LEARNING BY FAILURES – A TRANSFORMER CASE STUDY

A QUALITY PRESPECTIVE

A K Sharma, GM (IS) *M Misbahul Islam, Sr Manager (IS)*

Nishith Mehta DGM (IS) *Amit Kumar , Manager (IS)*

NTPC, Regional Inspection Office, Bhopal

INTRODUCTION

Power transformer is one of the most critical equipment of power system that defines reliability of the associated unit. A highly efficient machine wherein the manufacturer takes all possible measures including proven design, well established and comprehensive quality management system from sourcing of raw material to inward testing, In-process tests/checks as per well laid out quality plan, final tests/checks as per customer specification etc., transportation to site, proper storage and quality checks during erection and commissioning to ensure quality operation up to design life of transformers. Latest methodology is used for condition monitoring of transformer during its operation at site to ensure trouble free operation.

Despite all above measures taken, transformer problems/failures were observed at different stages of transformer design, manufacturing, storage etc.

This paper deals with some of the problems observed with respect to design, manufacturing, storage at site and learning from such problems.

1.0 DESIGN RELATED IN-PROCESS FAILURE

Construction and transformer detail:

Transformer	Generator Transformer
Power	315 MVA
Voltage	24 (LV) / 420/√3 KV (HV)
Current	11666.67 A / 1299.04 A
Vector Group	YNd11
Phase	Single
Class	420 KV

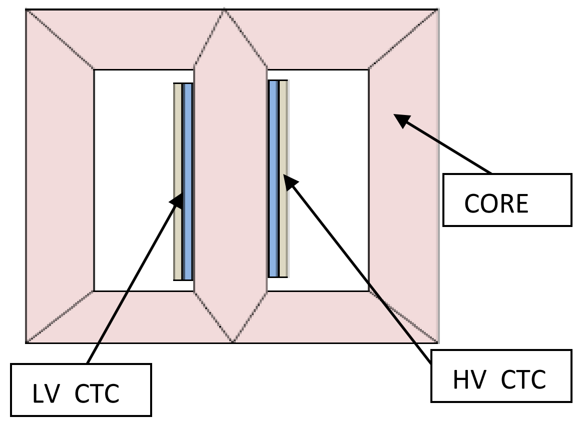


FIG. 1 315 MVA Generator Transformer

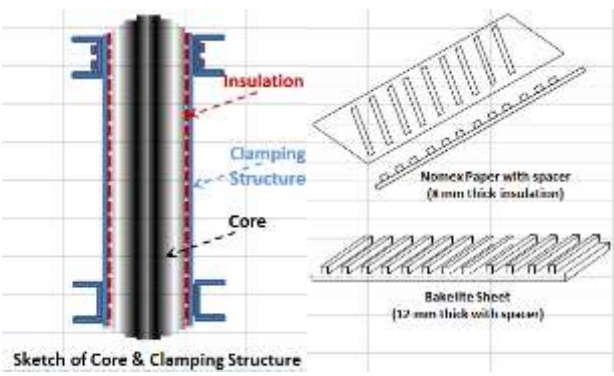
The design specification of GT was provided by a foreign collaborator to reputed and experienced Indian manufacturer. The subject transformer manufacturing was going on well with all quality checks and records till the Vapour Phase Drying (VPD) process. After VPD at the stage of servicing before tanking, as per scheduled check an isolation test at 10 KV between Core laminations and Core clamping structure was performed. On application of high voltage, voltage couldn't reach beyond the level of 8 KV and collapsed. On second attempt voltage collapsed only at 800 Volts.

It was a rare failure, least expected by the manufacturer and therefore the collaborator was called to review the failure and suggest the corrective actions. This test was successfully done a number of times till the failure, at different stages of transformer manufacturing as part of agreed quality plan.

Investigation of problem

Investigational isolation tests were done by separating various parts of core clamping structure. On investigation it was found that the HV side top and bottom, LV side top structures withstood the test. However, LV side bottom along with LV side clamp plate could not withstand the voltage.

