IMPROVEMENT OF RELIABILITY & LIFETIME OF OIL IMMERSED POWER TRANSFORMERS THROUGH CONDITION MONITORING

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Declaration

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

S.A.K.P. Samarasinghe
Date:

I endorse the declaration by the candidate.

Prof. H.Y.R. Perera

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Abstract

Power Transformers are very critical in any power system and they are very expensive. Maintaining the Reliability and Well-being of Power Transformers shall be the fundamental responsibility of Electrical Engineers. Proper periodical maintenance of Power Transformers, Carrying necessary tests including Condition Monitoring Tests and attending to foreseen faults will enhance the reliability and life time of them.

Fault diagnosis using the condition monitoring test results by skilled engineers and Keeping technical staff and required spare parts readily available will make the power system more reliable by avoiding unexpected and expensive outages.

Therefore it is important to have an Index for a transformer that can imply the present condition. Selected condition monitoring tests for the Winding and Insulation oil are used to determine the Transformer Fitness Index (FI) which will indicate the well-being of the transformer. Depending upon the Fitness Index, recommendations are made how to increase the lifetime (If Possible) and the reliability.

This thesis describes the insulation paper, Insulation Oil, faults and testing methods for winding and oil. In the literature survey, detailed study about the selected tests and analyzed available test results of various power transformers of Ceylon Electricity Board (CEB) by referring to IEEE, ICE standards and relevant books.

Two prequalification tests were selected to detect the moisture content in the insulation. If both prequalification tests are passed Fitness tests were done and FI values were calculated. Depending on the FI values, recommendations and statements on the transformer condition is described. Those statements will be very helpful for the improvement of reliability and life time of existing transformers and to take the decision which transformers are to be replaced and when to be replaced.

Acknowledgement

I express my sincere gratitude to Professor Ranjit Perera for all the encouragement, guidance and support given throughout my engineering career to make this task a success.

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List of Principal Symbols

CEB	-	Ceylon Electricity Board
FI	-	Fitness Index
OFI	-	Overall Fitness Index
IFT	-	Interfreshal Tension
DGA	-	Dissolved Gases Analysis
FRA	-	Frequency Response Analysis
PD	-	Partial Discharge
DP	-	Degree of Polymerization
MIO	-	Moisture in Oil
MIP	-	Moisture in Paper
Ppm	-	Parts Per Million
Ppb	-	Parts PerBillion
2FAL	-	2-furaldehyde
U1R	-	Unit No.1 R phase Transformer
U1Y	-	Unit No.1 Y phaseTransformer
U1B	-	Unit No.1 B phase Transformer
IR	-	Insulation Resistance
BV	-	Breakdown Voltage
DIRANA	-	Dielectric Response Analysis
TDCG	-	Total Dissolved Combustible Gasses
PFI	-	Probabilistic Fitness Index
POFI	-	Probabilistic Overall Fitness Index

Chapter 01

Introduction

1.1 Introduction to research topic

Ceylon Electricity Board (CEB) is the main electricity supplier to Sri Lanka established by the Ceylon Electricity act in 1969. There are approximately 80large power transformers in CEB owned Power Stations and an even larger number in the Grid Substations.

All of those power transformers have to be well maintained to achieve maximum possible service, so that CEB can supply a quality, efficient, reliable and economical power supply to the nation.

To maintain the reliability the instantaneous working conditions have to be monitored because at every instant they are subject to electrical, mechanical, thermal, and environmental stresses. Those stresses cause degradation of the insulation (Oil and Paper) and ultimately to failure leading to unexpected breakdowns and outages to the power system.

1.1.1 Research Problem

CEB has nearly 50 large power transformers which are older than 25 years. There are several faults developing in these transformers due to degradation of insulation and deterioration of various other components. Those old transformers will not last their maximum possible life unless they are carefully monitored and take proper remedial actions at the correct time. Few of such transformers in Laxapana complex were recommended for immediate removal from service, after testing for Furan.

If these faults are not continuously monitored and there are no defined health indexes, the transformers can fail at any time so that CEB will not have enough time to purchase a new transformer for replacement. Generally, procurements for such equipment take more than a year.

1.1.2 Research Objective

It is not a big issue for a developed or rich country to replace all the faulty transformers as and when they fail. But it is a critical decision for an organization like CEB in view of the financial constraints.

Therefore, replacement of transformers has to be done only when it is essential and proper condition monitoring will help to take the right decision, when to replace.

Therefore my objective is to find a Fitness Index and the estimated remaining life time, so that the maintenance staff can get an idea of the present condition of the transformer and necessary maintenance can be started accordingly.

1.1.3 Methodology

- Power transformer test reports were collected during the past few years from the power stations in Laxapana complex and few others. Some tests were carried out during the project progress and results were recorded.
- Two tests were used as pre-qualification tests to find out moisture in oil and moisture in insulation paper.
- If prequalification test is passed, three important tests were selected and the test results were analyzed. (DGA, Acidity, and Furan tests)
- Depending on the above analysis, condition of the transformers, the “Fitness Index” was introduced.
- Depending on the Fitness Index some statements are made indicating the present condition, recommended maintenance activities and future behavior of the transformer.

1.2 Introduction to Power Transformers

1.2.1 Components of a Power Transformer

- Tank
- Transformer Core
- Winding
- Tap Changer
- Oil Conservator
- Bushings
- Moisture Breather
- Insulating Oil
- Insulating Paper
- Cooling Mechanism
- Other Components

1.2.2 The Main Tank

Main Tank covers the Core, Windings and Insulating Oil. It protects the inner components and provides a means of cooling the transformer by absorbing the inside heat (Conduction) and emit the heat to the environment (Convection and Radiation) [6].

1.2.3 Transformer Core

Core makes the Magnetic Circuit and it provides a path for the magnetic flux and confines it to link all the turns of all the windings. It is made of Silicon alloyed steel in the past and now the cold-rolled grained oriented slip is developed to reduce hysteresis losses. These steel plates are called laminations and they are varnished for the insulation. In power transformers Magnesia is used as the surface insulation to reduce eddy currents.

1.2.4 Winding

Winding is basically the insulated coil which converts the electrical power from one voltage to another one or more voltages. The input power is supplied to the primary winding and the output power is received from the secondary winding (and tertiary if any).

Made of high conductivity copper and bound firmly with paper or cotton tapes with solid insulation. It is wound around the magnetic core and there is a large number of turns depending on the capacity.

1.2.5 Tap Changer

Tap changer allows percentage change in the output voltage ratio within certain limits so as to maintain the output voltage constant. It is available online or offline. Not all the Power transformers are equipped with a tap changer, but in new transformers either on load or offload tap changers are usually available. On load tap changer can change taps while conducting the full load current. Transformer has to be de-energized to change the taps of the off load tap changer.

1.2.6 Oil Conservator

The function of the oil Conservator is to maintain the required transformer oil level in the main tank and allowing oil expansion and contraction during temperature changes with breather.

1.2.7 Bushings

Bushings are the connection mechanism of the winding terminal to the outside of the transformer. It eliminates the extremely high stress field produce at the entry in to the main tank. Outer part of the bushing is made of Parceling and the inner part is consisting of paper foil wrapping, oil impregnated paper, epoxy and fiber glass [6]. In large Power transformers bushings are equipped with embedded current transformers.

1.2.8 Moisture Breather

The breather contains silica gel crystals which immediately absorb the atmospheric moisture and avoid moisture entering to the transformer tank. Transformers breathe during its operation due to load changes and the expansion of oil in the main tank. The color of the silica gel serves as an indication as to when it must be replaced.

1.2.9 Insulating Oil

Insulating oil provides both cooling and electrical insulation. Its electrical insulation strength degrades with high water content and acidity. Acidity will also increase the rate of oil ageing, which in turn will result in more moisture and acids. Next to this, moisture and acidity will also enhance the rate of paper ageing. The cooling properties of the oil are negatively influenced by sludge and/or bad viscosity. Hence, the oil quality is crucial for the transformer condition and can be diagnosed, by the color, Interface Tension and Breakdown Voltage.

Insulating oil is Mineral oil that is used in the oil immersed transformers to insulate the windings from transformer tank or earth, and to insulate high voltage winding from low voltage winding. NITRO-10GBN, NITRO LIBRA and SHEL DELLA are some brands of insulating oil used in transformers in Sri Lanka. Some technical properties are mentioned below.

- Breakdown Voltage – Above 70kV
- Moisture content – 5 -30ppm
- Acidity – Below 0.01 mg KOH/g
- Color – Colorless

Insulating oil must meet stringent international standards such as IEC 60296. Some of the properties are chemical purity, stability against deterioration by thermal aging, stability against oxidation, a satisfactory viscosity curve at low temperatures, and good dielectric withstand capability.[16], [17].

1.2.10 Insulating Paper

Insulating paper provides electrical insulation between windings. The quality of the electrical insulation is mainly determined by its mechanical strength, which ensures that the paper holds its position. The ageing of the paper is accelerated by high temperatures, high water content, and acidity.

Main characteristics are withstanding impulse and transient surges, short circuit withstand of the mechanical and thermal stresses. Transfer heat away from the inner core to the oil, Insulation paper is made of cellulose material in Pine trees or Press board- made from polyester laminated boards. With aging of the insulating paper the dielectric strength decreases due to collecting and accumulation of moisture in to the paper.

Due to Partial Discharge, aging contaminants and thermal decomposition the paper get deteriorated and produces combustible gases like CO, H_2, CH_4, C_2H_2, C_2H_4, C_2H_6 and noncombustible gases like CO_2. The rate at which they are produced depends exponentially on the temperature and directly on the volume of material at that temperature. Because of the volume effect, a large, heated volume of insulation at moderate temperature will produce the same quantity of gas as a smaller volume at a higher temperature. [1]

1.2.11 Cooling Mechanism

Cooling mechanism consists of Radiator fins with cooling fans (ONAF) or radiator fins without cooling fans (ONAN) or oil circulation pump with oil cooler using water (OFW).

1.2.12 Other Components

Other components include serge arrester, Gas activated relay (Bukholtz), winding and oil temperature measuring system, pressure relief devices ect..

1.3 Reliability of Power Transformers

For a Transformer the reliability is defined as the Probability that the transformer will perform in a satisfactory manner for a given period when used under specific operating conditions. It is a quantitative term that represents the possibility of failure within a specified time period.

Power transformers shall be highly reliable than other transformers because the contribution to the power system is higher. As an example, reliability of a 300MVA power transformer in a 2000MW power system, heavily contributes to the reliability of the system. Another important fact is, if a series connected power transformer fails the power generation in the particular generator is completely lost.

Therefore to improve the reliability, actions have to be taken to minimize the failures and minimize the outage time. For that, condition of the Power transformers should be regularly monitored and necessary precautions have to be taken. Skilled maintenance crew, required spare parts, a spare transformer and maintenance tools should be readily available at the power Station.

1.4 Lifetime of Power Transformers

The lifetime of transformers can be categorized as economical life and technical life. After the capital cost is completely depreciated, the economical life is said to be over. But technically the transformer might be healthy even after the economical life. When the degradation of insulation paper takes place, until the paper become brittle and transformer losses become unbearable for the healthy operation the technical life is said to be over [11].

Generally there is no particular definition for the economical life or technical life. IEEE C57.91-1995 describes the life span as 20 years. In practice, oil filled transformers are designed for 30to 40 years [20].Factors that affect the lifetime of transformers are described in Section 2.2.

1.5 What is condition monitoring?

Condition monitoring is continuous collection of parameter data from the equipment and the analysis thereof to determine the risk of unexpected incapacity and the availability of capacity.
With respect to a Power Transformer mainly, following conditions can be monitored,

1. Condition of insulation Oil
2. Condition of Paper Insulation
3. Condition of the Winding
4. Condition of the Bushings

Chapter 02

Industry Related Problems

2.1 Transformer Faults and Failures

Transformers are designed to operate for decades. They have to be maintained in accordance with the maintenance manual and the international standards. The condition monitoring is also strongly recommended. Still they fail due to following reasons [6].

- Poor workmanship at the factory,
- Inadequate transformer design,
- Incorrect handling procedures,
- Incorrect packaging for transport,
- Incorrect installations.
- Operator errors,
- Overloading beyond its capability,
- Inadequate surge protection and subsequent line surges,
- Improper, insufficient maintenance,
- Lightning and switching surges,

2.1.1 Failure Rates of Transformers With respect to the age

Failure can occur at any time when it is in use. Generally the risk of failure increases with the life time. With past experience expected life of a power transformer can be assumed to be 40 years. To get an idea, here are some survey results for number of failures with the age at failure.

Age at Failure (Years)	No of Failures
0-5	9
6-10	6
11-15	9
16-20	9
21-25	10
Above 25	16
Age Unknown	35

Table 2.1: Failure Rates of Transformers With respect to the age

Source: Analysis of Transformer Failures- International Association of Engineering Insurers 2003 [4].

Following figure illustrate the Failure pattern of a transformer with respect to the age.

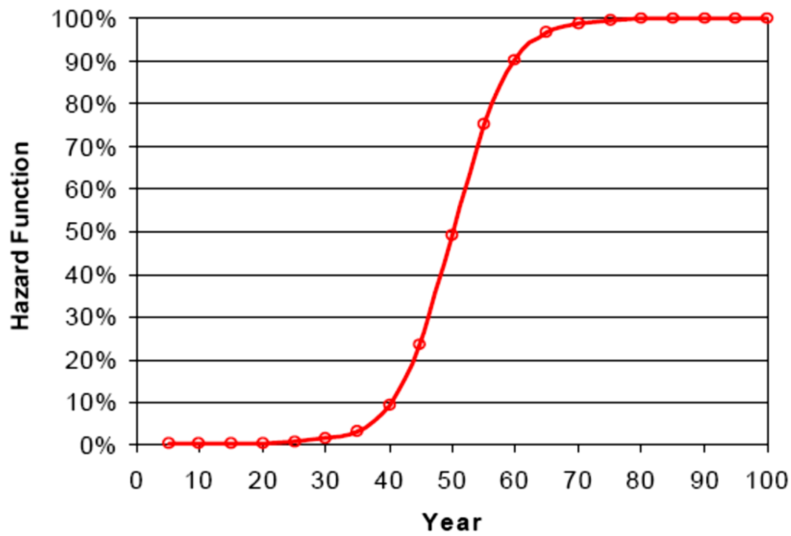

Figure 2.1: Transformer Failure Function

Source: Analysis of Transformer Failures- International Association of Engineering Insurers 2003 [4].

Transformer age is not a cause for failure. But there are factors depending on age which causes the failure [4]. An aged insulation system reduces both the mechanical and dielectric-withstand strength of the transformer. Transformers are subjected to faults that result in high radial and compressive forces due to the age. Mainly due to the increment of load demand with the system growth, the operating stresses increase. In this thesis the age is not considered as direct cause for the remaining life time. Instead, the faulty conditions caused by age such as insulation paper and oil degradation are considered. Summary on status of transformers of the Laxapana Complex are given below.

Power Station	Capacity MVA	Cooling	Manufactured year	Replaced In	Life time at replacement (Years)
Old Laxapana Stage 01	3 × 6.33	ONAN ONAF	1989	2012	23
Old Laxapana Stage 02	6 ×5.33	OFW	1958	2012	54
Wimalasurendra	6 ×10.5	OFW	1963	2012	49
Samanala	6 × 17.9	OFW ONAF	1965	2002, 2014	37 48 Years
New Laxapana	6 ×24	ONAF	1974	2013	39
Canyon	2 ×38	ONAF	1983, 1989	-	-

Table 2.2: Power Transformer Details available in the Laxapana Complex as at 2014[3]

Average life time of the replaced transformers is 42 years.

2.1.2 Failure Rates of Transformers With respect to the Cause

According to the reported failures, the leading cause of transformer failures is "insulation failure". This category includes inadequate or defective installation, insulation deterioration, and short circuits.

Cause of Failure	No of Failures
Insulation Failure	24
Design/Material/Workmanship	22
Unknown	15
Oil Contamination	4
Overloading	5
Fire /Explosion	3
Line Surge	4
Improper Maintenance /Operation	5
Flood	2
Loose Connection	6
Lightning	3
Moisture	1
Total Failures	94

Table 2.3: Transformer Failure Rates with respect to the cause

Source: Analysis of Transformer Failures- International Association of Engineering Insurers 2003 [4]

In this thesis the main causes of failure, the insulation failures are taken into special consideration. The condition of winding, paper insulation and oil insulation are monitored by means of several tests.

