Experimental and Theoretical Determination of Voltage Stress on Insulation of Industrial Motor Winding

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Abstract— **Failure of many large industrial motors due to insulation failure is caused by stresses generated by steep fronted transient voltages. The severity of such transients and degree of voltage stress on the motor winding depends up on the overall system to which motor is connected. In this paper an Electromagnetic Transient Program (EMTP™) is used to determine the voltage distribution in the line end coil of motor winding. In order to determine voltage, a coil manufactured for 6.6 kV class motor having ten turns is considered for analysis. The coil is represented as an electrical network with inductance, mutual coupling as well as series and shunt capacitance. The network is analyzed with the help of EMTP™ for surge of different rise times. The results presented in this paper shows that generated transients are sufficient to cause severe inter turn fault. There is good compatibility between computed and measured voltage for standard impulse voltage.**

Keyword- Voltage stress, insulation failure, line end coil, inters turn voltage distribution.

I. Introduction

Large industrial motors are commonly used to drive process equipments, which are critical to sustaining plant production in large industrial establishment. Failure of motor causes the serious economic consequences, far beyond the repairing cost of motor. Surveys conducted to assess the reliability of motors in utilities and industrial applications have found that stator insulation accounted for nearly one third of all motors failures. Further, in most of the cases the failures are reported to have occurred as a result of inter turn fault often located in end coil of the winding. W Z Gandhare [1] reported that switching surges can stress the turn-turn and turn to ground insulation beyond its withstand capability. Authors reported that impulse voltage at breaker terminal is higher than motor terminal. Sayeed Ul Haq et. al. [2] reported that group of coils are selected to apply voltage endurance test. Report suggested that coils having thinnest insulation are failed at 20 kV. It is observed [3] that stator winding faults account for a large percentage of the failure of machine. About 37 % of faults are due to inter turn insulation failure. The complete analysis of black out in Libya [4] is due to failure of surge arresters and protective equipments. It is reported that other preventive counter measures are to be considered. E Safaan [5] reported that multi break vacuum switch has high dielectric strength restoration during switching operations. For waves with rise time 0.1 µs, the withstand voltages [6] are of the order of 5 p.u. and more. It is therefore a matter of growing concern to motor designer to know the magnitude of over voltage and its steepness likely to appear at the motor terminals. Voltage distribution [7, 8] becomes distinctly non-linear across turns within a coil for surge fronts below 1 µs, whereas non-uniformity across coils begins for surge fronts shorter than about 3 µs. As per Carlo Petrarca et al. [9] voltage stress is not distributed uniformly among the coil and distribution depends upon the rise time of the impinging surge and parameters of the coil. This requires further investigations for computing the influence of fast surges on the motor winding insulation.

The present paper discusses the non-linear voltage distribution in the 6.6 kV industrial motor winding and voltage drop across turns for different rise times. In this paper turn to ground and inter turn voltages of 6.6 kV motor coil are calculated using Electromagnetic Transient Program (EMTP™). The parameters of equivalent electrical network, like series and shunt capacitance, self inductance of each turn and mutual inductances between individual turns are calculated. Using Electromagnetic Transient Program (EMTP™) the voltage distribution along the coil is calculated for fast surge voltage applied at line end. In the experimental measurement, known voltage of desired shape is applied at the terminal and voltage distribution along the turn is measured.

II. SWITCHING SURGES

Switching over voltages are generated during opening and closing operation of circuit breaker. These are mostly due to current chopping or re-ignition. Current chopping is due to premature interruption of current where as re-ignition is due to slower rate of recovery of voltage between the gap compared to rate of voltage build up between them.

A. *Influence of Switching Surges on High Voltage Motors*

During the switching on/off of high voltage motor controlled by circuit breaker, two types of over voltages are encountered:

a) Maximum voltage to earth
b) Maximum peak to peak voltage

The unipolar component (Maximum voltage to earth) of the switching surge stresses the main insulation of the motor with respect to earth. The bipolar surge (Maximum peak to peak voltage) stresses the inter turn insulation of the line end coil most.

The switching over voltages are characterized by high frequency amplitude which, intern depends on the circuit parameters. These steep fronted transient voltages can cause unequal voltage distribution across the motor winding coils with high values of inter turn voltage stresses at the line end coils. The repeated steep fronted surges may damage the insulation of motor.

III. CIRCUIT REPRESENTATION

A general arrangement of turns and coil sides of a stator is shown in Fig. 1.

