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Investigation on the Resonant Oscillations in an 11 kV Distribution Transformer under Standard and Chopped Lightning Impulse Overvoltages with Different Shield Placement Configurations

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Abstract: This paper presents an investigation on the resonant oscillations of an 11 kV layer-type winding transformer under standard and chopped lightning impulse overvoltage conditions based on calculated parameters. The resistances, inductances and capacitances were calculated in order to develop the transformer winding equivalent circuit. The impulse overvoltages were applied to the high voltage (HV) winding and the resonant oscillations were simulated for each of the layers based on different electrostatic shield placement configurations. It is found that the placement of grounded shields between layer 13 and layer 14 results in the highest resonant oscillation and non-linear initial voltage distribution. The oscillation and linear stress distributions are at the lowest for shield placement between the HV and low voltage (LV) windings.

Keywords: resonant oscillations; impulse overvoltages; electrostatic shields; transformer windings

1. Introduction

Transformers can be subjected to surges such as lightning strikes, switching discharges and other various conditions. These events have the potential to create abnormal stresses in the windings which can lead to insulation failures. The study of electrical stresses on winding insulations can assist in the improvement of the design and selection of required protection. Generally, transformers are tested in laboratories under various standard impulses as part of the routine acceptance tests [1–4]. These tests are normally used to evaluate the breakdown strength of winding insulations. In-depth study on initial voltage distributions and stresses impose on the winding insulations can be carried out through transformer winding equivalent circuits modelling [5–7].

Generally, a transformer's winding responses under impulses are mainly dependent on the design and system configuration. A number of studies have been carried out to examine the transient overvoltage surge propagations through simulations and experimental setups [8–13]. Under impulses, resonances in transformers could be initiated due to a frequency of the oscillating components that is

similar to its frequency responses [14,15]. This phenomenon can be avoided by placement of electrostatic shields at specified locations in the windings to improve the non-linearity of the voltage distribution.

The effect of electrostatic shields on the voltage distributions of windings has been studied in [16–20]. A study in [21] reveals that the placement of a grounded shield between high voltage (HV) and low voltage (LV) windings has no impact on reducing the internal resonance frequencies of the voltage gradients. Currently, the study on the shield placements impact to the resonant surge distributions in the transformer windings are still lacking and needs further investigation.

This paper presents a study to examine the resonant oscillation distributions of 11 kV distribution transformers with consideration on different electrostatic shield placement configurations. The objective of the current study is to provide a generic overview on the voltage responses of the winding under Standard Lightning Impulse (SLI) and Chopped Lightning Impulse (CLI) conditions. Since the line end of windings are usually subjected to lightning surges, the study focuses on the HV side only. The transformer winding resistance, self-inductance, capacitance and mutual inductance (RLCM) equivalent circuit are subjected to standard (1.2/50 μ s) and chopped (chopped at 6 μ s) lightning impulses of which the internal resonant overvoltages in the windings are studied.

2. Resonant Overvoltage in Transformer Winding

The resonant overvoltages could exert electrical stresses on the insulation of the transformer windings. The resonant overvoltages can be characterized by the factor, α as given in Equation (1) [3,18,19]:

$$\alpha = \sqrt{\frac{C_g}{C_s}} \quad (1)$$

where C_g and C_s are the ground and series capacitances of the winding. The non-linear behaviour of the voltage distribution in the windings due to the impulse depends on its amplitude. The initial voltage distribution in the windings due to lightning overvoltage can be seen in Figure 1. It is a result of average amplitude of the resonant oscillations. Each types of transformer winding has its own α . A linear voltage distribution, i.e., a uniform stress, is obtained when α is 0, which indicates low resonance in the transformer winding [22]. As α deviates from 0, the non-linearity of the voltage distribution increases and leads to the reduction of the overvoltage withstand capability of the winding insulation. The voltage distribution along the winding under an oscillatory surge can change the potential gradient between two adjacent layers which will result in a high voltage at the outer layer of the windings. This non-linear behaviour of the initial voltage distribution can be improved by increasing the series capacitances or decreasing the ground capacitances, i.e., using a shunt capacitance in order to calibrate the α close to 0 [23]. Several other studies have also been conducted to reduce the α based on approaches such as network function—the Luci approach and synthesis ladder network [24,25].

Figure 1. Illustration on the initial voltage distribution in the transformer winding model.

