Comprehensive modeling of Dry type foil winding transformer to analyse inter turn insulation under Lightning Impulse Voltage

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***Abstract*— In the event of a lightning impulse to the high voltage terminal of a dry type transformer, uneven impulse stress occurs on its windings. The impulse voltage may further shoot up owing to resonance condition which results in additional turn to turn and coil to coil voltage difference. In this paper, comprehensive modeling of transformer is done by calculating circuit parameter of transformer for each turn. Self and mutual inductances are calculated for each turn using finite element analysis (FEA) and validated with analytical calculation. Further, impulse voltage behavior is studied at every turn by using LTSpice software. The voltage stresses thus got is used to analyze dielectric strength of insulating material by using ANSYS Maxwell software. This study was carried out on Dry type foil winding transformer. The achieved results indicate that electrical stress between turn to turn is drastically improved by designing initial turn of HV coil from outer side than inner side of HV winding.**

Keywords—LTSpice, Lightning impulse, transformer modeling, Dry type foil winding

I. Introduction

Lightning impulse comprises of frequencies from tens of kilohertz to several megahertz and characterized by a very high-voltage (HV) rate of rise du/dt and may have a negative influence on the windings of transformers [1]. The winding inductances have no effect on the initial voltage distribution since the magnetic field requires a finite time to build up. When the applied voltage is maintained for a sufficient time (50 to 100 microseconds), appreciable current begin to flow in the inductances eventually leading to the uniform voltage distribution. Since there is difference between the initial and final voltage distributions, a transient phenomenon takes place during which the voltage distribution readjusts itself from the initial to final value [3]. This unfavorable phenomenon may result in deterioration in the insulation and ultimately lead to a dielectric breakdown [2].

Many studies have been done to investigate transient performance of transformer during switching of breaker for identifying behavior of transformer winding and protection method against very fast transient [1, 2, 4, 6]. Impulse analysis in transformer mainly focuses on initial voltage distribution with respect to winding length [9]. Now it is required to closely analyze minor insulation or inter turn insulation in order to optimize the design and to get better life expectancy of transformer.

This study is mainly aimed on measurement of voltage generated between turns during lightning impulse by using LTSpice software. Further, this study is extended to electrostatic analysis in ANSYS Maxwell software to analyze electrical stresses generated between minor insulation and suggestions have been made to overcome the stresses. Detailed modeling of HV winding has been done by considering self and mutual inductance and capacitance of each turn.

II. Modeling of Dry Type Transformer

A. Winding model description

Lumped parameter modeling of transformer strongly depends upon type of winding and its configuration. Fig.1 shows a three phase dry type transformer considered for the study.

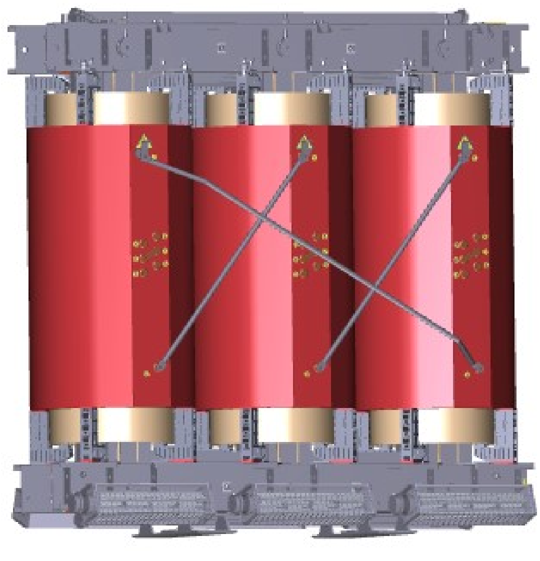

Fig. 1. Test transformer.

Both LV and HV winding are made of foil-type layers. In HV winding each turn represents one layer and each coil consists of N no of turns.

B. HV winding representation

The geometrical structure of one phase is shown in Fig.2. First foil turn of HV coil starts from inner side of HV winding and continues up to N^{th} turn, hence 1^{st} turn is nearer to LV winding and N^{th} turn is on the farther end of LV winding. Since first turn is nearer to LV winding, it has a strong capacitance with LV winding.