Fig.1. Snap shot of a 6.6 kV ten turn motor coil

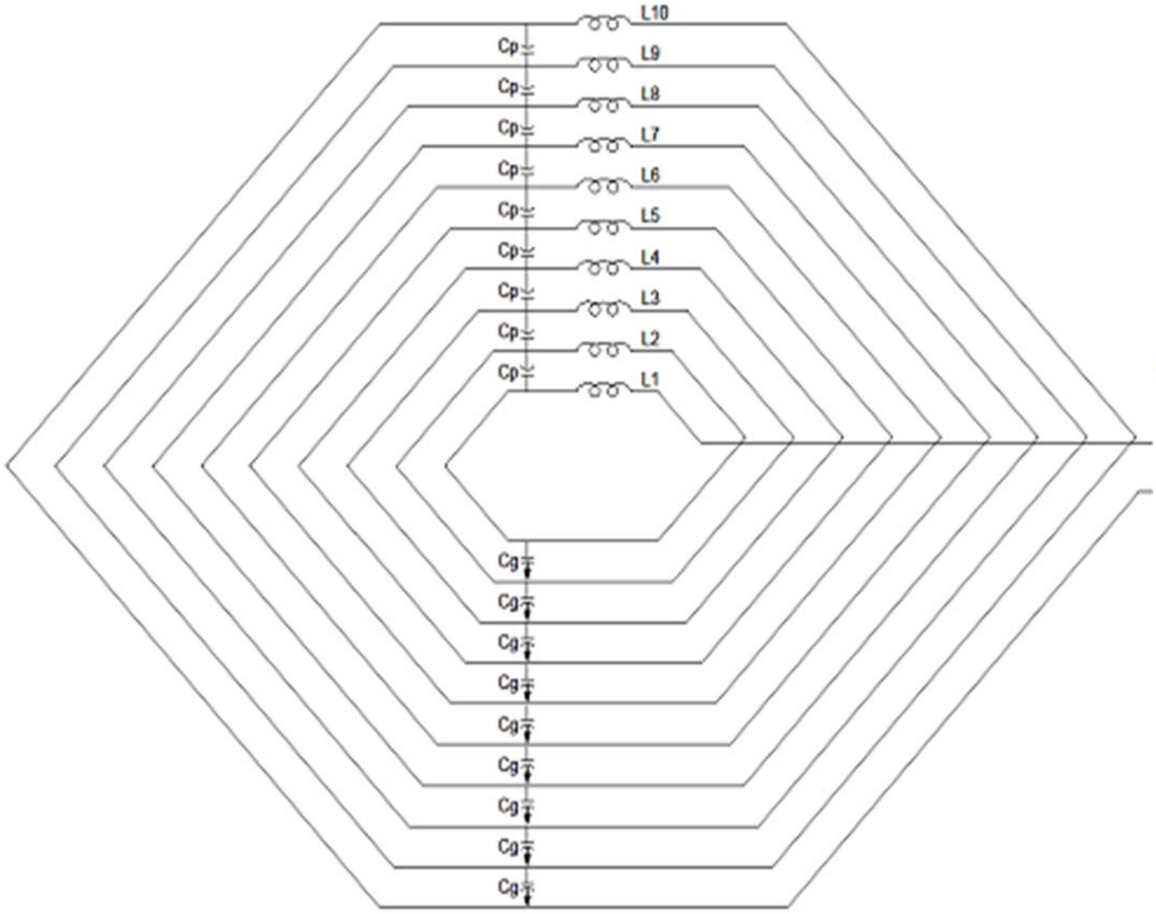

Fig. 2. Schematic diagram of ten turn motor coil

The coil of Fig 1 used for investigation is of diamond shape in which ten turns are wound one above the other by incorporating minor on individual turns and major insulation on combined turns. Since the coil has both the insulation viz. minor between turns and major on combined assembly, hence it will contribute to capacitance between turn to turn and turn to ground.