An electrostatic shield is used to increase the series capacitance which could increase the uniformity of the voltage and dielectric stress distributions in the windings. Normally, aluminum foils with pre-determined thickness are inserted at selected locations in the HV windings. Eddy current losses and transformer physical geometry are taken into consideration for selection of the appropriate shield thickness. On the other hand, the placement of the electrostatic shield depends on the location of the overvoltage surges. A study in [26] has placed the electrostatic shield at the outer layer of the HV winding due to overvoltage surges occurrence at that location. The resonant oscillations in the windings due to external transient overvoltage surges are generally different for each transformer. This is due to the fact that the RLCM parameters for the transformer equivalent circuit depend on the mechanical construction.

3. Methodology

3.1. The Overall Framework of The Modeling of Transformer Winding

The overall framework to study the effect of shield placement in the distribution transformer can be seen in Figure 2. A standard lightning impulse and chopped lightning impulses were generated based on MATLAB Simulink. The geometrical specifications of the given distribution transformer were used to compute the RLCM parameters of both the HV and LV windings. Next, the simulated voltage distribution was compared with the calculated voltage distribution. The final step was to carry out analysis for the different placements of shield in the HV winding based on MATLAB Simulink.

Figure 2. Framework to examine the effect of shield on the surge voltage distribution in the HV winding.

3.2. Generation of Standard and Chopped Lightning Impulse Voltage

A SLI of 1.2/50 μs [3] was generated based on circuit shown in Figure 3a. The resultant standard lightning impulse is shown in Figure 3b.

Figure 3. (a) Standard lightning impulse generator circuit; (b) 1.2/50 μs standard lightning impulse voltage waveform.

The parameters for the impulse generator circuit are given in Table 1. SLI was injected to the outermost layer of the HV winding. The impulse capacitor $C1$, is charged through resistor R_{ch} . An ideal switch is used to trigger the sphere gap and the voltage in $C1$ discharges immediately through damping resistor R_f , discharge resistor R_t and load capacitor C_l . IGBT is used to represent the sphere gap since it has the ability to trigger in micro seconds without the generation of any harmonics. The parameters of the SLI generator circuit were calculated according to [27].

Table 1. Parameters for standard lightning impulse generator circuit.

Parameters	Values
R_{ch}	18 K Ω
$C1$	10 μF
C_l	0.5 μF
R_f	0.84 Ω
R_t	5.96 Ω

Travelling waves can be generated from nearby lightning strikes which can be suppressed by surge arresters. This event can be represented as a CLI with a high steep front and a chopped front/tail. Under CLI, the voltage stresses in the windings depend on the rise, tail and chopping times. Generally, the lightning impulse is chopped between $2\ \mu\text{s}$ and $6\ \mu\text{s}$ [3]. The current study considered that the SLI was chopped at $6\ \mu\text{s}$ to ensure that the waveform was tail-chopped after it reached its peak. The circuit used to generate the CLI is shown in Figure 4a. The waveform of CLI can be observed in Figure 4b. The parameters of the CLI are shown in Table 2. The functions of the IGBT, resistors and capacitors were the same as that of the SLI. The parameters were calculated according to [28] and IEEE C57.98 [29] for CLI.

(a)

(b)

Figure 4. (a) Chopped lightning impulse generator circuit; (b) chopped lightning impulse at $6\ \mu\text{s}$.

Table 2. Parameters for chopped lightning impulse generator circuit.

Parameters	Values
R_{ch}	$18\ \text{K}\Omega$
C_{in}	$0.05\ \mu\text{F}$
C_L	$10\ \text{nF}$
R_f	$333.33\ \Omega$
R_t	$20\ \Omega$

3.3. Calculation of RLCM Parameters

A Dyn11 layer type transformer with rating of 160 kVA, 11/0.415 kV as shown in Figure 5 was investigated. It is a layered helical HV winding with a layered foil LV winding. The overall

cross-sectional and front cross-sectional views for a single-phase winding can be seen in Figure 5a,b. The geometry specifications for the HV and LV windings are listed in Tables 3 and 4.

Figure 5. (a) Overall cross-sectional; (b) front cross-sectional view of the winding for a single phase.

Table 3. HV winding geometry specification.

Parameters	Values
Number of turns	82
Number of layers	14
Conductor/turn thickness	3.15 mm
Insulation thickness between layers	0.17 mm
Insulation thickness between turns	0.17 mm
Height of HV winding (including allowance)	279.00 mm
Insulation between HV-LV windings	4.03 mm
Distance from centre of core to end of HV winding	96.65 mm
Distance from centre of the core to end of HV winding	145.95 mm

Table 4. LV winding geometry specification.

