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Preclusion of partial discharge from transformer insulation - a design perspective

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Transformer operative life expectancy is governed by its insulation condition which is a complex arrangement of paper and pressboards submerged in mineral oil. It experiences persistent ageing due to steady physical and chemical deprivation being exposed to electrical and thermal stress in-service. The presence and or occurrences of even a minor defect in insulation can develop local concentration of electric field initiating partial discharges under normal operating voltages as well as under different electric excitation conditions. This Paper describes the different overstressed zones inside the transformer which need be taken care at design stage to reduce the chances of generation of partial discharges due to high electric field concentrations. Paper also discusses the methodology adopted by transformer designers to reduce the local concentration of electric field at particular zones and thereby reducing the chances of initiation of partial discharges. ELAX-

2D software based on Finite Element Method (FEM) was used to demonstrate the electrically overstressed zones inside the transformers and appropriateness of different methodologies adopted to preclude the partial discharges from transformer insulation. Partial Discharge test was conducted on analysed transformers and results were discussed to prove efficacy of the methodologies adopted to manufacture Partial Discharge free transformers.

Keywords: *Partial Discharge (PD), Finite Element Method (FEM), ELAX -2D, Insulating Kraft Paper, Pressboard, UHV class transformer, Dielectric Insulation*

1.0 INTRODUCTION

Operating life span of the Transformers merely depends upon the healthiness of the insulation. Health of the insulation is governed by electrical and thermal stresses faced during its entire working life. Two main insulations i.e. Solid Insulation (Kraft paper, crepe paper, low density and high density pressboards, and Permawood) and Liquid insulation (Naphthenic and Paraffinic hydrocarbon based insulating liquids) form a complex geometry of Transformer insulation. Combination of both insulations proved ability as a mixed dielectric for transformers up to EHV/UHV range [1, 2]. Figure 1 shows the multidimensional structure of mix dielectric i.e. solid and liquid insulation. Different insulation materials inside transformers are in series with each other, so they share the stress in inverse proportion to their permittivity under AC voltage applications. The permittivity of oil & solid insulation is 2.2 & 4.4 respectively. Due to mismatch in permittivity, oil experiences almost twice the stress in comparison with pressboard (or paper) under ac excitation conditions [3]. Also, oil has less dielectric voltage withstand strength compared with pressboard. Therefore, oil duct between two windings or windings

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to earth should be designed adequately using pressboard cylinders to keep the oil stresses lower than permissible values [3]. Role of the, transformer designer is to limit appearance of electric stress across insulation under any working or test condition under their withstand level with some additional safety margins considering the manufacturing constraints to completely preclude partial discharges from the transformer insulations [4, 5, 6, 7].

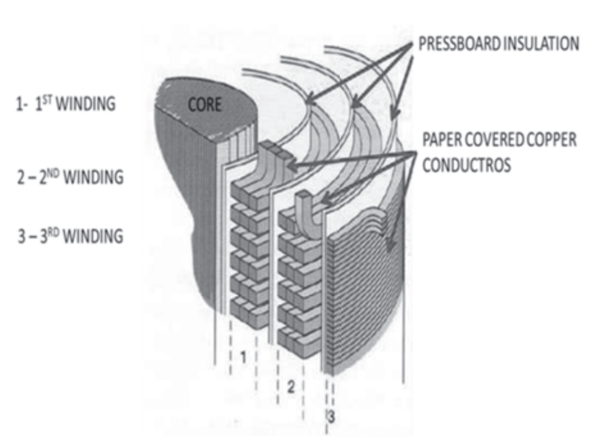

FIG. 1: CROSS SECTION OF THE CONCENTRICALLY ARRANGED CORE-WINDING ASSEMBLY WITH MIX INSULATION – PAPER, PRESSBOARD AND ALL SURROUNDED BY OIL [8]

During its entire life span, transformer has to withstand different voltages (i.e. lightning impulse, power frequency voltage, switching voltages, transient voltage, and overvoltages), as well as normal rated voltages. Distribution of electric stresses in windings is different for different test voltage conditions. When, the electrical stresses across particular insulation structure exceeds their withstand able limits (well defined in ref. [1, 3]), generation of partial discharges and consequential chances of catastrophic failure of the transformers in due course of time is foreseen. Therefore high voltage transformer insulation requires intensive examination at design stage by mathematical calculations or with the help of computer program based on FEM to add reliability to the transformer performance [9]. The paper discussed about mix dielectric insulations structure inside transformer, basics of partial discharge, Potential locations of partial discharges, and reasons for their occurrences. Paper also presents different approaches, methods and/or materials developed to decrease electric stresses arise at different zones inside the transformers using FEM based analysis. In the end, case studies were discussed to showcase the usefulness of the different methodologies to manufacture a "Partial Discharge Free" transformer.