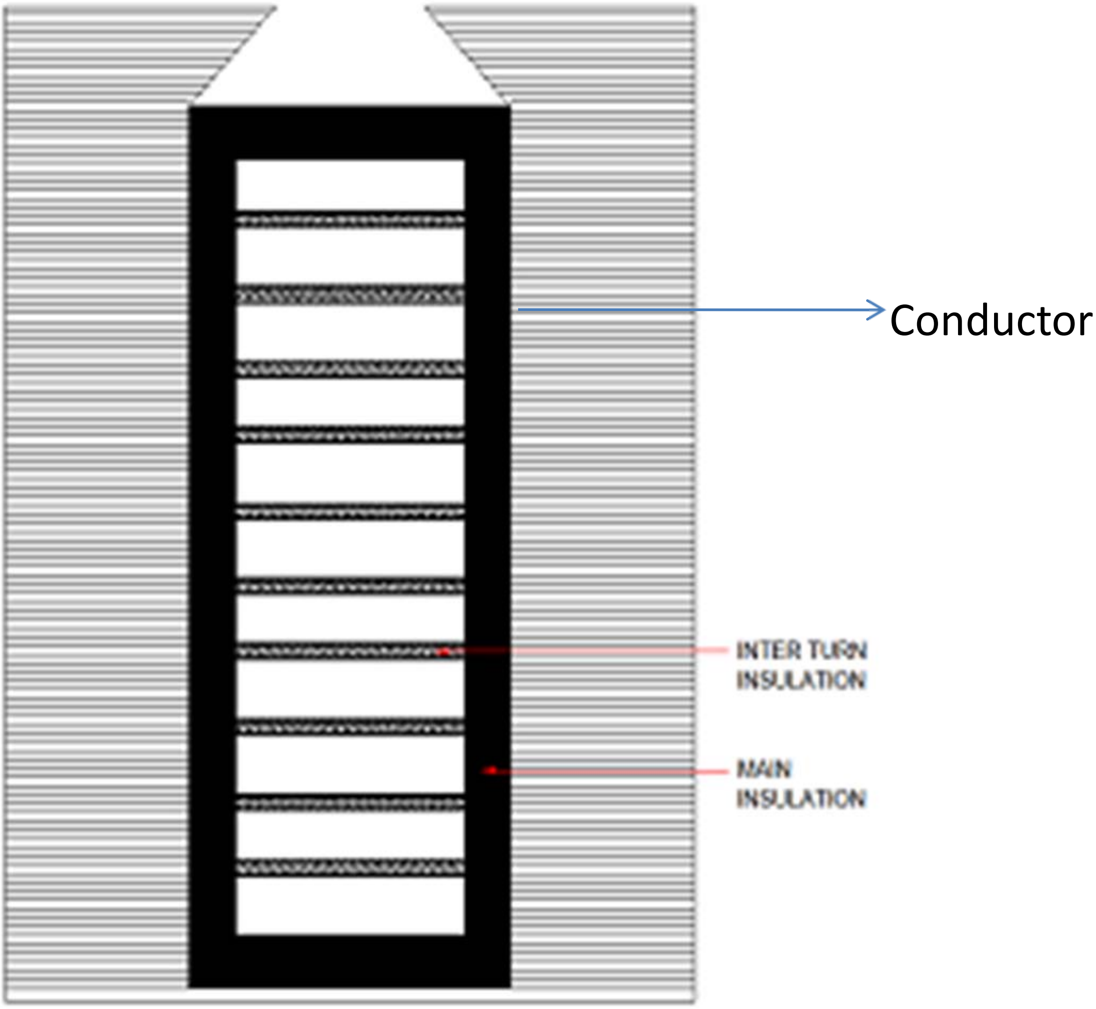

Fig. 3. Schematic diagram of coils mounted in the slot

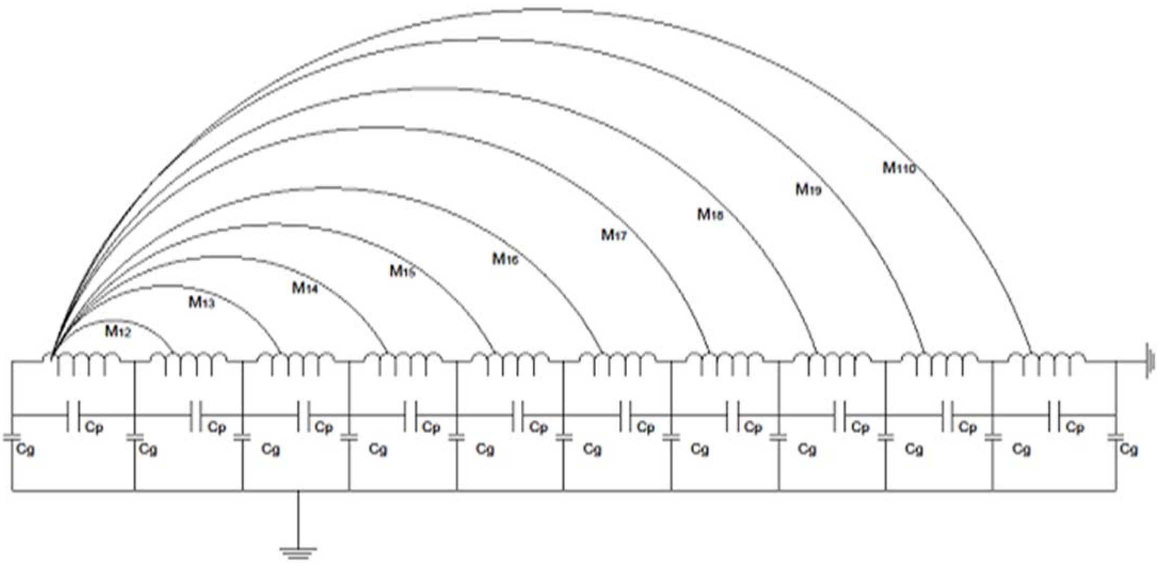

Fig. 4. Equivalent electric circuit of 6.6 kV ten turn motor coil

IV. CALCULATION OF ELECTRICAL PARAMETER

The winding parameters for all the turns in the electrical network are required for an accurate determination of transient voltage distribution in the winding. The shunt and series capacitances are calculated using geometrical and electrical data such as core length, mean length of the turn, thickness of insulation i.e. inter turn and main insulation, conductor size and width etc., based on standard formula for parallel plate electrode.