Parameters	Values
Height of LV winding	290 mm
Number of layers	24
Diameter of the core	125 mm
Insulation between core and LV winding	3.13 mm
Distance from core to LV winding	65.63 mm
Conductor thickness of each layer	1 mm
Insulation thickness between LV layers	0.13 mm
Distance between core and end of LV layers	92.96 mm
Internal width of the tank	383.15 mm
Relative permittivity, ϵ_r	3.3

3.3.1. Calculation of Inductance

(a) Self-inductance of the HV winding

The inductances of layer 1 to layer 14 of the HV winding were obtained based on Equation (2) individually under the assumption that the corresponding layer as a single layer as shown in Figure 6 [30]. Furthermore, according to [30], Equation (2) is valid for HV winding since it is a helical type winding with $b > 0.8a$:

$$L = \frac{N^2 a^2}{9a + 10b} \mu H \quad (2)$$

where N is the number of turns in a layer, a is the total distance from the centre of the core and b is the height of the winding.

(b) Mutual inductance of the HV winding

Mutual inductances, M between layers in the winding were computed using Equations (3) and (4) [31]:

$$M_{ij} = \mu_0 N_i N_j \sqrt{r_i r_j} \frac{2}{k} \left[\left(1 - \frac{k^2}{2} \right) K[k] - E[k] \right] H \quad (3)$$

$$k = \sqrt{\frac{4r_i r_j}{z^2 + (r_i + r_j)^2}} H \quad (4)$$

where μ_0 is the permeability of free space, N_i and N_j are the number of turns in layer i and j , respectively. r_i and r_j are the radius of layer i and layer j , respectively. $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kinds, respectively. The term z is the axial distance between layer i and layer j .

Figure 6. Sectional detail of 14th layer considered as a single layer helical winding.

(c) Self-inductance of the LV winding

The inductances of the LV winding were determined according to Equation (5) since the individual copper foils were considered in a lumped configuration as shown in Figure 7 [30]:

$$L = \frac{0.8N^2 a^2}{6a + 9b + 10c} \mu H \quad (5)$$

where N is the number of turns in a layer, a is the total distance from the centre of the core, b is the height of the winding and c is the thickness of the winding.

Figure 7. Sectional detail of layers 1 to 24 of LV winding considered in a lumped configuration.

3.3.2. Calculation of Resistance

The resistances for both the HV and LV windings were calculated based on Figure 8. R_o is the outer radius, R_i is the inner radius, L is the length of the winding and D_{cond} is the diameter of the conductor.

Figure 8. Winding parameters for resistance calculation for HV winding.

The ratio of the effective occupied area and actual cross-sectional area of the winding can be determined by Equations (6)–(8), respectively:

$$A_T = D_{cond}^2 \quad (6)$$

$$A_c = \frac{1}{4} \pi D_{cond}^2 \quad (7)$$

$$\frac{A_c}{A_T} = \frac{\pi}{4} \quad (8)$$

where A_T is the total cross-sectional area of the conductor and A_c is the effective occupied area of the conductor. It is assumed that the position of each of the inner layers for the winding is at a slightly different helix angle to the subsequent outer layer of the winding in order to ensure the subsequent layer turns would not be in the layer gaps. The layer of the winding with the helix angle can be seen in Figure 9.

A constant ratio, F was adopted and termed as a ‘winding filling factor’. It was assumed that F as $\pi/4$. The winding resistance, R_c was determined based on Equation (9):

$$R_c = \frac{4\rho(R_o^2 - R_i^2)L}{D_{cond}^4} \Omega \quad (9)$$

where the resistivity of copper, ρ is $1.724 \times 10^{-5} \Omega\text{mm}$. The effect of the core on the resistance was considered as negligible due to the large distance between conductors and core.

Figure 9. Layer of the winding depicting helix angle.

3.3.3. Calculation of Capacitance

The capacitance between two adjacent turns, C_{tt} was determined based on Equation (10) and (11):

$$C_{tt} = (\varepsilon_{eq} \theta^* e^{(d_e/d_i)}) + \varepsilon_0 \cot(\theta^*/2) + \varepsilon_0 \cot(\pi/12) \quad (10)$$

$$\theta^* = \cos^{-1} \left(1 - \left(1/\varepsilon_{eq} \right) \ln(d_e/d_i) \right) \quad (11)$$

where ε_0 is the permittivity of air, ε_{eq} is the relative permittivity of insulation material, d_e is the external diameter of the winding and d_i is the internal diameter of the winding. If the number of turns per layer of the winding is n_t , the number of series capacitances along the one layer of the winding would be $n_t - 1$. The total series capacitance of a layer of the whole HV winding, C_{tt}' was obtained based on Equation (12):

$$C_{tt}' = \frac{C_{tt}}{n_t - 1} \quad (12)$$

The capacitance between two layers of the HV winding C_{ll} , was determined based on Equation (13) at $r = \infty$ [32,33]:

$$C_{ll} = \varepsilon_0 \varepsilon_r 2\pi w / \ln(1 + d/r) = \varepsilon_0 \varepsilon_r 2\pi \frac{rw}{d} \quad (13)$$

