Analysis of Failed and Working Power Transformer and Their Diagnostics

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Abstract—**The Transformer sustains various types of faults while in the working condition. There will be changes in electrical, mechanical and chemical properties in different parts of transformer before its failure. These changes in properties can be monitored by different condition monitoring methods. With proper analyzing the results of conditioning monitoring test the transformer can be easily saved from complete failure.**

In this paper various condition monitoring methodologies and its results analysis are explained by discussing the different case studies of failed and saved transformers.

Keywords— Dissolve Gas Analysis (DGA), Sweep frequency Response Analysis (SFRA), Transformer (TF), Partial Discharge (P.D), Winding (Wdg.), Resonance Frequency (RF)

I. Introduction

Transformer is very important and costly equipment in the Power system. Transformer while in the service faces various faults and suffers through mechanical and electrical stresses. Transformer condition monitoring is very essential factor to avoid catastrophic failure. Failure of transformer can be avoided by correct monitoring practices and perfect decision making and as the unwanted outages.

The transformer test results at the time of commissioning /Factory testing are the finger prints of healthy transformers. The routine tests mentioned in this paper and its results are compared with initial test results of transformer. The changes in the results determine the changes in the electrical/mechanical/chemical properties of transformer. These changes in the properties are symptoms of abnormality developed in the transformer which indicates that transformer is in the verge of failure. With proper analyzing the transformer routine test results we can pin point the location and exact cause of abnormalities in the transformer. By taking corrective measures on correct time we can avoid the failure of transformer and increase the stability of system.

For this diagnosis purpose some diagnosis techniques i.e SFRA [explaining in reference 4] , Capacitance and Tan Delta measurement [explaining in reference 3] , Dissolve gas Analysis (DGA) [explaining in reference 1] , Partial Discharge (P.D) [explaining in reference 5] , Furan Analysis[explaining in reference 2] along with low voltage site test are used.

Some case studies are carried out of failed power transformers which are analyzed and necessary points are kept in front so that considerable failure of transformer can be avoided.

As per section II.[B], the transformer sustains various types of the faults. Due to the above faults the electrical and mechanical stresses were developed inside the transformer.

The transformer is tested for special testing and routine testing. From routine testing of transformer we indirectly create behavior/finger prints of healthy transformer. In table representing special test & routine test as below there is brief explanation of testing & its objective.

The change in the behavior of transformer which is detected in diagnostic testing indicates that there is something abnormal happening in the transformer. The different diagnostic testing has its own identification/ significance which help in analyze the type of faults mention in II [B].
For correct and realistic analysis we are going to make two different sections.

Step 1 :
In this the finger prints / original test reports at site of transformer are collected. Then the frequency of testing and its test reports are closely monitor. By analyzing the different types of the failed transformer of different categories; the root causes of the failure as well as the abnormal methods & monitoring practices are pin point. From that the standard methodology of monitoring & preventive actions are identified in order to save the transformers as per actual site condition.

Step 2:
From step 1 the standard methodology of monitoring & preventive actions are finalized as per actual site condition. As per that monitoring practice the various transformers are monitored for their behavior .Each test reports are compared with its original test reports.

If any abnormality observed or any results matching with previous case studies then the fast and correct action /decision making will be carried out which indirectly save the transformer from failure.

As per above steps the main aim is to obtain the finger prints i.e initial/commissioning site test reports of healthy transformer which is failed .The various test involves are