2.0 PARTIAL DISCHARGE

Partial Discharge (PD) – "Localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor." – As per IEC 60270-2000 [10].

Partial Discharge activity can occur at any point in the insulation system, where the electric field strength of that portion exceeds the withstand ability of the insulating material i.e. mixed dielectric. PD usually begins due to presence of voids or cracks or impurities inside solid dielectric or at dielectric interfaces of solid or liquid dielectrics, or in bubbles formed or present in liquid dielectrics. Due to mismatch in dielectric constant between the voids, cracks, gas-filled voids, bubbles (i.e. damaged or impure insulation) compared to surrounding dielectric (healthy insulation), the electric field stress appearing across such defects is much higher compared to an equivalent distance of dielectric. This becomes a source of generation of partial discharge inside the insulation [11]. PD can also take place lengthwise on the surface of solid insulating materials if the surface tangential electric field is high enough to cause a failure of the insulator surface i.e. called creep discharge [2].

PD performance of a transformer is viewed as quality assurance test and is a routine test for transformers above 66 kV class. IEC 60076-3 Standard requires value of Partial discharges at 1.5 p.u. test voltage for one hour should not exceed 250 pC [12]. However, Indian customers specify 100 pC as the maximum limiting value at 1.5 p.u. To make Transformers partial Discharge free, transformer designers need to attain such stringent requirements.

3.0 INTRODUCTION TO ELAX -2D SOTWARE

Transformer insulation is a very complicated structure of oil and pressboards. The stress calculation of such a complicated structure is very difficult task. Classical or empirical formulae are available to calculate appeared electric stress at different locations. But these methods are tedious and time consuming and at the same time inaccurate. Alternately, now-a-days, state-of-the art software based on finite element methods is commercially available which can precisely calculate electric stress inside transformers at various locations. For simulation purpose, FEM based ELAX-2D software from VIT, Ukraine was used which is suitably loaded with all transformer conductive and insulating materials library for easy user interface.

4.0 VOLTAGE STRESSES AT DIFFERENT LOCATIONS INSIDE TRANSFORMER

As explained in Reference 3, inside the transformer, different electrical stresses are appeared at different locations under different test voltage conditions. To identify various electrically critical stressed zone inside the transformers, FEM based study was conducted using ELAX –

2D software to demonstrate three different locations which observe differing electric stress conditions. These three distinct locations are defined as follows:

A. Vertical Zone

B. Horizontal Zone

C. Intermediate Zone in the radius

Figure 2 shows the distribution of equipotential lines under the one minute power frequency test voltage condition obtained from ELAX – 2D software. In vertical zone designated as "A" in figure 2, equipotential lines are parallel to pressboard cylinders, creates homogenous stress zone as higher diameter of the winding creates a

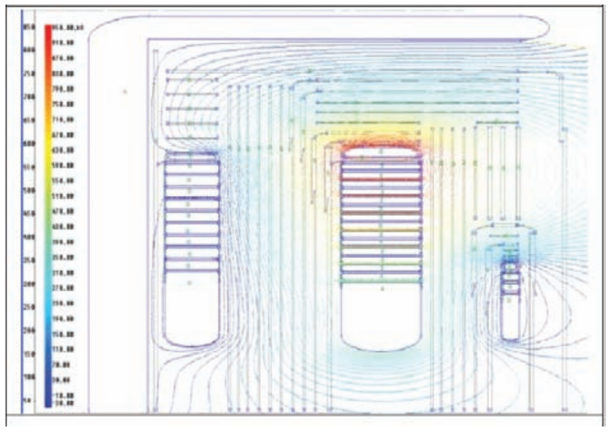

FIG. 2: MAIN OIL GAP & DIFFERENT HIGHLY STRESSED ZONES IN TRANSFORMERS: A: VERTICAL SECTION, B: HORIZONTAL SECTION, C: RADIAL SECTION

bigger electrode. In the Horizontal insulation zone, designated as "B" in figure 2, is heterogeneous electric field region. Here the effective gap is determined by the number of barriers and shield element configuration – such as static end rings and yoke shields – which make the electric field comparatively homogeneous. The radially stressed zone C is the most critical zone which needs a special consideration by the transformer designer due to crawling of equipotential lines near end zones of the windings [3].

5.0 APPROACHES TO REDUCE ELECTRIC STRESS

Stringent test standards, global price competitive markets and need to reduce the impact on environment; challenge the transformer engineers to design and manufacture "Partial Discharge Free" transformers with optimum insulation requirements. In practical case, perfect impregnation of solid insulation and generation of uniform dielectric field at every zone inside transformer may not be possible, and hence particular amount of partial discharge always occurs.

