17th IMEKO TC 10 and EUROLAB Virtual Conference
"Global Trends in Testing, Diagnostics & Inspection for 2030"
October 20-22, 2020.

Testing, diagnosis and rectification of high dissipation factor in large power transformer

Somil Joshi [1], Girish Pathak[2]

[1]CGPISL, Mandideep, India, somil.joshi@cgglobal.com, 9041013650
[2]CGPISL, Mandideep, India, girish.pathak@cgglobal.com, 9713064491

Abstract – **Power transformer are high-priced and major device in electrical power system. Their overall healthiness and operating life is primarily dependent on insulation system. Insulation system of transformer is complex electrical network comprising series and shunt capacitance. These capacitance comprises of insulating components like oil, wood, paper and pre compressed boards (PCBs). As these materials are hygroscopic and moisture prone. Hence fault identification and rectification in insulation system becomes critical. There are several methods available for accessing the power transformer insulation. This paper demonstrates a practical experience, methodology of testing and diagnosis. Through testing components responsible for high dissipation factor were identified. The diagnostic technique helped in swift and economical replacement of faulty insulation components. Thus, high dissipation factor problem rectified and transformer was restored back to service**

Keywords – ***Transformers, insulation systems, dissipation factor, capacitance, winding.***

I. INTRODUCTION

Transformers are static devices. Their functionality is to transform voltage levels through conductive and inductive methods at constant power. It is well established fact that entire power system reliability is dependent primarily on healthiness of power transformer. Failure, outage of an in-service transformer may lead to blackout and generation loss. To ensure overall health and eliminate possible failures, transformer insulation is accessed on routine basis. In-service transformers are subjected to voltage stresses due to power frequency voltage, switching surges and transient over voltages arising due to travelling waves in transmission lines. These stresses critically affect winding to ground, winding to winding, turn to turn and inter-disc insulation.

Bulk of transformer failures, are usually related to faults in these particular combinations. Therefore, routine diagnostic measurements carried on regular basis ensure reliability of in-service transformer. These diagnostic measurements comprise of dissipation factor and insulation resistance measurements. Insulation resistance is DC voltage application particularly done at 5 kV for high voltage windings. The test is indicative of dryness and impurities present in insulation. On other hand, the dissipation factor measurement is AC voltage application in range of 1-10 kV at power frequency of 50/60 Hz. The purpose of measurement at power frequency is to analyze healthiness and response of insulation system at power frequency. These measurement are recorded, for future reference purpose. In general, majority of dissipation factor kit manufacturers integrates dissipation factor with capacitance measurement. However, capacitance of an insulation system is predominantly dependent on its geometry, dimensions and number of windings.

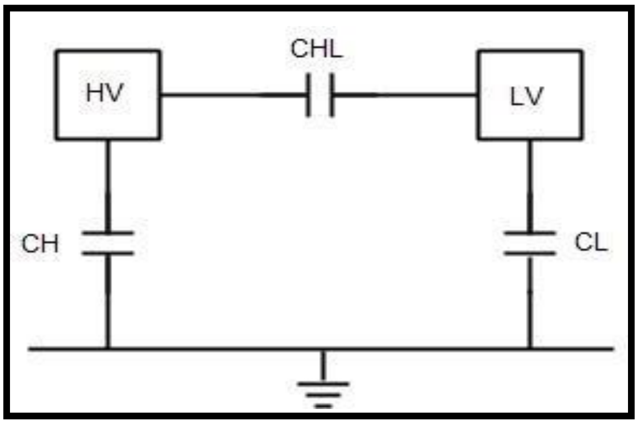

Fig.1 Insulation arrangement of an auto transformer.

Fig.1 shows insulation structure of an auto transformer. Here HV, LV are high and low voltage winding terminals. CHL is insulation capacitance between HV and LV winding, CH insulation capacitance between HV winding and tank. CL is insulation capacitance between LV winding and tank. Here tank terminal is grounded. During dissipation factor measurement, this grounded terminal is connected with measurement kit. Dissipation factor measurement of CHL is performed in ungrounded specimen terminal (UST) mode, whereas CH and CL insulation are accessed in grounded specimen terminal with guard (GST-g) mode. During measurement of dissipation factor and capacitance in UST mode, AC voltage is supplied to HV terminal and measurement cable is connected to LV terminal. However in GST-g mode the measurement terminal is done from ground terminal.