2.1.3 Transformer Failure Types

The most severe faults:

- Discharges of high energy (D2)
  - High energy arcing,
  - Flashovers and short circuits with current through insulations, resulting in extensive damage to paper,
  - Large formation of carbon particles in oil,
  - Metal fusion,
- Thermal faults of temperatures between 300°C and 700°C (T2)
  - Defective contacts,
  - Defective crimped joints,
  - Circulating currents
- Thermal faults of temperatures > 700°C (T3)
  - Large circulating currents between tank and core,
  - short circuits in laminations
  - Extremely bad contacts/joints
- Low Energy Discharges (D1)
  - Partial discharges of the sparking- type, inducing carbonized punctures in paper.
  - Low-energy arcing, inducing surface tracking of paper and carbon particles in oil.

The less severe faults:

- Partial Discharge
  - Discharges in gas bubbles
  - Voids trapped in paper, as a result of poor drying or poor oil-impregnation
- Thermal faults of temperatures < 300 °C (T1)
  - Overloading,
  - Blocked oil ducts

2.2 Lifetime reducing factors of a Power Transformer

- ✓ Degradation of insulation paper or the insulation material
- ✓ Degradation of the insulation oil
- ✓ Overheating of the Core and Winding
- ✓ Abnormal Loading Patterns

2.2.1 Measurement of Degradation

To predict the expected life or the present condition of a transformer there should be precisely measurable and quality parameters which are directly linked to the actual condition of the transformer. In practice such quality parameters may not be available or accessible, and information from other sources may be required.

In this study, all possible explicit quality parameters are considered. Explicit parameters are an observable/measurable quantity, and grouped into direct and indirect explicit parameters. Direct explicit parameters are directly linked to the degradation process, indirect explicit parameters are related but not directly linked to degradation process and require additional processing to extract information on their impact on the degradation process.

An example of a direct explicit parameter is the Degree of Polymerization (DP) which is measured in the Furan Test. It is a measurable quantity that is directly linked to the degradation process, and is a direct measure of the degree of degradation.

Partial discharge (PD) activity is an example of an indirect explicit parameter. It is again a measurable quantity, but it is not directly linked to a specific degradation mechanism, and may originate from various sources. This is not used in this thesis. Instead of Partial Discharge, dissolved gas analysis (DGA) is used which also is an indirect explicit parameter.

2.2.2. Degradation of Insulation Paper

Insulation failures were the leading cause of failure in the above survey described in Section 2.1.2. There are four factors that are responsible for insulation deterioration.

Overheating,
Oxidation,
Acidity,
Moisture

The highest temperature feels at the insulation paper which is immediately next to the high voltage winding. High temperature can affect the thermal life of the insulation paper. Every 8ºC above the rated insulated temperature will halve the life of the insulation (Maximum winding temp 105ºC and maximum top oil temperature 100ºC according to IEC 60076-2: 1993) [15].

Then transformer has to be de-rated. If the transformer sustains the same rating with full load the degradation process accelerates. Overheating can cause De-polymerization of cellulose. Oxidation of the cellulose can create byproducts like CO, CO_2, acidic compounds and water presence of which accelerates the degradation [1].

The accurate measurement of temperature of transformer winding is very important. In addition to the conventional method of thermal imaging there are new technologies like use of fiber optic sensors inserted inside the transformer winding to read an accurate result. The average age of the transformers that failed due to insulation failure was 18 years [4].

2.2.3 Degradation of insulation oil

Insulation oil gets deteriorated by various causes. Mainly due to the ingress of moisture, overheating, oxidizing and dissolved acidic compound in oil. Properties of insulating oil and technical details of insulating oil were discussed in Section 1.2.9 above.

Moisture enters to the transformer by means of several ways. Leaky seals at bushings, tap changer, coolers, radiators, pipe lines can allow moisture to enter in to the transformer. In high humidity days the possibility of entering moisture through leaks is higher. At the time of installation of the transformer necessary actions are taken to avoid entering moisture in to the transformer. However this cannot be completely avoided. Small amounts of moisture enter in to the transformer at the time of installation. The same thing can happen when it is directly exposed to the air at the time of maintenance or repair. Improper breather can cause moisture to enter in to the transformer. Moisture in side can react with the oil and paper to create dissolved gasses such as H_2, C_2H_2, CH_4, C_2H_4, C_2H_6 and generate more moisture. This can happen with aging and will lead to lower the insulation resistance. 0.1% - 0.2% (wt/wt) water increases per year due to oil and paper degradation.

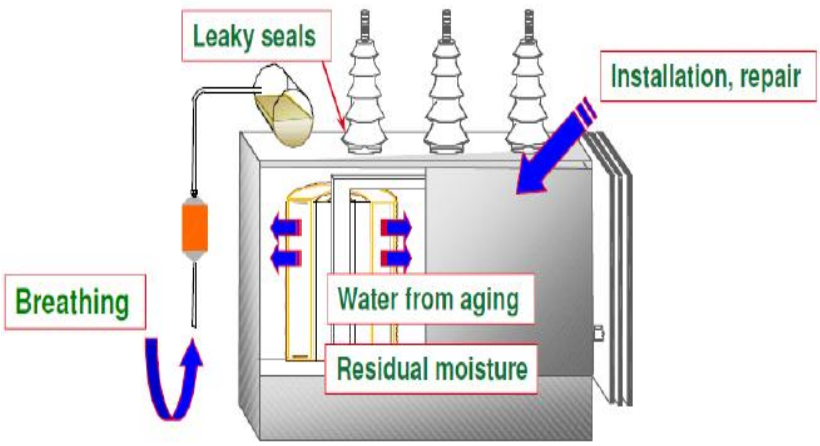

Figure 2.2: Moisture Ingress Methods

Residual moisture in the solid insulation (paper, press board, wood, resin impregnated materials etc.,) is not removed during factory dry out. About 0.5 -1% (wt/wt) water is left in paper when leaving the factory.

Condition	Rate
Direct exposure of oil impregnated insulation to air RH 75% @ 20°C RH 40% @ 20°C	Press board of surface area 1000 m^2 up to 0.5 mm depth 13.5 kg in 16 hrs 8.1 kg in 16 hrs
Molecular flow Via capillaries in seals Via loose gaskets	 <1-5 g per year <30-40 g per year
Viscous flow of air Adequate sealing Inadequate sealing	 600 g per year 15 g in a day
Operation with free breathing	6 kg per year
Insufficient sealing with rain water present	200 g in an hour (liquid water)

Table 2.4: Upper Estimate of the rate of water contamination [22]

2.2.4 Overheating of Core & Winding

When a transformer is loaded the Core and Winding get heated up. The Heat is transferred to the insulating oil and there are cooling mechanisms to stabilize the temperature. There are situations where the maximum temperature rise is reached and surpassed. If the transformer continues to run without timely maintenance of the cooling system the heat transfer will not properly happen and the winding and core are overheated. Due to some faults such as High Resistance Tap changer Contacts, internal arcing, high current switching can happen and it causes overheating. It is directly affected to the life of the insulation oil and insulation paper. Therefore, overheating of core and winding will affect the life time of transformers.

2.2.5 Abnormal Loading Patterns

When the transformer is loaded beyond its rated capacity hot spots can form. The Winding, Core and oil temperatures can go high. In that case the situation is similar to that described in section 2.2.4. Apart from that transient overloading can cause to reduce the life time. To analyze the transient and other abnormal loading patterns real-time data logging is required for at least 10 years. Such data could not be found within the CEB and therefore, the relation with Abnormal Loading Pattern and the expected life time were not discussed in this thesis.

Chapter 03

Condition Assessment Tests

3.1 Introduction to Transformer Tests

There are lots of tests that can be used to detect excising faults in a transformer. They can be categorized in many ways such as Visual Inspection, Color Inspection of Oil, Electrical Test, Chemical tests, Gas tests, Moisture Test, on site test, Factory Tests and Laboratory tests.

3.2 Insulation oil testing

3.2.1 Visual Inspection of Oil Colour

This is the first indication of oxidation of insulation oil. Early warning can be acquired by regular inspection of insulation oil color. Oil without water and oxidized contamination is very clear and becomes darker with the increasing moisture [9].

This test is not considered for the Fitness Index (FI) since this does not indicate quantitative results and a quantitative result can be obtained by moisture test, acidity test and other selected tests.

3.2.2. Moisture test (Conventional)

Method of entering moisture in to the transformer was discussed in Section 2.2.3 above. Moisture content is measured in parts per million (ppm).

Though, the bulk of water (around 80%) resides in the solid insulation (pressboard, paper), these quantities could not be directly assessed until recent past. Indirect methods (conventional) were used for this. This is firstly, relative moisture saturation (RS in %), as the ratio of the actual water vapor pressure to the saturation water vapor pressure, having the same physical meaning like the well-known relative humidity in gases. Secondly, water content is used, calculated by the ratio of water mass to insulation mass and given in % for cellulose materials and ppm for oil.

State of the art practices are to use equilibrium diagrams, where one tries to derive the moisture content in paper/pressboard from moisture content in oil (ppm), [19]. In recent years, dielectric response methods were developed, which deduce moisture in paper and pressboard from dielectric properties of the insulation. Dielectric response analysis is discussed in Section 3.3.3.

Conventional method of measuring moisture was, collecting an oil sample, measuring the moisture content in the sample and then using equivalent curves to predict the amount of moisture in the insulation paper. Small changes in inside temperature significantly change the dissolved water content in the oil but slightly change the water content in the paper. Therefore the measured water content of the oil is corrected to a defined temperature. Usually, 20 °C is the reference temperature.

Temperature Correction factor for Moisture in oil. $F = 2.24 \times e^{(-0.04T)}$ [9]

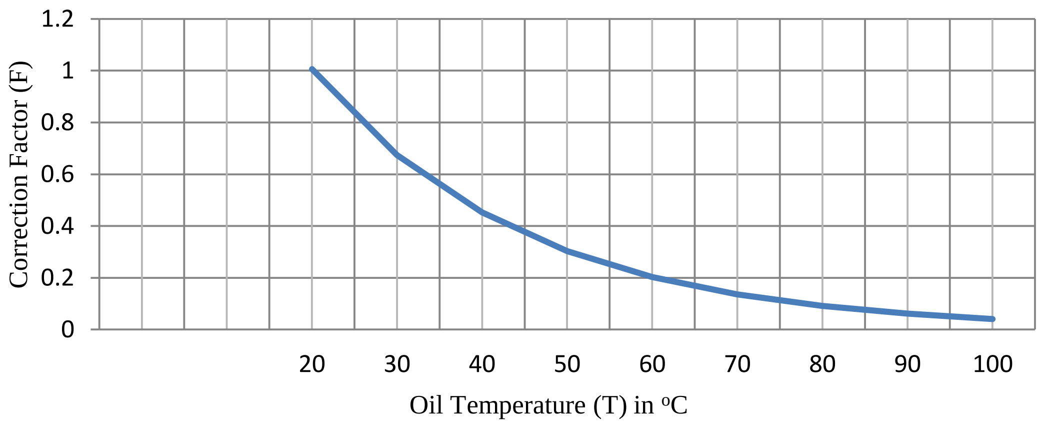

Figure 3.1: Temperature correction factor for moisture in oil

Water solubility (Ws) of oil is determined using, $Log(Ws) = 7.0895 - \frac{1567}{T}$
Temperature (T) is in Kelvin (K). [9]
Relative Saturation of Moisture in Oil (%), $RS\,\% = \frac{Water\ ppm}{Ws} \times 100\,\%$

Moisture in Paper/ Press board can be determined using the following equilibrium curve of Water in Paper & Oil plotted using experimental data. This equilibrium curves are built by various persons and shows slightly different results (E.g. Giffin, Oommen and Shell) [12].However, the FRA is more accurate than this conventional method for detecting moisture in paper/ pressboard. FRA is discussed in Section 3.3.3

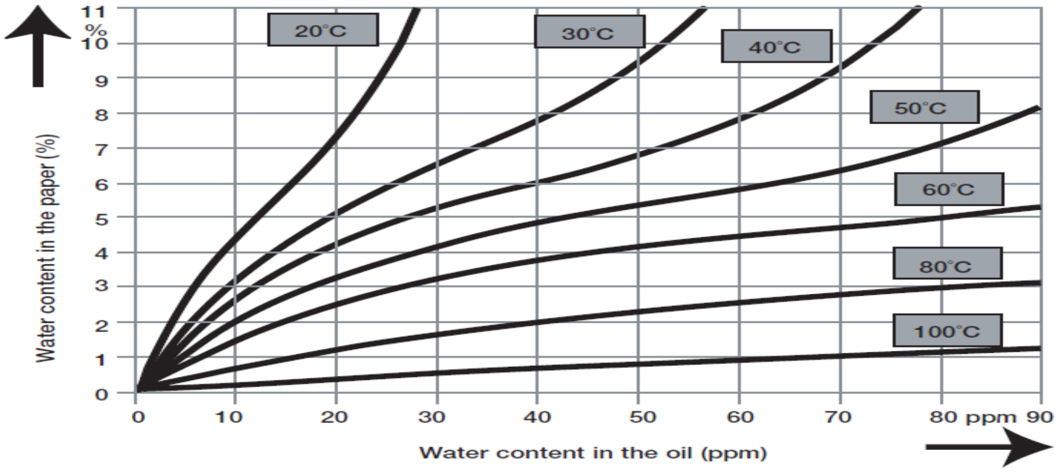

Figure 3.2: Equilibrium of Water in Paper & Oil

Guideline for Interpretation of Moisture in Paper

Percent Saturation water in oil, Adjusted to 20°C	Condition of Cellulosic Insulation
0-5%	Dry Insulation
6-20%	Moderate Wet insulation
21-30%	Wet insulation
Above 31%	Extremely wet insulation

Table 3.1: Guideline for Interpretation of Moisture in Paper
Source: IEEE 62:1995 (B6)

Guide for Acceptance and maintenance of Insulating Oil

IEEE Categorization	Voltage	ppm
New Fluid in New Equipment	<69kV	20
	69< kV <230	10
	kV > 230	10
Serviced Aged Fluid	<69kV	35
	69< kV <230	25
	kV > 230	20

Table 3.2: Guide for Acceptance and maintenance of Insulating Oil
Source: IEEE C57.106.2006

Under this test, only moisture in oil (MIO) is considered for this thesis. MIP is found from the Frequency Response Analysis (FRA).

3.2.3 Acidity test

Acids are created in the transformer oil due to acidic oxidation products. Acids mix with water and other solid contaminants to decrease the dielectric strength of oil. Further, acid is responsible for the corrosion of metal parts of the transformer.

The rate of increasing the Acidity of transformer oil is a good indication of the aging rate of the transformer and a good guide for determining when the oil should be replaced or filtered. According to IEEE C57.106.1991 [23], maximum acceptable acidity level for acceptance of new transformers is 0.03 mg KOH/g, for continuous usage is 0.2 mg KOH/g (Group II of [23]). Recondition or reclaim level of Acidity is 0.5 mg KOH/g (Group III of [23]). Failure Acidity level is 0.5 mg KOH /g (Failure probability P_4 is 100% of [24]).

If acidity level increasing beyond the continuous usage limits, sludge (Oxidation by Products) creates and damage to the paper insulation cannot be prevented. Acidity builds up exponentially [9].

3.2.4 Breakdown Voltage

The oil breakdown voltage is a measure of the ability to withstand electric voltages. Clean, dry oils have high breakdown voltages. The presence of moisture or solid particles reduces the breakdown voltage. IEC 60156 provides a breakdown voltage threshold below which the oil needs to be treated or replaced.

Reduction of breakdown voltage is mainly due to moisture and partly due to oil oxidation. The part affected by increase of water is reversible and can be recovered by drying. The water content is directly measured at the moisture test and the other oxidation products (gases) are detected by DGA, Acidity test. Therefore, Breakdown Strength test is not considered for the Fitness Index (FI).

3.2.5 Furan Analysis

The paper insulation is made of cellulose fibers and cellulose is made of fiber molecules. The structure of cellulose polymer consists of glucose molecules. Average number of monomers in a cellulose polymer chain is called the Degree of Polymerization (DP). In new paper insulation, one cellulose polymer chain consists of more than 1000 to 1500 monomers. DP value is 1000 to 1500. When the insulation is old DP value decreased gradually.

The transformer is said to be failed when the DP value is 200 [20].DP value is directly related to the transformer's remaining life time.

If a part of paper insulation can be taken out to measure the DP value, the remaining life can be accurately predicted. But it is not practical to take a sample of paper insulation from an oil immersed transformer without a long outage.

An alternative method for estimating the DP value of the paper insulation is using an oil sample. Since some byproducts are formed during ageing and get dissolved in oil, the oil can therefore be analyzed for Furan content.