For simulation, pressboard material (high density, with 4.2 permittivity), oil impregnated paper insulation (Kraft paper with 4.5 permittivity) is used. The paper describes special components & their arrangement in insulation structure to preclude partial discharges. Special Components like, L-Ring made of 0.5 mm or 1 mm pressboard or press paper; contoured angular washer made of 2 mm to 3 mm pressboard; Static End Ring (SER) (made of wood, copper wire and paper insulation) to reduce the electrical stresses at various locations to preclude occurrences of PD. Total oil gap between HV winding and LV winding are divided into small oil ducts by properly arranging pressboard cylinders to improve its with standability of electric stress [4, 5, 6, 7, 9]. Paper describes calculation to distribute oil ducts between high voltage and low voltage windings.

5.1 'L'-Ring:

As discussed in section 5, Figure 3 showcases (from ELAX-2D software) crawling of equipotential lines near end zone of the regulating winding which lead to very high electric stresses on winding corners which can be source of initiation of partial discharge.

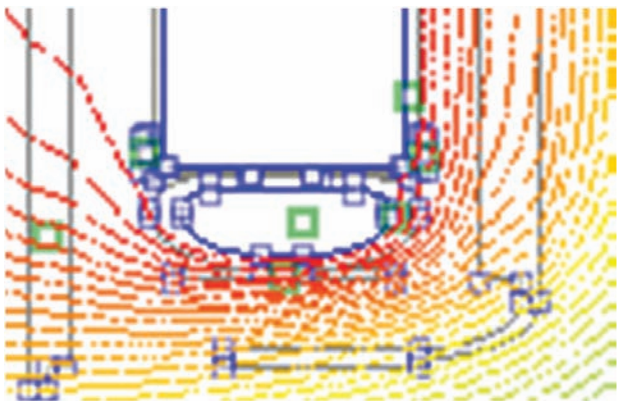

FIG 3: CRAWLING OF EQUIPOTENTIAL LINES NEAR END ZONE OF WINDING

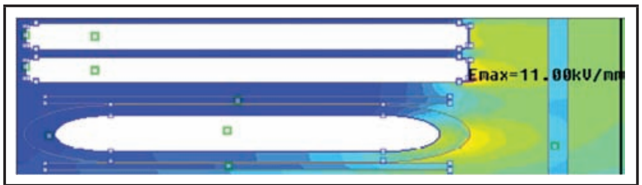

FIG 4: MAXIMUM ELECTRIC FIELD STRENGTH OBSERVED AT WINDIND CORNER WITHOUT 'L'- RING

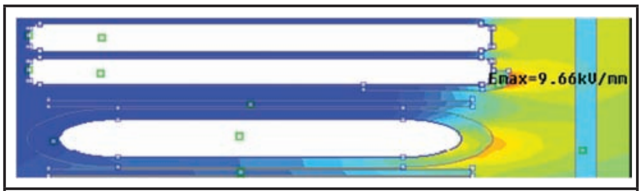

FIG 5: MAXIMUM ELECTRIC FIELD STRENGTH OBSERVED AT WINDING CORNER WITH 'L'- RING

Figure 4 demonstrate location of maximum electric field strength i.e. 11 kVrms/mm (obtained from ELAX-2D) which can be source of initiation of partial discharges. To protect the end corner of winding, 'L'- Ring made up of pressboard material is placed which reduces the electrical stress faced by oil duct. Figure 5 showcases the effectiveness of the 'L'- Ring (using ELAX-2D software) which reduces the maximum electric field at the corner of the winding from 11 kVrms/mm to 9.66 kVrms/mm.

TABLE 1

EFFECTIVENESS OF 'L'-RING AT END ZONE OF WINDING CORNER

RESULT OBTAINED FROM ELAX-2D SOFTWARE

	Electric Field Strength in kVrms/mm
Without "L"-Ring	11.00
With "L"-Ring	9.66

Remark: 12% reduction in maximum electric field strength is observed using 'L' – Ring

Table 1 explains the usefulness of 'L'- Ring in reduction of electric field strength faced by nearest oil duct. The result shows that, use of 'L'-Ring in this particular case reduces the electric field stress up to 12 % at the insulation interface which helps in reducing the chances of partial discharge generation.