where w is the width of the layer, d is the distance between two layers (length of the average electric flux line between two conductors), and r is the curvature radius of the winding. The C_{ll} from layer 1 to layer 12 of the HV winding were determined based on Equation (13). The capacitance between end phase of the winding and the transformer tank, C_{gt} was obtained based on Equation (14) [34]:

$$C_{gt} = \frac{0.75 \times 2\pi \varepsilon_0 \varepsilon_r h'}{\ln(t/d_o)} F \quad (14)$$

where $h' = h + d$, h is the height of the winding, d_o is the outer diameter of the inner layer, d is the gap between two layers, t is the internal width of the tank. The windings are concentrically arranged around the core. It can be treated as a cylindrical capacitance and thus the corresponding C_{gt} can be obtained based on Equation (15) [34,35]:

$$C_{gt} = \frac{2\pi \varepsilon_0 \varepsilon_r h'}{\ln(d_i/d_o)} F \quad (15)$$

where $h' = h + d$ (to compensate for fringing of the field at the ends), d_i is the inner diameter of the outer winding, d_o is the outer diameter of the inner winding, d is the distance between d_i and

d_o . The distributed capacitance from line end to the transformer tank was determined based on Equation (16):

$$C_{gt}' = \frac{C_{gt}}{3} F \quad (16)$$

The HV winding is wound around the HV-LV intermediate barrier insulation with 31 layers, which in-turn wound on the 24 layers of copper foil for the LV winding as shown in Figure 10.

Figure 10. Top view of the winding for a single phase.

The capacitance of the HV-LV intermediate barrier, C_{HV-LV} and the capacitance between two LV winding turns, $C_{LV,tt}$ was determined based on Equation (17) [34]:

$$C_{HV-LV} = C_{LV,tt} = \frac{2\pi\epsilon_0\epsilon_r h}{\ln(d_i/d_o)} F \quad (17)$$

The $C_{resultant}$ is the capacitance of the LV winding to the core which was calculated based on the capacitance of all 24 layers of LV winding as seen in Equation (18):

$$\frac{1}{C_{resultant}} = \frac{1}{C_{LV,tt,1}} + \frac{1}{C_{LV,tt,2}} + \dots + \frac{1}{C_{LV,tt,24}} \quad (18)$$

There is a space between two adjacent layers which consists of oil impregnated insulation paper wrapped around the copper conductors of the HV winding. The permittivity, ϵ_{res} of the gap was determined based on Equation (19) with consideration on the two adjacent layers:

$$\frac{1}{\epsilon_{res}} = \left[\frac{1}{\epsilon_{paper}} \times \frac{d_{paper}}{d_{Tot}} \right] + \left[\frac{1}{\epsilon_{ins}} \times \frac{d_{ins}}{d_{Tot}} \right] \quad (19)$$

where d_{paper} is the thickness of paper insulation, d_{ins} is the thickness of the insulation coating, d_{Tot} is the distance between two layers. The series capacitances of the winding layer were calculated based on the ratio between turn-to-turn capacitance over number of turns of that particular layer. The equivalent layer capacitance of two layers, C_{ll}' was transformed at the input of the winding circuit. Next, the equivalent turn-to-turn capacitance, C_{tt}' was multiplied with the square of the turns ratio of the two layers to the entire winding based on Equation (20):

$$C_{ll}' = \frac{(N_{L,i} + N_{L,i+1})^2}{\left[\sum_{K=1}^{N_{Layer}} N_{L,K} \right]^2} \times C_{tt}' \quad (20)$$

where $N_{L,i}$ is the number of turns in the i -th layer of the winding and $N_{L,i+1}$ is the number of turns in the $(i+1)$ -th layer of the winding. The C_{ll} , between outermost two layers of the HV winding was

determined based on Equation (13). The equivalent layer-to-layer capacitance for the layers wound in opposite direction is 1/3rd of the static capacitance between two layers and was determined based on Equation (21):

$$C_{ll, equ} = C_{ll} / 3 \quad (21)$$

$$C_{ll}' = C_{ll, equ} \quad (22)$$

The equivalent layer capacitance of two layers, $C_{ll, equ}$, in Equation (22) was obtained based on Equation (21) and transformed into a capacitor at the winding input C_{ll}'' . This capacitance, C_{ll}'' was considered to be in parallel to the layer winding. The capacitance, $C_{ll, 2ndLayer}$ was calculated accordingly. For the capacitance of layer 2, i.e., layer 13 of HV winding was calculated for C_{ll}' and $C_{ll, 2}''$. Turn-to-turn capacitance of the layer 14 was also determined based on Equation (10). The capacitance for LV winding was obtained based on Equation (23):

$$C_{ll, LV} = 2\pi\epsilon_0\epsilon_r \frac{h}{\log(dio/doi)} \quad (23)$$

where h is the LV winding height, dio is the inner diameter of outer winding, doi is the outer diameter of inner winding that can be seen in Figure 11 and ϵ_r is the relative permittivity.