In this paper a single-phase auto-transformer is addressed. The vector group of transformer is YNa0d11 in three phase bank. The transformer was in-service at site, the high dissipation factor was observed during routine maintenance. The winding arrangement of is shown in Fig.2.

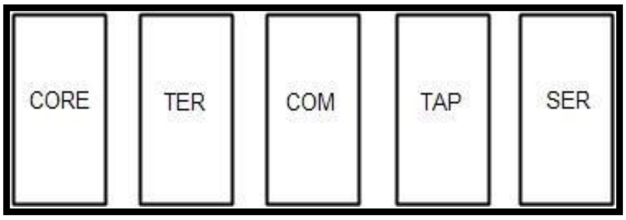

Fig-2: The arrangement of windings from core.

The winding arrangement from CORE is TERTIARY-COMMON-TAP-SERIES. SERIES winding end is connected with common winding start. This electrical connection, the conductive transfer of energy is possible in addition to the inductive transformer. The, TAP winding is connected to neutral end of COMMON winding. This type of electrical connection makes the transformer as variable voltage variable flux (VFVV). Table-1 shows measurement combinations of an auto transformer, with configuration of insulation accessed and measurement mode selected on measuring kit. As, an auto transformer have SERIES and COMMON windings electrically connected, therefore equivalent winding configuration and geometry is similar to that of a two winding transformer shown in Fig-1.

Table1.Winding Combination with insulation configuration and measuring mode of an auto transformer.

S.No	Measurement configuration	Configuration	Mode
1	(HV+IV+N)/(LV)	CHL	UST
2	(HV+IV+N)/(LV+E)	CHL+CH	GST
3	(HV+IV+N)/E	CH	GST-g
4	LV/(HV+IV+N)	CLH	UST
5	LV/(HV+IV+N+E)	CLH+CL	GST
6	LV/E	CL	GST-g

II. DESCRIPTION OF THE METHOD

The method of testing, diagnosis and rectification includes set of measurements performed in step by step manner over a period of time. Initially, dissipation factor measurement was performed on-site during routine maintenance. But, even after performing repetitive measurements at site repeaitively high dissipation value was recorded. Transformer was transported to factory for additional tests and rectification. At factory, oil filling under vacuum was done after achieving oil parameters per standards through filtration. After, adequate settling of transformer oil dissipation factor measurement was performed as per Table-1. High dissipation factor was observed again during factory measurement. To, elminate ambiguity in transformer oil quality. Transformer oil was drained and measurement was repeated again as per Table-1. These two measurement were performed at two different insulating conditions. Still the measurement performed in oil drained condition gave high dissipation factor values.

For clear localization and identification of faulty winding insulation section, an additional dissipation measurement was performed. Since, it is an auto-transformer with neutral end tap winding. The tap winding was isolated from SERIES+COMMON winding. The modifications are shown in Fig-3. After separation of TAP winding from SERIES+COMMON winding dissipation factor measurements was performed as per Table-2 given below.

Table 2. Test case of additional power factor test, with winding combination and measurement mode.

Test Case	Winding Combination	Mode	Terminal Guarded
A	(H1-X1-R4)/E	GST-g	(TS+TE) & (Y1+Y2)
B	(H1-X1-R4) /(Y1+Y2)	UST	NONE
C	(TS+TE)/E	GST-g	(TS+TE) & (H1-X1-R4)
D	(TE+TE)/ (H1-X1-R4)	UST	NONE

In Table-2, H1 is high voltage terminal of SERIES winding, X1 is COMMON winding terminal, and R4 terminal is end of SERIES + COMMON winding. This R4 terminal is separated from TAP winding start TS, TE is end of TAP winding, Y1 and Y2 are start and finish of TERTIARY winding respectively. The description of winding terminals are shown in Fig-3.