5.2 Analysis of Gap between Low voltage & High voltage winding:

The gap between the high voltage winding and low voltage winding is called "HI-LO" gap. For concentric winding arrangements, electric field in this region is homogenous. The total oil gap is divided in to several small ducts of oil using pressboard cylinders, to reduce electric stress. Figure 6 shows distribution of equipotential lines for Auto Transformers in the HI-LO gap. In such case, Average stress between HI- LO gap can be calculates by [4, 5, 6, 7, and 9],

$$E_{av} = \frac{E}{X - 0.5 \times Y} \quad ...(1)$$

Where,

E_{av} = Average Stress

X = Total HI-LO Gap in mm

Y = Total Solid Insulation in HI-LO

Similarly, in such cases electric field imposed on various oil ducts is inversely proportional to their permittivities. The electrical stress observed by each oil duct can be calculated using formulae given in reference. If the permittivities of the oil ducts with thickness d_1, d_2, d_3,…d_n are ε_1, ε_2, ε_3, ε_4… ε_n respectively, and applied voltage across gap is U, electric stress in the part of d_1 thickness can be calculated using [4, 5, 6, 7, 9], [2]

$$E_1 = \frac{U}{\varepsilon 1\left(\frac{d1}{\varepsilon 1}+\frac{d2}{\varepsilon 2}+\cdots+\frac{dn}{\varepsilon n}\right)} \quad ...(2)$$

In other oil ducts,

$$E_2 = \mathrm{E}_1 \times \frac{\varepsilon_1}{\varepsilon_2} \quad ...(3)$$

$$E_3 = \mathrm{E}_1 \times \frac{\varepsilon_1}{\varepsilon_3} \quad ...(4)$$

$$E_n = \mathrm{E}_1 \times \frac{\varepsilon_1}{\varepsilon_n} \quad ...(5)$$

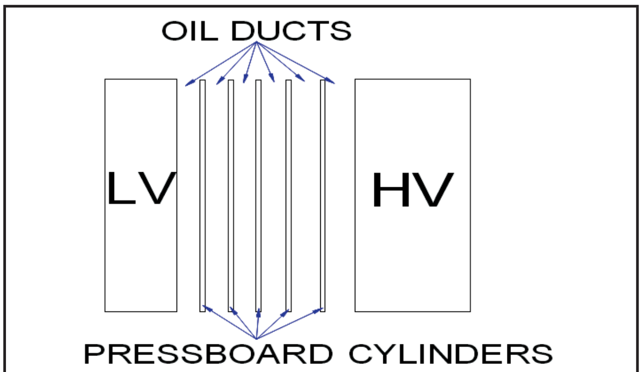

FIG 6: SUBDIVIDED GAP BETWEEN LV WINDING AND HV WINDING [1]

Table 2 shows the calculated maximum stress in each duct due to winding geometry, allowed stress for oil duct [9] and calculated safety factor for a small transformer with 29 mm HI-LO gap. Total HI-Lo gap is divided into 4 small oil ducts of 6 mm using 3 pressboard cylinders.

Maximum calculated stress in each oil duct is calculated using above formula in kV/mm and allowable stress in kV/mm in particular oil duct derived from ref. [3].Safety factor is calculated based on ratio of allowed stress in oil duct to calculated maximum stress in oil duct.

TABLE 2

CALCULATION OF AVERAGE STRESS AND INDIVIDUAL STRESS IN OIL DUCT OF HILO GAPS

Applied Voltage (kVrms)				140
Total HI-LO gap (mm)				29
No of Pressboard Cylinders in HI-LO Gap				3
No of Oil duct created with Pressboard cylinders				4
Average Stress in Mix Dielectric (kVrms/mm) [Using Formula 2]				5.48
No of Oil Duct	Size of the Duct (mm)	Calculated Max. Stress in Oil duct – (A) (kVrms/m m) [Using Formula 2]	Allowable stress in Oil duct using weidman□s curve figure – (B) (kVrms/ mm) [3]	Calculated Safety Factor (B/A)
1	6	6.01	7.75	1.29
2	6	5.78	9.23	1.60
3	6	5.58	9.23	1.65
4	6	5.40	7.75	1.44

5.3 Angular Washer:

Near end zone of the windings crawling of equipotential lines cut the solid insulation tangentially that increases probability of surface discharge. To reduce this tangential stress, placing the solid insulation in parallel to equipotential lines with better radius can reduce the stress and can help preclude the partial discharges in this highly stressed zone [3, 8].

The efficacy of angular washer can be clarified from figure 7 (A) and Figure 7 (B). The creepage stress along the portion 3 – 4 in figure 7 (B) of the contoured angular washer is much less than corresponding non contoured angular washer portion 1 – 2 in figure 7 (A). Angular washer not only provide advantage in terms of creepage discharges but also reduces the oil duct size in critical stress zone thereby providing better dielectric withstand ability (smaller the duct better withstand capability) [4, 7, 9].