During thermal ageing, large quantities of furanic compounds can be generated when cellulosic materials are exposed to very high temperatures (typically above 120°C). The rate of accumulation will also be a function of other factors: oxygen concentration and water content. Once formed, the furanic compounds can then survive for prolonged periods of time in bulk oil. The types of furanic compounds that can be formed are tabulated below.

Compound		Due to
2-Furfurol alcohol	2FOL	High Moisture, wet insulation
2-Furaldehyde	2FAL	Cellulose Deterioration
2-Acetyl Furan	2ACF	Rare, Hard to measure
5-Methyl-2-furaldehyde	5MEF	Shock, Lightning, severe overheating
5-Hydroxymethyl-2-furaldehyde	5HMF	Oxidation, Active Fault

Table 3.3: Five Furanic components

Out of the above five 2-furaldehyde (2FAL) is the most stable by produce of cellulose deterioration. The laboratory tests have revealed that 2FAL, when it's formed, is stable for years. Therefore, it is used as an indicator in order to predict the paper DP value [20].

Chendong found the below empirical relationship between 2FAL value and DP value.

$$\text{Log}(2FAL) = 1.51 - 0.0035\ DP \quad [20]$$

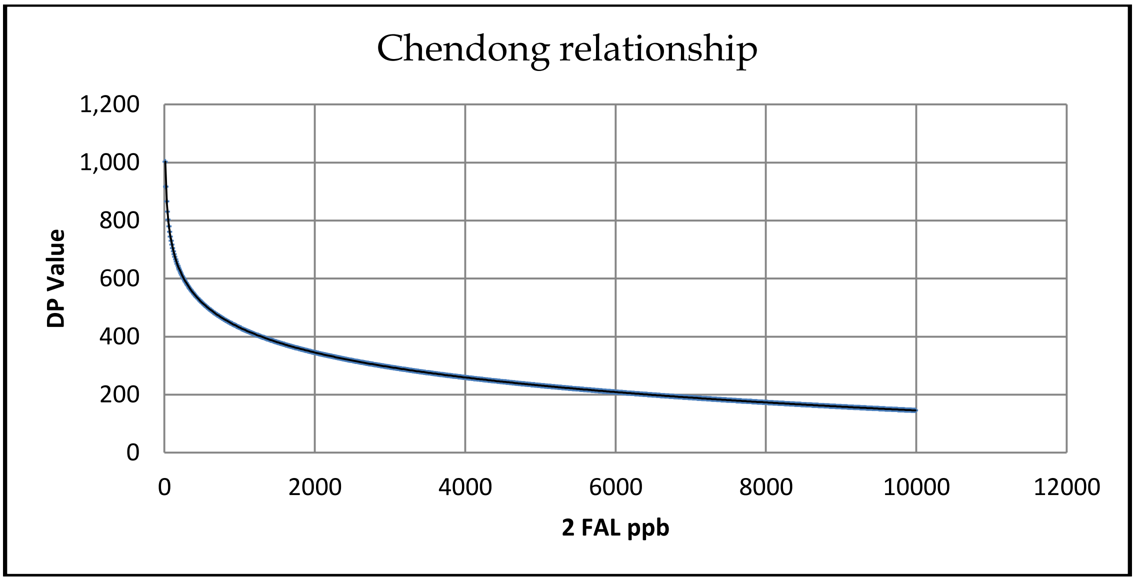

Figure 3.3: Chendong relationship

3.2.6 Interfacial Tension (IFT)

The interface tension between oil and water provides information regarding the presence of soluble polar contaminants in the oil. As ageing progresses, however, the rate of change in the interface tension slows down. This consequently makes it more difficult to interpret the test data concerning this parameter. An acceptable range of tensions is defined in IEC 60422. Careful interpretation of test data is vital, because a low interface tension may indicate sludge deposition on the windings. This can lead to temperature management problems under heavy loads [9].

3.2.7 Dissolved Gasses Analysis (DGA)

Dissolved Gasses Analysis is a powerful tool available to detect faults in oil immersed transformers. This has the ability to detect gases generated by Arcing, Partial discharge, Low energy sparking, Severe overloading, overheating in the insulation system. Detects gases dissolved in oil quantitatively.

Under normal operating conditions very little amount of dielectric fluids occurs. When a thermal or electrical fault develops insulation oil and the paper insulation decompose and create low molecular weight decomposed gasses like Hydrogen, Methane, Acetylene, Ethylene, Ethane, Carbon Dioxide and Carbon Monoxide.

The test can be done either connecting the test equipment online or by taking oil sample out depending on the test equipment. In both cases transformer is energized and no outage is required. Therefore, the DGA is considered as a very useful and economical test method.

Figure 3.4: MYRKOSS" DG Analyzer

Equipment Used in CEB for this is"MYRKOSS" DG Analyzer and a picture is shown below.

Dissolved gasses are generated either by decomposition of the insulating paper or insulation oil or by formation of various combustible and noncombustible gases due to internal fault, aging and other chemical reactions in the transformer.

Insulation Oil Molecule

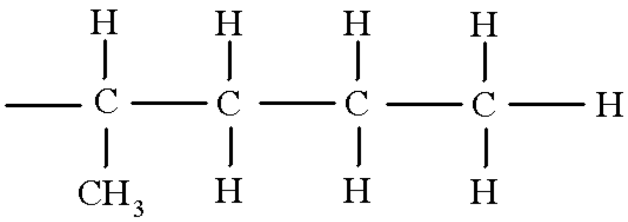

Figure 3.5: Insulation Oil Molecule

Due to various faults these bonds break and form following gasses.

- Hydrogen -H_2,
- Methane - CH_4,
- Acetylene - C_2H_2,
- Ethylene - C_2H_4
- Ethane -C_2H_6

Cellulose Paper Molecule

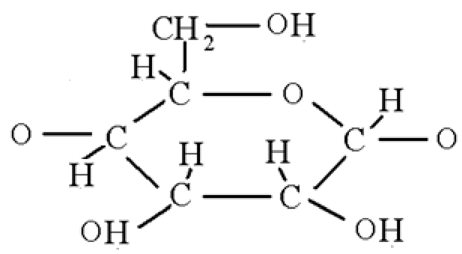

Figure 3.6: Cellulose Paper Molecule

Due to various faults the bonds in this molecule too break and form following gasses.

- Hydrogen - H_2
- Carbon Monoxide - CO
- Methane - CH_4
- Carbon Dioxide - CO_2
- Ethane - C_2H_6
- Ethylene - C_2H_4
- Oxygen - O_2
- Acetylene - C_2H_2

In DGA these gasses are measured in the oil sample and used to determine the faulty condition of the transformer.

There are several ways to interpret the faults by using the dissolved gasses.

1. Straight Limits
2. Key Gas Method
3. Dörnenburg Ratios
4. Roger's Ratios
5. Duval Triangle

3.2.7.1 Straight Limits

The recommended gas levels in various sources are compared with the test results. For a better performance, gas levels should be within the recommended ranges.

	H_2	CO	CH_4	C_2H_6	C_2H_4	C_2H_2	CO_2
IEC60599 Typical Range	60-150	540-900	40-110	50-90	60-280	3-50	5100-13000

Table 3.4: IEC Recommended Dissolved Gasses Levels

3.2.7.2 Key Gas Method

IEEE has defined key gases and according to the key gas content the probable fault can be predicted.

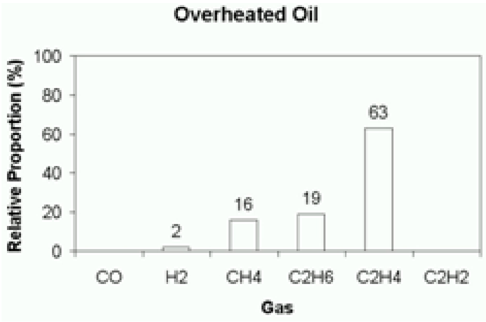

Figure 3.7a: Key Gasses-C_2H_4

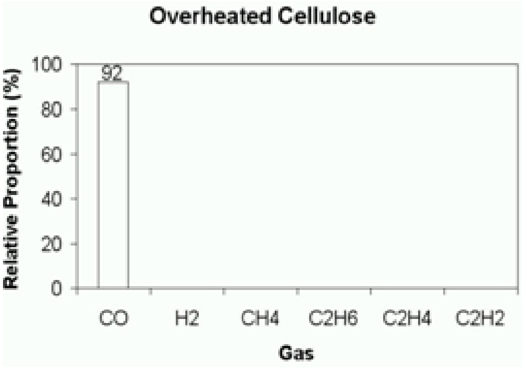

Figure 3.7b: Key Gasses-CO

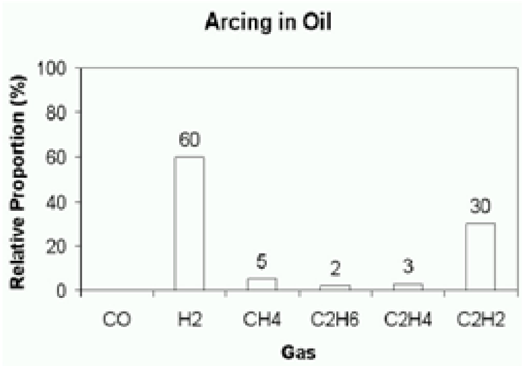

Figure 3.7c: Key Gasses-H_2 and C_2H_2

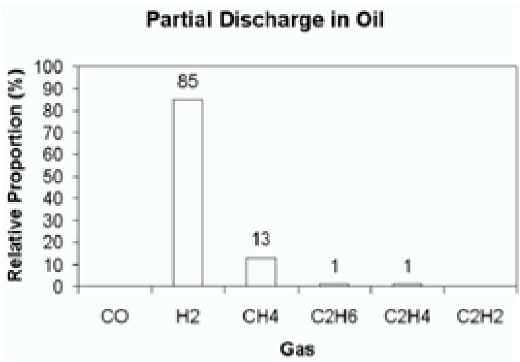

Figure 3.7d: Key Gasses – H_2

3.2.7.3 Dörnenburg Ratios

This method is based on gases ratio and it is described in IEEE C57.104 2008. Following figure is the summery of the Dörnenburg Ratios method.

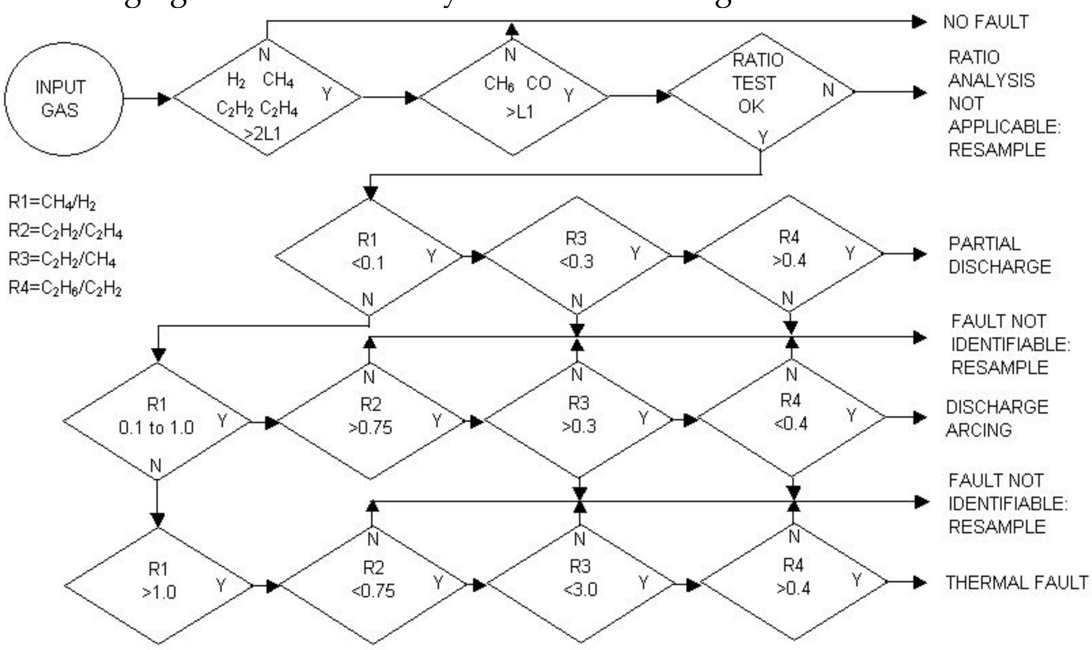

Figure 3.8: Dörnenburg Ratios method flow chart

3.2.7.4 Roger's Ratios

This method is also described in IEEE C57.104 2008 and based on gas ratios. Following figure is the summery of the Roger's Ratios method.

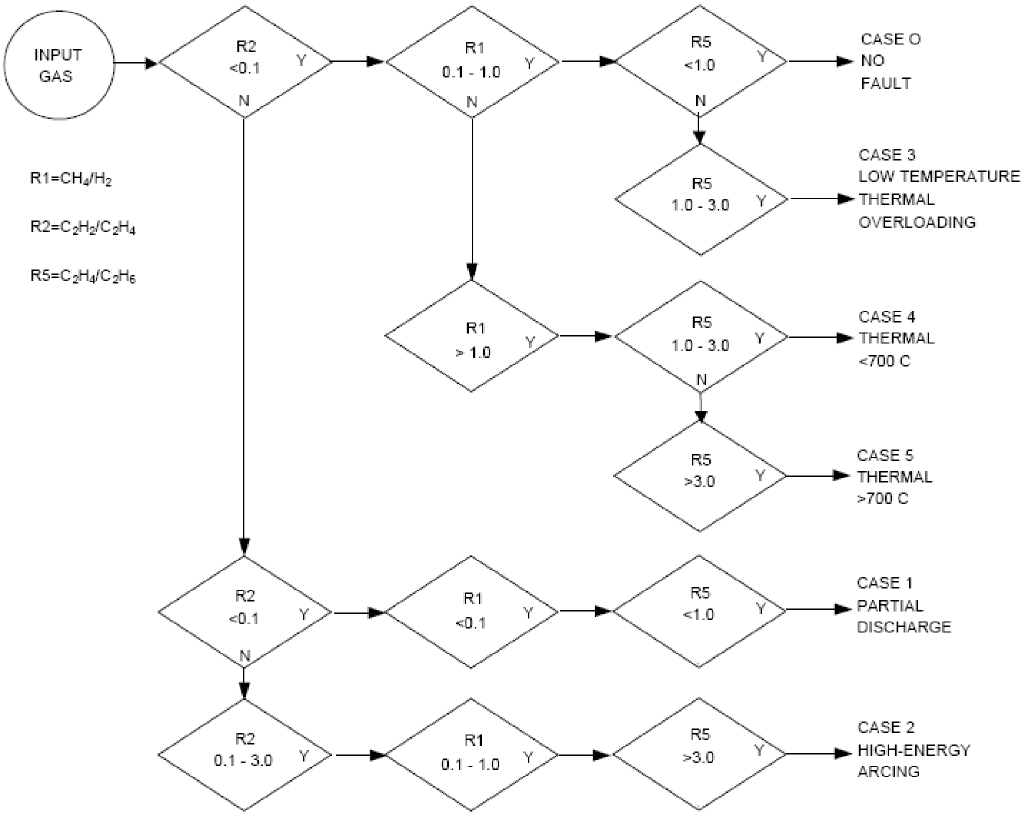

Figure 3.9: Roger's Ratios method flow chart

3.2.7.5 Duval Triangle

The triangle method plots the relative % of CH_4, C_2H_4 and C_2H_2 on each side of the triangle, from 0% to 100%. This is described in IEC 60599 [27].

The 6 main zones of faults are indicated in the triangle, plus a DT zone (mixture of thermal and electrical faults). The 6 zones are described in section 2.1.3. Each DGA analysis received from the lab will always give only one point in the triangle. The zone in which the point falls in the Triangle will identify the fault responsible for the DGA results.