Figure 11. Sectional detail of the LV winding for a single phase.

3.4. Transformer Model

The transformer equivalent RLC circuit including the mutual inductances between the layers computed according to Equation (3) and (4) used in this study can be seen in Figure 12a. The schematic diagram of the 12 layers of the HV winding in the subsystem can be seen in Figure 12b. The calculated RLC parameters of the HV winding are shown in Table 5. The lumped LV winding parameters can be seen in Table 6. In this study, only the transient resonance from the time of the applied impulse is considered. In addition, the effects of transformer core are not considered due to the magnetizing inductance of the core is not dominant in this high frequency model [36,37]. The current required to charge the capacitive elements in the transformer equivalent circuit was calculated to ensure no magnetizing currents were generated in the circuit model. The transformers were assumed to operate based on standard tapping condition for all cases.

Figure 12. (a) Transformer equivalent circuit with 14 HV layers in the winding and lumped LV winding; (b) Schematic diagram from layer 1 to layer 12 of HV winding in the subsystem.

Table 5. RLC parameters of the HV winding.

Layers	R (Ω)	L (μ H)	C _{ll} (pF)
14	1.7637	1349	159.65
13	1.7231	1295	155.93
12	1.6825	1246	152.22
11	1.6420	1297	148.51
10	1.6014	1146	144.80
09	1.5609	1097	141.09
08	1.5203	1048	137.37
07	1.4798	1001	133.66
06	1.4392	954	129.95
05	1.3986	908	126.24
04	1.3581	863	122.53
03	1.3175	818	118.82
02	1.2770	775	115.11
01	1.2364	732	-

Table 6. RLC parameters of the LV winding.

Parameters	Values
C_{gt}'	11.805 pF
C_{HV-LV}	1033.7 pF
$C_{resultant}$	1396.1 pF
L_{LV}	0.059 μ H
R_{LV}	86.6784 Ω

3.5. Comparison between Simulated and Calculated Voltage Distribution

The reliability and accuracy of the simulation depends on the validity of the transformer equivalent circuit. The voltage distribution of the layers of HV winding that had been obtained through simulated model was compared with numerical calculation based on Equation (24) [19,38]:

$$V_{dist} = \frac{V_p \cosh(\alpha/l)x}{\cosh \alpha} \quad (24)$$

where l is the height of the winding, x is the layer distance from the neutral point, V_p is the voltage peak of input impulse and V_{dist} is the voltage distribution of each layer. The value of coefficient, α was determined based on Equation (1).

The simulated and calculated voltages obtained at the peak point of the standard lightning impulse for the unshielded winding model are shown in Figure 13. The simulated voltage shows a slight variation as compared to the calculated voltage. The calculated voltage has a visible drop from layer 14 to layer 13 due to the presence of ground capacitance between outermost layer (layer 14) of the HV winding and the tank. The simulated voltage decreases almost linearly from outer to inner layers of the winding and it is higher than the calculated voltage. The calculated voltage continues to decrease almost linearly for the other layers. This phenomenon of sudden voltage drop along the layers would exert voltage stresses on the insulation of winding layers [38–41]. The slight difference between the simulated and calculated voltage distributions along the layers might be due to several assumptions made during the simulation. For simulated voltage, the allowance of the HV winding geometry height could not be considered for individual RLCM determination. For calculated voltage, the allowance of height is taken into consideration in voltage calculation at each of the layers for the HV winding. Other reason could be due to the impulse peak time is considered in the simulated voltage but not in the calculated voltage. Additionally, the α value is considered in the calculated voltage but not in the simulated voltage.

Figure 13. Comparison between simulated and calculated voltage distributions under standard lightning impulse for all layers of the unshielded winding.

3.6. Case 1: Transformer Model with Shield Placement between Layer 14 and Layer 13

An electrostatic shield with thickness and length of 0.075 mm and 279 mm was placed between layers 14 and layer 13 of the HV windings as shown in Figure 14. The shield was placed as floating (at constant potential). The RLC parameters from layer 1 to layer 13 remained unchanged. The HV winding at layer 14 was moved 0.075 mm away from layer 13 to facilitate the electrostatic shield, thereby changing the RLC parameters of the layer 14 as shown in Table 7. Since the aim of electrostatic shield was to increase the series capacitance and subsequently calibrate α close to 0, the layer-to-layer capacitance between layer 14 and shield as well as between shield and layer 13 were calculated on the basis that the shield act as another layer. The modified transformer winding model and the modified RLC values of the layer 14 can be seen in Figure 14 and Table 7, respectively.