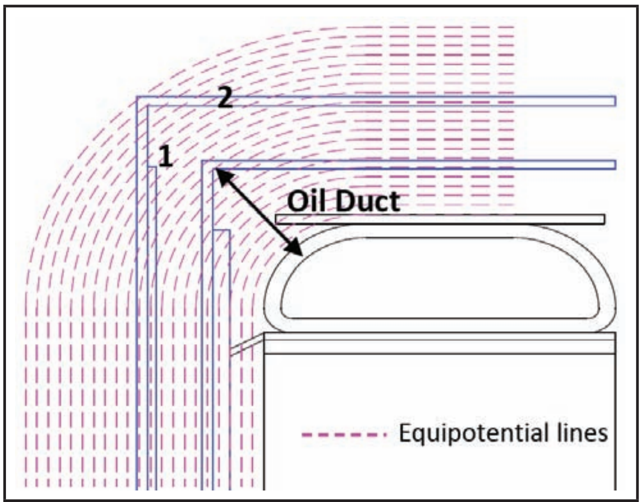

FIG 7 (A): NON CONTOURED ANGULAR WASHER

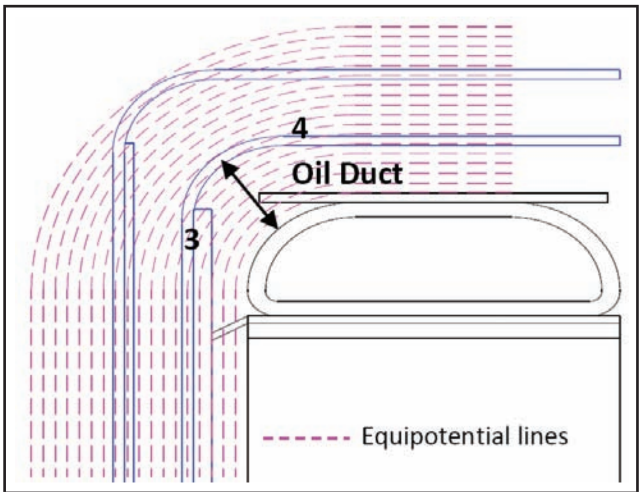

FIG 7 (B): CONTOURED ANGULAR WASHER

ELAX-2D based study was also conducted for no contoured and contoured angular washer to check their effectiveness. Figure 8 shown distributions of equipotential lines when no contoured angular washer was used and due to that the maximum tangential stress is 1.66 kV/mm compared to contoured angular washer shown in figure 9 where maximum tangential stress is reduced to 1.35kV/mm. This proves the effectiveness of a contoured angular washer.

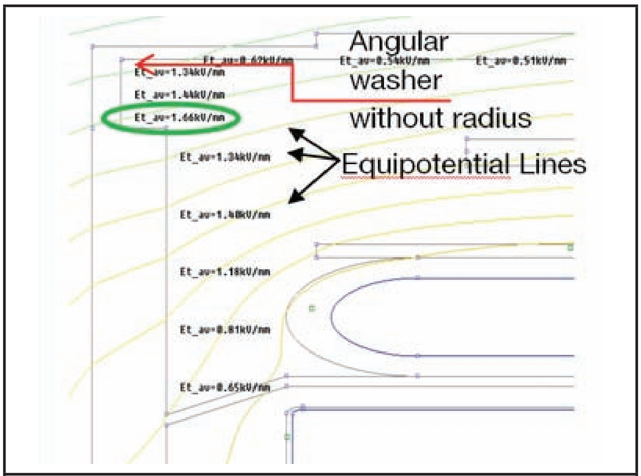

FIG. 8: NON CONTOURED ANGULAR WASHER

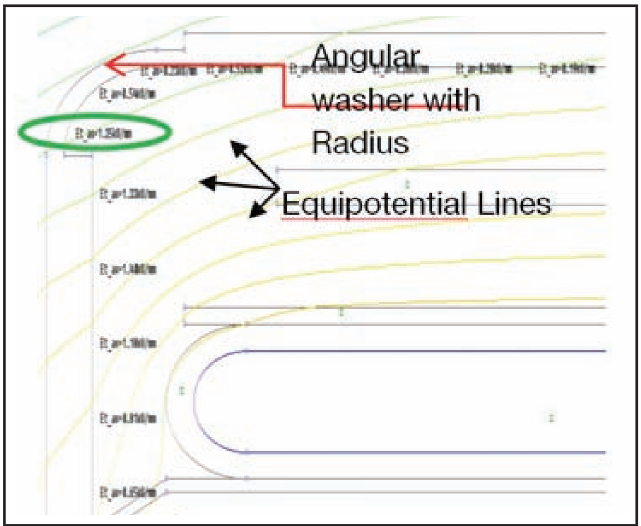

FIG 9: CONTOURED ANGULAR WASHER

TABLE 3

CALCULATION OF MAXIMUM TANGENTIAL FIELD STRESS WITH CONTOURED & NONCONTOURED ANGULAR WASHER

Result obtained from ELAX-2D software

	Calculated maximum tangential field Strength (kVrms/mm)
Noncontoured Angular Washer	1.66
Contoured Angular washer	1.35
Remark: Contoured angular washer reduces the tangential stress approximately 18% compared to non contoured angular washer	

Table 3 gives the concluding results and effectiveness of the angular washer at winding end. Total advantage of reduction in field strength achieved with angular washer is approximately 18%.