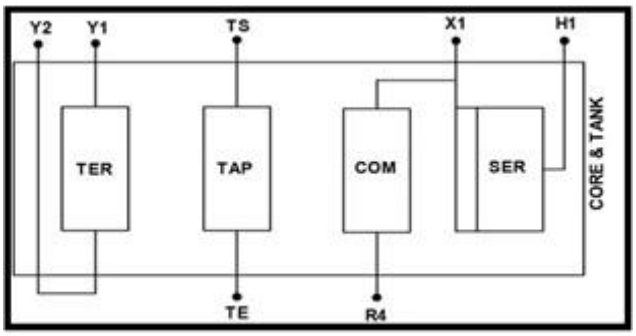

Fig-3: Arrangement of winding terminals during additional dissipation factor test.

In test case A of Table-2, H1-X1-R4 terminals were shorted together, supplied with voltage and measurement was done with respect to ground terminal. Grounded specimen terminal with guard (GST-g) was selected in measurement kit to guard TS, TE and Y1, Y2 terminals. In this case insulation of SERIES+COMMON winding was checked with respect to ground. In test case B of measurement SERIES+COMMON winding terminals H1, X1, R4 and TERTIARY winding terminals Y1, Y2 were shorted respectively and measurement was performed by giving supply voltage to H1-X1-R4 terminal. In this case insulation between SERIES+COMMON and TERTIARY winding is checked. The test case C of measurement involved checking TAP (TS+TE) winding with respect to earth. In this case winding terminals TS & TE were shorted, supplied with voltage and measurement was performed with respect to ground after selecting grounded specimen terminal with guard mode (GST-g) in measurement kit. In this case TERTIARY winding terminals Y1, Y2 and H1, X1, R4 were guarded. Insulation between TAP winding and grounded terminal was checked in case C. In test case D, TAP winding terminals TS, TE were shorted and supplied with voltage while measurement cable is connected to SERIES+COMMON (H1-X1-R4) winding. In this measurement insulation between TAP winding and SERIES+COMMON winding is checked. Measurement, was performed in ungrounded specimen terminal (UST) mode.

III. RESULTS AND DISCUSSIONS

For identification and rectification, initially the dissipation factor was measured as per combinations given in Table-1. The transformer was in oil filled condition and test voltage was 10 kV at 50 Hz. The measurement results are shown in Table-3.

Table 3. Test results of dissipation factor performed at 10 kV as per Table-1 in oil filled condition.

S. No.	(pF)	Ic (mA)	Ir (µA)	Power (watts)	Dissipation Factor (%)
1	2686.96	8.443	10.80	0.108	0.128
2	7911.10	24.859	114.8	1.148	0.462
3	5223.71	16.414	105.7	1.057	0.644
4	2686.30	8.442	12.66	0.127	0.150
5	12700.85	39.915	77.83	0.780	0.195
6	10009.86	31.456	65.42	0.655	0.208

From Table-3, it was observed that dissipation factor in particular for HV+IV+N/E combination gave high value. For better identification and clear interpretation, the dissipation factor measurement of individual HV+IV+N/E combination was performed with test voltage range of 1-10 kV, with discrete step size of 1 kV at 50 Hz frequency. The dissipation factor demonstrated a rising trend with rise in test voltage magnitude. The results of the measurement are reported in Table-4. Here, it was observed that with increase in applied voltage the insulation system draws more power. The resistive component of leakage current (Ir) increased approximately six times when applied test voltage raised five times. Similarly, resistive component of leakage current approximately increased fifteen times when applied test voltage was raised from 1 to 10 kV. Moreover (Ir) is observed with step increase in test voltage. Above measurement gave an idea that SERIES and COMMON winding insulation had unstable insulation condition as dissipation factor showed linearly rising trend with linear increase in measurement voltage.

Table 4. Dissipation factor test result of (HV+IV+N/E) combination performed at discrete voltage steps from 1-10 kV in oil filled condition.

Voltage (kV)	Ic (mA)	Ir (µA)	Power (watt)	Dissipation Factor (%)
1	1.639	6.637	0.007	0.405
2	3.275	13.49	0.027	0.412
3	4.918	21.39	0.064	0.435
4	6.559	30.10	0.121	0.459
5	8.207	40.13	0.201	0.489
6	9.843	50.59	0.304	0.514
7	11.483	62.46	0.437	0.544
8	13.125	74.81	0.599	0.570
9	14.767	88.89	0.801	0.602
10	16.414	105.7	1.057	0.644

The results reported in Table-4 were obtained after performing measurement in oil filled condition. Hence, to eliminate the ambiguity of high dissipation factor due to contaminated oil. The transformer oil was drained completely. The measuement as described in Table-1 was performed again at 5 kV. It was observed that HV+IV+N/E combination still showed high dissipation factor value of 0.713 %. This measurement eliminated possibility of impurities present in transformer oil being the probable cause of variation in dissipation factor with variation in applied test voltage. It was clear now that HV+IV+N/E (CH) insulation with respect to ground terminal was unstable. The results of measurement are reported in Table-5.