In all calculations of self and mutual inductances, well established formulae [10] have been used. The DC resistance value of the turn is found to be small and normally neglected in the analysis. But since, conductor offer more resistance at higher frequencies (MHz) due to skin effect, it may be worth considering to see its influence on damping. However, in the present analysis the resistance has not been taken into account.

TABLE I
Geometric specification of 6.6 kV motor coil

Length of mean turn	2640 mm
Main insulation	1.55mm
Minor insulation	0.2 mm
Conductor height	7mm
Conductor width	3 mm
Core length	1940 mm

$$L_s = 2 \times 10^{-7} \times L\left[\left(2log_e\left(L \div \sqrt{S}\right) + \emptyset\right) + \mu/4\right] \quad (1)$$

Where,
Ls=inductance in mH
δ= Radius of cross section of conductor by equating it to circular cross section
δ is calculated on the basis of area of cross section of rectangular conductor
L is length of mean turn (mm)
S is enclosed area of the hexagonal coil
= b*core length +2√p (p-a) (p-a) (p-b)
Where,
b is coil width
p=2a+b/s
a is length of overhang portion in mm.
s is L/6.
μ=1 of non magnetic materials
Similarly, the mutual inductances are calculated using equation (2) as given below.

$$M_{ij} = 1.2 \times 10^{-6} \times s\left[log_e k - 0.15152 + \frac{0.395}{k} + 0.1160/k^2\right] \quad (2)$$

Where,
M_{ij} is Mutual inductance between two conductors (mH)
k is "s/d_{ij}" and d_{ij} is distance between i and j turn.

Electrical parameters calculated using above equations (1) and (2) yield the values, as given in Table 2.

Table 2
Self and mutual inductance matrix

3.2	2.3	2	1.8	1.6	1.5	1.4	1.3	1.2	1.2
2.3	3.2	2.3	2	1.8	1.6	1.5	1.4	1.3	1.2
2	2.3	3.2	2.3	2	1.8	1.6	1.5	1.4	1.3
1.8	2	2.3	3.2	2.3	2	1.8	1.6	1.5	1.4
1.6	1.8	2	2.3	3.2	2.3	2	1.8	1.6	1.5
1.5	1.6	1.8	2	2.3	3.2	2.3	2	1.8	1.6
1.4	1.5	1.6	1.8	2	2.3	3.2	2.3	2	1.8
1.3	1.4	1.5	1.6	1.8	2	2.3	3.2	2.3	2
1.2	1.3	1.4	1.5	1.6	1.8	2	2.3	3.2	2.3
1.2	1.2	1.3	1.4	1.5	1.6	1.8	2	2.3	3.2

In above matrix all values are in mH.

Capacitance between turn to turn and turn to ground is calculated using standard formula as given in equation (3) and (4).

$$C_p = 8.854 \times 10^{-9} \times \epsilon_m \times w_c \times \frac{L}{T} \quad (3)$$

$$C_g = 8.854 \times 10^{-9} \times \epsilon_m \times w_c \times \frac{L}{T_m} \quad (4)$$

Where,

ϵ_m is relative permittivity of minor insulating material
W_c is width of conductor (mm)
T is thickness of minor insulation (mm)
T_m is thickness of major insulation (mm)
H_c is 2 × axial height of conductor (mm)
For ground capacitance only slot region is considered where as for turn to turn capacitance total rectangular length is considered. Calculation produce the value as inter turn capacitance, Cp= 1472.95 pF and node to ground voltage, Cg= 1496 pF.

V. CALCULATION OF TRANSIENT VOLTAGE DISTRIBUTION IN THE WINDING

To calculate transient voltage distribution in stator winding of 6.6 kV motor, an Electromagnetic Transient Program is used. The input Parameter to the EMTP™ data sheet is given in Table 3. Correspondingly, series and ground capacitances are distributed along the line end coil and entered as input to EMTP™. Input voltage for 6.6 kV motor coil is considered in conformity with IEC 34-15, 1995 [11] as given in equation (5).

$$U_p = 4U_n + 5\text{kV} \quad (5)$$

Where,
U_p = Rated lightning impulse withstand voltage
U_n = Rated system voltage
For surge voltage distribution 65 % of impulse voltage is applied. At the line end i.e. at node-1, 1.2/50 µs impulse voltage of 32.4 kV is applied and distribution of voltage along the coil is computed. Similarly fast surge voltage of 24.68 kV and 20.93 kV are calculated for 0.3/3 µs, and 0.1/5 µs. Voltages with above magnitude and rate of rise are applied to the coil.