The aim of this study is to analyze voltage difference between turns, hence it is required to calculate inductance and capacitance for every turn. Inductance matrix is formed by considering each turn of the coil and its mutual inductance with respect to all other remaining turn within the coil, hence inductance matrix for each coil is of NxN.

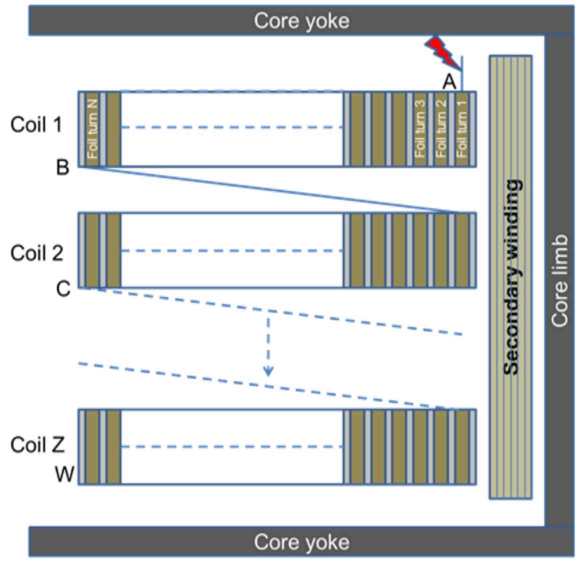

Fig. 2. Test transformer configuration.

Layer to layer capacitance, coil to coil capacitance for each turn and LV to HV capacitance is considered to make study more accurate. Since dry type transformer doesn't have tank, ground capacitance with respect to tank is neglected for this study. Equivalent circuit can be simplified by rearranging capacitances [4].

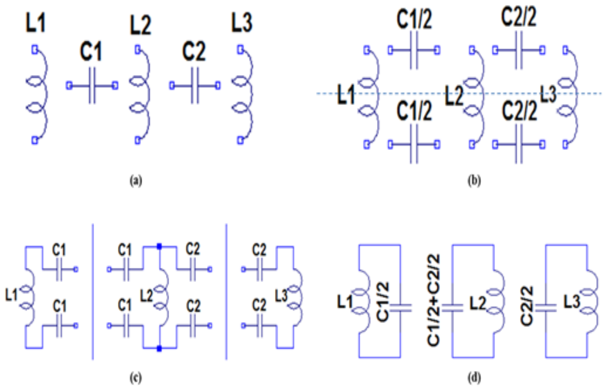

Fig. 3. Rearranging turn to turn capacitance.

Fig.3 (a) represents inductance and capacitance network for three turns, L1, L2, L3 are the inductances of turn 1, 2, 3 respectively and C1, C2 are capacitances between turn 1-2 and turn 2-3 respectively. Above circuit can be simplified by assuming an equipotential line in the middle of the coil as shown in Fig.3 (b) [4].

Hence C1/2 and C2/2 are added to the edges of the coils L1, L2, L3 respectively. The circuit can further be streamlined by considering an equipotential surface between layers, which is explained in Fig.3 (c) [4,5]. Hence the capacitance between layers can be added as a cross-over capacitance at each layer with the value half from each side. After this simplification each layer is represented by one inductance and one capacitance as shown in Fig.3 (d)

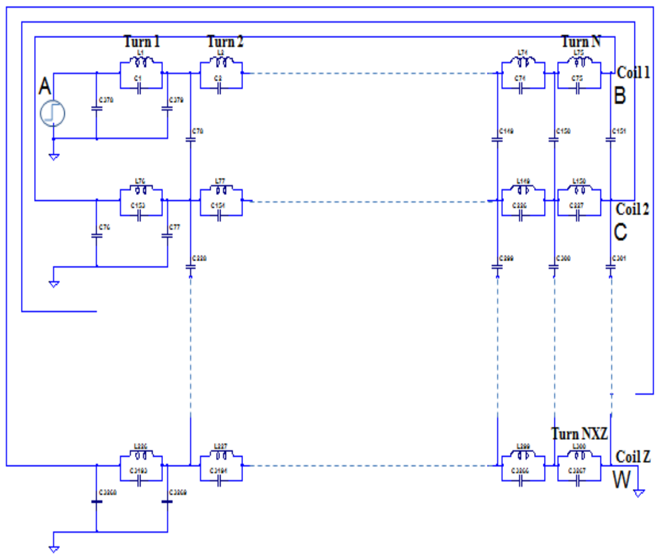

Fig. 4. Equivalent circuit of HV winding.