An 8 MM insulation of Nomex paper board was used to withstand 10 KV between clamp structure and core. Although Nomex paper is having good electrical properties but mechanically it is compressible (soft). Due to compression of insulation paper the designed thickness got reduced and the insulation failed to withstand 10 KV voltage.



Proposed corrective action

The details of failure were reviewed by the design group of collaborator and the Indian manufacturer. It was observed that the Indian manufacturer conventionally is using Bakelite plate in between the core and clamp along with paper insulation to provide specified dielectric strength. Bakelite is non-compressive having good mechanical strength and therefore more suited to withstand the technical requirement. Hence, it was agreed that the manufacturing be redone using Bakelite plate after replacement of Nomex sheet.

In this case whole process was rewind up to core building stage i.e. unlacing of core, removal of coils, removal of whole insulation between the core and clamp and so. Now, the Bakelite sheet having channels for oil flow along with nomex paper was used as new insulation between Core laminations and Core clamping structure. After VPD again the test was performed and the new insulation got passed in Isolation test of 10 KV.

There were other three generator transformers in manufacturing where in nomex paper had already been used in line with recommendations of foreign collaborator.

All the transformer cores were dismantled, Nomex paper was removed, bakelite sheets were replaced and the core was rebuilt. The time taken to rebuild each transformer core was one month.

The Indian manufacturer at design stage commented use of Bakelite sheet in view of compression of Nomex Board. However, the collaborator, changed the specification to Nomex paper leading to failure. Considering the application use of Bakelite was the right option.

B. **Manufacturing process related failure at final testing**

Construction and transformer detail:

Transformer	**StationTransformer**
Power	**50 MVA**
Voltage	11.5 (LV) / 400 KV (HV)
Current	2510.22 A/ 72.17 A
Vector Group	YNyn0
Phase	**Three**
Class	**400 KV**

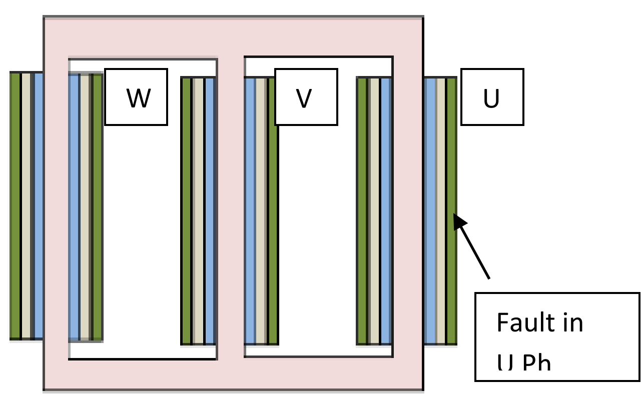
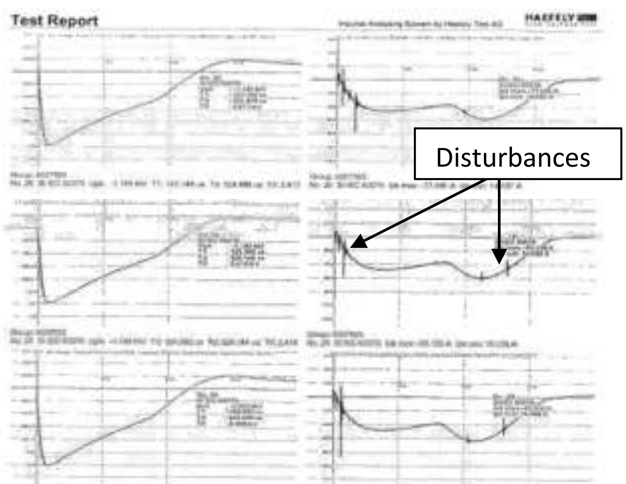


FIG. 2 : 50 MVA STATION TRANSFORMER

This station transformer successfully passed various low voltage tests, IR (Insulation Resistance), Temperature Rise, No Load Loss up to 110% voltage and separate source test.