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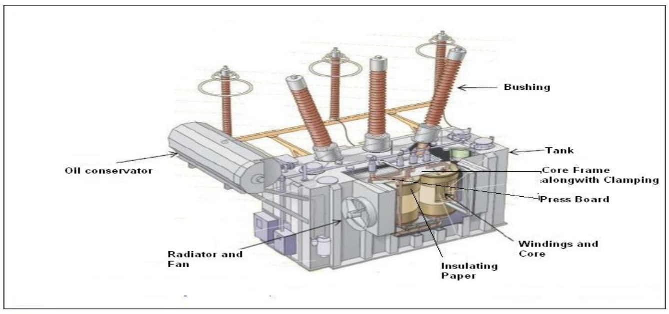
Table 1.Various special tests and routine tests		
Special Test		
Sr.No	Name of Test	Objective of Test
1	Dissolve Gas Analysis (DGA)	This test is useful to identify the faults gases i.e Hydrogen (H_2), Carbon Monoxide (CO), Carbon Dioxide(CO_2), Ethylene(C_2H_4), Ethane(C_2H_6), Methane(CH_4), wh ich can be generated due to different types of faults.
2	Capacitance and Tan Delta Measurement	The rise in tan delta and capacitance value causes the failure of bushing, winding. Hence this test is useful to monitor the healthiness of insulation including oil.
3	Sweep Frequency Response Analysis (SFRA):	The SFRA test is useful to monitorTransformer components such as windings, core, and insulation can be represented by equivalent circuits comprising resistors, capacitors, and self or mutual inductance whose values will be altered by a mechanical fault and electrical faults within the transformer
4	Furan Analysis	The degradation process of insulating paper resulting the depolymerization of cellulose,Producing glucose monomer and furan componants due to chemical reactions.Most often, the following five furan compounds are measured : 2-furaldehyde (2FAL), 5-methyl-2-furaldehyde (5M2F), 5-hydroxymethyl-2-furaldehyde (5H2F), 2-acetyl furan (2ACF), 2-furfurol (2FOL)
5	Polarization Index (P.I):	The Polarization index is the ratio of the 10 min IR value to 1 min IR value .This test is carried out for measuring the insulation between HV winding to Earth, HV winding to LV winding, LV winding to Earth
Routine Test		
Sr No.	**Name of Test**	**Objective of Test**
1	Open Circuit Test	To find inter turn short circuit of the winding, represent the core healthiness by calculating the core loss
2	Short Circuit Test	To find analysis of inter turn ,inter winding, winding to earth healthiness & to calculate the copper loss
3	Magnetic Balance Test	To check healthiness of the core. It is useful to interpret the failure of the core lamination.
4	Winding Resistance Test	To check the winding resistance, winding connection, loose contacts etc
5	Excitation Test	To check healthiness of the magnetic core structure i.e core bolt insulation breakdown, shorted lamination, shorted winding, etc.

II.[A] CONSTRUCTION OF POWER TRANSFORMER

The overlook on construction of the power transformer is useful to correlate with corresponding faults in the transformer and causes, the list of parts of transformer are as follows.



II.[B] THE VARIOUS FAULTS SUSTAIN BY TF.

Table 2.Types of faults sustained by Transformer				
Internal Faults		**External Faults**		**Design Defects**
Electrical Fault	**Mechanical Faults**	**Electrical Fault**	**Mechanical Faults**	
Short Circuit 1.Interturn 2.Inter Wdg. 3.Turn to E 4.Wdg. to Core 5.OLTC S.C	Loose connection between winding leads to bushings	Close phase to phase short circuit	Damage of bushing	Inadequate specification of TF
Open Circuit 1.In Interturn 2.Opening of star /earthing 3.OLTC O.C	Loose connection between core and frame	Close phase to earth short circuit	Blocking of cooling pipes	Faulty TF design
Over loading of TF Uneven loading	Improper connection of core to E	Lightening	Damages of oil gaskets	Faulty material used
Failuare of insulation like Oil ; Paper insulation; Bushings	Puncture of air balloon in conservator	Presence Of high harmonic contains in load		Poor workman ship
Failure of core due to 1.Core Buckling 2.Damages core laminations 3.Core heating				

III. CASE STUDY

3.1 Detail of Transformer: - 50 MVA, 132/ 22 kV, % Z = 9.52 % (At tap No. 5),

The above transformer was in working condition, which was commissioned on 28.3.13, and failed on dtd 01.08.14. We have collected some test report after failure of transformer, to analysis the cause of the failure.