VI. COMPARISON OF EXPERIMENTAL AND COMPUTED RESULTS

The test setup is arranged at BHEL corporate R&D. The coil on which experiment is done is wrapped with aluminum foil on the straight portion only and grounded to simulate core effect. The remaining portion on either side is retained as it is to replicate the effect of overhang. The setup consists of a Haefley make current surge generator, a digital oscilloscope and high frequency probe with *10 reductions to measure output voltage. The insulation of the turns is removed to have direct access to the copper conductor for voltage measurement.

Fig. 5. Experimental setup with 6.6 kV coil

As shown in Fig 5 the ten turn coil is connected to surge generator through a cable. A part of insulation is removed from the overhang region of coil to empower the probes of the oscilloscope to make contact with the turns. In order to measure the turn to ground voltage coil is grounded through a thin wire. The exposed conductors in the coil prevent the use of high voltage surges in the experiment, thus a low voltage surge generator is used. The computed and measured turn to ground voltages are given in Table 3. Measured voltage in percentage is recorded with digital oscilloscope during experiment. Oscillograms of experiment are plotted in Fig. 6a-d. It has been observed from Fig. 7 that computed voltages and measured voltage differ by a maximum of 21 %. Turn to ground voltages computed by EMTP™ and measured in laboratory have slightly difference. Such difference may have occurred since the theoretical model dos not considered increase in resistance due to skin effect.

Table 3
Measured and computed turn to ground voltages

Turn No.	% Measured voltage	% Computed voltage
1-G	96.1	94.75
2-G	87.1	91.27
3-G	78	88.27
4-G	69.5	85.49
5-G	59.5	81.48
6-G	49.5	65.34
7-G	40	52.27
8-G	30.4	37.25
9-G	20	27.72
10-G	7.8	14.04