Fig. 4 shows final equivalent circuit of HV winding with lumped parameter. First turn of each HV coil has capacitance with respect to LV winding. This can be considered as gound capacitance [6]. The capacitances from first and last coil to core i.e. ground are very small in this case. It can be seen from Fig. 2 that only a part of the surface of the coil is nearer to core hence capcitance from coil to core is neglected as it is mostly the geometry of the surface that influences the value [7]. Coil to coil capacitance is considered for every turn to analyse voltage distribution accurately.

C. Determination of lumped parameters

1) Capacitance

As shown in Fig. 4 there are three types of capacitances present in the circuit. (i) Turn to turn capacitance, (ii) Coil to coil capacitance for each turn and (iii) HV to LV capacitance. Since it is a foil type winding, turn to turn and HV to LV capacitance can be straight away calculated by using basic formula of cylindrical capacitors. For better accuracy capacitance of individual turn of coil 1 is calculated with respect to respective turn of coil 2 instead of calculating coil to coil capacitance by considering N turn as a one plate. Parallel plate capacitance formula was used to calculate Coil to coil capacitance for each turn.

2) Inductance Calculation

According to calculation methodology in [8], the mutual inductance between foil-type turns is calculated by

$$M = 2\pi\mu_0(R_1R_2)^{3/2}n_1n_2[Q_1 - Q_2 + Q_3 - Q_4] \quad (1)$$

$$Where\ R_1 = radius\ of\ first\ coil$$

$$R_2 = radius\ of\ second\ coil$$

$$n_1, n_2 = no\ of\ coil\ turns \text{ per unit length}$$

$$Q_i = \frac{\sqrt{R_1R_2}}{2\pi}\int_0^{\pi}\frac{\sqrt{R_1^2 + R_2^2 + z_i^2 - 2R_1R_2\cos\varphi}}{R_1^2 + R_2^2 - 2R_1R_2\cos\varphi}sin^2\varphi d\varphi \quad (2)$$

$$i = 1,2,3,4$$

$$z_1 = l_1 + l_2 + s \qquad z_2 = l_1 - l_2 + s$$

$$z_3 = -l_1 - l_2 + s \qquad z_4 = -l_1 + l_2 + s$$

$$Here\ l_1 = half\ foil\ height\ of\ first\ coil$$

$$l_2 = half\ foil\ height\ of\ second\ coil$$

$$s = axial\ distance\ between\ coil\ center$$

And self-inductance is calculated by

$$L = 4\pi\mu_0 n^2 R^3\left[\frac{2}{\pi}\int_0^{\frac{\pi}{2}}\frac{Asin^2\emptyset + Bcos^2\emptyset}{\sqrt{sin^2\emptyset + k^2cos^2\emptyset}}d\emptyset - \frac{2}{3\pi}\right] \quad (3)$$

$$Here\ k = \frac{h^2}{4R^2 + h^2}$$

$$A = \frac{1}{3\sqrt{1-k^2}}$$

$$B = \frac{2k^2}{3\sqrt{1-k^2}}$$

$$h = winding\ height \quad R = winding\ radius$$

The self-inductance of first turn and mutual inductance between first and second turn of the first coil is calculated using these formulae. Then, 2D-axisymmetric model is developed for first two turn and same inductances are calculated using commercial FEA software ANSYS Maxwell. The results are compared in table 1.

TABLE I. COMPARISON OF ANALYTICAL AND FEA RESULTS

	Analytical Result	FEA Result
Self-Inductance of 1st Coil	1.2191 µH	1.2167 µH
Mutual Inductance between 1st and 2nd Coil	1.2025 µH	1.2036 µH

After FEA methodology is validated with analytical calculation, it is then extended to calculate self and mutual inductance of complete N turns in the coil.

III. TRANSIENT ANALYSIS

Standard lightning impulse i.e. 1.2/50µs was applied to equivalent circuit shown in Fig. 4 and voltage distribution between turns has been analyzed by using LTSpice software. An impulse voltage of 170kVp is applied to 33kV HV winding as per IEC_60076_3.