The following tests were carried out while commissioning i.e on dated 28.3.13 on site the routine test & special test as mentioned in section no.05 are carried out thoroughly. The test results are found in order. In consultation with manufacturer the TF charged & stood OK.

As per manufacturer recommendation, the DGA test of TF was carried out after a year. While going through the results key gases was found in rising trend, these are as follows,

Table 3 DGA test results					
Gas	On dtd 14.02.13	On dtd 04.04.14	On dtd 13.03.14	On dtd 30.04.14	On dtd 06.06.14
(H2)	BDL	39	68	69	70
(CO)	8	**98**	**100**	**131**	**121**
(CO2)	19	**98**	**296**	**403**	**713**
(CH4)	BDL	17	7	9	4
(C_2H_4)	BDL	9	3	4	7
(C_2H_6)	BDL	7	BDL	BDL	BDL
(C2H2)	BDL	**22.7**	**16**	**16**	**26**
TDCG		193	194	229	228

Observation from DGA after one year:-

1. The DGA test was carried out after one year commissioning.
2. The Acetylene gas representing high arcing fault is in rising trend, Carbon monoxide & carbon dioxide representing rise in decomposition / degradation of cellulose material.

3. As well from ratio analysis 101 code is obtain which indicates continuous sparking in oil between bad connection of different potential or to floating potential breakdown of oil between solid material.
4. There was Partial Discharge in the TF as per ratio analysis.
5. The DGA was carried out by different kits & get compared by each other.

As DGA was in rising trend no other test was carried out on TF. During above monitoring, on dated 01.08.14, the above TF was failed on 22 kV feeder fault on indication of R phase Diff. relay operated, Buchholz relay alarm.

After tripping of T/F, it is seen that Buchholz Alarm was persisting hence flame test carried out. Bluish flame observed with heavy fault present of gases.

After failure of TF following test were carried

Open Circuit Test (Volts)						Mag. Current Test (3ph.) in mA				Mag. Current Test 1ph mA		
VRN	VYN	VBN	Vrn	Vyn	Vbn	IR	IY	IB	IN	IR	IY	IB
238	239	239	35.5	37.6	37.6	400	34	34.3	310	390	1.5	1.4

Initial Open Circuit & Magnetising Current Test

Open Circuit Test (Volts)						Mag. Current Test (1ph.)in mA		
VRN	VYN	VBN	Vrn	Vyn	Vbn	IR	IY	IB
247.5	249	249	38	39	39.18	4.5	2.4	3.0

Short Circuit Test after failure:

VRN	VYN	VBN	IR	IY	IB	IN	Ir	Iy	Ib	In
237	239	238	6.3	6.4	6.45	0.12	38	39.3	40.2	1.15

Short Circuit Test during commissioning:

VRN	VYN	VBN	IR	IY	IB	IN	Ir	Iy	Ib	In
247.3	248.9	248	7	7	7.3	0.2	43	43	43	1.8

Observation from OC & SC test
1. As SC test not deviated from original results while magnetizing currents in OC test are on higher side, therefore, there might be internal short circuit in the TF.
2. From OC it comes to noticed that the magnetizing current at no load is about 7 to 10 % less of SC current. There might be 10 % of R phase LV winding internal short circuit to earth.

Magnetic Balance Test after TF failure:

	Prim.Voltages (V)			Sec. Voltages (V)		
Voltage applied	VRN	VYN	VBN	Vrn	Vyn	Vbn
VRN	238	205	15.1	35.4	32.2	2.41
VYN	1.3	241	239	0.17	37.7	37.4
VBN	0.45	239	240	0.054	37.4	37.5

Magnetic Balance Test during commissioning:

	Prim.Voltages (V)			Sec. Voltages (V)		
Voltage applied	VRN	VYN	VBN	Vrn	Vyn	Vbn
VRN	247.70	204.50	39.67	40.27	33.59	6.60
VYN	82.22	249.60	165.37	13.67	40.64	27.90
VBN	19.36	232.20	249.30	3.10	38.00	40.67

Observation from Magnetic Balance test:-
1. The magnetic balance test during commissioning is found to be abnormal. But as per manufacturer & it recommendation TF was charged.
2. As R phase LV winding is partially short, therefore no EMF was developed in the HV R phase resulted into total flux density get concentrated to Y & B phase core limb.
3. The flux linkages to R phase core are almost zero due to LV short circuit. Indicating healthy core & magnetic circuit.