Legend:

PD	-	Partial Discharge (Eg. Corona)
D1	-	Low Energy Discharge (Eg. Low energy arcing)
D2	-	High Energy Discharge (Eg. Flashovers)
T1	-	Thermal Fault below 300^{o}C (Eg. Overloading)
T2	-	Thermal Faults below 700^{o}C above 300^{o}C (Defective Contacts)
T3	-	Thermal Faults above 700^{o}C (Short circuit in laminations)
DT	-	Electrical and Thermal Faults

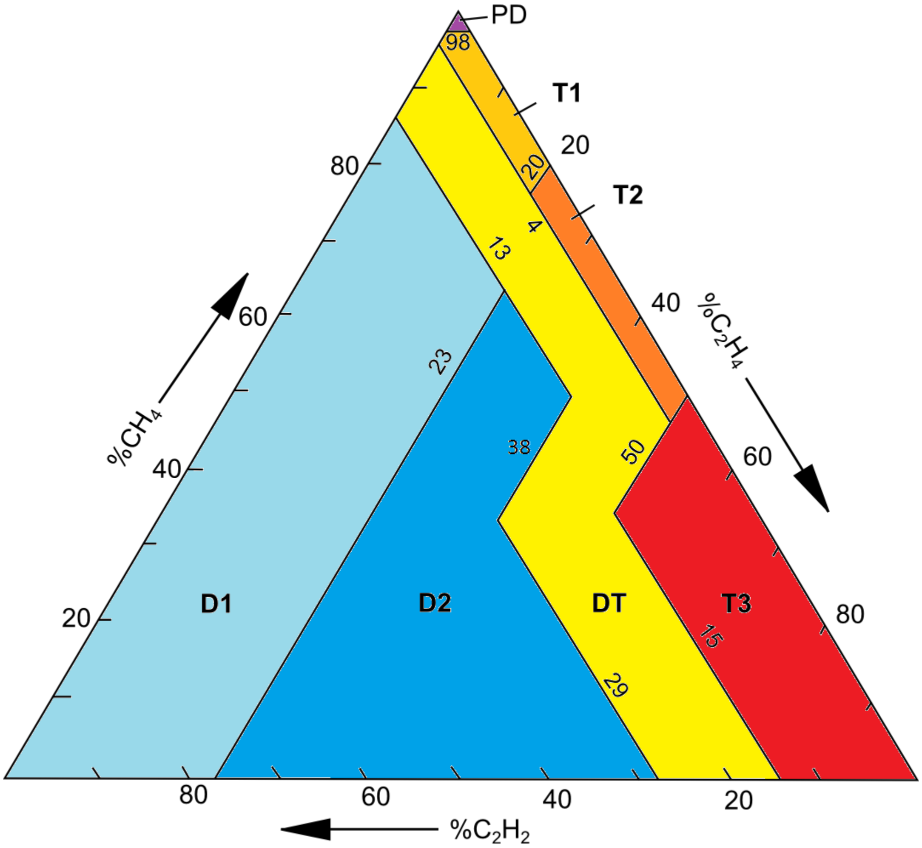

Figure 3.10: Duval Triangle

3.3 Winding Testing

3.3.1 Winding Resistance Test

Winding resistance is measured in both primary and secondary windings. For a three phase transformer, measurements are made phase to phase regardless of the winding configuration (either wye or delta). Test values are compared with the commissioning values. If all readings are within one percent of each other then they are acceptable.

Winding resistances are measured in transformers to check for loose connections, broken strands and high contact resistance in tap changers. The tap changer is most vulnerable for higher contact resistances in transformers. Deposit of various contaminations on conductor parts, oxidation and loose connections of contact joints are some causes for increase of tap changer resistance. Tap changer can be either on load or off load.

High resistance electrical connections dissipate power and create hot spots inside transformers. If it is hot enough it can break up oil chemically and can damage the insulation around. New chemical components are formed which may weaken the insulation further. If a winding resistance test was not done and transformer continued to load Buhholz relay or Differential may detect when the fault get worse. If winding resistance is measured regularly impending faults can be detected early.

Resistance of unused tap positions will be higher due to corrosion. The test values shall be compared with commissioning values. For the compression the result has to be converted to similar temperature. Measurements are normally converted to a standard reference temperature equal to the rated average winding temperature rise plus 20°C. The conversions are accomplished by the following formula:

$$R_s = \frac{R_m(T_s + T_k)}{(T_m + T_k)}$$

Where, R_s = resistance at desired temperature Ts
R_m = measured resistance
T_s= desired reference temperature
T_m = temperature at which resistance was measured
T_k = 234.5 (Copper), = 225 (Aluminum)

3.3.2 Insulation Resistance (IR)

The insulation resistance is measured to determine the insulation of the transformer's windings to earth, between windings. The reading can be compared with the commissioned values and can be used as a reference for future measurements during operating.

By comparing the results obtained in insulation resistance measurements with periodical measurements, the insulation conditions can be evaluated. For comparison they have to be at the same temperature (e.g. *20°C* reference temperature). The test voltage is DC and it can be 1000*V dc, 2500Vdc, 5000V dc or 10,000V dc*. The test voltage depends on the transformer’s rated voltage as shown in Table 3.6.

The measuring points are "between the windings and between winding and tank", The temperature and humidity during test should also be recorded because both factors are affected to the reading. Since the insulation of oil and insulation of paper are implied from the moisture, acidity and FRA tests, IR reading is not considered for the Fitness Index calculations.

The values at 1st min and 10th min after the voltage is applied should be recorded. The ratio of the value in 10th minute to value in 1st minute is given as “polarization index (PI) “. The correction factor of temperature values (by multiplying) measured in transformer oil (Corrected to *20°C)* is given in table 3.5[5].

Insulation Resistance Conversion Factor at 20°C			
Oil Temperature °C	Conversion Factor	Oil Temperature °C	Conversion Factor
20	1	65	22.4
25	1.4	70	31.75
30	1.98	75	44.7
35	2.8	80	63.5
40	3.95	85	89.8
45	5.6	90	127
50	7.85	95	180
55	11.2	100	254
60	15.85		

Table 3.5: Extracted from NETA Standards Table 10.14

Transformer Insulation Resistance (NETA Table 10.5)		
Transformer Rated Voltage (V)	Min DC Test Voltage (V)	Recommended minimum Insulation Resistance in Oil filled Transformers (MΩ at 20°C)
0-600	1000	100
601-5000	2500	1000
Greater than 5000	5000	5000

Table 3.6: Extracted from NETA Standards Table 10.05

3.3.3. Frequency Response Analysis (FRA)

Frequency response analysis (FRA) consists of measuring the impedance of the transformer windings over a wide range of frequencies and comparing the results of these measurements with a reference value set. Dissipation factor (DF) or Tan (δ) is measured and the moisture content in the Insulation Paper and the oil conductivity is derived.

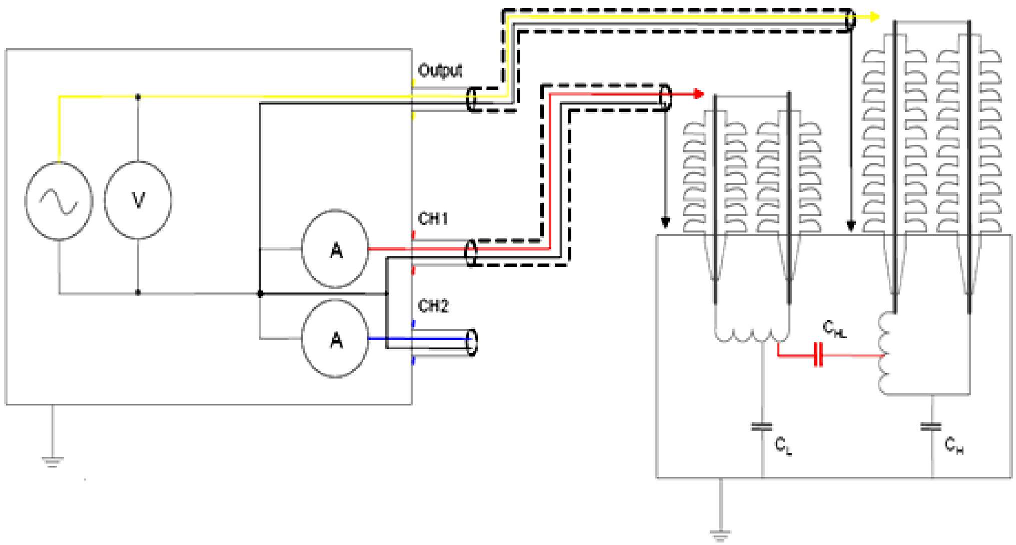

Figure 3.11: Connection diagram of DIRANA

The above diagram shows the connection of the testing equipment. FRA determines the Dielectric Behavior of Oil-Paper-Insulations. The Dielectric Response Analyzer (DIRANA) is used in CEB for this test.
The DF Vs Frequency curve is the output of the DIRANA [21].

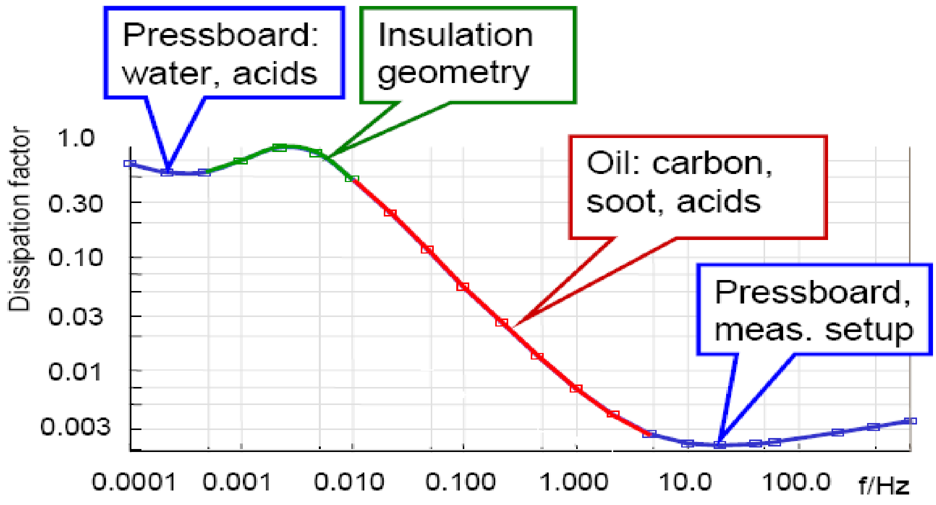

Figure 3.12: DF Vs Frequency sweep (Region Identification) [21]

The resultant curve then compares with large numbers of curves in the database of the DIRANA and finds the best matching curve for the particular test. The data base is created using large numbers of laboratory tests. Depending on the region of the curve (Shown in Green, Yellow, Orange and red color in the Figure: 4.2) the condition of the paper/pressboard, Insulation geometry and Insulation oil can be expressed. The curve changes depending on the condition of the paper/pressboard and oil as shown in the Figure: 3.13. Sample curves for new, moderate and aged transformers are shown in Figure: 3.14. The Conductivity of Insulation oil and Moisture percentage in paper insulation is calculated in the DIRANA.

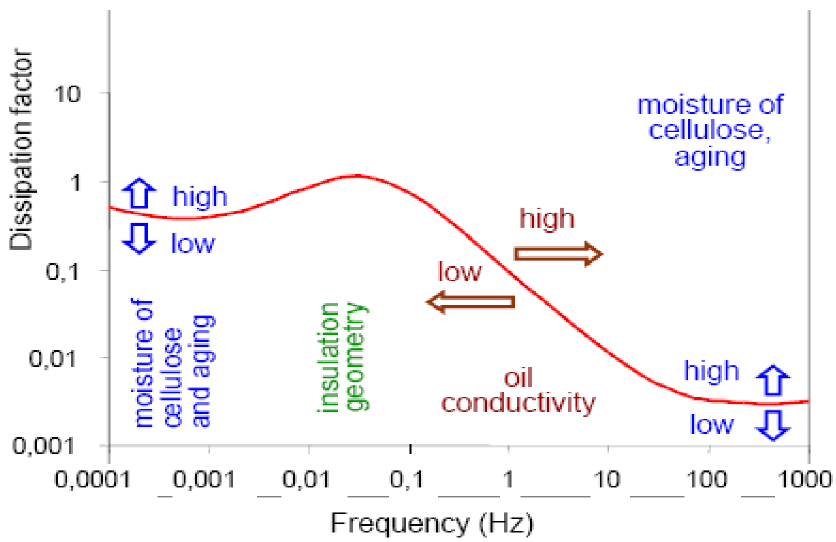

Figure 3.13: DIRANA Curve Identification [21]

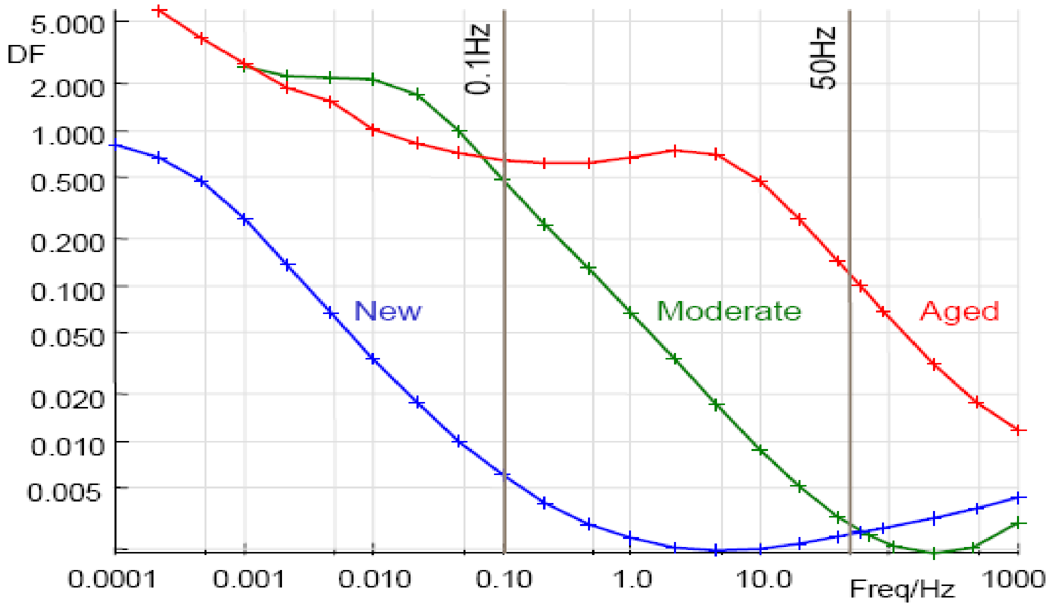

Figure 3.14 : Sample DIRANA Curves [21]

3.3.4 Partial Discharge Measurement (PD)

Partial discharge can occur due to the presence of floating particles, cavities, or sharp points. These PD sources may be derived from their location, frequency, and charge of the occurring PD. With an adequate set of knowledge rules it is possible to determine what types of defects and faults are present, such as, loose connections, loss of insulation material, floating particles in the oil, air bubbles in the oil, voltage sparking due to eddy currents, etc. PD is particularly useful for sensitive measurements in "noisy" environments. PD is not considered in this thesis due to unavailability of PD sensing instruments in the used transformers. PD can be detected from DGA.

3.4 Selection of Suitable Tests

Two prequalification tests were selected to identify the Moisture content of the insulation. Test for Moisture content in the Paper Insulation (MIP) and a test for moisture content in the Oil insulation (MIO) are the tests for moisture in insulation. MIP is found using Dielectric Response Analysis and MIO is found using conventional oil tests.

Three main tests were selected to find the Fitness Index (FI) namely Acidity, Dissolved Gasses Test and Furan test.

3.4.1 Moisture Test

Moisture decreases the dielectric withstands strength of oil and paper, accelerates paper aging and causes the emission of bubbles at high temperatures. No transformer outages are required for Moisture test. Oil sample can be taken while the transformers are energized. Moisture in oil can be minimized by Drying either online or offline.

3.4.2 Frequency Response Analysis (FRA)

FRA is described in Section 3.3.3. It can be used to determine the Moisture percentage in the paper insulation. Here, the Moisture in Paper Insulation is more accurately measured compared to the conventional methods. Moisture in paper also can be minimized by Drying either online or offline.

3.4.3 Furan Analysis

The DP value is direct explicit parameter for the remaining life described in Section 2.2.1. Chendong, De Pablo and Burton have built relationships for (Furanic components) 2FAL and DP value. Mostly used Chendong relationship is used for calculation of the FI value in this thesis. No transformer outages are required for Furan test. Furan content is assumed to be independent from generating Dissolved gasses and Acidity.

3.4.4. Dissolved Gasses Analysis (DGA)

Dissolved gasses are indirect explicit parameter which is indirectly related to the transformer life time. This is described in Section 2.2.1. No transformer outages are required for DGA. Oil sample can be taken while the transformers are energized. Overheating of Insulation Paper, Oxidation of Paper and Oil, Partial Discharges, can be determined by DGA. Therefore DGA is considered in the FI calculations and assumed to be independent from generating Furan and Acidity.