Figure 14. Transformer winding model with different cases of shield placement.

Table 7. Modified RLC parameters of HV winding with shield placement between layer 14 and layer 13.

Parameters	Values
C14shield	394.65 pF
Cshield13	385.81 pF
L14	1350 μ H
R14	1.7646 Ω

3.7. Case 2: Transformer Model with Grounded Shield Placement between Layer 14 and Layer 13

The aim of this investigation was to observe any potential variation on the voltage stress under the impulse overvoltage surge with grounded shield. The height of the shield is the same as that of layers of HV winding, hence the distance between shield and tank would be same. Due to this reason, the ground capacitance is the same as that of layer 14 and tank. The transformer winding model with grounded shield in between layer 14 and layer 13 can be seen in Figure 14.

3.8. Case 3: Transformer Model with Shield Placement between Layer 14 and Layer 13 and between Layer 13 and Layer 12

The effect of two shields placement between layer 14 and layer 13 as well as between layer 13 and layer 12 were also investigated. The distance between the core and layer 14 of the HV winding was increased by 0.15 mm due to the placement of two shields. The layer-to-layer capacitances were calculated between layer 14 and shield as well as between shield and layer 13. The same procedure was carried out for placement of shield between layer 13 and layer 12. The inductance and resistance values of layer 13 and layer 14 were modified to 142.705 mm and 146.1 mm, respectively. The transformer model with shield placement between layer 14 and layer 13 and between layer 13 and layer 12 can be seen in Figure 14 and the modified RLC parameters can be seen in Table 8.

Table 8. Modified RLC parameters of HV winding with shield placement between layer 14 and layer 13 and between layer 13 and layer 12.

Parameters	Values
C14shield	394.86 pF
Cshield13	386.02 pF
C13shield	385.58 pF
Cshield12	376.74 pF
L14	1351 μ H
L13	1298 μ H
R14	1.7655 Ω
R13	1.7240 Ω

3.9. Case 4: Transformer Model with Shield Placement between HV and LV Winding

The electrostatic shield placement between HV and LV windings could reduce the capacitor coupling effect [42]. This approach could suppress the high resonant surges. The shield placement between HV and LV windings can be seen in Figure 14 and the modified RLC parameters can be seen in Tables 9 and 10.

Table 9. Modified RLC parameters of HV winding for each of the layers with shield placement between HV and LV windings.

Layers	R (Ω)	L (μ H)	C _{ll} (pF)
14	1.7646	1350	159.73
13	1.7270	1298	156.02
12	1.6835	1247	152.31
11	1.6429	1298	148.59
10	1.6023	1147	144.88
09	1.5618	1098	141.17
08	1.5212	1049	137.46
07	1.4807	1011	133.75
06	1.4401	955	130.04
05	1.3996	909	126.32
04	1.3590	864	122.61
03	1.3184	819	118.90
02	1.2779	776	115.19
01	1.2373	733	-

Table 10. Modified RLC parameters of LV winding with shield placement between HV and LV windings.

Parameters	Values
C_{gt}'	11.805 pF
C_{HV-LV}	1695.2 nF
$C_{resultant}$	1396.1 pF
L_{LV}	0.059 μ H
R_{LV}	86.6784 Ω

4. Results

The eddy current loss was calculated and found to be small as compared to the total loss of the transformer at full load, and hence it was neglected in the present work. The voltage distributions for all 14 layers of the HV winding were determined for the surge analysis. However, only three outer layers waveforms are shown since the external applied impulse should affect mostly on the outermost layers of the winding.

4.1. Surge Voltage Distribution under Standard Lightning Impulse

The surge voltage distributions under SLI for an unshielded HV winding can be seen in Figure 15. The voltages are lower at the instant of the SLI peak. V14top is the applied impulse voltage, V14end, V13end and V12end are the voltages at the end of layer 14, layer 13 and layer 12, respectively. V14end, V13end and V12end are 6%, 16% and 25% lower than V14top at the time of impulse peak. The phenomena of resonant oscillations are expected due to the presence of the RLCM elements in the winding equivalent circuit.

Figure 15. Surge voltage waveforms for unshielded winding under SLI.

