Transformer Failure Analysis:Reasons and Methods

Jaspreet Singh
Punjab State Power Corporation Ltd,
Moga, Punjab, India

Sanjeev Singh
Electrical & Instrumentation Engineering Department
SLIET Longowal, India

***Abstract*— This paper presents a detailed analysis of Transformer failure reasons and methods in conjunction with a real time data of the electrical transmission and distribution system to find the reasons and its remedies for better capacity utilization and reliability. The analysis is carried out using data collected from one zone of a city based substation having four circles of Punjab state power corporation limited (PSPCL). The analysis is carried out in accordance with IEEE standards and summarized to present the reasons and possible remedial measures for prevention of transformer failures.**

***Keywords*— Transformer failure, insulation failure, harmonics, power quality (PQ), distribution transformers.**

I. INTRODUCTION

Transformer is a static machine with very high efficiency and rugged construction. The rate of failure of distribution transformers in India is higher (12-17%) as compared to developed countries (2-3%). This high failure rate is cause of concern to all the Distribution Companies (Discoms) in the country. Every year, nearly 200 Crore of Indian Rupees (INR) are spent by the Discoms for repair and replacement of distribution transformers [1]. The loss becomes enormous due to the transformer failure, if the revenue loss for supply outage is also taken into consideration. It has become a serious problem due to increasing failure rate every year [1-8].

The role of transformer begins at generating station as the power is generated at maximum value of 11 KV in generating stations in India, far away from the load centres. This power needs stepping up to extra high voltages for reduction of current thereby the losses during transmission. Thereafter it is stepped down to 66/11KV at substations for primary distribution network and further stepped down to 11KV/400V using distribution transformers for secondary distribution system to feed consumers of different categories e.g. domestic, commercial etc. Distribution system consists of 11KV feeders; Distribution transformers and low tension (LT) three phase 4 wire systems. So the distribution transformer is a most important component of the distribution system to provide uninterrupted power supply to the consumers and it should be highly reliable and efficient.

The transformer failures result in loss, not only on account of repair or replacement of failed transformer, but also, the revenue loss to the utility on account of power not supplied to the consumers. Other important disadvantage is reduced reliability of the system, because of frequent failure of power supply. The risk of failure is defined as the product of probability of failure and consequences [2]. To improve the reliability of the system and to reduce the risk of failure, it is important to bring down the failure rates. This requires a systematic study of distribution transformer failures which further needs a real time data collection for failure of distribution transformer from the field. There are various international standards [9-15] formulated to incorporate above concern about transformer failures.

This paper aims at the reasons of transformer failure in distribution system so that in future these problems may be avoided to save the distribution transformers failure and huge money loss of the Discoms along with improvement in quality and reliability of the distribution system. The paper is presented in six main sections, namely introduction, basic components of a Transformer prone to failure, reasons of transformer failures, Transformer failure investigations, Remedial measures and conclusion.

II. TRANSFORMER COMPONENTS AND FAILURE

The distribution transformer consists of Magnetic circuit (Core, yoke and clamp structures), Electrical circuit (windings and insulation), Terminals, bushings, tank, oil, radiator, conservator and breather as main parts. The transformer can fail due to failure of any of the component as discussed below.

A. Core

The core of transformer carries magnetic flux and provides mechanical strength to the transformer. The core fails due to DC magnetisation or displacement of the core steel during the construction of transformer.

B. Winding

Function of the windings is to carry current in the transformer and they are arranged as cylindrical shells around the core limb where each strand is wrapped with paper insulation. In addition to dielectric stress and thermal requirements the windings have to withstand mechanical forces that may cause winding displacement. Such forces can appear during short circuit and lightening. Windings mostly fail due to short circuit or transient over voltage.

The short circuit of windings may occur due to various reasons i.e. mechanical fault in the windings during the construction of transformer or fault in insulating material or hot spot creation or generation of copper sludge or low oil level in the transformer. Transient Overvoltage may result due to lightening or wrong connection of transformer or short circuit in the LT system.