3.4.5. Acidity Test

Since the acidity level is responsible for the Degradation of Insulation Paper, as discussed in Section 2.2.2 this is also considered in the FI calculations. No transformer outages are required for acidity test. Oil sample can be taken while the transformers are energized. Acidity is assumed to be independent from generating Furan and Dissolved gasses.

Chapter 04

Pre-Qualification & Fitness Tests

4.1 Pre-qualification tests

Pre qualification tests are, testing for Moisture in Oil and testing for Moisture in Insulation Paper. These two tests are considered as pre qualification tests for calculating Fitness Indexes.

As per the standards if the tests values are better than a certain values pre qualification tests are passed and carried forward to other test for calculating Fitness Indexes.

4.1.1 Analysis for Moisture in Oil and Test Results

According to IEC the Maximum Allowable Moisture in Oil is 30ppm. According to the IEEE the Maximum Allowable Moisture in Oil is 25ppm. When the oil temperature value is corrected to 20^{o}C the IEEE recommended value is 5ppm.

$$\text{Moisture ppm Correction Factor } (20^{\circ}C) = 2.24 \times e^{-0.04T}$$

T = Sampling Temperature

The qualification mark is considered as 5ppm at 20°C as per the IEEE recommendation.

Following recommendations are made referring to the MIO ppm value.

- If, MIO < 5ppm - Filtering Not Essential but regardless of MIO recommended to filter oil annually.
- If, 5ppm <MIO < 25ppm, - Filter Until moisture reaches 5ppm at 20°C (Online Filtering will be sufficient if and Outage is costly)
- If, MIO > 25ppm - Fast drying is recommended (Offline), Check possible ways of moisture ingress.

Test Results for MIO

For this thesis Moisture in Oil (MIO) test results were acquired from the conventional methods.

U1-R phase transformer of Samanala Power Station was tested for MIO continuously for a two year period and the results are shown in Figure. 4.1.

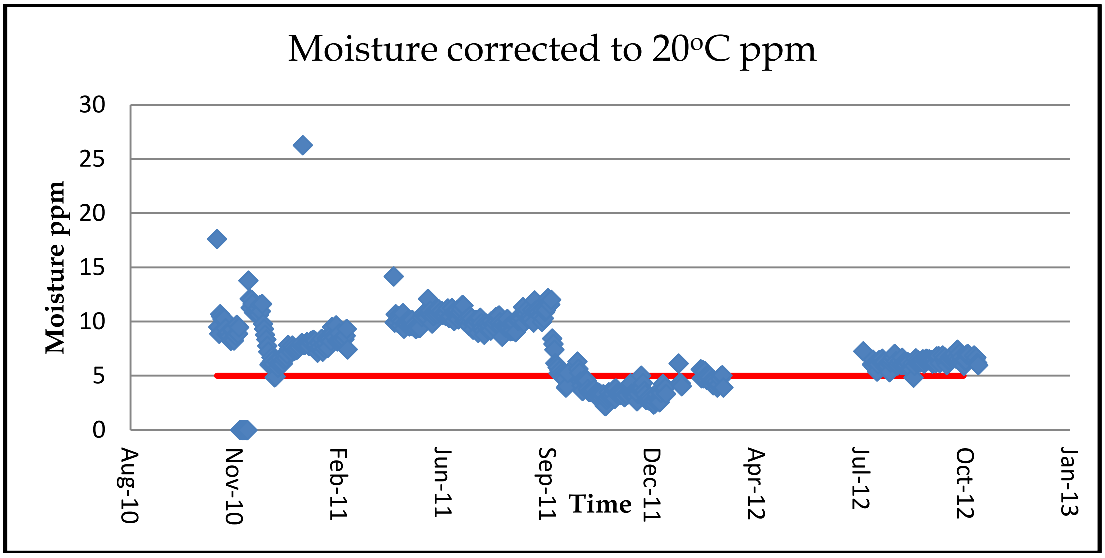

Figure 4.1: Moisture ppm Vs Time

Transformer	U1R	U1Y	U1B
Moisture ppm at 20°C As at 2012-08-29	3.5	2.7	3.5

Table 4.1: Moisture content of U1 Transformer

Test results if U1R transformer is slightly different in the Table and Figure because two measurement have been measured from two instrument. The table is considered for the evaluation.

Therefore prequalification for MIO is passed for all three transformers of U1 generator.

4.1.2 Analysis for Moisture in Paper and Test Results

The method and the instrument used are described in Section 3.3.3.It is described that the condition of the paper insulation according to the moisture content in Paper Insulation and grouped into four categories in the IEC 60422.

Category	Moisture Content%	Color
Dry	Below 2.2	
Moderately Wet	2.2 – 3.7	
Wet	3.7 – 4.8	
Extremely Wet	Above 4.8	

Table 4.2: Color Categorization for MIP

Source: IEC Standard 60422 [9]

The qualification mark is considered as 2.2% as per the IEC recommendation.

Moisture in Paper cannot be directly removed at the site. Paper Moisture can be removed by special drying process at the factory. Paper has to be undergone drying at the transformer's manufacturing process prior to delivery.

Oil Filtration is the only available option at the site. It takes longer time to remove moisture in paper than moisture in oil.

Following recommendations are made referring to the MIP parentage.

- If, MIP < 2.2% - Filtering Not Essential but regardless of MIO recommended to filter oil annually.
- If, 2.2% <MIP< 3.7%, - Filter Until moisture reaches 2.2% (Online Filtering may be sufficient if and Outage is costly)
- If, 3.7% <MIP<4.8% - Fast drying is recommended (Offline), Check possible ways of moisture ingress.
- If, 4.8% < MIP – Paper is extremely wet. Filtering may not work. IF further increasing remove from the service.

Test Results

The test method is described in the Section 3.3.3. Tan (δ) is plotted against the range of frequencies and the graph is compared with a series of graphs constructed in laboratory conditions. Figures 4.2, 4.3, 4.4 respectively are the test results of Unit 01 R, Y and B phase Transformers of Samanala Power Station.

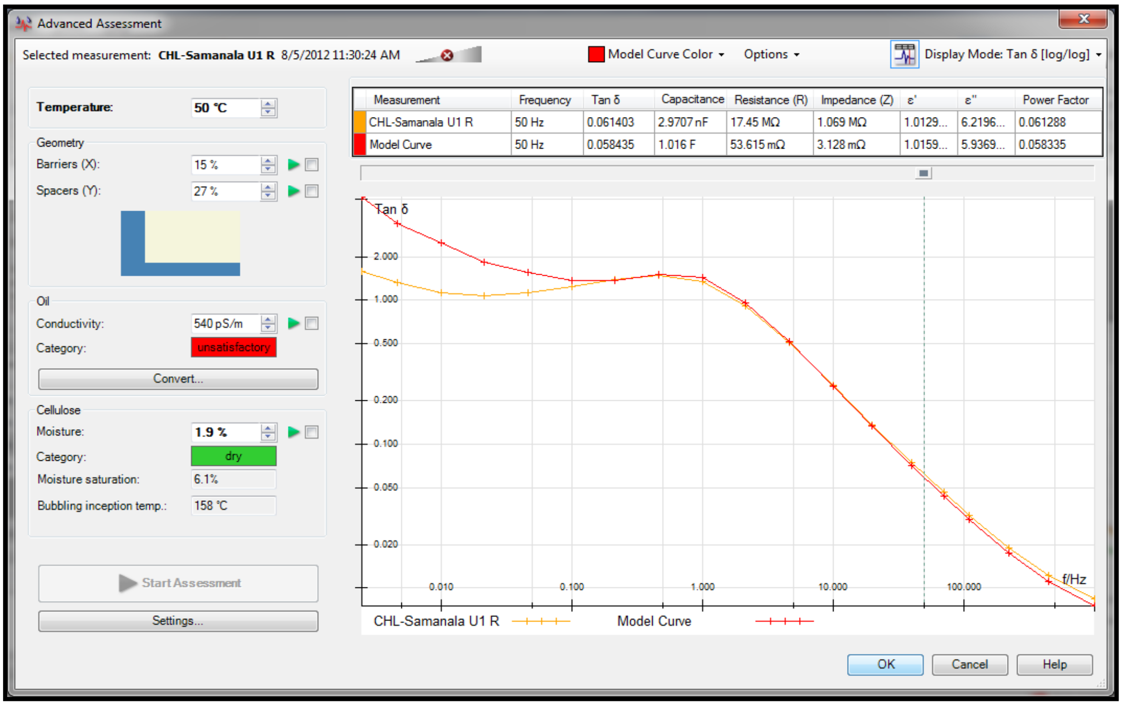

Figure 4.2: Unit 01- R phase Transformer DIRANA test result.[3]

Moisture in Paper is 1.9% of U1R transformer.

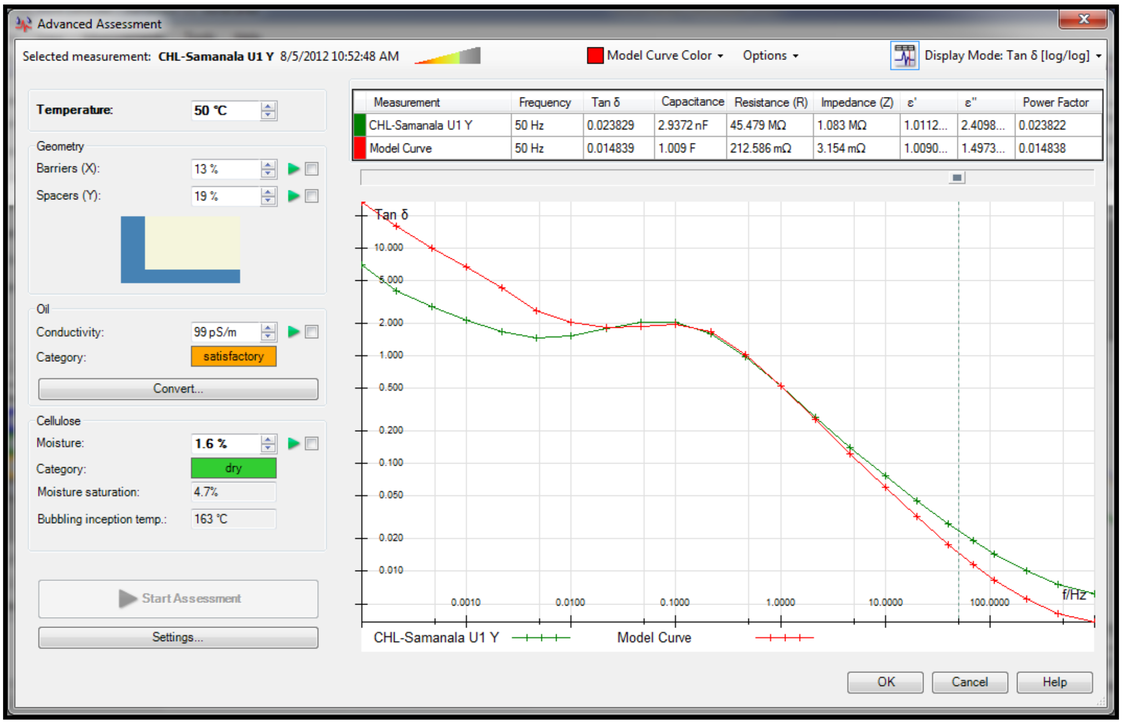

Figure 4.3: Unit 01- Y phase Transformer DIRANA test result.[3]

Moisture in Paper is 1.6% of U1Y transformer

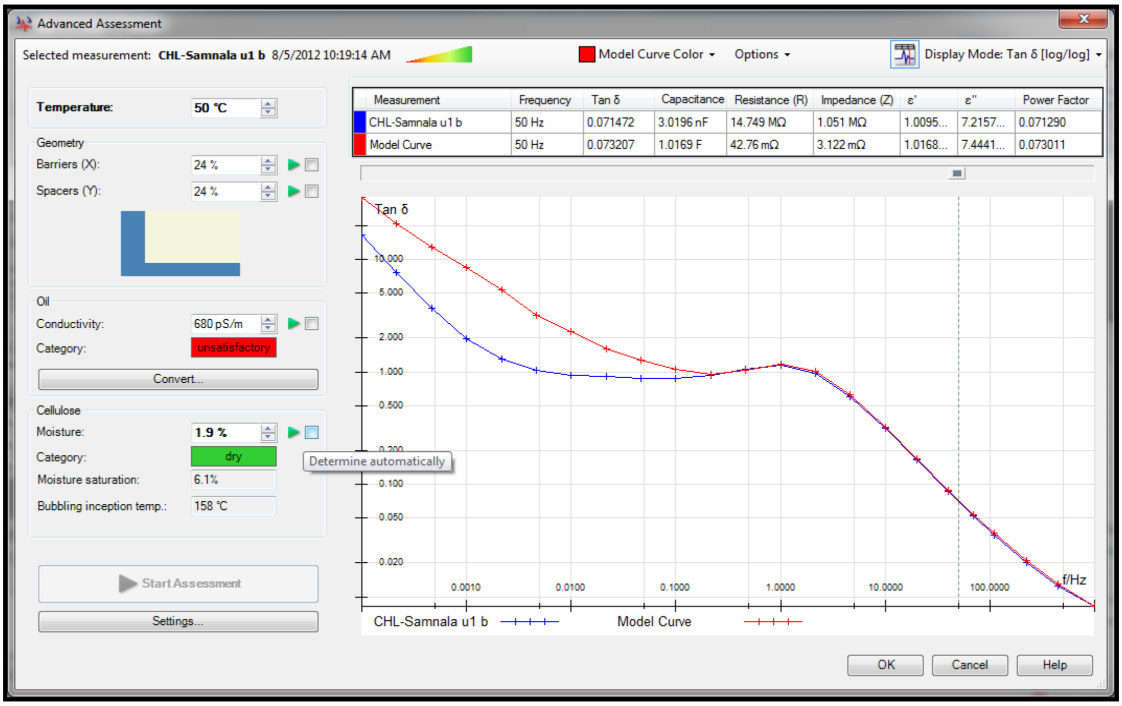

Figure 4.4: Unit 01- B phase Transformer DIRANA test result.[3]

Moisture in Paper is 1.9% of U1B transformer.

Therefore prequalification test is passed for MIP for all transformers of U1 Generator.

4.2 Fitness Tests

If both pre qualification tests are passed, then below fitness tests have to be done.

4.2.1 Analysis for Acidity and Test Results

According to IEEE C57.106.1991 [23], maximum acceptable acidity level for acceptance of new transformers is 0.03 mg KOH/g.
Acidity level for continues usage is 0.2 mg KOH/g (Group II of [23]). Recondition or reclaim level of Acidity is 0.5 mg KOH/g (Group III of [23]). Failure Acidity level is 0.5 mg KOH /g (Failure probability P_4 is 100% of [24]).

A transformer's oil life is assumed to be over if the acidity level reached 0.5 mg KOH/g referring to above statements.

Following figure shows acidity tests which has been done for 52 transformers of various ages [25], [2].

Unlike gases acidity creation is exponential. It is not significant during the first 10 years [24]. It is revealed in the test results in following Figure 4.5.

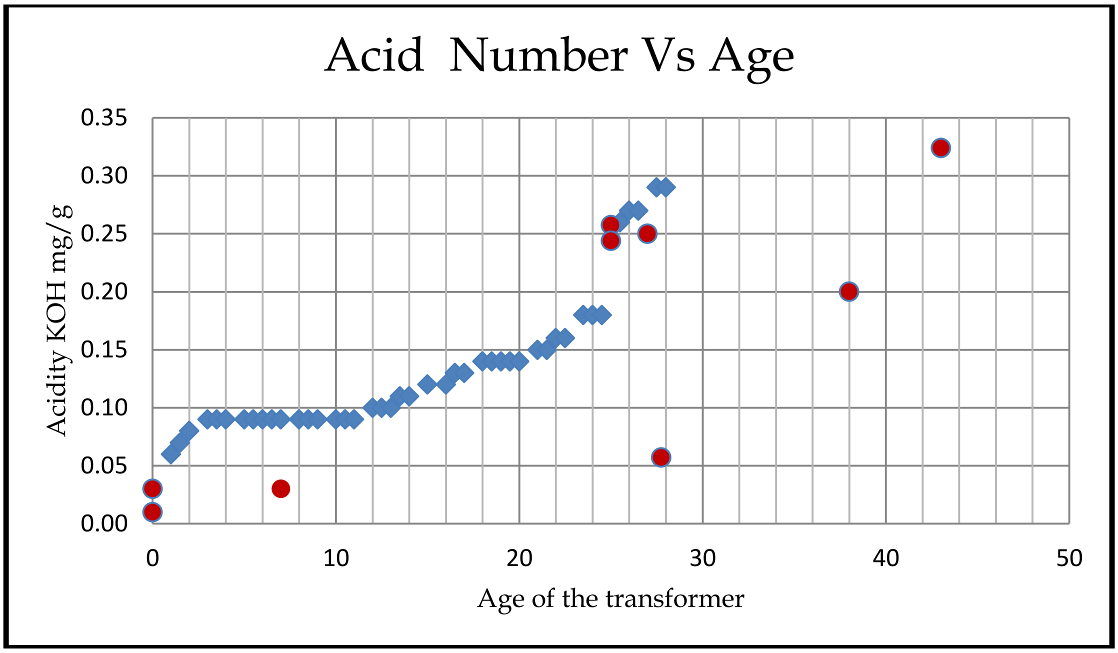

Figure 4.5: Acidity concentrations Vs age.