Fig. 6a. Measured node 1 to ground voltage

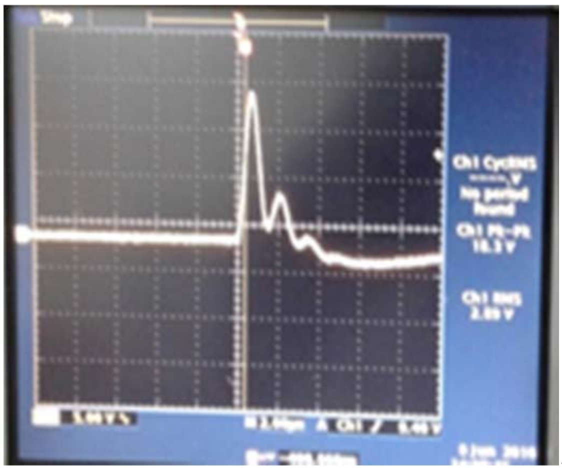

Fig. 6b. Measured node 2 to ground voltage

Fig. 6c. Measured node 7 to ground voltage

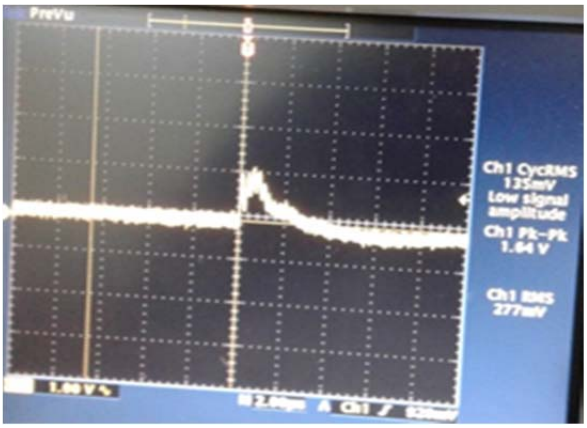

Fig. 6d. Measured node 10 to ground voltage

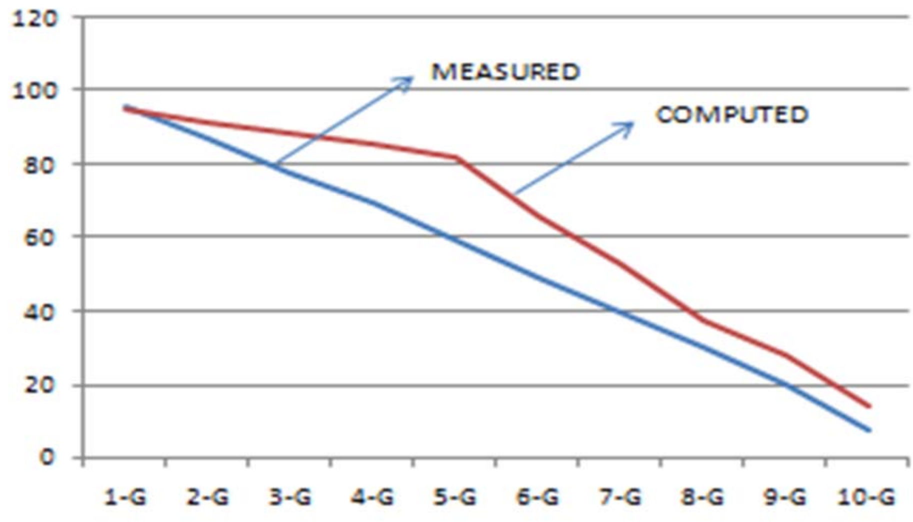

Fig 7. Comparison of measured and computed turn to ground voltages

VII. DISCUSSIONS OF RESULTS

The model circuit of the ten turn motor coil is simulated with EMTP™. The simulation result shown in Fig. 8-9 describes non linear nature of impulse voltage distribution among the coil and turns of motor winding. Since the impulse voltage has high rate of rise, the distribution of voltage between various turns is non-linear. Superimposed minor oscillation on every voltage is because of merging impact of inductance and capacitances. Distribution of peak turn to ground voltages for impulse and fast surges is shown in Table 4 and wave shapes for fast surges are shown in Fig. 10- 11.

TABLE 4
Node to ground voltages for impulse and fast surges (0.3/3 and 0.1/5µs)

Node number	Peak node to ground voltage for impulse (KV)	Peak node to ground voltage for 0.3/3 µsec (KV)	Peak node to ground voltage for 0.1/5 µsec (KV)
2-G	29.57	19.72	15.4
3-G	28.6	20	15
4-G	27.7	20	14.3
5-G	26.4	19.75	13.5
6-G	21.17	18.75	11.9
6-G	17	16.75	10.06
8-G	12.07	14.75	7.9
9-G	8.98	11.1	5.66
10-G	4.55	5.83	2.9

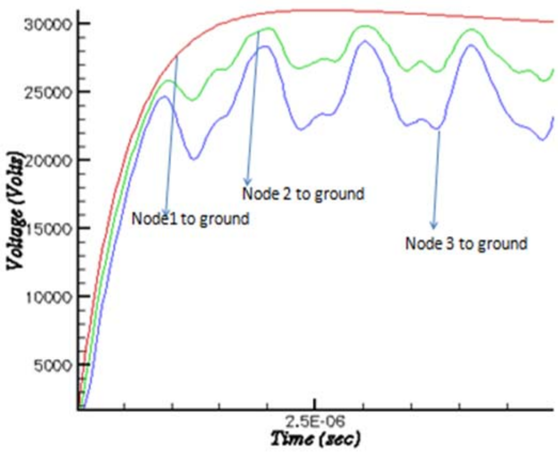

Fig 8. Turn to ground voltage for impulse

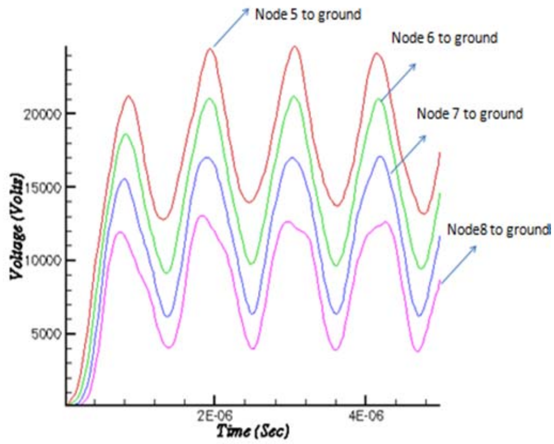

Fig. 9. Turn to ground voltage for impulse

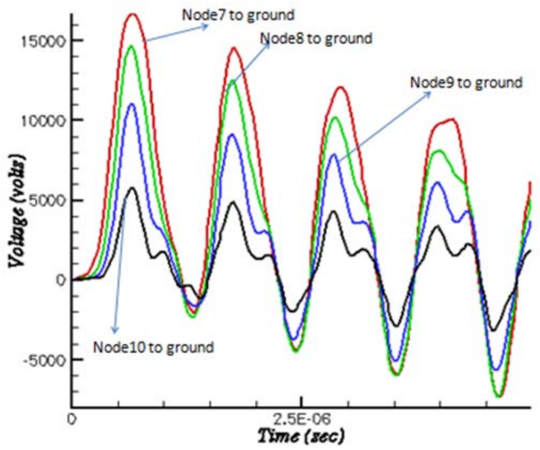

Fig. 10. Turn to ground voltage for fast surge (0.3/3 µs)