5.4 Static End Ring (SER):

Static End Ring is used in transformer for windings with power frequency test voltages of 140 kVrms or more. Static End Ring is made up of densified wood material with aluminized crepe paper and a thin copper conductor buried in the slot provided on circumference of the densified wood ring. Main Purpose of Static End Ring is [4, 5, 6, 7, 9, and 13]:

(a) To provide smooth electrode profile for AC voltage distribution and to control electric stress within the limit at critical locations. SER with a large corner radius provides large equipotential surface which reduces the stress concentration at the line end.

(b) To increase the series capacitance of winding for uniform and better LI distribution along the length of winding.

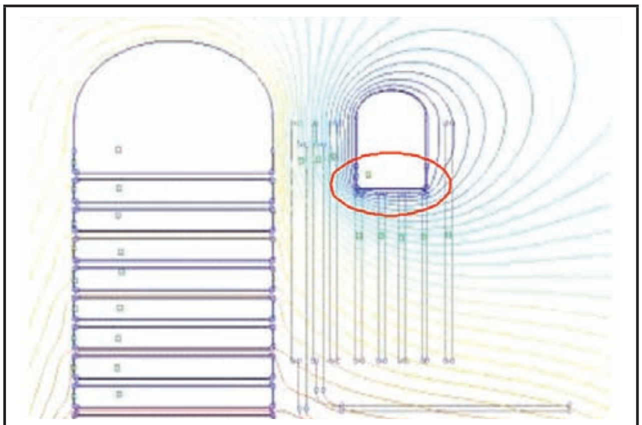

FIG 10 (A): WITHOUT SER FEM ANALYSIS- CRAWLING OF EQUIPOTENTIAL LINE NEAR EARTHED WINDING CORNER WITHOUT SER

ELAX-2D software based analysis was performed to understand the usefulness of the SER. Here, Lightning Impulse voltage is applied to HV winding for analysis purpose. Figure 10 (a) explains the distribution of equipotential lines without SER. Due to crawling of equipotential lines near earthed winding (highlighted with red line) the maximum electric field strength observed is 38.92kVp/mm on low voltage earthed winding as shown in Figure 10 (b).

Figure 11 (a) explains the location of SER at winding end zone which offered smooth electrode profile and due to presence of SER restructuring of the equipotential lines at the earthed winding corner is observed. The maximum electric field strength observed in the presence of SER is greatly reduced to 23.24kVp/mm as shown in figure 11 (b).