By using the exponential regression methods following relationship was found between the age and the Acidity level.

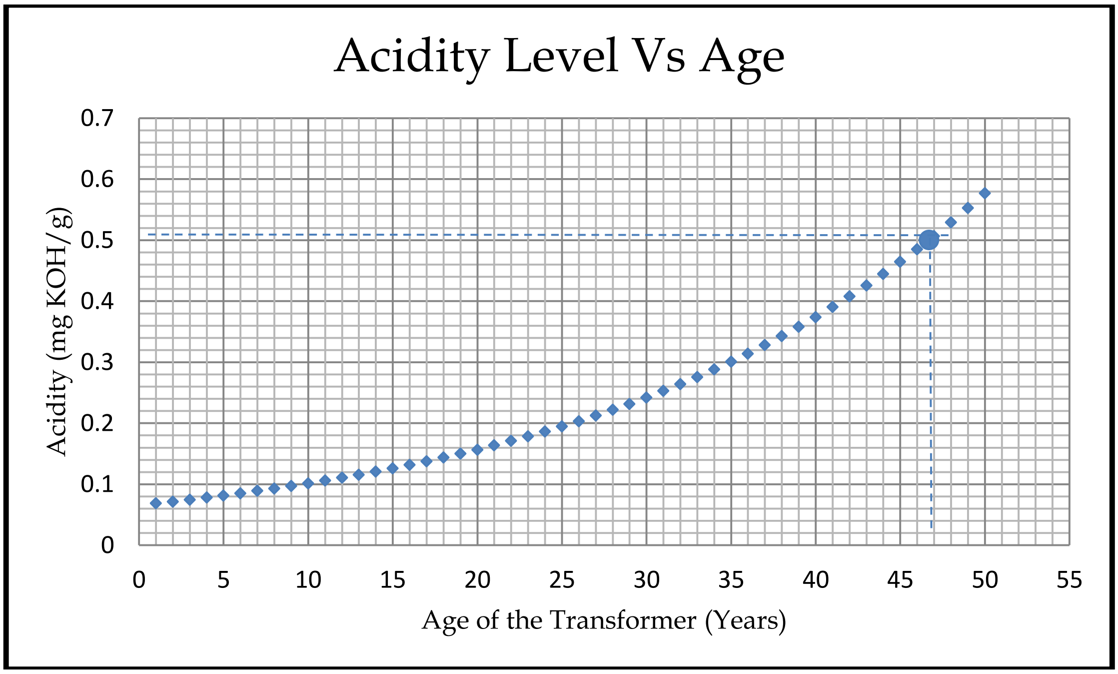

Figure 4.6: Acidity concentrations Vs age. (Regression)

$$Acidity = 0.0658 \times e^{0.0434 \times Age}$$

According to the above relationship the acidity level will reach to the critical level (0.5 mg KOH/g) after 46.7 Years. But the expected life of a transformer is considered as 25 for this thesis.

Therefore the above relationship was modified and acidity level was plotted against per unit age.

$$Acidity = 0.0658 \times e^{0.0434 \times Age(pu)}$$

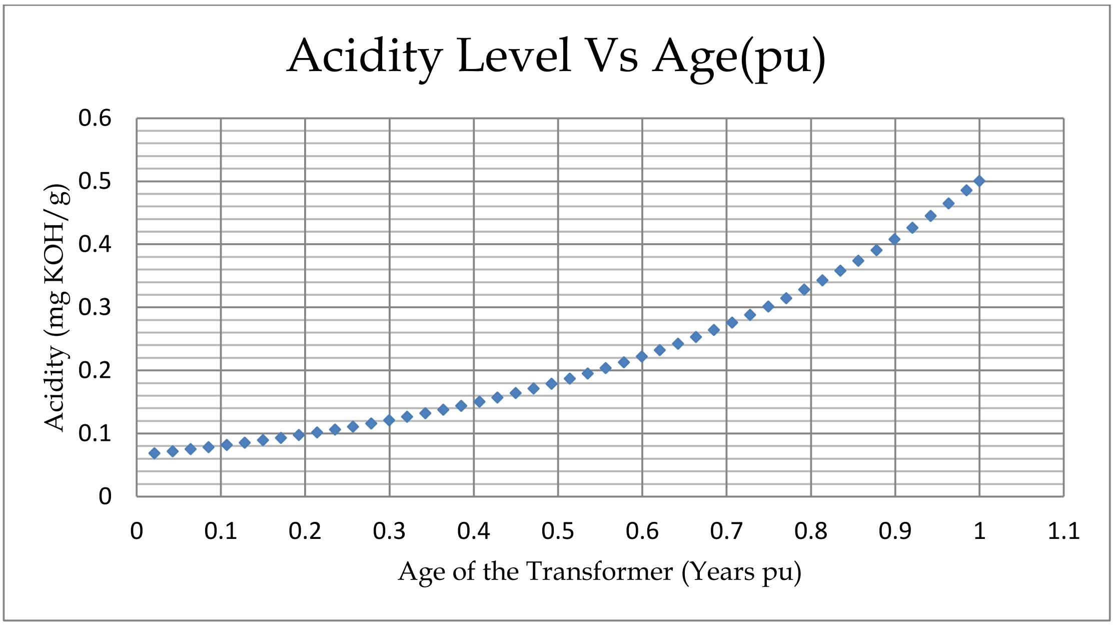

Figure 4.7: Acidity concentrations Vs age. (pu)

FI Acidity = Remaining Life time as a percentage.

$$Remaining\ Life\ as\ a\ persontage = (1 - Age(pu)) \times 100$$

If, $FI_{Acidity}$ = 80% ~ 100% Annual online Oil filtering is recommended.
If, $FI_{Acidity}$ = 45% ~ 79% Start online Acidity filtering
If, $FI_{Acidity}$ = 25% ~ 44% Offline Fullers Earth Filtering is recommended.
If, $FI_{Acidity}$ = 12% ~ 24% Remove Sludge
If, $FI_{Acidity}$= 00 % ~ 11% Get ready to Replace oil

Acidity test results for Unit No 01 transformers of Samanala Power Station.

Date	Unit 01-R TF	Unit 01-Y TF	Unit 01-B TF
2010/11/26	0.132 mg KOH/g	Test Not Done	Test Not Done
2010/12/07	0.115 mg KOH/g	Test Not Done	Test Not Done
2012/08/29	0.130 mg KOH/g	0.155mg KOH/g	0.324 mg KOH/g

Table 4.3: Acidity Test result of U1 Transformers of Samanala Power Station [2], [3]

Acidity based Fitness Indexes for Unit No 01 R, Y and B transformers of Samanala Power Station were found as follows.

Transformer	U1R	U1Y	U1B
$FI_{Acidity}$	68%	61.5%	20%

Table 4.4: $FI_{Acidity}$ based on the test carried out on 29th August 2012.

Therefore offline acidity filtering is recommended for U1R and U1Y transformers. It is recommended to remove sludge in U1B transformer.

4.2.2 Dissolved Gasses Analysis & Test Results (DGA)

Total Dissolved gas percentage and the gasses generation rates are categorized in to four groups in the IEEE C57. 104. 2008 [1].

	TDCG Level (μL/L)	TDCG Rate (μL/L/day)	Sampling Intervals and operating procedures for gas generation rates	
			Sampling Interval	Operating Procedure
Condition 4	>4630	>30	Daily	Consider Removal From Service Advice Manufacturer
		10 to 30	Daily	
		<10	Weekly	Exercise Extreme Caution Analyze for individual gas Plan Outage Advice Manufacturer
Condition 3	1921 to 4630	>30	Weekly	Exercise Extreme Caution Analyze for individual gas Plan Outage Advice Manufacturer
		10 to 30	Weekly	
		<10	Monthly	
Condition 2	721 to 1920	>30	Monthly	Exercise Caution Analyze for individual gas Determine Load Dependence
		10 to 30	Monthly	
		<10	Quarterly	
Condition 1	≤720	>30	Monthly	Exercise Caution Analyze for individual gas Determine Load Dependence
		10 to 30	Quarterly	Continue Normal Operation
		<10	Annual	

Table 4.5: IEEE Recommended Dissolved Gasses Levels

The TDCG = Addition of all the combustible dissolved gasses (CO_2 is not combustible)

$$TDCG = H_2 + C_2H_4 + CH_4 + C_2H_2 + C_2H_6 + CO$$

The most important fact of the table 4.5 is the Total Dissolved Combustible Gases level above 4630 ppm in condition 4. It is described in the above IEEE standard and the Condition 4 says "TDCG exceeding this value indicates excessive decomposition. Continued operation could results in failure of the transformer."

According to the above the failure level of TDCG level is assumed as 4630ppm.
FI_{DGA} = 100% at TDCG = 0ppm,
FI_{DGA} = 0%at TDCG = 4630ppm.
The rate of change of TDCG is explained in IEEE C57.104.2008 [2].

$$R = Rate\ of\ Change\ in\ TCDG\ = \frac{(S_T - S_o)}{T}$$

R = Rate of Change in TDCG (micro liters /Liters/Day)
S_o= First Sample (micro liters/Liter)
S_T= Second Sample (micro liters/Liter)
T=Time (Days)

Since the total life time is expected as 25 years and the TDCG variation throughout the whole life span is 4630ppm the normal TDCG rate be calculated as follows.

$$Normal\ TDCG\ Rate = \frac{4630}{25\ \times 365} =\ 0.5\ ppm\ per\ day$$

This means TDCG rate less than 0.5 ppm per day is completely acceptable. It can be assumed that there are no faults or the fault has been cleared when TDCG is equal or less than 0.5ppm per day. [27]

Then, Remaining life of a transformer with respect to DGA can be calculated. In any case if the rate of change in TDCG is below 0.5 ppm per day, the estimated rate of change is assumed as 0.5 ppm per day. Otherwise the expected life could be over estimated.

$$FI_{DGA} =\ Remaining\ Life\ as\ a\ persantage$$

Example:
If, the TDCG level is 980ppm and the TCDG rate is 1ppm per day at the age of 12 years.

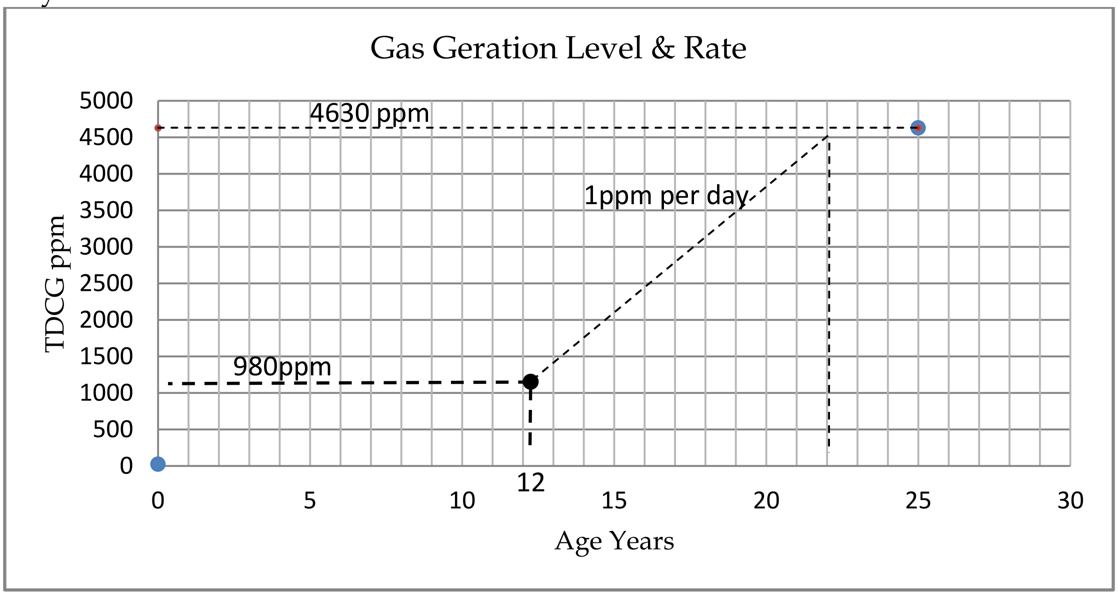

Figure 4.8: Remaining Life calculation using DGA, Example

This transformer is (4630-980) 3650ppm away from the failure level. It is reaching the 4630ppm at a rate of 1ppm per day. Therefore it takes another (3650/1) 3650 days to reach the failure.

Therefore it has another (3650/365) 10 years to failure at the present gas generation rate.

$$FI_{DGA} = \frac{10}{25} \times 100 = 40\%$$

Test Results and Calculation

Dissolved Gasses Test Result of Unit No 01 Generator Transformer of Samanala Power Station.

Unit	U1R - SAMANALA P.S	
Serial Number	285686	
Test Date	16/12/2011	03/02/2012
Dissolved Gas Analysis (DGA)		
H2 (Hydrogen) ppm	29	28
CH4 (Methane) ppm	64	21
C2H6 (Ethane) ppm	226	242
C2H4 (Ethylene) ppm	17	15
C2H2 (Acetylene) ppm	0	0
CO (Carbon Monoxide) ppm	420	474
CO2 (Carbon Dioxide) ppm	2270	2842
Total Dissolved Combustible Gas (TDCG)	756	780

Table 4.6: DGA test results for U1R Transformer.

$\boldsymbol{Rate\ of\ Change\ in\ TDCG = \frac{780-756}{49}}$ **= 0.49**

Expected remaining life of U1R transformer of Samanala Power Station

= (4630 – 780)/(0.5 X 365) = 21 Years

$\boldsymbol{FI_{DGA,U1R} = 21/25 \times 100 = 84\%}$

Unit	U1Y - SAMANALA P.S	
Serial Number	285691	
Test Date	16/12/2011	03/02/2012
Dissolved Gas Analysis (DGA)		
H2 (Hydrogen) ppm	30	28
CH4 (Methane) ppm	23	0
C2H6 (Ethane) ppm	19	18
C2H4 (Ethylene) ppm	0	0
C2H2 (Acetylene) ppm	0	0
CO (Carbon Monoxide) ppm	658	708
CO2 (Carbon Dioxide) ppm	4287	4713
Total Combustible Gas (TCG)	730	754

Table 4.7: DGA test results for U1Y Transformer.

$\boldsymbol{Rate\ of\ Change\ in\ TDCG = \frac{754-730}{49}}$ **= 0.49**

Expected remaining life of U1R transformer of Samanala Power Station

= (4630 – 754)/ (0.5 X 365) = 21 Years

$\boldsymbol{FI_{DGA,U1Y} = 21/25 \times 100 = 84\%}$

4.2.2.1 Comparison with Dissolved Gasses Assessment Methods

1. **Straight Limit Method:** In the Straight Limit method the result is compared with the IEE 60599 values. In the above result from the test done on 3rd February 2012 for the R Phase transformer, only C_2H_6 level has

increased beyond the upper standard values. It causes FI_{DGA} of U1R transformer to be 84%. CO level of U1Y transformer is closer to the upper limit of 900ppm.

2. Key Gas Method:

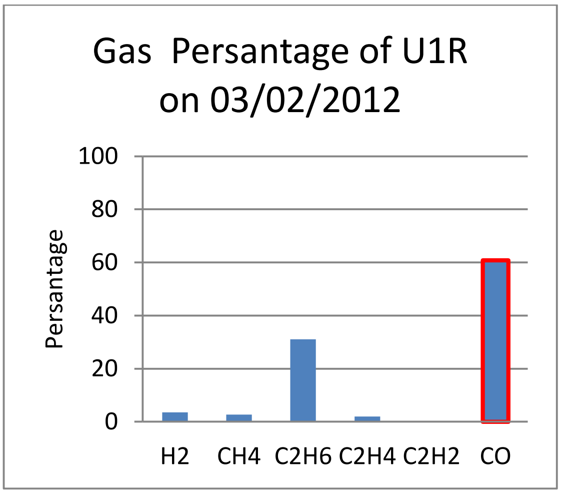

Figure 4.9: Key Gases of U1R Transformer

This type of gas combination cannot be strongly described by key gas method. But presence of large quantities of CO and a little of C_2H_6 indicates that there has been "Paper Overheating" (Thermal-Cellulose) inside the transformer [1].