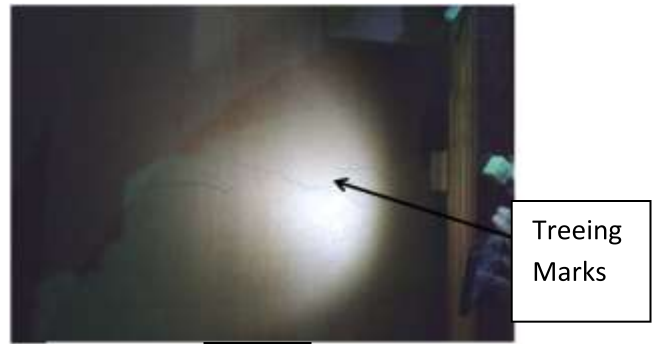
Subsequently switching Impulse test (SI) was conducted. This test was successful on ‘V’ & ‘W’ phase HV terminals at 100% test level of 1175 KVp. However, HV ‘U’ phase terminal sustain the 100% BIL level with no distortion in voltage trace but, **disturbances were noticed in current oscillograms of** all three shots, near the starting point and also near end of the current trace.



Pic 1 : Disturbances observed in current oscillogram.

Internal inspection of transformer was carried out with following observations

i. Internal surface of tank was clear and there were no blackening marks etc.
ii. No abnormality noticed in the vicinity of any HV, LV or Tapping Leads. The OLTC was also clean and there was no abnormality.
iii. However Tracking/ treeing marks observed on the outer surface of outermost pressboard barrier of U-phase coil (Pic.2). These marks were on diametrically opposite side of HV lead & approximately at centre location vertically. The progression of treeing/ tracking marks was in horizontal direction i.e. along horizontal periphery of outer surface of outermost barrier in the vicinity of high voltage discs.
iv. No abnormality was observed on inner surface of the outermost barrier.



Pic 2

v. The remaining 5 nos. pressboard barriers over the U-phase coil were opened and no abnormality was noticed.
vi. Detailed inspection carried on U phase HV winding and no abnormality was noticed.
vii. No abnormality was observed in V & W phase or at any other location in the transformer.

The findings are hereunder -

a) The failure was a result of surface discharge phenomena i.e. treeing/ tracking on outer surface of outermost pressboard barrier.
b) Various literatures related to this phenomena was studied and after analysis the phenomena, it emerged that fundamentally such treeing/tracking can be attributed to either of the following reasons :

i) Quality of insulation item

ii) Quality of transformer oil

iii) Presence of high quantum of polar/ metallic contaminants

iv) Excessive moisture on the Pressboard surface

c) Each probable cause was studied and all relevant data/ results were analysed to fixed the underlying cause of treeing or not. Following are the findings

1. **Quality of insulation item**: The supplier Test certificate of the pressboard lot used was reviewed and found in order. Also Pressboard samples of the affected area of tracking/treeing, location of other healthy locations of same outermost barrier, Innermost healthy barrier Were drawn and

sent to manufacturer own lab for possible tests on oil soaked pressboard. The following tests found in order

a) Ash content (allowed 1% max)

1. tracking/ treeing location: 0.48%

2. other healthy location of same outermost barrier : 0.51%

3. Innermost barrier: 0.35%

b) Presence of metallic particles: No metallic particles present in all the samples

c) BDV of tested samples is as under-

1. tracking/ treeing location: 27.7 kV/mm

2. other healthy location of same outermost

barrier : 28.6 kV/mm

3. Innermost barrier : 38.9 kV/mm

Lower BDV values of outermost barrier as compared to minimum value of 30 kV/mm is due to the effect of treeing/tracking and moisture ingress in the outermost barrier.

Though treeing/ tracking takes place, but BDV is not drastically deteriorated and only marginally lower and BDV of 3rd sample and other tests results indicates inherent healthiness of pressboard material.

Also the outermost pressboard barrier is at the least stress zone where stress is not more than 5 kV/mm.

Hence, the test results and analysis indicates that the pressboard material quality is in order.

2. **Quality of transformer oil:** The oil parameters were tested before filling, then its filtration was carried out and it was again tested before final testing. None of the test results indicate any abnormality. The same oil has been used for testing of other transformer and no abnormality has been noticed.