Table 5. Dissipation factor test results performed at 5 kV as per Table-1 after draining oil.

S. No.	(pF)	Ic (mA)	Ir (µA)	Power (watts)	Dissipation Factor (%)
1	1566.60	2.461	3.297	0.016	0.134
2	5299.16	8.217	42.89	0.214	0.522
3	3633.52	5.757	41.04	0.205	0.713

Though, the above measurement implied HV+IV+N winding combination had unstable insulation condition. Still, it was indistinct which insulating components were accountable for this unstable condition. For proper identification and localization of faulty insulation section additional dissipation test was performed. As HV+IV+N winding is combination of SERIES & COMMON winding elecrtrically in series with TAP winding. Hence, modification as described Fig-3 was made and measurement was performed as per Table-2 at 5 kV. Results of additional power factor test are reported in Table-6.

Table 6. Additional dissipation factor test results in oil drained condition at 5 kV as per Table-2.

Test Case	(pF)	Ic (mA)	Ir (µA)	Power (watt)	Dissipa-tion Factor (%)
A	2755.42	4.330	28.058	0.140	0.648
B	2205.10	3.465	6.930	0.035	0.200
C	905.23	1.422	7.877	0.039	0.554
D	1522.08	3.392	5.115	0.018	0.152

In Table-6, for test case A, dissipation factor of SERIES+COMMON winding (H1-X1-R4) with respect to ground terminal in GST-g mode showed high dissipation factor value of 0.648 %. In test case B, dissipation factor of SERIES+COMMON winding (H1-X1-R4) with respect to TERTIARY (Y1+Y2) winding gave considerably lower value of 0.200 %. Hence, it was confirmed that insulation between SERIES+COMMON winding and TERTIARY winding is healthy. However, dissipation factor recorded in case A confirmed that the insulation between SERIES+COMMON winding with respect to ground is fault prone and requires attention.Similarly, from measurement in case C it was found, TAP (TS+TE) to ground insulation is to be further investigated after dismantling the coil. The case D measurement showed dissipation factor value in limits. Which indicated insulation between TAP winding and TERTIARY winding was healthy and does not requires any physical assessment.

Below are some pictures after dismantling SERIES+COMMON and TAP winding. The perma wood coil support platform was found broken and burnt.

Fig-4: Broken and burn marks were found on permawood ring of coil support platform.

The burnt portion of insulation was making entire insulation conducting in nature. Thus a sharp rise in resistive component of leakage current (Ir) was observed in Table-4 when supply voltage was gradually increased from 1 to 10 kV.

Fig-5: Burn marks on other side of the permawood ring.

Fig-6: Formation of creep path due to continuous

Fig-7: Series + Common winding during dismantling.

Thus, additional dissipation factor test performed as per Table-2 proved helpful in identification of faulty insulation component. These types of faults in insulation are initially minor in nature. But, continued operation and ignorance of damaged insulation may lead to blackouts and loss of generation. After replacing the perma wood ring, the transformer was again re-assembled, refurbished by CGPISL T-3 division norms and was offered for final routine testing as per IEC 60076. During, routine test dissipation factor measurment was performed as per Table-1. The measured values are shown in Table-7.

Table 7. Dissipation factor test results performed at 10 kV as per Table-1 during routine test.

S No	(pF)	Ic (mA)	Ir (µA)	Power (watt)	Dissipation Factor (%)
1	2677.67	8.415	12.53	0.125	0.149
2	7842.26	24.643	51.25	0.513	0.208
3	5165.17	16.231	39.76	0.398	0.245
4	2676.83	8.412	13.12	0.131	0.156
5	12633.70	39.700	76.62	0.758	0.193
6	9951.33	31.268	63.78	0.639	0.204

All routine tests were conducted on transformer in line with IEC 60076-1. High voltage dielectric tests were performed as per IEC 60076-3. The transformer withstood lighting impulse, switching impulse, applied voltage and partial discharge test. To, reassure insulation health after completion of routine tests dissipation factor measurement was repeated again as per Table-1. The test was performed at 10 kV and it was observed that dissipation factor of HV+IV+N/E combination in GST-g mode was within the limits even after performing high voltage dielectric testing. This confirmed that transformer insulation is stable. Table-8 shows dissipation factor measurement results after completion of all tests.