C. Tank

Tank encloses the transformer core and windings as a physical protection as well as serves as container for oil used as coolant. It has to withstand environmental stresses such as corrosive atmosphere, high humidity and sun radiations. The tank is inspected for oil leakage, excessive corrosion, dents and other signs of rough handling. Internal arcing in an oil filled transformer can instantly vaporize surrounding oil which can lead to a high gas pressure inside the transformer and rupture the tank.

D. Solid Insulation

Solid insulation, made of cellulose base products such as press board and paper, is used between the windings for electrical isolation. Cellulose consists of long chain of glucose rings which degrades with time leading to shorter chains. Condition of paper is indicated by degree of polymerization (DP) as average number of these rings in the chain [3]. New paper has DP between 1200-1400 where as DP < 200 means that the paper has a poor mechanical strength and may no longer withstand short circuit and other mechanical forces. This solid insulation is the weakest link in the transformer insulation system.

Solid insulation gets mechanical damage due to movement of the transformer or forces generated during short circuits. Faults in insulating material may occur due to generation of $CuSO_4$ or hot spots created due to low quantity of oil or overloading of transformer.

E. Transformer Oil

The transformer oil provides insulation between windings along with desired cooling in the transformer. Transformer oil is a highly refined product from mineral crude oil and consists of hydrocarbon composition such as paraffin, naphthalene and aromatic oils [8].

The failure of cooling oil causes due to two reasons either malfunction of the oil circulation or poor heat transfer to secondary cooling circuit. This leads to increased viscosity of the oil in the transformer and too high temperature in the second cooling circuit. Moisture and oxygen coupled with heat are the major cause of oil contamination leading to generation of conducting particles. Thereby temperature inside the transformer will rise and failure of oil insulation results in a short circuit.

F. Bushings

Bushings are used to take out the winding terminals outside the tank with electrical insulation to connect the transformer with the power system. The bushings used are generally two types slid bushings and capacitance graded bushing. The solid bushing has a central conductor and porcelain or epoxy insulation around it.

The main failure mode of bushing is short circuit. It may be due to material faults in the insulation or due to damage. The damage can occur due to sabotage, during shipping or due to flying parts from other failed equipment. Damages, cracks in the porcelain and bad gaskets provide ingress of water inside insulation of the bushing leading to its failure.

III. TRANSFORMER FAILURE MODES

A transformer can fail due to combination of electrical, mechanical or thermal factors [4] and it is always difficult to find out a particular mode of failure. Most of the transformers fails due failure of insulation. So the transformer may fail electrically due to failure of insulation which may be result from electrical, mechanical or thermal stress.

A. Electrical Factors

There are various electrical factors for transformer failures which can be broadly classified in to following three categories: Transient or overvoltage conditions; Lightening and switching surges; Partial discharge.

B. Mechanical factors

Mechanical factors result in damage to the transformer windings rupturing its solid insulation. If the damage is acute the transformer may fail electrically. Winding of transformer may rupture due to electromechanical forces or damage during shipping. The other reason for failure may be as given below.

- Electromagnetic Forces;
- Shipping of the transformer;
- Buckling of the innermost winding;
- Conductor tipping;
- Conductor telescoping;
- Spiral Tightening;
- End ring crushing;
- Failure of coil clamping system;
- Displacement of transformers leads.

C. Thermal Factors

The cellulose insulation of transformer degrades with time due to heat generation during normal loading of transformer. It results in decrease in dielectric strength of the insulation and weakens the insulation to rupture under normal voltage conditions. The other reasons for failure may be as given below.

- Transformer overloading for prolonged period;
- Operation of transformer on nonlinear loads;
- Failure of cooling system;
- Blockage of oil ducts;
- Operation of transformer in an overexcited condition;
- Operation of transformer in high ambient temperature.