4.1.1. Case 1: Surge Voltage Distribution for the Transformer Model with Shield Placement between Layer 14 and Layer 13

With floating shield placement between layer 14 and layer 13 in the HV winding, the voltage resonances slightly decrease at time between $6 \mu\text{s}$ and $18 \mu\text{s}$ as seen in Figure 16. It is due to the reduction of electromagnetic interference with the shield [43] between layer 14 and layer 13. V14end, V13end and V12end are 11%, 19% and 27% lower than V14top at the time of impulse peak. The voltage for each of the layers due to shield placement between layer 14 and layer 13 is almost close to unshielded winding.

Figure 16. Surge voltage waveforms for shield placement between layer 14 and layer 13 of HV winding under SLI.

4.1.2. Case 2: Surge Voltage Distribution for the Transformer Model with Grounded Shield Placement between Layer 14 and 13

Grounded shield placement between layer 14 and layer 13 in the HV winding has an adverse effect on the surge voltage distribution as shown in Figure 17. The voltage resonances changes from positive to negative and vice versa due to the effect of inductive (positive effect) and capacitive (negative effect) elements in the circuit model. V14end, V13end and V12end are 60%, 63% and 66% lower than V14top at the time of impulse peak. The grounding of the shield diverts the surge voltage from the winding layers to ground, thereby inducing sudden voltage drop between the layer 14 and layer 13 and lead to the high resonant oscillation.

Figure 17. Surge voltage waveforms for grounded shield placement between layer 14 and 13 of HV winding under SLI.

4.1.3. Case 3: Surge Voltage Distribution for the Transformer Model with Shield Placement between Layer 14 and 13 and between Layer 13 and 12

The effect of floating potential shield placement between layer 14 and 13 as well as between layer 13 and 12 on the surge voltage distribution in the HV winding can be seen in Figure 18. The voltage resonant oscillations slightly decrease as compare to Figure 15 at time between 6 μ s and 19 μ s. An exertion of sudden voltage stresses in the layers will affect the magnetic flux distribution in the core. This event will be reflected on the resonant oscillations of the winding and leads to reduction of the voltage drop [44]. V14end, V13end and V12end are 8%, 19% and 28% lower than V14top at the time of impulse peak.

Figure 18. Surge voltage waveforms for shield placement between layer 14 and layer 13 and between layer 13 and layer 12 of HV winding under SLI.

4.1.4. Case 4: Surge Voltage Distribution for the Transformer Model with Shield Placement between HV and LV Windings

The voltage resonant oscillations are clearly damped whereby the amplitudes maintain lower than SLI with shield placement between HV and LV windings can be seen in Figure 19. V14end, V13end and V12end are 6%, 18% and 28% lower than V14top at the time of impulse peak.

Figure 19. Surge voltage waveforms for shield placement between HV and LV windings under SLI.

4.2. Surge Voltage Distribution under Chopped Lightning Impulse

The surge voltage distributions for an unshielded winding under the CLI chopped at $6 \mu\text{s}$ can be seen in Figure 20. The resonant oscillations in the winding with different shield placements can be seen in Figures 21–24 respectively. Without shield, V14end, V13end and V12end are 12%, 20% and 27% lower than the V14top at the time of impulse peak.

Figure 20. Surge voltage waveforms for unshielded winding under CLI.

4.2.1. Case 1: Surge Voltage Distribution for the Transformer Model with Shield Placement between Layer 14 and Layer 13

Since CLI has a high frequency oscillation, the capacitive voltage could increase and lead to the increment of voltage resonances caused by the grounded shield [45]. V14end, V13end and V12end are 9%, 19% and 27% lower than V14top at the time of impulse peak with shield placement between layer 14 and layer 13 can be seen in Figure 21. The voltage drops between layers are lower than the unshielded winding at the time of impulse peak in Figure 20. However, quite a few resonant oscillations are generated in the transformer model at time between $6 \mu\text{s}$ and $28 \mu\text{s}$.

Figure 21. Surge voltage waveforms for shield placement between layer 14 and 13 under CLI.

4.2.2. Case 2: Surge Voltage Distribution for the Transformer Model with Grounded Shield Placement between Layer 14 and Layer 13

V14end, V13end and V12end are 57%, 61% and 64% lower than the V14top amplitude at the time of impulse peak with grounded shield placement between layer 14 and layer 13. Similar apparent resonant oscillations as in SLI are observed at time between 1.5 μ s and 50 μ s can be seen in Figure 22.

Figure 22. Surge voltage waveforms for grounded shield placement between layer 14 and layer 13.

4.2.3. Case 3: Surge Voltage Distribution for the Transformer Model with Shield Placement between Layer 14 and Layer 13 and between Layer 13 and Layer 12

With shield placement between layer 14 and layer 13 as well as between layer 13 and layer 12, the peak of voltage resonant distribution of V14end under CLI at between time 6 μ s to 15 μ s decreases from 0.75 p.u. to 0.5 p.u. which can be seen in Figure 23. However, there is not much variation in term of resonance as compared to shield placement between layer 14 and layer 13. V14end, V13end and V12end are 10%, 19% and 28% lower than V14top at the time of impulse peak.