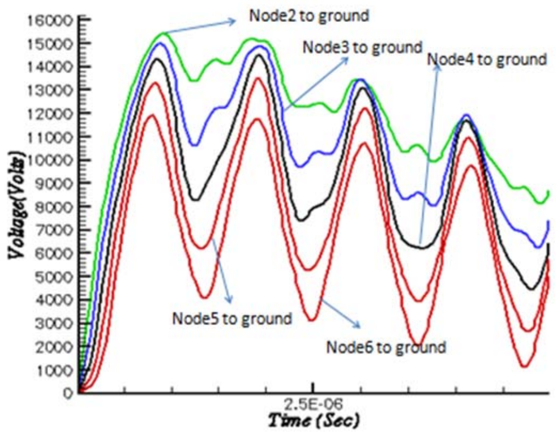

Fig. 11. Turn to ground voltage for fast surge (0.1/5 µs)

It has been perceived from Fig. 10-11 that steepness of voltage increases as the rise time decreases from 0.3/3 to 0.1/5 µs. Over voltages with rise time 0.1/5 µs are unevenly distributed in the motor winding and they stress turn insulation of last turns. Overlying minor oscillation on each voltage at node 2 to earth node is due to combined effect of both inductance and capacitances. In addition to this, the superimposed oscillation is more pronounced than what is obtained in case of impulse voltage. Inter turn voltage distribution for fast surges are given in Table 6 and related wave shapes are shown in Fig.13-16. A closer look at Table 5 depicts electric stress is higher for 0.3/3 µs pulse compared to 0.1/5 µs.

Between turns	Peak Inter turn voltage for 0.3/3 µs (kV)	Stress kV/mm for 0.3/3 µs (kV)	Peak Inter turn voltage 0.1/5 µs (kV)	Stress kV/mm for 0.1/5 µs (kV)
1-2	5.26	26.4	2.8	14
2-3	4.91	24.6	2.7	13.5
3-4	3.92	19.6	2.63	13.14
4-5	4	20	2.68	13.4
5-6	3.66	18.4	2.3	11.5
6-7	3.52	17.6	2.27	11.34
7-8	4.20	21	2.57	12.84
8-9	4.27	21.4	2.75	13.74
9-10	5.30	26.6	2.76	13.8
10-11	5.84	29.2	2.91	14.54

TABLE 5
Inter turn voltage distribution for fast surge voltage (0.3/3 µs and 0.1/5µsec)