Winding resistance test:

L.V Winding resistance test after TF failure all values in mΩ				**L.V Winding resistance test during commissioning**		
Tap No.	**r-n**	**y-n**	**b-n**	**r-n**	**y-n**	**b-n**
5(N)	17.268	12.672	12.83	12.31	12.37	12.39

H.V Winding resistance test after TF failure all values in mΩ				**H.V Winding resistance test during commissioning in mΩ**		
Tap No.	**R-N (mΩ)**	**Y-N (mΩ)**	**B-N (mΩ)**	**R-N (mΩ)**	**Y-N (mΩ)**	**B-N (mΩ)**
1	581.6	555.3	556.5	548.90	550.20	550.00
5N	549.0	524.4	525.7	518.20	519.10	520.00
17	452.0	431.4	433.0	426.40	426.10	428.40

Observation from Winding resistance measurement test:-

1. The HV & LV winding resistance in view of R phase have winding resistance on higher side.
2. The LV winding might have get short circuited with earth & also the damage LV winding inside TF damages HV winding that result into partial increase in HV winding resistance.

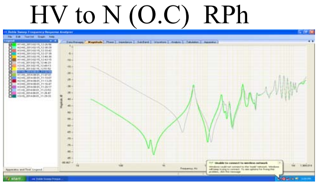
Polarisation Index Test at Oil Temp: 36°C

	PI test during TF commissioning all vaiue in GΩ				**PI test after TF failure all vaiue in GΩ**			
Between	15 Sec	1 min	10 min	PI	15 Sec	1 min	10 min	PI
HV- E	1.44	2.62	6.4	2.45	8.68	14.44	22.44	1.66
LV- E	1.08	3.29	24.47	7.53	← Break down →			
HV- LV	2.21	4.24	20.6	4.85	16.64	23.3	23.64	1.01

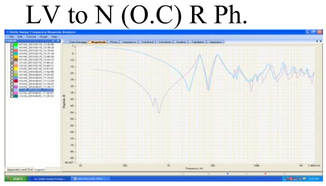
Observation from Polarization Index test
1. There is LV winding to earth short circuited inside TF.
2. The LV winding damages HV winding which may results into poor PI between HV to LV.

Sweep Frequency Response Analysis (SFRA)

HV to N (O.C) RPh



LV to N (O.C) R Ph.



Observation from SFRA Test

1. From the above graph it may be conclude that there may be chances of axial displacement of HV / LV winding, there is major damage of LV winding which can be short circuited.

Probable sequence of operation in view of failure of TF

- From DGA it comes to noticed that there are low energy dissipation faults at the time of commissioning which will get reflect in DGA ratio analysis.
- During service due to closer LV feeder fault that low energy dissipation fault get converted into high energy dissipation faults
- Due to high energy dissipation in side TF, the LV winding insulation between inter turn & core might have decomposed therefore CO2 & CO gases get increased.
- Due to failure / weaken of LV winding insulation, the LV winding get short circuited with core during heavy 22 kV feeder fault which reflects into PI
- Due to short circuit of LV to earth heavy mechanical forces acting on LV winding resulted into damaging HV winding also which reflected into winding resistance & SFRA.
- As R phase LV winding damages along with partial core, the magnetic flux maximum get linkages with Y & B phase this reflects in magnetic balance test.
- As per SFRA during short circuit the inductive reactance (short circuit between inter turn LV winding) get decreased which resulted into decreasing into resonance frequency & increasing into magnitude.

