature and these measurements verify the findings. The oil moisture in transformers can be compared with standardised measurement like Oomen curves to estimate the moisture in cellulosic insulation and is mainly used in life assessment of transformers.

Appendix C. Moisture estimation tool

A screen capture of the moisture estimation tool is depicted in Figure C-1. With three input values: (1. Time exposed to atmosphere, 2. Vacuum cycle time and 3. targeted moisture) the moisture remaining after tightening, moisture remaining after the vacuum cycle and the time remaining to reach target moisture can be obtained as output.

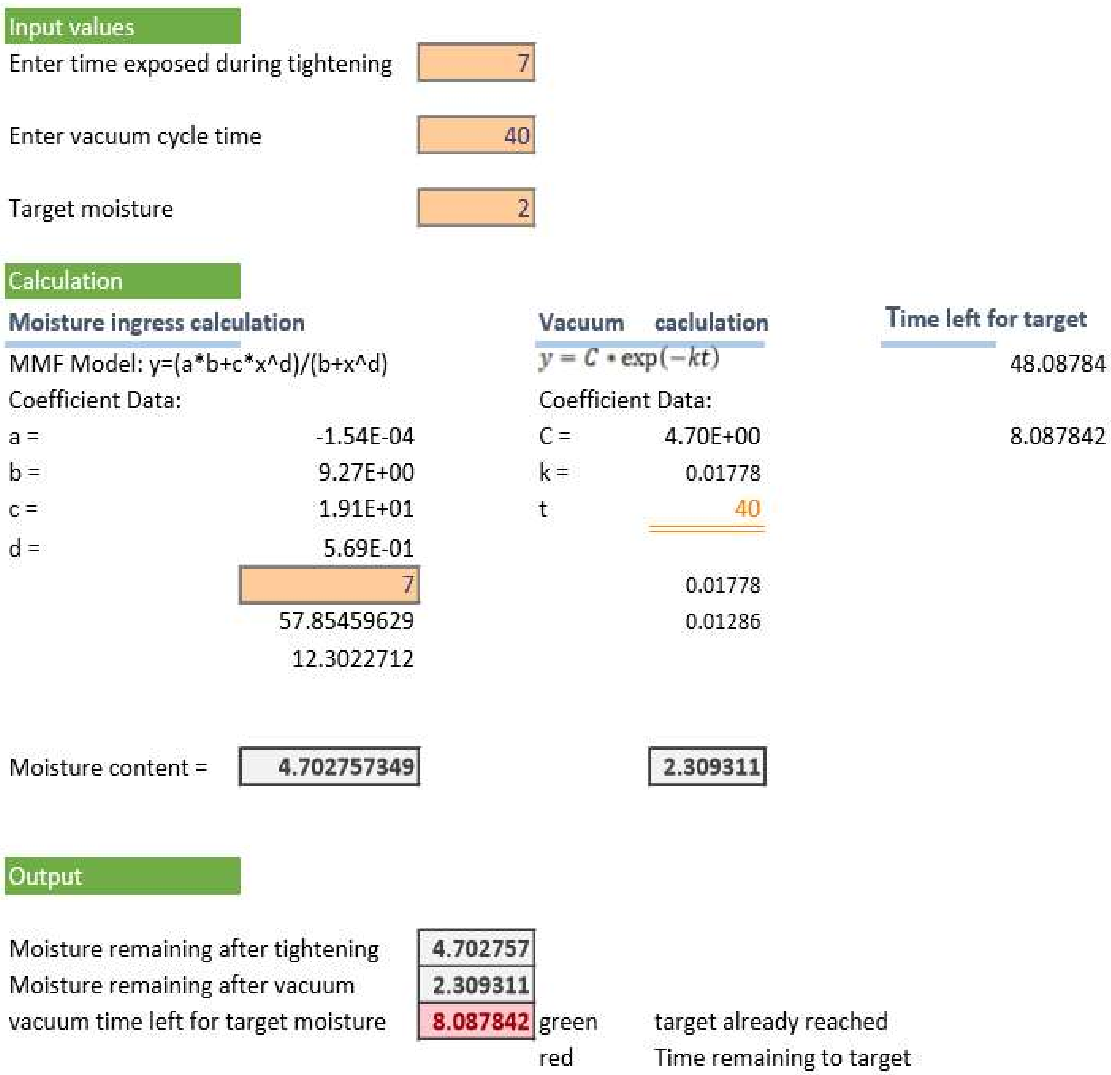


Figure C-1: Moisture estimation tool

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