IV. TRANSFORMER FAILURE INVESTIGATION

To conduct failure analysis on distribution transformers IEEE standard C57.125 “Guide for Failure Investigation, Documentation, and Analysis for Power Transformer and Shunt Reactors [9] is used. It provides a procedure to perform failure analysis on transformers to find out the most probable cause of transformer failure.

A failure investigation generally starts with no supply complaints from the affected area where the distribution transformer has failed. When failure is confirmed, then onsite investigation and testing is conducted to collect vital data from site. Before conducting the failure investigation all historical data related to transformer must be gathered. The failed transformer is inspected externally, internally and finally teardown is performed so that analysis to be done to find out the cause of failure of transformer.

A. Preparation for information gathering

Before conducting the onsite investigation, documents related to the history of the condition of the transformer must be collected which will stand very helpful during the onsite inspection, which may include:

- Routine inspection reports;

- Maintenance work records including reports on past problems;
- Historical DGA results;
- Historical oil test results;
- Transformer name plate ratings;
- Factory test data reports;
- Loading data at the time of failure;
- List of any faults or switching event in the system just prior to failure.

B. *Onsite Inspection*

A quick onsite inspection of a failed transformer is necessary to collect the vital data which may be destroyed during restoration of supply. Onsite inspection consists of examining the external conditions around the failed transformer and thorough examination of transformer.

External Conditions: On arriving at site before starting the visual inspection the conditions all around the transformer, first examine, interview the peoples in the vicinity at site about any abnormality they saw during normal operation or during the time of failure. Investigator has to look for any unusual sounds, odors, debris expelled from transformer or accessories, foreign objects in area, any evidence of vandalism, load on transformer, system disturbances and any dead animal in area.

Transformer conditions: Investigator to look for following visible abnormalities in the transformer main tank for bulging, cracks, leaks, sign of overheating, oil spill or fire, oil level in main tank, oil level in conservator, damage to radiators, damage to conservator and bushings for leaks, broken porcelain, holes in caps and tracking. If no visible damage is found externally, then next step is to conduct diagnostic testing of transformer.

C. *Diagnostic Testing*

When there is no visible damage is found in external examination of transformer. Then diagnostic tests are conducted to find out fault and to give indication of repair. Test data should be recorded carefully and several tests may be interpreted together to diagnose a problem. Samples of insulating oil for testing must be taken prior to opening the transformer for inspection. Following tests can be conducted on transformer.

Insulation Resistance: Winding to winding, winding to ground, core to ground, dielectric absorption (Polarization Index).

Other tests: Transformer Turn ratio; Winding DC Resistance; Oil dielectric breakdown; Excitation (low voltage)

Before performing field tests, safety precautions should be taken to ensure that the transformer is disconnected from all power and auxiliary sources and has been properly earthed.

D. *Internal Inspection*

When the results of diagnosis test indicate the failure of transformer, an internal inspection is performed on site to determine the location of fault and extent of damage. Transformer oil is removed for inspection, the exposure time must be kept to a minimum to reduce moisture entrance into the tank. Internal abnormalities may include.

- The odor of burnt insulation, burnt oil, color of oil, indication of moisture and its location and free water in tank and amount.
- Evidence of burns, discoloration, or deposits due to arc or stray flux overheating on tank walls, bushing terminals, copper connectors.
- Evidence of loose connection or splices to bushings, collar, spacers etc.
- Displacement of winding and leads.
- Condition of core and evidence of core damage.

E. *Tear down Inspection*

If the internal inspection of do not provide any cause of failure of transformer, then it is necessary to perform de tank the transformer to identify the cause of failure. The core is bring out of tank for inspection which can provide following evidences of failure

- Damage to core (breakdown of core insulation).
- Evidence of tracking results from dielectric breakdown.
- Evidence of radial and axial failure.
- Evidence of mechanical failure.
- Evidence of thermal failure.

V. FAILURE ANALYSIS

After collecting from on-site and off-site the data must be thoroughly studied before reaching any conclusion in service distribution transformer results in mechanical damage and electrical failure. The energy from the power system can cause both to occur. So care must be taken while reporting cause and effects.