From above test results of failed TF & its observation following conclusion can be drawn:-

1. The frequency of DGA testing of TF needs to be modified as TF DGA should be carried out within one month after taking load on TF & needs to be repeated after 03 months.
2. The SFRA of TF needs to be repeated after 06 months for new TF along with Tan delta of winding & excitation currents for ease of monitoring & further action.
3. If the key gases like C2H2, CH4,C2H4,C2H6, CO2, CO, H2 are in rising trend then take immediate action consulting with manufacturer.
4. Probably used calibrated DGA kits on site for quick decision making.
5. Tan delta test, SFRA, PI & excitation test gives idea of fault inside TF with help of DGA ration analysis tool.
6. TF having commissioning year less than 02 years needs to be tested half yearly & closely monitored.

L.V Winding Found Damaged

3.2 Case Study.

Transformer Details : MVA: 25, Volts at No Load : 132/33,Service Life: More than 10 Years

The said TF is in service, The TF was tripped on dtd 01.04.2015 on following indication

Relay Indication	Window Indication
O.S.R (Oil surge relay), Master trip 86.	Transformer internal fault

The TF kept out of service from previous case studies, It is recommended for internal inspection of OLTC. During inspection it was found that the Bakelite barrier plate in OLTC found to be burnt.

The overhauling of OLTC after replacement of Bakelite plate was carried out and Transformer low voltage test as follow.

Open Circuit &Magnetizing Current

Before tripping:

Tap No.	Open Circuit Test (Volts)						Mag. Current Test (1ph.) in mA		
	VRN	VYN	VBN	Vrn	Vyn	Vbn	IR	IY	IB
1	235	232	233	56.3	56	55	1.9	1.0	1.9
5	235	232	233	56.3	56	55	1.8	1	1.8
13	235	232	233	56.3	56	55	2	1.4	2.1
17	235	232	233	56.3	56	55	2.1	1.5	2.3

After overhauling:

Tap No.	Open Circuit Test (Volts)						Mag. Current Test (1ph.) in mA		
	VRN	VYN	VBN	Vrn	Vyn	Vbn	IR	IY	IB
1	408	409	409	97.3	97.5	97.7	1.3	0.8	1.4
5	404	405	405	101	101	101	1.6	1.1	1.6
13	405	404	402	100	101	101.3	2.1	1.8	7.8
17	406	403	404	99.1	100	101	2.4	2.3	23.2

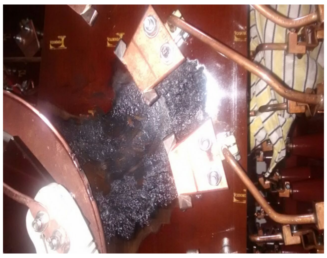
Observation from open Circuit and magnetizing current test:

1. From test results it was found that the results are normal from Tap no. 1 to 9.From tap no. 10 to 17 No load magnetizing current goes on increasing.

2.The increasing trend shows carbonization in OLTC contact, considerable open circuit from tap no.10 to 17.

Action Taken :

1.From above observation it was insisted to open OLTC chamber till that not to charge transformer.
2.The OLTC chamber was opened and checked for any abnormality .
3.The spring tension for fixed contact and moving contact from tap no. 9 to 17 found to be loose for B ph.
4.The spring tension was properly adjusted and fixed contacts were replaced where required.
5.Transformer charged after satisfactory test results.



Conclusion:

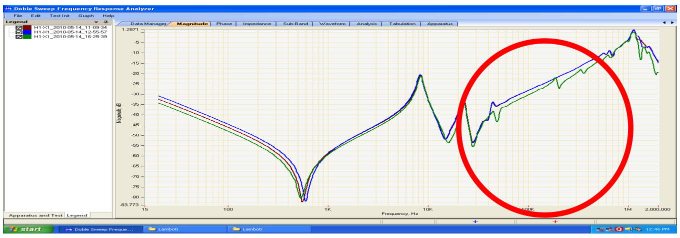
With proper monitoring steps and hard abministrative decision in view of life of transformer ,we avoid total failure of transformer and increases the service life of transformer.