All NxZ no of turns are modeled using a total of NxZ inductors and [2(NxZ) +2Z] capacitors. The line with sampling point and the thick line as shown in Fig.5 indicate voltage difference between 1st and 2nd turn and 2nd and 3rd turn respectively. Major voltage difference was observed between first two turns i.e. 22kV and rest of the layers has voltage difference less than 4kV. Hence electrostatic study was performed on first two turns to check the electric stress vs insulation strength.

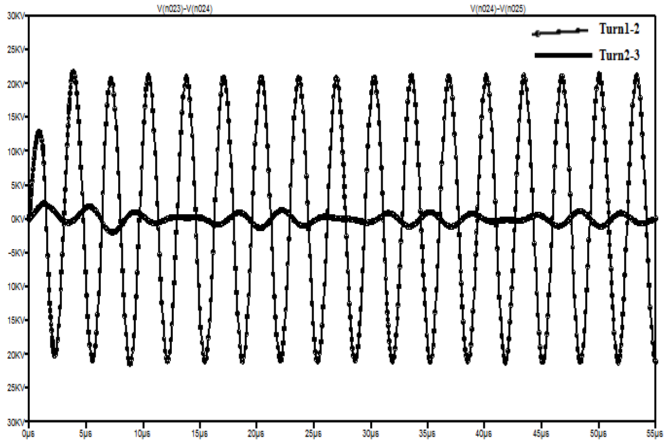

Fig. 5. Voltage difference between 1st and 2nd turn, 2nd and 3rd turn.

IV. ELECTROSTATIC ANALYSIS

The input for electrostatic analysis is taken from output of transient analysis. 2D-axisymmetric model of turn to turn insulation is modeled in ANSYS Maxwell software as shown in Fig. 6. 22kV is applied to turn 1 and 2nd turn is at ground potential, Fig. 7 gives idea about how equipotential lines are passing and voltage is distributed across the insulation.

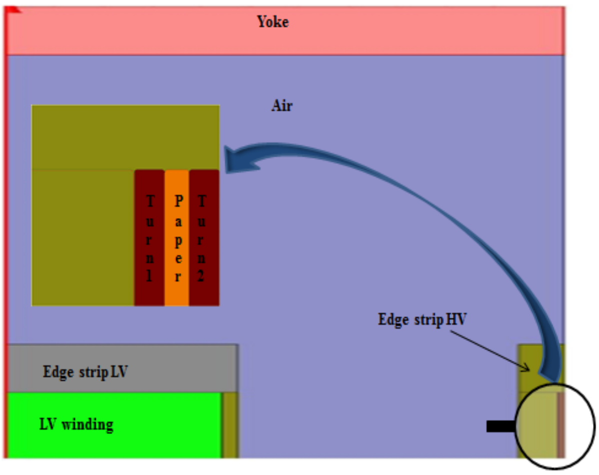

Fig. 6. 2D-axisymmetry geometry for turn to turn insulation analysis

Highest electrical stresses coming out from the analysis is at the edge of the turn as shown in Fig. 7. Safety margin is calculated by considering electrical stress and insulation strength, which is 11% for the corner of inter turn insulation. Whereas safety margin for insulation across turn is 41%.

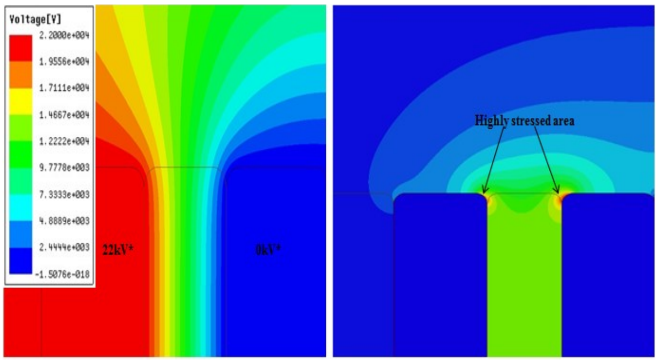

Fig. 7. Equipotential surface and Electric field plot for turn to turn.

Since voltage difference between turns is very high, the stress value is also quite high at the edges. Stresses at the edge can be reduced by improving corner radius but it being a foil type winding, there is a limitation to corner radius for such a thin layer. To overcome the problem of voltage stress, a change in winding configuration is suggested. The new winding configuration is shown in Fig. 8.