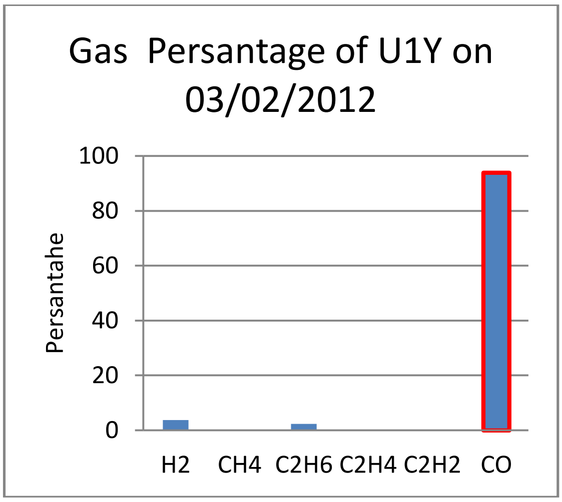

Figure 4.10: Key Gases of U1Y Transformer

Presence of large quantities of CO indicates that there has been "Paper Overheating" (Thermal-Cellulose) inside the transformer [1]. The overheating of U1Y is higher than U1R.

3. Dörnenburg Ratio Method: According to this method there is no fault in both U1R and U1Y transformers.

4. Roger's Ratios Method:

U1R on 2011-12-16 – No result
U1R on 2012-02-03 – No Fault
U1Y on 2011-12-16 – No Fault
U1Y on 2012-02-03 – No result

5. Duval Triangle Method

U1R transformer on 2011-12-16 and 2012-02-03: Fault T2
U1Y transformer on 2011-12-16 and 2012-02-03: No result

4.2.3 Furan Analysis and test results

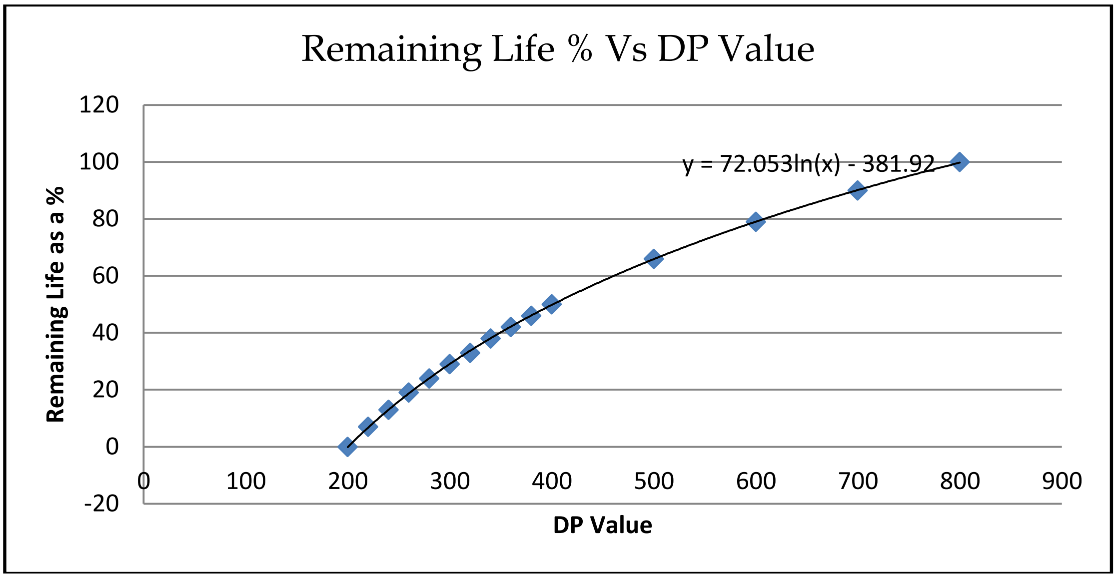

Figure 4.11: Remaining Life % Vs Degree of Polymerization [7]

The relationship extracted from [7] (*Assessing Remnant Life of Transformer based on Furan Content in Transformer Oil and Degree of Polymerization of Solid insulation)* and [14] *(Predication of Life of Transformer insulation by developing Relationship between Degree of Polymerization and 2- Furfural)* is,

Remaining Life % = 72.05 ln (DP Value) - 381.9

Test Results

Following is the graph for remaining life (%) Vs DP value of 28 transformers in CEB-owned hydro power stations [3].

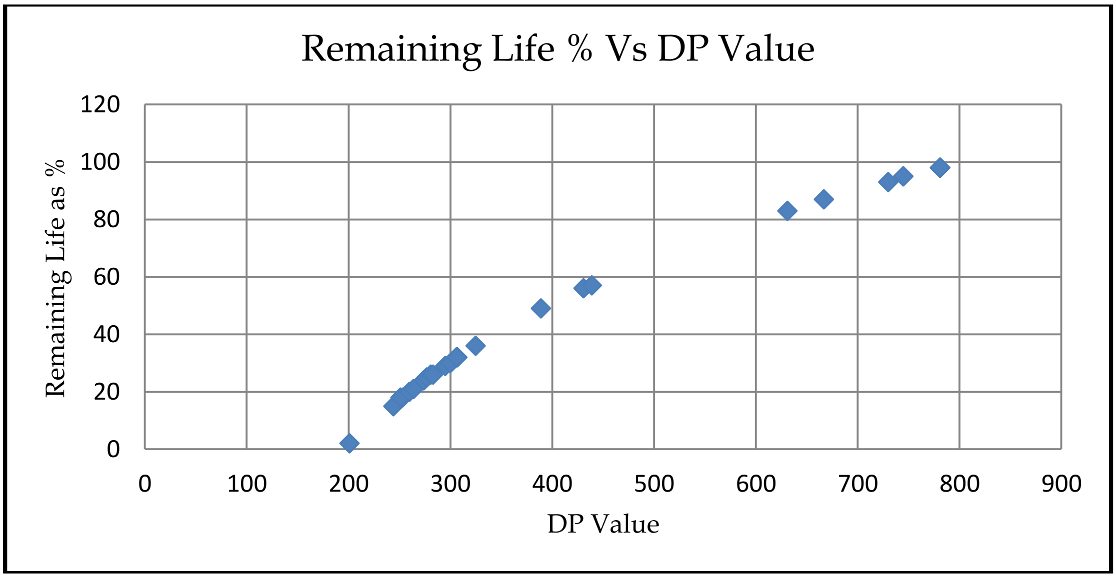

Figure 4.12: Remaining Life Vs Degree of Polymerization (Test Results)

By using the regression methods it was found the following logarithmic relationship between the DP Value and the Remaining Life.

$$\text{Remaining Life } \% = 70.86\ln(\text{DP Value}) - 373.87$$

There is only a slight different between the two relationships. FI_{Furan} is determined using the relationship in Figure: 4.11 because the remaining life is assumed to be linearly related to the Fitness Index. When DP ≤ 200, $FI\text{-}_{Furan}$ equals 0% and when DP ≥ 800, $FI\text{-}_{Furan}$ equals 100%.

$FI\text{-}_{Furan}$ = Remaining Life as a percentage

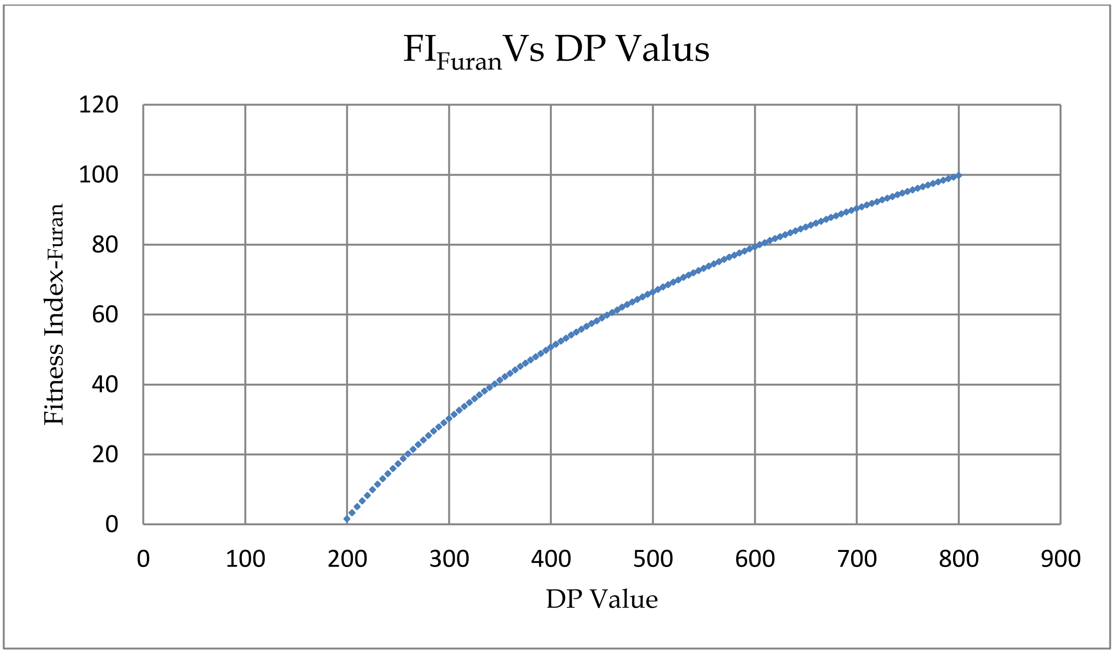

Figure 4.13: FI_{Furan} Vs Degree of Polymerization

- FI_{Furan} 76%-100% Repeat the test in every 5 years
- FI_{Furan} 51%-75% Repeat the test in every 2 years, Analyze the trend.
- FI_{Furan} 21%-50% Repeat the test in every year, critically analyze remaining life
- FI_{Furan} at 20% Get ready to replace the transformer.
- FI_{Furan} = 0% Shall Remove from Service immediately

Furan test results

Table 4.8 shows the test results of all the transformers in CEB-owned hydro power stations. 5 Components were tested as described in Section 3.2.5. Only the 2FAL was detected in this test for the Furan analysis. All of them are measured in parts per billion (ppb).

No.	T.F. Name	S.N	Age Years	2FAL ppb	DP	Remaining Age %
1	Samanala U1R	285686	47	6390	201	0
2	New Laxapana U2Y	1933666	40	4540	244	14
3	Victoria U1R	801884	29	4220	253	17
4	Victoria U3B	801877	29	4280	251	16
5	Victoria U1Y	801885	29	3990	260	19
6	Victoria U2B	801883	29	3840	264	20
7	Victoria U1B	801886	29	3550	274	23
8	Victoria U3R	801878	29	3460	277	23
9	Victoria U2R	801881	29	3360	281	24
10	Victoria U3Y	801879	29	3300	283	25
11	Victoria U2Y	801882	29	3000	295	28
12	New Laxapana U2B	1933662	40	2880	300	29
13	New Laxapana U2R	1933660	40	2720	307	31
14	Samanalawewa U1	AFW1854100	24	2740	306	30
15	Ukuwela U1	89964	37	1240	325	35
16	Samanala U1Y	285691	47	1410	389	48
17	Samanalawewa U2	AFW1854200	24	1000	431	55
18	Udawalawa U2	93076	46	940	439	56
19	Samanala U1B	285689	47	200	631	83
20	Canyon U1	H27932	27	150	667	87
21	Randenigala Spare	102537	27	90	730	93
22	Randenigala U1R	102536	27	80	745	95
23	Randenigala U1Y	102533	27	80	745	95
24	Canyon Spare	AN69060T1	32	60	781	98
25	Randenigala U1B	102535	27	60	781	98
26	Randenigala U2Y	102532	27	60	781	98
27	Rantambe U1	102539	28	60	781	98
28	Rantambe U2	102538	28	60	781	98
28	Samanala U2R	4810873	6	<50	800	100
29	Samanala U2Y	4810875	6	<50	800	100
30	Samanala U2B	4810876	6	<50	800	100
31	New Laxapana U1R	5412763	0	<50	800	100
32	New Laxapana U1Y	5412764	0	<50	800	100
33	New Laxapana U1B	5412765	0	<50	800	100
34	Victoria Spare	801880	29	<50	800	100
35	Ukuwela U2	898512	22	<50	800	100
36	Udawalawa U1	301301	1	<50	800	100
37	Canyon U2	AJ69002T1	25	<50	800	100
38	Randenigala U2R	102534	27	<50	800	100
39	Randenigala U2B	102571	27	50	800	100
40	Bowatanna	5BA151401	36	<50	800	100
41	Kotmale U3R	7476016	27	<50	800	100
42	Kotmale U3Y	7476014	27	<50	800	100
43	Kotmale U3B	7288042	30	<50	800	100

Table 4.8: Furan test result of hydro power stations in CEB [3]

Following graph shows the DP value vs 2FAL ppb of all the transformers in CEB-owned hydro power station.

FI_{Furan} of U1R transformer of Samanala Power Station = 0%
FI_{Furan} of U1Y transformer of Samanala Power Station = 49%
FI_{Furan} of U1B transformer of Samanala Power Station = 83%

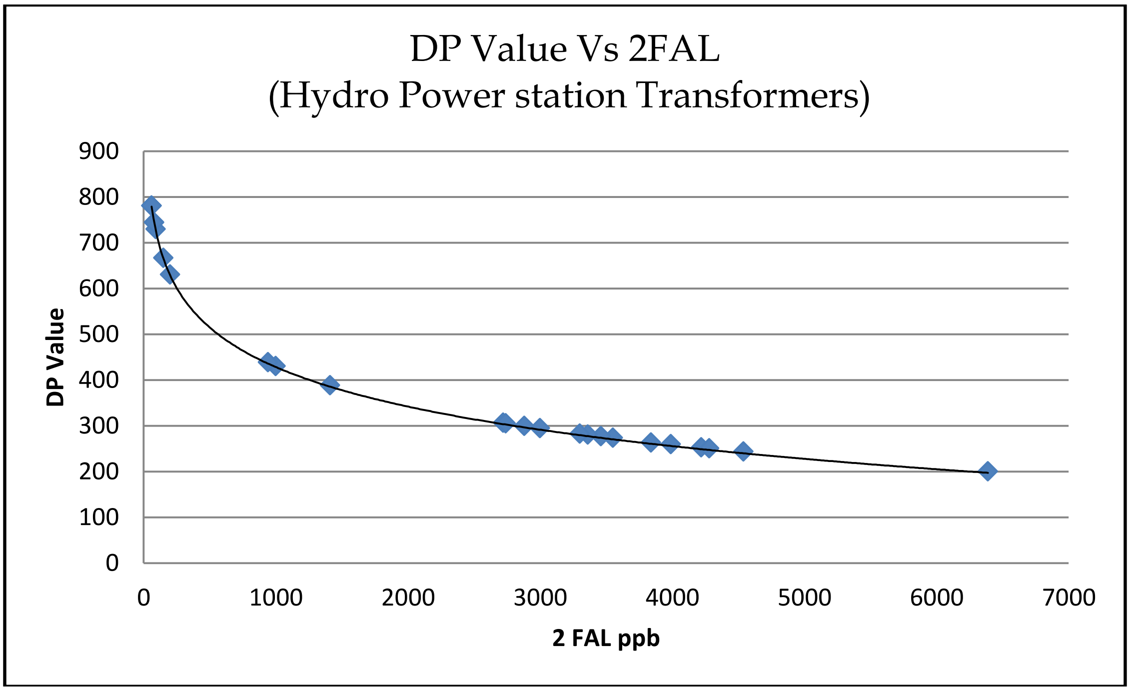

Figure 4.14: Degree of Polymerization Vs 2FAL ppb

4.2.3.1 Important Facts on Furan

Furan Test result illustrates the condition of the Solid Insulation rather than the oil insulation.
Although an outage is not necessary for the Furan test this test is very expensive since it is a special laboratory test which require to measure values in parts per billion (ppb). This facility is not available in Sri Lanka.

Once the furanic components are generated the deterioration process cannot be stopped or reversed. It is accelerated when the transformer is exposed to very high temperatures (typically above 120°C). Presence of oxygen and moisture also accelerates the deterioration [20]. The acceleration of the deterioration process can be avoided by removing additional oxygen and moisture content by drying.