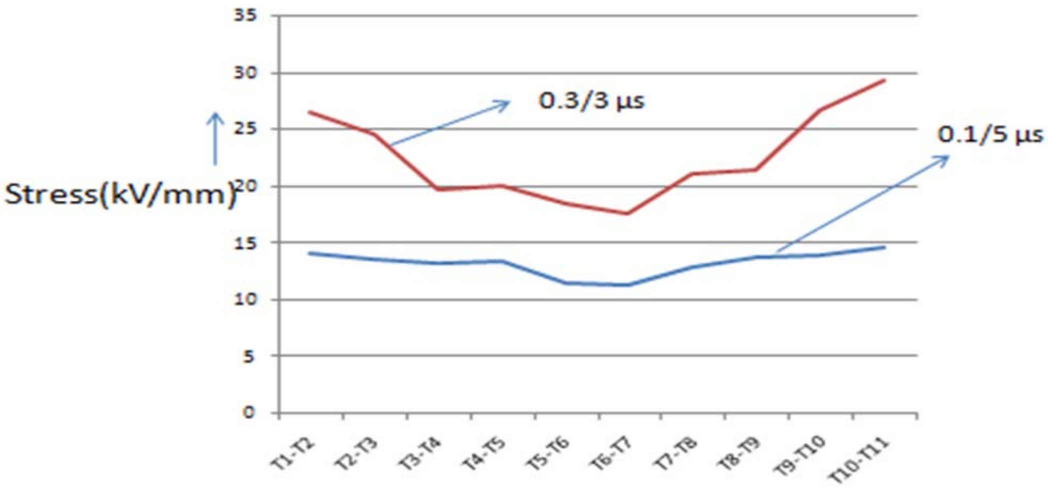

Fig 12. Voltage stress on 6.6 kV motor coil for different rise time

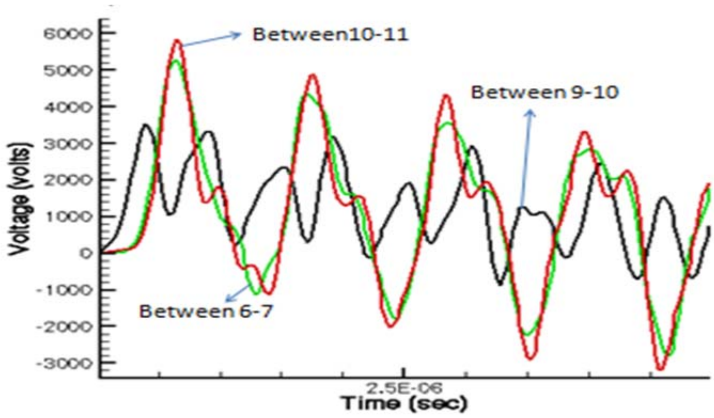

Fig. 13. Inter turn voltage distribution (0.3/3 µs)

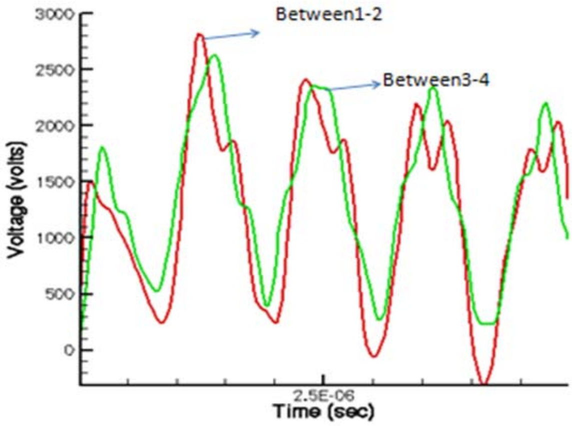

Fig. 14. Inter turn voltage distribution (0.1/5 µs)

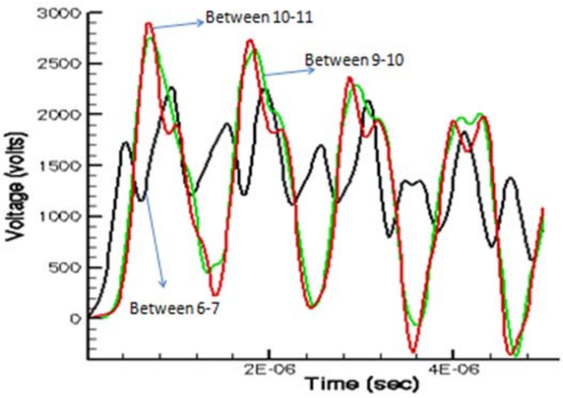

Fig. 15. Inter turn voltage distribution (0.1/5 µs)

Table 6 suggested that peak inter turn voltage drop for impulse, marginally differs between adjacent turns as well as both the ends.

Table 6. Inter turn voltage distribution and stress for impulse voltage

Between turns	Peak Inter turn voltage	Stress kV/mm
1-2	4.43	11.08
2-3	4.41	11.03
3-4	4.7	11.75
4-5	4.67	11.68
5-6	4.3	10.75
6-7	4.28	10.70
7-8	4.7	11.75
8-9	4.63	11.58
9-10	4.54	11.35
10-11	4.55	11.38

VIII. CONCLUSION

In this paper experimental and theoretical determination of transient voltage distribution in stator winding is presented. The turn to ground and inter -turn voltages are plotted for different rise times. It has been observed that voltage distribution becomes highly non-linear for impulse and fast surge 0.3/3 µs and 0.1/5 µs. Electric stress is higher for 0.3/3 µs pulse compared to 0.1/5 µs pulse. Results suggested that last inter turn insulation experience high stress. It has been also presumed that turn to ground voltages processed by EMTP™ and measured in lab have marginally contrast. Such distinction may have happened since the hypothetical model does not considered resistance.

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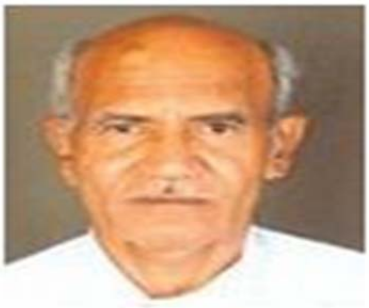

B.P.Singh graduated from the MIT Muzaffarpur, Bihar. He completed his M.E. (High Voltage) at IISc, Bangalore and Ph.D. at the University of Liverpool (UK).He worked for 30 years in BHEL R&D Centre as general manager. He has more than 150 research publications and has guided 8 Ph.D. Scholars and he is presently working as Director (R&D) SMEC.

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