Table.8 Test results of dissipation factor performed at 10 kV as per Table-1 after conducting routine test and high voltage dielectric test as per IEC 60076-3 in oil filled condition.

S No	(pF)	Ic (mA)	Ir (µA)	Power (watt)	Dissipation Factor (%)
1	2678.43	8.416	12.70	0.127	0.151
2	7841.78	24.640	51.99	0.520	0.211
3	5164.88	16.228	40.40	0.404	0.249
4	2676.88	8.413	12.53	0.126	0.149
5	12628.68	39.683	77.77	0.737	0.196
6	9948.48	31.261	61.27	0.612	0.196

After, comparing Table-3 and Table-8 it was observed that dissipation factor of HV+IV+N/E (CH) combination improved from 0.644 % to 0.249 % after replacement of burnt perma wood. Moreover, significant drop of 2.5 % was observed in resistive component of leakage current (Ir) which clearly indicates problem of high dissipation factor got rectified.

IV. CONCLUSIONS AND OUTLOOK

Insulation system of transformer includes paper, pre compressed boards (PCB) and wood as major insulation components. They account considerable percentage in transformer cost. Their total replacement in case of small faulty section is not economical. Moreover, for improvement of insulation, repetitive reprocessing like vacuum pressure drying (VPD) reduces mechanical strength and degree of polymerization (DP) to considerable extents. Hence concrete guidelines, proper testing and diagnosis methodology becomes economically helpful in fault identification. On basis of improved diagnostic techniques replacement of insulation components can be done swiftly. Thus enhancing life span of in-service transformers, avoiding blackouts and loss of generation.

V. ACKNOWLEDGMENTS

We express gratitude to our plant head Mr. Anirban Saha (General Manager T-3 Transformer Division Mandideep) and Mr. Ankur Pathak (Manager T-3 Technology Transformer Division Mandideep) for providing an opportunity to represent our organization in this conference. Their continuous support and motivation helped in bringing some abstract findings. In addition to this, we would gladly thank all team members of 1200 kV UHV transformer and reactor testing laboratory (T3 Transformer Division Mandideep) for their support and assistance.

REFERENCES

[1] Power Transformer Part-1: General International Electrotechnic Commission. (IEC)-60076-01.

[2] Power Transformer Part-3: Insulation levels, dielectric test and external clearances in air International Electrotechnic Commission (IEC)-60076-03.

[3] B. D. Malpure and K. Baburao, "Failure analysis & diagnostics of power transformer using dielectric dissipation factor," *2008 International Conference on Condition Monitoring and Diagnosis*, Beijing, 2008, pp. 497-501, doi: 10.1109/CMD.2008.4580334.

[4] Seyed Amidedin Mousavi, S. Hajilu, H. Kaboudvand, S. Sabaifard, N. Amini and E. Hasani, "Calculation the dissipation factor of power transformers insulation system using genetic algorithm," *2011 IEEE International Conference on Computer Applications and Industrial Electronics (ICCAIE)*, Penang, 2011, pp. 580-584, doi: 10.1109/ICCAIE.2011.6162201.

[5] I.A.R. Gray *"dissipation factor, power factor, relative permittivity (dielectric constant)"*.

[6] Maik Koch, Michael Krüger "The negative dissipation factor and the interpretation of the dielectric response of power transformers" *16th International Symposium on High Voltage Engineering, Cape Town, South Africa 24-28 August 2009.*

[7] G. Faria, M. Pereira, G. Lopes, J. Villibor, P. Tavares and I. Faria, "Evaluation of Capacitance and Dielectric Dissipation Factor of Distribution Transformers - Experimental Results," *2018 IEEE Electrical Insulation Conference (EIC)*, San Antonio, TX, 2018, pp. 336-339, doi: 10.1109/EIC.2018.8481052.