Therefore no recommendations are made according to the FI_{Furan} as done in previous tests. Only the Fitness can be estimated with this test. However, keeping the Moisture level in paper and insulation oil as low as possible can help to control the FI_{Furan}.

Once the end of life of the paper insulation is reached the transformer is also considered to have reached its end of life, because there is no cost effective method of replacing the insulation paper [20].

4.3 Calculation of Overall Fitness Index

If the two pre qualification tests are passed Fitness tests are done and the Fitness Index is calculated for individual tests.

4.3.1 Overall Fitness Index (OFI)

The overall fitness index is calculated by using the individual fitness indexes. Logically the worst case scenario is considered as the overall Fitness of the transformer. Hence the Lowest individual fitness is considered as the overall fitness index.

$OFI = Min\ (FI_A + FI_F + FI_{DGA})$

No	Transformer	Serial No.	Installed	Age as at 2013 (Years)	FI_A	FI_{DGA}	FI_F	OFI	Expected Life (Years)
1	U1R-Samanala	285686	1969	44	**66**	**84**	**2**	**2**	0.5
2	U1Y-Samanala	285691	1969	44	**58**	**85**	**45**	**45**	11.25
3	U1B-Samanala	285689	1969	44	**21**	**80**	**83**	**21**	5.25
4	U2R-Samanala	4810873	2006	7	**100**	**73**	**100**	**73**	18.25
5	U2Y- Samanala	4810874	2006	7	**100**	**96**	**100**	**96**	24
6	U2B- Samanala	4810876	2006	7	**100**	**79**	**100**	**79**	19.75
7	U1R-Samanala-N	5512865	2013	0	**100**	**73**	**100**	**73**	18.25
8	U1Y-Samanala-N	5512866	2013	0	**100**	**74**	**100**	**74**	18.5
9	U1B-Samanala-N	5512864	2013	0	**100**	**83**	**100**	**83**	20.75
10	Ukuwela U1	89964	1975	38	**85**	**93**	**36**	**36**	9
11	Ukuwela U2	P-89-8512	1990	23	**35**	**32**	**100**	**32**	8
12	Samanalawewa U2	AFW1854200	1988	25	**33**	**80**	**56**	**33**	8.25
13	Kukule U2	N5091102	2003	10	**100**	**96**	**100**	**96**	24

Table 4.9: OFI Values calculated for various transformers of CEB

4.3.2 Probabilistic Overall Fitness Index (POFI)

The overall fitness index (OFI) was calculated based on the present condition of insulation oil and it can be improved by considering the probability of improving the FI_{DGA} and FI_{A} with possible maintenance activities. FI_{F} cannot be improved because Furans ones created it cannot be reversed.

4.3.2.1 Improving FI_{DGA} (PFI_{DGA})

FI_{DGA} was calculated by considering the TDCG level and TDCG generation rate. It is assumed that the TDCG level increased from 0ppm to 4630ppm during its lifetime unless there is no special fault. The normal gas generation rate was 0.5ppm per day under normal conditions.

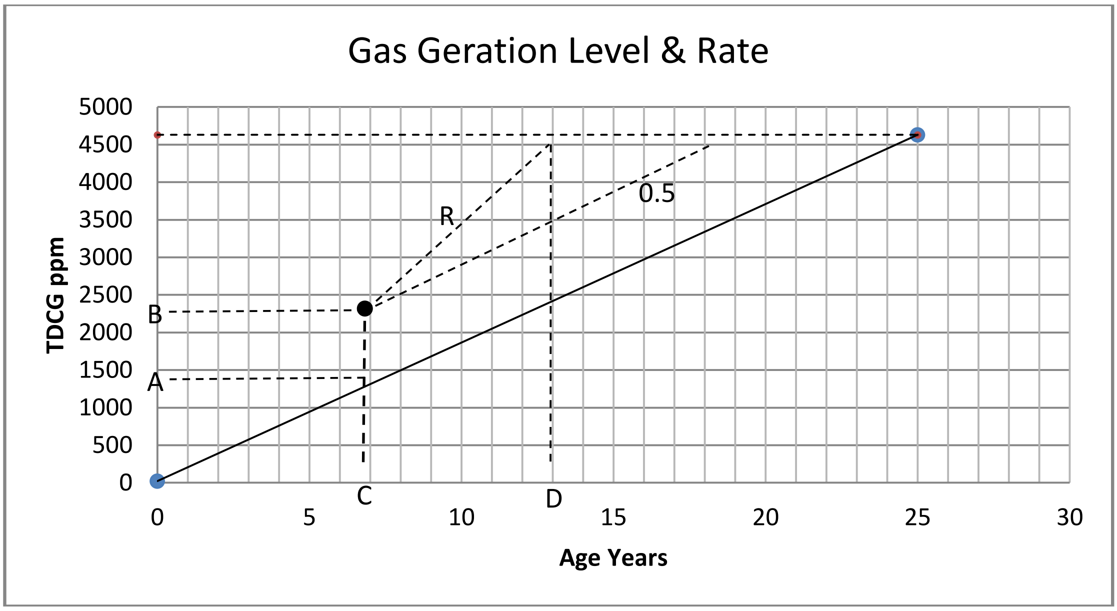

Figure 4.15: Gas generation level and rate (Theoretical & Practical)

Let's assume the DG test was done at the age of 'C' years and test results are as follows.
TDCG level is 'B' and TDCG rate is 'R'. The expected life is 'D' years if no maintenance is done.
At this age TDCG normal level shall be 'A'.

Now, the probability of improving TDCG level from 'B' to 'A' is to be estimated and it will depend on the continuity of fault and future maintenance. It is considered as 'P1'.

Similarly, the probability of improving TDCG rate from 'R' to 0.5ppm is to be estimated and it will depend on the continuity of the fault and future maintenance. It is considered as 'P2'.

Using the experience and past behavior of dissolved gas level and rate of change in TDCG, maintenance engineers are capable of estimating P1 and P2 for a particular transformer.

Considering above probabilities,

Probabilistic Remaining Life (Maintenance considered) =

$$\frac{4630-(B-A)(1-P1)-A}{365\,\{0.5+(R-0.5)(1-P2)\}}$$

If, 'B' is less than 'A' P1 is considered as 1.
If 'R' is less than 0.5, P2 is considered as 1.

Then the Probabilistic Fitness Index (PFI_{DGA}) for DGA is calculated as follows,

PFI_{DGA} = (Probabilistic Remaining life)/25 x 100

4.3.2.2 Improving FI_A (PFI_A)

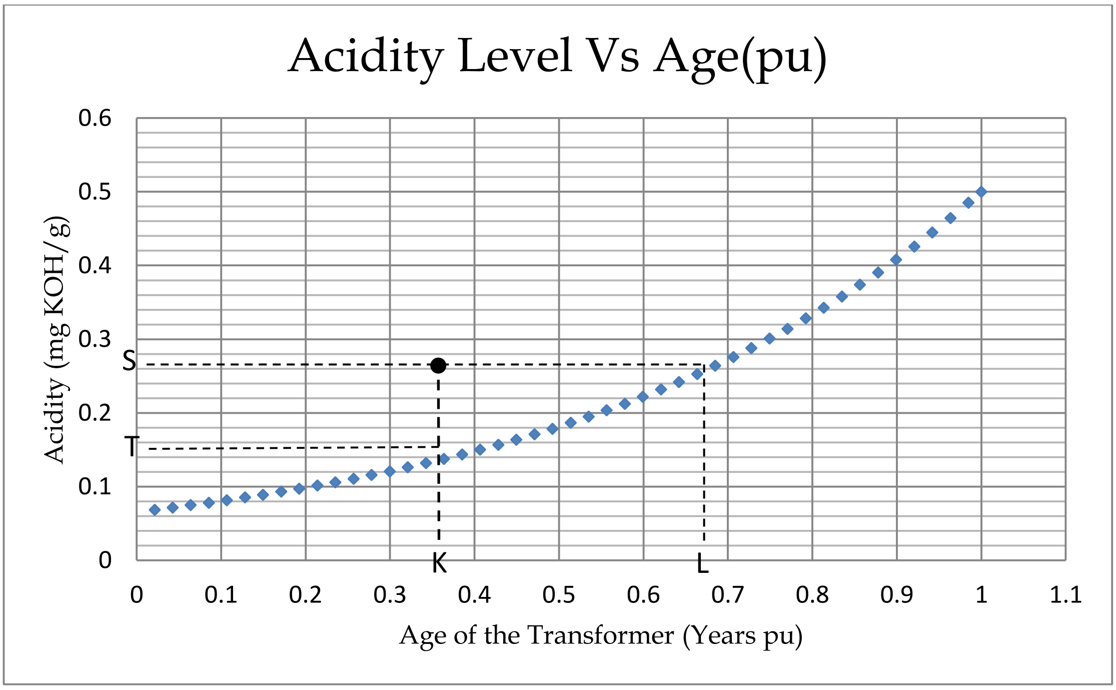

Figure 4.16: Acidity generation (Theoretical & Practical)

Let's assume the Acidity test was done at the age of 'K' years and the acidity level was 'S'.
At this age normal acidity level shall be 'T'.

Now, the probability of improving acidity level from 'S' to 'T' is to be estimated and it will depend on the continuity of fault and future maintenance. It is considered as 'P3'.

Using the experience and past behavior of acidity level maintenance engineers are capable of estimating the acidity improvement probability (P3) for a particular transformer.

Considering above probability,

$$Probabilistic\ Acidity\ Level = T + (S - T)(1 - P3)$$

$$Acidity\ Level = 0.0658 \times\ e^{0.0434\ \times Age(pu)}$$

$$log_e\left(\frac{Acidity\ Level}{0.0658}\right) =\ 0.0434\ \times Age(pu)$$

$$Probabilistic\ Expected\ age = \frac{log_e(\frac{Probabilistic\ Acidity\ Level}{0.0658})}{0.0434} \times 25$$

$$Probabilistic\ Expected\ age\ = \frac{log_e(\frac{T+(S-T)(1-P3)}{0.0658})}{0.0434} \times 25$$

PFI_A = (25- Probabilistic Expected age)/25

4.4 Expected Condition and Recommendations

OFI	Ranking	Condition	Estimated Life of Insulation
100%	Very Good	No attention Required	Could Live another 25 years or more
81% ~ 99%	Good	Nearly New, No noticeable defects or deterioration, No major intervention required.	May live another 20 to 25 years if well maintained.
61% ~80%	Fair	Some Defects or deterioration exist. Operation is not affected. But need to analyze individual "FI"s.	May Live another 15 to 20 years if well maintained.
41% ~ 60%	Poor	One or Many Defects exist. Immediate attention required before getting worse. Analyze individual "FI"s.	May Live another 10 to 15 years if well maintained.
21% ~ 40%	Bad	Serious problem exists at least in some portion of the TF. Operation is affected. Need immediate attention to Individual "FI"s and their recommendations.	May Live another 05 to 10 years if well maintained.
0% ~ 20%	Curtail	Very Series problem is exist at least in some portion of the TF. Pay attention to Individual FIs and their recommendations. Prepare for Major repair or replacement	May Live maximum 5 years if well maintained

Table 4.10: Expected Condition and Recommendations based on the OFI Value

Chapter 05

Reliability and Life Time

5.1 Improvement of Reliability

The Overall fitness index value can be considered as a good indicator for the reliability of the particular transformer. If the OFI is high the reliability is estimated to be high and there is no tendency of failure unless a fault due to sudden overheating or lightning. If the OFI is low the reliability is estimated to be low. There is a tendency of failure. Engineers have to carefully monitor the condition and do necessary tests such as Moisture, FRA, Acidity, DGA, and Furan. Then by applying necessary diagnosis techniques described in the Chapter 04 the reliability can be maintained at a higher level.

5.2 Diagnosis Methods

5.2.1 Transformer Drying

Basically there are three approaches for the drying of power transformers: off-site oven drying, onsite drying and on-line drying.

5.2.2. Off-Site Oven Drying

Off-site oven drying is the traditional drying technique used for new transformers in the factory.
High temperature applied together with low pressure dry the insulation. However, for an already Installed transformer, the transportation to a workshop can be very expensive. Additionally, the transformer will be off-line for a considerable length of time [21].

5.2.3 On-Site Drying (Off-Line Drying)

In the off line drying systems it is required to heat up the oil. The reason for heating is because moisture is transferred to the paper when the oil temperature is decreased. The Offline Oil filter contains few numbers of heaters. Here the transformer has to be de-energized. Therefore longer duration of oil filtering is not possible. Generally these filter plants have high flow rates so that several cycles of oil can be circulated within few days [21].

5.2.4 On-Line Drying

Here on-line drying systems dry the oil through continuous circulation. The transformer can be left in service and the oil will regain its dielectric strength very quickly. As the oil contains only a very small amount of water, typically half of 1 % of all the water in the transformer, this method of drying the solid insulation will take the months and years. Additionally, there is a risk that the inhibitors in the oil could be inadvertently removed [21].

5.2.5. Fullers Earth Filtering

Fullers Earth is a special type of material used with oil filters for removal of acids and soluble surface acting contaminants by adsorption. When treated the IFT of oil will be increased. All acids, gums, resins and other surface acting soluble contaminants are trapped and held within the media. [26]

5.3 Availability of transformers

Unless there is no fault or breakdown, transformers have to be available in the system. Under this section the availability of transformers will be discussed with respect to the selected condition monitoring tests.

The moisture test, Acidity test, Dissolved gas test and the Furan tests are carried out by taking oil sample either from the top of the transformer or bottom of the transformer. For the sampling, there is no outage required. In some cases outage may be required for sampling from the top oil, depending on the transformer arrangement. Therefore, the transformer is available to the system while the test is being carried out.

The DIRANA is done after disconnecting all the terminal connections of the transformer and around three hour outage is required for the measuring of MIP. Therefore this test causes an outage. However, periodical maintenances are done, once in a month, once in a year etc. Thus, if the DIRANA is scheduled to the same outage where we do maintenance the availability is not affected due to condition monitoring tests.

5.4 Life Time

The average life time of previously used transformers in Laxapana Complex was 42 years. IEEE C57.91-1995 describes the life span as 20 years. In practice, oil filled transformers are designed for 30 to 40 years [20]. In this thesis the technical life span of a transformer is considered as 25 years which has OFI of 100%.

Chapter 06

Conclusion

Using two important condition assessment tests, moisture condition of the transformer was evaluated. Using the standard bench marks, pass mark was selected for moisture tests. These two tests were called as pre qualification tests. If pre qualification tests are passed three Fitness tests were selected to find the Fitness Index. If prequalification tests are failed, the relevant recommendations under each tests has to be carry out. Necessary drying techniques are described in section 5.2.

Three fitness tests were selected which critically affect to the life of the transformer and individual fitness index were calculated for each Acidity level, Dissolved gasses level and Furanic component level.

The OFI value is only an indication for the transformer fitness. It can be used to compare the fitness of various transformers. OFI values of the same transformer measured time to time can also be compared to analyze the life of transformer. The calculated overall fitness index implies the life expectation.

According to the OFI, expected condition of the transformer and recommendations are given in the Table 4.10. Diagnosis has to be done considering the individual Fitness Index values rather than the OFI value.

6.1 Future Work

6.1.1 Loading Patterns of Transformer

Loading pattern is a main cause for the reduction of life time expectation of a transformer. If the transformer is continuously loaded to its rated value, not exceeding the rated capacity, the loading pattern will not affect for the life time. Information on Operation & Maintenance history (O & M), Unusual operating temperatures indicated by gauges and continuous monitoring, abnormal temperatures indicated by infrared scanning, nearby lightning strikes or through faults, abnormally high corona presence, abnormally high external temperatures, Problems with auxiliary systems (fans, radiators, cooling water piping, pumps, motors, controls, and indicating and protection devices), also have to be used in the estimation of expected life.

Apart from the above accidents, sometimes transformers are intentionally overloaded for a short time within the safe operating limits. The transformer lifetime is affected by this action [18].

Due to the limited time, it was not possible to acquire sufficient abnormal loading patterns from the available transformers. Such abnormal loading conditions are mostly not recorded. It is required to use abnormal loading patterns for about 10 years to reveal proper relationship between the expected life time and the abnormal loading cycles.

6.1.2. Other Necessary Tests

In this thesis only five tests were used. MIO and MIP are tested for estimation of moisture content and DGA, Acidity and Furan were tested to estimate the expected life time. Other tests also can be taken in to account for further analysis. But the cost for the particular test and the requirement of de-energizing (Outage Cost) has to be considered.

References

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