Case Study 3.3

Transformer Details :Make :MVA: 1 X 167 (1 Ph Unit),Volts at No Load : 400/220/33 kV, Dt.of Comm. : 2010

1.During pre commissioning testing it was found that the SFRA test results of B Ph ICT unit was not matching with factory test report and sister unit.
2.All other low voltage test and special test mention above are carried out, the test results found in order.
3.The matter was refer to manufacturer for abnormal SFRA results.
4.As per instruction and clearance from manufacturer the ICT was charged and stood ok.

SFRA GRAPH



HV to LV R Ph , Y Ph , B Ph (Open Circuit Test)

Observation from SFRA :

From the SFRA test results loss of clamping pressure was observed for the B ph unit. As well there might be problem involving core portion & joints etc.

Action Taken :

1.As per guideline the frequency of tests are closely followed including DGA results.
2.The test results except DGA found normal.
3.In DGA the presence of acetylene was detected hence the frequency of DGA is increased i.e fortnightly DGA results are monitored which shows increasing trend of Acetylene.
4.The matter was refer to manufacturer and strongly insist for internal inspection.
5.The ICT was opened for internal inspection.

Observation in internal Inspection and History of ICT.

1.Tightness of core bolt, winding insulation and lead tightening was confirmed.
2.finaly it was coordinately decided to lift transformer winding for checking any damages to the core behind winding.
3.There was failure of interlamination insulation of core below transformer winding. Due to failure of interlamination insulation the eddy current produces in the affected core area.
4.Due to flow of eddy current the area of core get heated which also affect the insulation of winding near neutral as ‘ Paramalli ring between winding and core get displaced .
5.Which causes production of Acetylene gas in the ICT.

History:

After throughout investigation some events were emerged i.e the transformer was dashed to tree branches which results into minor displacement of Paramalli ring.
As fault was involved close to the ICT neutral it was not reflected in any pre commissioning low voltage test.
After attending the above problem the ICT charged and stood OK.

Case Study 3.4

MVA : 100,Volts at No Load : 220KV/22KV-22Kv,Year of Repair : 2012
The above transformer was commissioned on 13.04.2013, and failed on dtd 05.07.2016.

As per manufacturer recommendation, the DGA test of TF was carried out after a year. While going through the results key gases was found normal.
During above monitoring, on dated 05.07.16 the above TF was failed on 22 kV feeder fault on Differential Protection

After failure of the transformer was tested for following tests are as follows
Open Circuit Test after failure

T	VR-N	VY-N	VB-N	Vr1-n1	Vy1-n1	Vb1-n1	Vr2-n2	Vy2-n2	Vb2-n2
9b	244	244	240	24.9	22.7	23.9	24.4	0.00	23.9

HV and LV1 and LV2 magnetizing current after failure

HV

T	VR-N	VY-N	VB-N	IR	IY	IB
9b	244	244	240	2.1 mA	1600 mA	2.10 mA

LV2

T	VR-N	VY-N	VB-N	IR	IY	IB
9b	247.00	247.60	246.50	194 mA	>32A	230 mA

Short Circuit Test after failure:

Supply- VR-N -243.2 VY-N -245.6 VB-N-243.3

	HV				LV2			
T	IR (A)	IY (A)	IB (A)	IN (A)	Ir2 (A)	Iy2 (A)	Ib2 (A)	In2 (A)
9b	2.67	2.62	2.69	0.14	16.0	6.94	13.8	6.57

Observation from OC & SC test
1. The voltage is not induced in the Y phase of LV2 winding which shows inter turn short circuit in side Y phase of LV2.
2. Above fact is confirmed as HV no load magnetizing current & LV no load magnetizing currents is very high.
3. The Short circuit test represent partial short circuit of LV2 Y phase that is why the short circuit current split up. Due to partial inter turn short circuit the impedance of transformer reduces excess rise of magnetizing current.