3. **Presence of high quantum of polar/ metallic contaminants** :No presence of metallic particles found on pressboard samples tested. Also no dust, dirt, metallic inclusions etc. observed on the pressboard surface.
4. **Excessive moisture on the Pressboard surface :** Processing records were studied and no abnormality was observed, indicating that moisture extraction was proper after processing.

   However during study of various data at subsequent manufacturing stages, it was observed that there was a problem in air drying plant during this period and hence the air used during bushings mounting at case fitting stage was not fully dry. Thus probably the moisture present in the air has possibly settled and trapped locally on outer surface of outer pressboard barrier and during application of 100 % Switching impulse of 1175 kVp, has caused treeing/surface discharges and disturbances in current waveform

Root cause of the problems

Problem was due to exposure of outermost pressboard barrier to moisture during bushings mounting at case fitting stage as the dry air contained moisture. Dry air dewpoint was not measured by the manufacturer before using it for the bushing mounting operation.

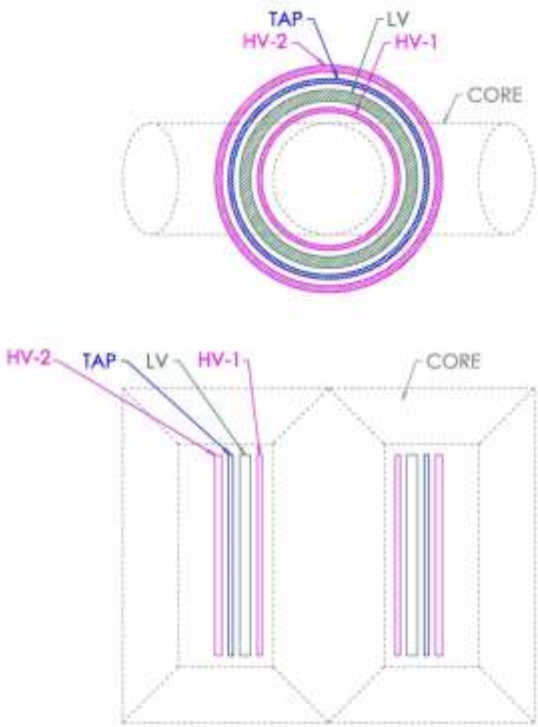
To avoid such problem following measures has been taken:

A) It was communicated to manufacturer to measure the dewpoint of dry air before its application.
B) A checkpoint in QAP is also added in which NTPC will verify the dew point of dry air measured by the manufacturer.

C. Manufacturing process and long storage related failure

Construction and transformer detail:

Transformer	**Generator Transformer**
Power	**82 MVA**
Voltage	13.8 KV (LV) / 420v3 KV (HV)
Current	5942.03 A (LV) / 338.1 (HV) A
Vector Group	YNd11
Phase	**Single**
Class	**420 KV**



HV1 IS 15 % OF HV2

a. 82 MVA, 13.8/420 kV, 1-Phase Generator Transformer (GT) was manufactured and dispatched for a Hydro Electric Project of NTPC Ltd. After receipt at site, GT was kept stored in N2 filled condition for almost 2 years and then in oil filled condition for 4 years till its commissioning.

b. After commissioning, first DGA of GT conducted revealed C2H2 of 13 ppm and after 2 week DGA result for C2H2 was 15 ppm. GT was taken out of service and after degassing, GT was charged again with zero C2H2 and next DGA was taken after few months that showed presence of high fault gases as under and GT was taken out of service for internal inspection.

c.