A. *Analysis of Mechanical Failure of Windings*

To thoroughly analyze distribution transformer failure, an understanding of the axial and radial forces causing mechanical deformation to winding is required. The direction of forces and mechanism of failure in core type transformer is different from the mechanism in shell type transformer. Further winding type has different strengths to resist conductor moment under short circuit forces. The stiffness of the insulation system, the rigidity of the winding clamping system, the strength of the conductors and the elasticity of the coil play a role in determining the winding response to electromagnetic forces.

1) Winding Failure Modes for Core Type Transformers

i) Radial Tension Failure

Forces directed radially outward can cause conductors to stretch. Moderate deformation can contribute to axial instability and collapse of the coil. It can also cause the conductor insulation to tear. In extreme cases, the stretched conductors can break when the material elastic limit is exceeded.

ii) Radial Compression Failure

Forces directed radially inward can cause conductor buckling or mechanical failure of the winding.

iii) Axial Expansion Failure

Opposing forces directed axially towards clamping plates can cause these plates to bend or break, or can cause jack bolts to bend or shear. The conductors will tend to separate at winding locations where current flow in opposite directions.

These forces can also cause conductors to tilt, allowing axial instability. Improper clamping or alignment may allow winding conductors to shift axially.

iv) Axial Compression Failure

Opposing forces directed axially towards winding centres can cause collapse of the winding. If the conductors tilt, the windings become unstable and collapse.

v) Axial Telescoping Failure

This term is used to describe the moment of individual winding relative to one another (i.e. outer winding moving upward or downward relative to inner winding.) or to describe the axial instability of a single winding (i.e. outer turns moving upward or downward relative to inner turns). Any mechanical failure of the clamping system would allow winding to move in opposite vertical direction relative to one another, thereby telescoping. The axial instability of an individual winding could result from radial tension failure, radial compression failure or from axial collapse. The result of these failure might cause conductors to slip or under one another and collapse inward, thereby telescoping.

vi) End Turn Failure

End turn experiences combined radial and axial forces. The resultant of these forces tends to tilt the outside turns and twist the ends inward towards the core leg.

vii) Spiral Tightening

Combined radial and axial forces can cause the entire inner winding to spiral and tighten, leading to circumferential displacement of the conductors and radial spacers.

2) Winding Failure Modes for Shell Type Transformers

i) Radial Forces

Small radial components of force can develop on the edges of the coil. When coil heights are tapped to obtain graded insulation, the radial forces are greater than usual. Forces directed radially outward can caud=se conductors to stretch.

ii) Axial Forces

Within the coil group, the axial forces are attractive, thus placing the conductors, insulation and spacer block under compression. These forces exert beam stresses on the conductors, which try to bend the conductors between the spacer blocks. The axial forces between the coil groups of different windings are forces of repulsion and try to force the coils against the ends of the core window laminations. These forces stress the major insulation between the winding and the core, and are extended through the core to the transformer tank. The axial force of repulsion between the coil groups load the tensile stress members in the tank in the core and coil support T beams.

B. Analysis of Electrical Failure

Transformer failure can be caused by transient surges. In such failures, the transformer insulation withstand should be checked with arrestor discharge voltage to ensure proper insulation coordination. Lightening, over-excitation, switching surges, winding resonance, turn to turn short circuit, layer to layer short circuit, partial discharges, insulation tracking, static electrification of oil and flashovers are all forms of electrical failure modes. Once internal electrical failure occurs, all fields are upset and force vectors become abnormal. Stresses are on materials in this ways which are not anticipated. Under these circumstances, fault analysis becomes very complex. Often, the sequence of events, first causes, and original weaknesses may not be determined by from inspection of the internal damage. External evidences and transformer accessories typically provide the clues to analyze the fault sequences. Various types of voltages that can exist in the transformer windings and associated parts discussed here for purpose of analysis

i) Normal low frequency system operating voltages

These are generated ac system voltage appearing at the transformer terminals. These voltages can be expressed in rms value and depends upon the transformer connections (star or delta) for phase to phase or phase to neutral voltages.