V. Revised Winding Model

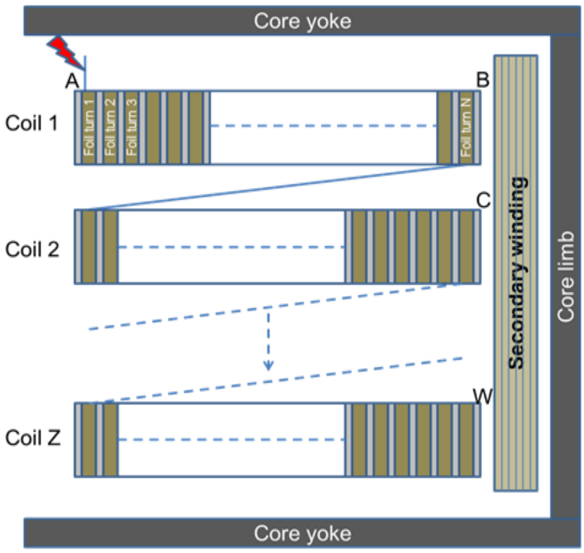

Fig. 8. Rewound HV winding.

HV winding is rewound by keeping all parameters constant but in the new configuration first foil turn of HV coil starts from outer side of HV winding and continued up to Nth turn, hence 1st turn is farther from LV winding and Nth turn is nearer to LV winding. Since first turn is far away from LV winding, there is no capacitance between first turn and LV winding. Hence ground capacitance will come in to picture only after (N-1)th turn. Equivalent circuit is also modified as described above and transient analysis was performed on rewound winding. The results are shown in Fig. 9.

It can be seen from Fig. 9 that voltage difference between 1st two turns are drastically reduced from 22kV to 3.5kV. Also, voltage difference between rests of the turns is observed less than 3kV. Once again electrostatic study was carried out with new value of voltages, table II shows the comparison between two winding design.

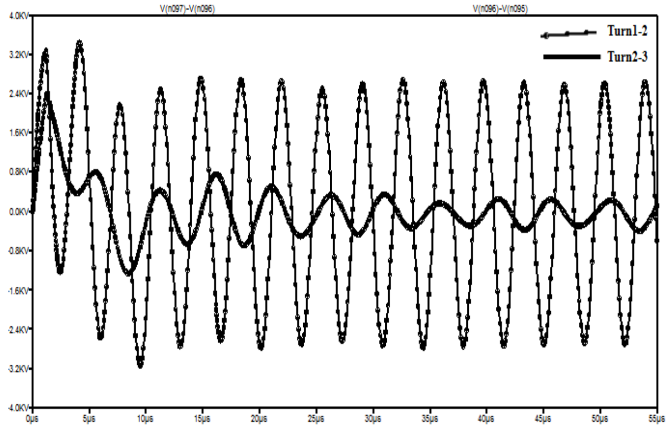

Fig. 9. Voltage difference between turns.

TABLE II. Comparison of Existing and Proposed Winding Configuration

	Inter turn Voltage	Safety margin at edge Insulation	Safety margin across insulation
Existing winding configuration	22kV	11%	41%
Proposed winding configuration	3.5kV	80%	90%
% improvement	84.09%	69%	49%

VI. Conclusion

Detailed modeling of Dry type foil winding transformer is done by considering each turn. This study explains the methodology to analyze inter turn insulation under Lightning Impulse Voltage or any kind of transient response when each individual turn is modeled as shown in equivalent circuit, Fig. 4. A validated FEA model is developed to calculate self and mutual Inductance matrix of NxN. Impulse voltage distribution is analyzed using LTSpice software, which provided input voltage for electrostatic study to find out electrical stress on the insulation.

Analysis shows how winding configuration affects voltage distribution between turns. Only by changing winding start and end points/direction of winding, a big difference in voltage can be observed between inter turns. Since in initial design ground capacitance comes in to picture in the first turn itself, major voltage was dropped between first two turns, whereas in the modified design ground capacitance comes after (N-1)th turn and by that time voltage gets distributed uniformly. Hence the study indicates that ground capacitance plays an important role in voltage distribution during Impulse. It is observed that more than 84% improvement can be achieved in voltage difference between turns by changing winding configuration, which directly replicates in reduction of electrical stress on inter turn insulation more than 82% and safety margin was improved in the range of 50% to 70%.

VII. ACKNOWLEDGEMENT

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