During internal inspection by manufacturer, problem

DGA	PPM	IEEE LIMITS
H2	550	100
CH4	80	120
CO	83	350
CO2	1634	2500
C2H4	125	50
C2H6	40	65
C2H2	141	1

was found in brazing joints of HV line lead connector and LV lead connectors (2.1 & 2.2 terminals). Same was rectified after lifting the bell tank cover in repair bay after thorough internal inspection. After completion of dry out cycles and electrical testing, GT was re-commissioned. After re-commissioning, C2H2 gas was again found in DGA results and its concentration gradually increased from 2 PPM to 40 PPM in about 2 months.

d. After few days GT developed fault leading to failure. Unit was not in operation. GT was in back charged condition from 400 kV side.

e. As per schedule GT was loaded approx. 2 hours per day and total loading hours were 111 hours approx. in last 55 days of operation. Thus, GT remained in back charged condition and synchronized through GCB (Generator circuit breaker) as and when as per load schedule.

f. Pressure Relief Valve-1&2, Buchholz relay stage 1 & 2 of the GT operated during the fault.

g. GT differential, Overall differential got operated.

Impact of the failure detected/observed as :

a. Top tank severe bulging noticed at rim location on LV side with heavy leakage of oil and fire. Fire got extinguished immediately. (Pic. 1)


Pic. 1


Pic. 2

b. LV side tank rim badly distorted with the gap of about 8 inches with shearing of rim bolts. (Pic. 2)
c. LV bushing porcelain at (2.1) terminal found damaged. Clamping member of (2.2) terminal found dislodged.
d. HV bushing overhead connector found sheared and found disconnected. However HV bushing appeared to be intact.
e. Bus-duct post insulator in the vicinity of LV bushing connection found shattered.
f. Although LAVT cubicle of Y & R phases were intact but the LAVT of B phase door got opened with shifting of PT. The associated LA was found damaged.
g. Buchholz relay found sheared at conservator end. Gas collecting device dislodged.
h. No damage noticed in the coolers, associated pipe work, conservator assembly, and Motor drive unit and marshalling box of the GT.
i. The failed GT transported to manufacturer works for further investigation.

Detail of failure analysis : Further Physical inspection & investigation tests of the GT were carried out at manufacturer works and following are the observations-

a. Low voltage tests i.e. Ratio, Magnetizing current, Windings resistance, IR values of core isolation & yoke shunts isolation were carried out. HV winding resistance found approx. 25% higher, which indicate breaking of 1 conductor out of total 4 parallel conductors in HV winding. All other test result found in order.
b. Coil assembly outer pressboard barriers near bottom LV lead take off (2.2) and upto center height of coil assembly found severely damaged and blackened. Pressboard barrier on other peripheral and near HV line lead take out of coil found intact. (Pic. 3)
c. Flashover marks found in one of steel bracket of LV bottom lead takeoff busbar support. The Udel wood support of copper bus-bar was found broken and blackened. (Pic. 4)


Pic. 3


Pic. 4

d. Coil assembly removed from core leg for further inspection of individual windings.

e. No physical abnormality observed in core assembly. No physical abnormality observed in Tap changer, tapping leads, HV line lead take off and LV top lead take off (2.1).
f. HV-II: Pressboard barrier immediately near the winding found blackened and punctured at the middle (line disc of HV winding) at radial location of above bottom LV Lead takeoff. (Pic. 5)
g. On LV side, out of total 6 nos. pressboard barriers over HV winding, only 1 no. found in position as above. Other 5 nos. barriers were shattered and fallen off from the GT tank opening at site and in transit. Some broken pieces with tracking and blackening marks were found inside the tank. (Pic. 6)
h. All six nos. HV winding outer barrier sections on the HV bushing takeoff side were found intact
with no tracking marks.

Pic. 5

Pic. 6

i. On removal of barrier, melted HV winding strands at the location of punctured pressboard barrier was observed. (Pic. 7)
j. No physical abnormalities observed in Tap Winding and HV- I (approx. 15%) winding.
k. No abnormality observed in Pressboard barriers between HV, TAP & LV windings