ii) Normal low frequency induced voltages

These are voltages induced in the winding by currents flowing in adjacent windings and conducting parts within the transformer or by dc components.

iii) Abnormal low frequency system operating voltages

These voltages are of short term ac voltages caused by over excitation, un balance loading or fault conditions that are typically removed from the system by operation of protective relay.

iv) Abnormal high frequency system voltages

These voltages are transient voltages typically caused by lightening, winding resonance or system switching. High frequency voltages generally produce greater dielectric stress than low frequency voltages in the winding turns nearest to the transformer terminal connections.

v) Abnormal high frequency and low frequency voltages from other causes

These voltages arise from external solar or DC disturbances or internal fluid phenomenon such as possibility of charge separation on insulating surfaces, changes in electric field distribution due to particle initiated discharge or progressive winding failure from developing turn to turn faults

VI. RESULTS AND DISCUSSIONS

Punjab State Power Corporation (PSPCL) is a utility responsible for Generation and Distribution of Power in the state of Punjab. It has a very large consumer base consisting of domestic, commercial, industrial and agriculture loads divided in four zones. It has large number of distribution transformers feeding the consumers. The transformer failure rate is above 15% which is a huge loss to the organization. According to IEEE Std. 57.100 [10] the life of liquid immersed transformer is 20.55 years. So large number of distribution transformers are failing prematurely. In this paper a city base sub division is selected and a failure analysis in conducted on failed transformers from 2010 to 2015 to find out the cause of failure of distribution transformers. Data on Transformer failure has been collected for a one zone of PSPCL including four circles named as C1, C2, C3 and C4 for the year 2010 to 2015 given hereunder.

Table 1: Transformers failed during 2010-2015

Transformer Failure in West Zone					
Year	C1	C2	C3	C4	Total
2010	1992	3017	3424	1425	9858
2011	2259	3402	4019	2367	12047
2012	2474	3184	3589	3774	13021
2013	2589	3418	4133	5717	15857
2014	2645	3615	4189	5792	16241
2015	2512	3602	4286	5855	16255

Table No. 1 gives yearly number of failure of distribution transformers of one west zone consisting of four circles indicating increasing trend of failure. Which indicate huge asset loss to the organization per year, is worth of crores of rupees. To find out the root cause of such a high failure of transformer one city sub division is selected and failure analysis is conducted continuously from 2010 to 2015 on transformers of various capacities shown in table no. 2. Onsite inspection, external inspection, diagnostic testing, internal inspection and tear down analysis are performed as per IEEE standard C57.125 to find out cause of failure of distribution transformer.

Table 2: Year wise capacity wise failure of transformer

Transformer Failure in City Sub Division						
Capacity	2010	2011	2012	2013	2014	2015
6.3 kVA	2	2	1	3	1	8
10 kVA	5	4	0	3	5	10
16 kVA	2	3	11	0	12	8
25 kVA	12	16	15	17	16	19
63 kVA	9	9	11	15	18	12
100 kVA	11	13	12	19	16	17
200 kVA	0	0	0	8	1	0
300 kVA	0	0	0	1	0	0
500 kVA	0	0	0	0	0	1
Total	41	47	50	66	69	75

On the basis of the failure analysis conducted, the causes of failure of transformer are listed in Table 3. The most common cause of failure of transformer is insulation failure; it deteriorates due to heat, oxidation, acidity and moisture. Line surges such as switching surges, voltage spikes, line faults and distribution abnormalities. Prolonged overloading, improper maintenance, moisture and oil contamination are also the potential causes of failure.