Magnetic Balance Test after TF failure: at 9b

	Prim.Voltages (V)			Sec. Voltages (V)		
	VRN	VYN	VBN	Vr1n1	Vy1n1	Vb1n1
VRN	247	0.51	243	24.73	0.05	24.38
VYN	103	248	140	10.32	23.15	14.06
VBN	241	0.52	246.	24.25	0.05	24.61
	Prim.Voltages (V)			Sec. Voltages (V)		
	VRN	VYN	VBN	Vr2n2	Vy2n2	Vb2n2
VRN	247	0.51	243	24.70	0.00	24.40
VYN	103	248	140	10.25	0.00	13.98
VBN	241	0.52	246.	24.25	0.00	24.60

Observation from Magnetic Balance test:
1. Due to inter turn shorting Y Ph of LV 2 winding the flux produces in the core is not utilized by LV 2 winding which results in to absence of voltage in LV 2 winding. Hence the total flux utilized by B Ph of LV 2 winding.

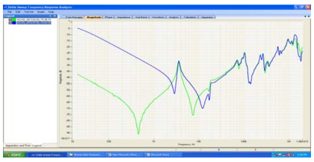
Winding resistance test :

H.V Winding resistance test after TF failure @27°C				L.V 2 Winding resistance test during commissioning@27°C		
Tap No.	**R-N (µΩ)**	**Y-N (µΩ)**	**B-N (µΩ)**	**R-N (mΩ)**	**Y-N (mΩ)**	**B-N (mΩ)**
9	1100	1100	1200	9.987	956.6 µΩ	9.922

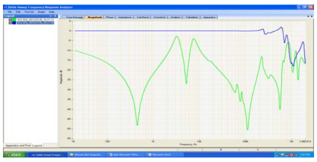
Observation from winding resistance test :
1. The drop in winding resistance value represent bypassing of inter turn winding due short circuit.

Sweep Frequency Response Analysis (SFRA)

HV Y-N O.C



LV2 O.C Y-N



Observation from SFRA Test :
1.From above graph it is seen that the magnitude in dB increases with decrease in resonance frequency which shows the series resistance of LV 2 winding decreases tremendously.
2.As a result, The impedance of winding is much lesser than core impedance due to inter turn short circuit in LV 2 winding therefore, The resonance frequency follow the path of shorted winding bypassing core portion.

Probable sequence of operation in view of failure of TF:

1.From previous experience we were monitoring DGA test results but no abnormality found from results.
2.There might be problem in mechanical design of transformer in view of sustaining the heavy fault currents , axial and radial mechanical forces on winding.
3.The transformer is feeding 8 no. of feeders and having average tripping of 12 no. daily .Due to short circuit faults on ongoing feeder the heavy short circuit current flowing through the transformer which produces vary high axial forces on transformer windings.
4.Due to that axial forces the insulation i.e the spacers provided for guiding the flow of oil get displaced from their position during each faults which results into cumulative displacement of insulting spacers between inter turn.
5.As the inter turn insulation of winding got weaker & due to heavy short circuit fault, the total LV 2 winding get failed i.e short circuit.
From above test results of failed TF & its observation following conclusion can be drawn :-
1. The SFRA of TF needs to be repeated after 06 months for new TF along with Tan delta of winding & excitation currents for ease of monitoring & further action. If there is minute variation in the results then carried out low voltage tests.
2. The transformer 50 MVA and above should insist for heat run test as per IEC standard.

IV. CONCLUSION:

From proper Analysis of various test results and correlate the outcome results with previous working and failed power transformer experience ,the line of action can be easily chalk out. The important issue is action taking and decision making in time. As decision taken from above analysis is cleared, ICTs, transformers will be easily saved from failure which is cleared from above case studies & guideline.

With the help of analysis & interpretation of results the minor abnormalities in the working TFs are find out & preventive majors are taken on time will save TFs from catastrophic failure.

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