Pic. 7

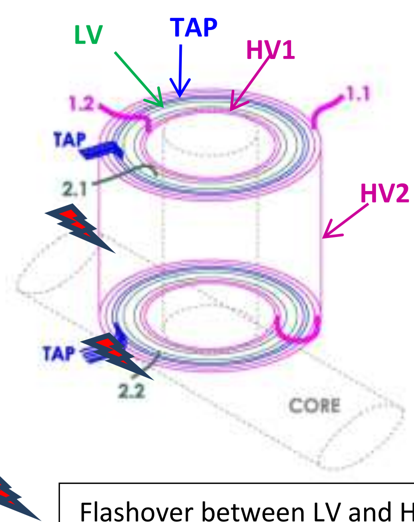
Pic. 8

l. Bottom LV Lead Take Off (2.2) was found having localized insulation burning and melted copper, immediately below the outer insulation barriers and below HV burnt conductors. The takeoff lead 2.1 and LV winding do not have any other abnormal physical observation. (Pic. 8)
m. Burning mark of approx. 4 mm dia. and 3 mm deep also found in Udel wood bottom ring support of coil assembly below LV lead burn mark position.

FAILURE PHENOMENA AND PROBABLE REASONS OF FAILURE:

The failure phenomena was deliberated and various data related to design, manufacturing & testing, site storage, commissioning tests, earlier DGA issues of the GT were studied in detail. The findings are hereunder –

a. From the observation and further deliberations, it is inferred that the GT failure is due to arcing between 400 kV HV winding line disc to 13.8 kV LV bottom lead take off through outer pressboard barriers. This type of failure mode is unique and no previous incidence of this nature has been experienced.
b. There was a ground fault also inside the transformer after occurrence of the fault which is corroborated with physical finding of flashover marks on one of steel bracket (ground potential) of LV bottom lead take-off bus-bar support.**(sketch of failure)**



Flashover between LV and HV following the creepage discharge path

c. Due to flashover between HV winding and LV bottom lead, LV voltage momentarily picked up high voltage and which probably exceeded the LV insulation level causing flashover of LV bottom lead to ground and further failure of LV busduct post insulator and associated LA taken place.
d. The DGA results prior to the GT failure was indicating only gradual increase of Acetylene with no companion gases and not indicative of such type of failure.
e. The arcing phenomena through the surface of outer pressboard barrier is inferred to be due to treeing/tracking on the surface of pressboard barriers and treeing/ tracking appeared to be initiated since first charging of the GT. Treeing/ tracking is a slow process and this could not have been suspected and detected in the earlier DGA result analysis and internal inspections of the GT. This treeing/ tracking were generating lower amount of DGA and would have been aggravated over the period of operation of the GT, leading to permanent failure of pressboard insulation and direct flashover between HV winding to LV lead.
f. Various literatures related to this type of failure was studied and it emerged that fundamentally such treeing/tracking can be attributable to either of the following reasons :

i) Quality of insulation item

ii) Quality of transformer oil

iii) Presence of high quantum of polar/ metallic contaminants

iv) Excessive moisture on the Pressboard surface

a. To check the quality of insulation, Pressboard samples drawn from unaffected outermost 3 mm tk. barrier, Sample from innermost 1.5 tk. barrier of unaffected area and Sample from innermost 1.5 tk. barrier of affected barrier tested at as per IEC 60641 for all possible tests on oil soaked pressboard i.e. ash content, Presence of metallic particles and BDV. Test report attached as Annex-3. All the values are in order, hence quality of insulation is not the reason of the problem.
b. The oil parameters were tested before commissioning and during operation and no violation of parameters like BDV, PPM, Tan delta etc. were reported. This is ruled out as root cause of failure.