During failure analysis quite a large number of transformers reported in other category, whose cause of failure is other than the listed in Table 3. It is suspected that most of the transformers from this are failed due to nonlinear loading of the transformer. The change in the electric load profile has created continued power quality problems. The most important contributor to power quality problems is the customer's use of sensitive type nonlinear load in all sectors. Nonlinear type loads contribute to the degradation in the electric supply's Power Quality through the generation of harmonics. Harmonics results in increased losses in transformer hence more heating is resulted which derates the capacity of which may result in premature failure of transformer. Work is in progress to find out no of transformer failures due to power quality problems.

Table 3: Causes of transformer Failure

Cause of Failure	No of Failure
Insulation failure	92
Manufacturing Defects	22
Overloading	30
Line surge	70
Improper Maintenance	19
Lightening	14
Sabotage	2
Moisture	21
Oil Contamination	20
Other	58

VII. CONCLUSION

In this paper failure modes of transformer are discussed and failure analysis of distribution transformer carried out on one sub division of PSPCL. Failure analysis is carried out on transformers of various capacity failed between 2010-2015. Onsite inspection, external inspection, diagnostic testing, internal inspection and tear down analysis are performed as per IEEE standard C57.125 to find out cause of failure of distribution transformer. This analysis reveals that insulation failure and line surges are the major cause of the failure of transformer. Large no of transformers are also failing due to manufacturing defects, overloading, improper maintenance, moisture and oil contamination. There are transformers for which actual cause of failure is not known, which are supposed to be failed due to power quality problems.

REFERENCES

[1] Singh, R. and Singh, A, "Causes of failure of distribution transformers in India," in *Proc. 9th International Conference on Environment and Electrical Engineering (EEEIC)*, Prague, Czech Republic ,2010.

[2] Mohsen Akbari, P. Khazaee, I. Sabetghadam and P. Karimifard "Failure Modes and Effects Analysis (FMEA) for Power Transformers," in *Proc.* 28th International Conference on Power System, Tehran, Iran, 4-6, November 2013.

[3] D. Linhjell T. J. Painter L. E. Lundgaard, W. Hansen, "Aging of oil impregnated paper in power transformers," IEEE transactions on power delivery, 19(1), January 2004.

[4] William H. Bartley, HSB, "*Analysis of Transformer Failures*," Proceedings of the Thirty Six Annual Conference, Stockholm, 2003..

[5] S.S.Rajurkar and Amit R. Kulkarni, "Analysis of Power Transformer failure in Transmission utilities" in *Proc. 16th National Power Systems Conference*, 15th-17th December, 2010.

[6] A.K. Lokhanin G.Y. Shneider V.V. Sokolov V.M. Chornogostsky, "Internal insulation failure mechanisms of HV equipment under service conditions", 15-201 CIGRE Session 2002.

[7] George Edufull and Godfred Mensah, "An Investigation into Protection Integrity of Distribution Transformers - A Case Study," in *Proc. of the World Congress on Engineering 2010 Vol IIWCE 2010*, June 30 - July 2, 2010, London, U.K.

[8] N. A. Muhamad, B. T. Phung, T. R. Blackburn, K. X. Lai,"Comparative Study and Analysis of DGA Methods for Transformer Mineral Oil," *IEEE Power Tech*, Lausanne, pp 45-50, July 2007.

[9] IEEE Guide for Failure Investigation, Documentation and Analysis for Power Transformers and Shunt Reactors, IEEE Standard C57.125-1991.

[10] IEEE Standard Test Procedure for Thermal Evaluation of Oil-Immersed Distribution Transformers ANSI/IEEE Standard, C57.100-1986

[11] IEEE Guide for Interpretation of Gases generated in Oil filled Transformers, IEEE standard C57.104-1991,.

[12] IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment, IEEE standard C57.106-2002.

[13] IEEE Guide for Diagnostic field testing of Power Apparatus- Part I: Oil filled Power Transformers, Regulators, and Reactors, IEEE standard 62-1995.

[14] IEEE Guide for loading Mineral – Oil – Immersed Transformers, IEEE C57.911995.

[15] ANSI/IEEE C57.117 - 1986, "IEEE guide for reporting failure data for power transformers and shunt reactors on electric utility power systems,"