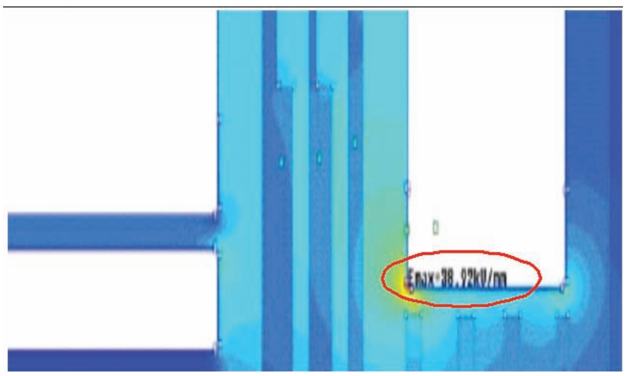

FIG 10 (B): WITHOUT SER FEM ANALYSIS- MAXIMUM FIELD STRENGTH OF 38.92 KVP/MM AT EARTHED WINDING CORNER WITHOUT SER

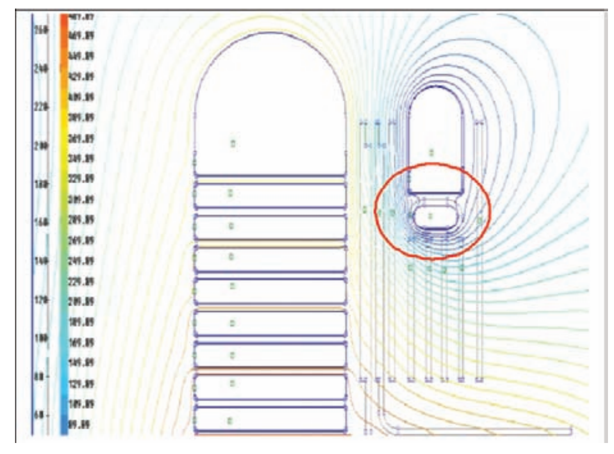

FIG 11 (A): WITH SER FEM ANALYSIS- SER REDUCES CONCENTRATION OF FIELD AT EARTHED WINDING CORNER

Table 4 gives the concluding results obtained from ELAX-2D software analysis and hence proved the effectiveness of SER at winding end zone with total reduction in electric field stress observed is approximately 40%. Also, the role of

SER in increasing the series capacitance is shown in Table 5. Approximately, 14% increase in series capacitance is observed using SER which helps in smooth distribution of lightning impulse voltage distribution throughout the winding. Likewise, different stressed zones of Transformer can be analysed using the ELAX-2D FEM based software for working clearances between live and earth part or between two live parts.

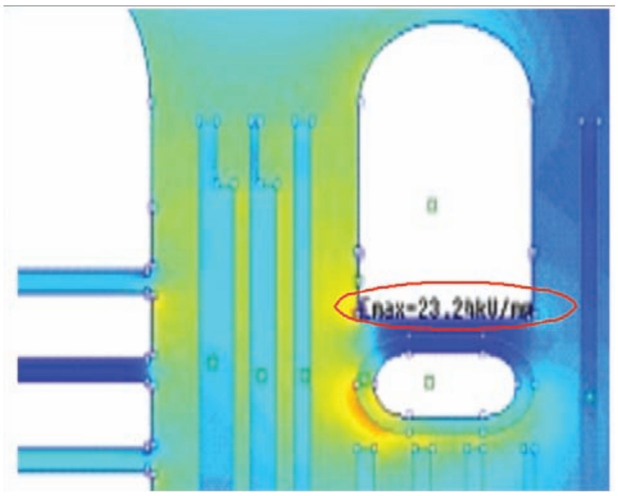

FIG 11 (B): WITH SER FEM ANALYSIS- REDUCED MAXIMUM FIELD STRENGTH TO 23.24KVP/MM AT EARTHED WINDING CORNER

TABLE 4

CALCULATION OF MAXIMUM ELECTRIC FIELD STRESS WITH AND WITHOUT STATIC END RING AT WINDING END ZONE

Result of FEM based Analysis	
	Calculated maximum electric Field Strength observed in kVp/mm
Without SER	38.92
With SER	23.24
Remark: 40% reduction in electric field strength was observed with and without SER.	

Also, highly non-uniform field patterns exist in the vicinity of high voltage leads between winding terminations and lower end bushing connections. The scatter of breakdown voltage for such a wide oil duct can be much higher resulting in lower dielectric strength. The proper analysis and effective solutions at all such locations inside transformer e.g. lead exits or barrier arrangement can lead to preclusion of the partial discharges from the transformer.

TABLE 5

CALCULATION OF SERIES CAPACITANCE WITH AND WITHOUT STATIC END RING FOR CONTINUOUS DISC WINDING

Capacitance is calculated using VLN software	Calculates capacitnace in pF
Without SER	573.31
With SER	665.30
Remark: 16% series capacitance increases by using SER in the winding.	

Case study of transformer analysed for partial discharge free performance is presented here by providing proper insulation structure as well as providing all above mentioned provisions to make it partial discharge free transformer. Also, some of the special considerations are also taken to smoothen out distribution of the lightning impulse wave like, use of partial shielded disc winding, SER at top as well as bottom of the winding [9].

6.0 CASE STUDIES

Case Study 1: 315 MVA, 400/220/33 kV Auto Transformer, with vector group Yna0d1 and having HV winding with centre lead construction is analysed for partial discharge free insulation design using ELAX -2D software. The BIL of the Transformer for Lightning Impulse test is 1300 kVp and for 1 minute power frequency test 570 kVrms. In analysis, core is considered at earth potential and windings are at one minute power frequency test voltage level. Transformer Design parameters are described in Table 6. For measurement of partial discharge, digital partial discharge meter MPD 600 from OMICRON was used which can measure electric discharge pulses [14].

ELAX-2D software was used to study the design insulation adequacy for power frequency test voltages to achieve partial discharge free transformers. In this transformer, all tactics discussed in section 5 was utilized to check the adequacy of the methods. Static End rings were used at each winding end, L-Rings are provided at top and bottom last discs of the winding. HI-Lo gap was also analysed for power frequency test voltages. After thorough study in software, Transformer was tested for actual partial discharge performance. Table 7, 8 and 9 respectively shows the test results of the partial discharge values obtained from test performed on the transformer for R, Y and B phase.