c. One of the probable reason contributing to the failure could be the presence of certain foreign conducting particle trapped between the two pressboard barriers, causing discharges and further damaging the barrier. This would have been aggravated till the occurrence of arcing and failure. However looking into the nature of treeing/ tracking over significantly larger surface area of the pressboard barriers (Pic. 6) possibility of failure due to foreign conducting particles is very remote.
d. Based on investigation and analysis, presence of localized trapped moisture in pressboard barrier appears to be the main reason of the failure. In Pic. 6 above, tree shaped white marks seen on the surface of some pressboard piece and black carbonized tree and tracking marks on the surface of another pressboard piece. Excessive moisture content in the pressboard significantly deteriorates dielectric strength on the surface and partial discharge inception voltage is reduced to a much lower voltage level. The white mark is the path of partial breakdown of cellulose due to localized moisture present in the pressboard. The partial discharge forms chain reaction and further aggravates at consistent voltage stress and stimulates the treeing process. The treeing process propagated towards lower/ ground potential and finally bridged the gap of high voltage to lower/ ground and leads to arcing.
e. Heavy arcing caused burning and decomposition of surrounding oil into gases resulting hydraulic dynamics of high pressure and damaged the transformer tank to a significant extent.
f. The moisture ingress in the GT is most probably due to longer storage of the GT for 2 years in N2 filled condition and then in oil filled condition for 4 years before charging and commissioning.
g. In the much longer storage period of GT for 6 years, moisture might have entered inside the GT from some gasket sealing joints and settled down in the hygroscopic cellulose insulation system.
h. The absorbed moisture in the thick pressboard barriers is very difficult to extract from normal vacuuming and hot oil circulation cycles of erection and commissioning of GT.
i. In this GT, the absorbed moisture was not completely removed in normal vacuuming and hot oil circulation cycles and some moisture left locally entrapped in the outer pressboard barriers.
j. The localized trapped moisture in the outer pressboard barriers of HV winding to tank will not reflected in the pre-commissioning tests results of insulation resistance (IR) and tan delta values of GT being outer insulations as this will have less effect on IR and tan delta values.

Root cause of problem

Improper removal of moisture in normal vacuum and hot oil circulation cycle from the GT, which was stored for very long period of six years in N2 filled condition and oil filled condition.

PREVENTIVE ACTION :

A. Erection, oil filling and commissioning of Large Power Transformer of 400 kV class to be taken up as soon as possible after receipt at site. In case longer storage is inevitable, Transformer may be kept in N2 gas filled condition up to 6 months with bi-weekly monitoring of N2 pressure. After that, Transformer to be stored filled with oil with regular six monthly monitoring of oil BDV and PPM. This is in line with manufacturer standard installation & commissioning manual.
B. A QA&I circular Ref No. CC:CQA:0000:999 Dt 20.12.2014 Already issued for storage of EHV/Generator transformer to be strictly followed.

C. For longer duration stored GT particularly of Hydro-electric sites experiencing longer rainy period, snowy season etc., rigorous dry out cycles measures e.g. N2 purging cycle & dew point measurement, extended vacuum cycle, external heating measure etc. may also be adopted.

Steps taken to improve the quality of transformer

Initially the problem found was in brazing joints of LV and HV leads. In order to improve the quality of brazing following steps are taken :

1. ***Checking of brazing joints by a team of senior officials comprising of BHEL Engg/QC/ Production being done at manufacturing stage.***
2. ***Random witness from NTPC side has been added in QAP rev-5.***
3. ***Extended heat run test at 110% rated current for 12 hrs /24 hrs with DGA analysis especially for repaired jobs and proposed to be introduced in QAP revision 05 for new ones. This test will reveal the poor joints by DGA analysis.***
4. ***Crimped joints are used where applicable with proper crimping procedure/specification added in QAP revision-5.***

The above corrective actions resulted in good DGA results at site during operation of this repaired subject GT.

Conclusion

Transformer manufacturing involves a number of processes and operations. It is extremely important that each process and operation is meticulously and religiously followed before handing over to next operation. It is equally important that all tests / checks to ensure successful completion of previous stage are successfully conducted before proceeding to next stage/operation . So that rework /repair is completely avoided.

Most of the time the transformer manufacturing is taken up against strict target dates and ,therefore, any repair/rework causes slippage against schedule dates besides loss of material, man-days etc.

It is advisable to identify the critical processes and a team of production/Quality control/ Design to be constituted to check successful completion of such critical stages/operation.

With above corrective actions a track record of supply of transformer and performance feedback was taken after commissioning at site. No site failure was reported.

References:

1. **IEC 60076-1,2,3 Transformers testings.**
2. **Internal reports of NTPC with manufacturer.**
3. **RCA reports of manufacturer.**