Figure 23. Surge voltage waveforms in a winding with shield between layer 14 and layer 13 and between layer 13 and layer 12 due to CLI.

4.2.4. Case 4: Surge Voltage Distribution for the Transformer Model with Shield Placement between HV and LV Windings

With shield placement between HV and LV windings, the resonances are suppressed from the time of chopping at $6 \mu\text{s}$ to the end of the impulse at $50 \mu\text{s}$ which can be seen in Figure 24. The voltage at V14end, V13end and V12end are 10%, 19% and 29% lower than V14top at the time of impulse peak. The resonant oscillations in the winding layers are minimum as compared to other previous cases.

Figure 24. Surge voltage waveforms in a winding with shield between HV and LV winding due to CLI.

4.3. Discussion on the Effect of Shield Placements on the Initial Surge Voltage Distribution

The oscillatory nature of the overvoltage surges in the windings due to the external SLI and CLI impulses are caused by the presence of passive RLCM elements in the transformer winding circuit [3]. The placement of shield conductor in the winding geometry would divert the generated voltage stresses on the surface of the shield as a result from the increment of series capacitance [18]. This phenomenon would calibrate α as close to 0 and lead to linear initial voltage distribution. The initial voltage distributions of the shielded winding for SLI and CLI are shown in Figures 25 and 26. The voltage distributions at the HV winding layers with respect to the time of applied impulse peak are considered for the comparison study between simulated and calculated voltage. Based on the current

simulation output, it is observed that pattern of resonant oscillations for SLI are severe as compare to CLI. It is known that the voltage distribution depends on the applied impulse magnitude and voltage gradients between turns and layers of the winding [16]. The variation in voltage distribution along the layers in the winding could initiate resonant oscillations that enhance the voltage gradients and lead to the insulation failure between the layers [21].

There is no significant effect of ungrounded shield placement between layer 14 and layer 13 in the HV winding on the initial voltage distribution as compare to unshielded for both SLI and CLI as shown in Figures 25 and 26. The same pattern is observed for ungrounded shield placement between layer 14 and layer 13 as well as between layer 13 and layer 12. For CLI, a minor deviation on the initial voltage distribution for ungrounded shield is found which is caused by capacitive division due to CLI operation at high frequency. The effect of shield placements for these cases are not apparent probably due the increment of the series capacitances is not sufficient to cause reduction on the overall resonant oscillation and improvement on the linearity of the initial voltage distribution.

Figure 25. The effect of shield on initial voltage distribution for SLI.

Figure 26. The effect of shield on initial voltage distribution for CLI.

Apparent reductions of the initial voltage distribution are observed for grounded shield placement between layer 14 and 13 as compared to unshielded, as shown in Figures 25 and 26. The grounded shield diverts the excessive surges generated in the circuit to the ground that lead to the steep voltage

drop between layer 14 and layer 13 and high resonant oscillation in the surge voltage waveforms. The sudden voltage drop can exert excess voltage stress and increases the possibility of insulation failure between layer 14 and layer 13 under both SLI and CLI.

The initial voltage distribution in the winding is more linear for ungrounded shield placement between HV and LV winding as compare to other shield configurations under SLI and CLI. Based on the study, the placement of ungrounded shield between HV and LV windings is the optimum practice against SLI and CLI. This placement leads to high series capacitance along all the layers of HV winding which sufficiently enough to suppress the resonant oscillations which in turn imposes stress on the insulation system of transformers.

5. Conclusions

Based on the case study, it is evident that the shield placement configurations have an effect on the resonant oscillations in the layers of the winding under SLI and CLI based on calculated parameters. The overvoltage surge distributions in the winding for grounded shield placement between layer 14 and layer 13 are non-linear of which high voltage stress would be exerted on layer 13 due to sudden voltage drop under both SLI and CLI. The effect of ungrounded shield placement between layer 14 and 13 is not significant on the initial voltage distribution. The same pattern is observed for ungrounded shield placement between layer 14 and layer 13 as well as between layer 13 and layer 12.

A linear initial voltage distribution is found for ungrounded shield placement between HV and LV windings of which a clear decrement of resonant oscillations in the winding is found. The linear initial voltage distribution will reduce the stress on the insulation system which maintain the reliability of transformers. Overall, the simulation output is only confirmed by the calculated parameter. In order to verify the finding, validation with the measurement output would be considered as part of the future study. Nevertheless, this study can assist the manufacturer a clear technical basis for shield placement in the future for effective protection of the transformer windings.

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