TRANSFORMER DESIGN PARAMETERS:

TABLE 6

DESIGN PARAMETERS

Parameters	Details
MVA rating	315
kV class	400/220/33
Type of Transformer	Auto
Core Diameter	900 mm
Core to Tertiary winding gap	20 mm
Tertiary to Common winding gap	68 mm
Common to Regulating winding Gap	68 mm
Regulating to Series winding gap	116 mm
Series winding paper covering	1.5 mm
Common winding paper covering	1.0 mm
Regulating winding paper covering	3.0 mm

TABLE 7

PARTIAL DISCHARGE TEST RESULTS

Sr. No	Applie d voltage level in kV	Time in mins as per IEC 60076 Part 3	Observed partial discharge in pico coulomb U- Phase HV	IV
1	212.18	5	5	10
2	266.74	B=5	12	24
3	412.23	C=40	withstood	
4	266.74	10	13	25
		20	12	25
		30	12	25
		40	11	24
		50	10	22
		D=60	12	25
5	212.18	5	6	10

The applied voltages are in accordance with IEC which specifies maximum partial discharge value of 250 pC at 1.5 p.u [12]. Table 7 explain the applied voltage for different duration as specified in IEC. The observed partial discharge values at different test voltages are given in table for U – Phase in Table 7. Similarly Table 8 gives the partial discharge values for V – Phase and Table 9 gives the partial discharge values for W – Phase. The results show that the transformer is almost a partial discharge free.

TABLE 8

PARTIAL DISCHARGE TEST RESULTS

Sr. N o	Applied voltage level in kV	Time in mins as per IEC 60076 Part 3	Observed partial discharge in pico coulomb V- Phase HV	IV
1	212.18	5	7	11
2	266.74	B=5	17	27
3	412.23	C=40	withstood	
4	266.74	10	15	22
		20	13	19
		30	14	20
		40	14	21
		50	15	22
		D=60	16	22
5	212.18	5	5	11

TABLE 9

PARTIAL DISCHARGE TEST RESULTS

Sr. No	Applied voltage level in kV	Time in mins as per IEC 60076 Part 3	Observed partial discharge in pico coulomb W- Phase HV	IV
1	212.18	5	6	9
2	266.74	B=5	11	17
3	412.23	C=40	withstood	
4	266.74	10	10	15
		20	12	20
		30	15	20
		40	18	30
		50	17	28
		D=60	18	28
5	212.18	5	10	20

Case Study 2: 30 MVA, 220/6.9 kV Power Transformer, with vector group YNyn0 and having a Top lead construction is analysed for partial discharge free insulation design. The BIL of the transformer for Lightning Impulse test is 950 kVp and for 1 minute power frequency test 395 kVrms.

Transformer Design parameters are described in Table 10. FEM based analysis is performed in the ELAX-2D software for Lightning Impulse test as well as for 1 minute power Frequency test and the insulation strength is to be checked for its adequacy with partial discharge free design. Table 11 describe the applied voltage for different duration as specified in IEC and observed partial discharge values.

TABLE 10
DESIGN PARAMETERS

Parameters	Details
MVA rating	30
kV class	220/6.9
Type of Transformer	Power
Core Diameter	509 mm
Core to LV winding gap	14 mm
LV to HV winding gap	102 mm
HV to Regulating winding Gap	67 mm
HV winding paper covering	1.1 mm
LV winding paper covering	0.7 mm
Regulating winding paper covering	2.0 mm

TABLE 11
PARTIAL DISCHARGE TEST RESULTS

Sr No	Time In Mins	Applied Voltage In Kv	Pd In Pc		
			U-Phase	V- Phase	W-Phase
1	Ambient Condition		6	6	5
2	5	212.17	20	15	12
3	5	240.46	Withstood	Withstood	Withstood
4	30	212.17	450-475	18	14

PD of U-Phase may be due to manufacturing problem. But it is still within limit.

7.0 CONCLUSIONS

PD free insulation design for power transformers need to consider many parameters; types of test voltages, test connections, electrode geometry, stressed area and withstand characteristics of cellulose-oil system. Details of insulation design approach for a PD free transformer is discussed to reduce the electric stress inside the insulation and to eliminate possibility of initiation of PD under any voltage conditions. FEM based analysis for various stress conditions at critical locations of a transformer are performed and compared with the industry accepted withstand values to realize partial discharge free performance. The obtained test results show that the partial discharges in the transformers are well within the values specified in the standard by taking effective measures at design stage to relieve electrical stress concentration as described in the paper.

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