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Inter turn and turn to ground voltages due to fast surges in a 6.6 kV industrial motor coil

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Failure of many large industrial motors is caused by voltage surges experienced by turn insulation in the windings. The turn insulations are subjected to high voltage due to fast surges appearing across the line end of the coil. The voltage distribution in motor winding for transient wave of fast surges is non-linear. In order to examine the voltage distribution, the L and C parameters of 6.6 kV industrial motor are calculated and an equivalent circuit is formulated. Electromagnetic Transient Program (EMTP™) is applied to calculate voltage distribution in the winding. Surges of different shapes, 0.1/5 µs, 0.2/2 µs and 0.3/3 µs are applied across the first coil with peak voltage specified in accordance with international standard. The results are compared with the voltage distribution due to standard lightning over voltage.

Keywords: Switching surges, high power industrial motors, *EMTP™*, fast surge, Motor coil.

1.0 INTRODUCTION

Heavy industries need large power motors for operation. The switching operations of the motors are carried out by medium voltage breakers of 11 kV and 6.6 kV. In many cases either a vacuum breaker or SF_6 breaker is used to perform the switching duties. These type of breakers are well known to cause multiple reignitions leading to fast surge generation. Such surge propagates through connected cable and enters into motor windings. Thus windings are subjected to non-linear stresses. Although windings are tested for various surge of specified magnitude [1], they still continue to fail in such abnormal operating conditions. Saeed Ul Haq *et al.* [2] reported that a group of coils failed due to weaker turn insulation. It was reported that the coils selected to apply voltage endurance test failed at 20 kV due to thin insulation. Motors, which are frequently, switched using minimum oil circuit breakers should be protected from over voltages with surge arrester [3]. Authors also suggested that surge arrester characteristics should be such that they limit the surges to a level of approximately 18 kV. Timothy et al. [4] discussed the calculation of self and mutual inductances and turn to turn as well as turn to ground capacitances to determine the surge impedance of each section for surge propagation studies. Gupta *et al*. [5] discussed that surge with long rise time may not cause damage to the motor turn insulation unless their magnitudes are extremely high. Report suggests that there is a good agreement between theoretical and experimental results. Carlo Petrarca *et al*. [6] have. stated that voltage stress is not distributed uniformly among the coil and that distribution depends upon the rise time of the impinging surge and parameters of the coil. It is observed [7] that stator winding faults account for a large percentage of the failure of machine. About 37 % of faults are due to turn to turn insulation failure. Dick and Gupta [8] carried out experiments with aged and unaged coils by subjecting them to

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number of surges with magnitude 3.0 to 7.8 pU. The result showed that there is no evidence of insulation degradation by these surges. However, insulation failure is dependent only on threshold value of surge which is close to breakdown voltage. Hence it is important to reduce the surge magnitude by connecting suitable surge arrester.

The present paper discusses the non-linear distribution of voltage in the 6.6 kV industrial motor winding and voltage drop across turns. The equivalent electrical parameters like series and shunt capacitance, self inductance of each turn and mutual inductances between individual turns were calculated. The equivalent electrical network is formulated by using all inductive and capacitive parameters. Using Electromagnetic Transient Program (EMTP™) the voltage distribution along the coil is calculated for fast surge voltage applied at line end.

2.0 COIL DESCRIPTION AND MODELING METHOD

The coil as shown in figure 1, used for investigation is of diamond shape. It has six turns wound one above the other by incorporating minor insulation on individual turns and major insulation on total turns.

FIG 1. SNAP OF 6.6 KV MOTOR COIL

Schematic diagram of the coil representing six turns of coil is shown in figure 3 and its placement in a slot is shown in figure 2. It is to be noted that two coil sides of different phases are housed in the same slot.

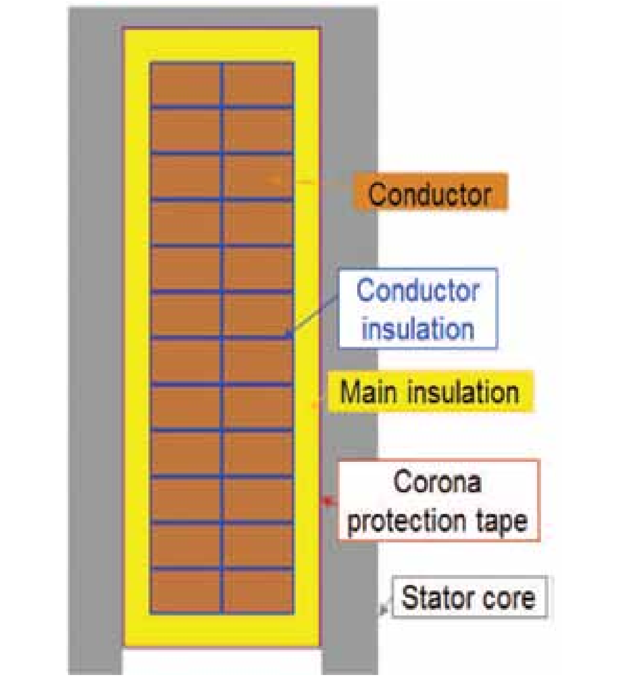

FIG 2. SCHEMATIC DIAGRAM OF COILS MOUNTED IN THE SLOT

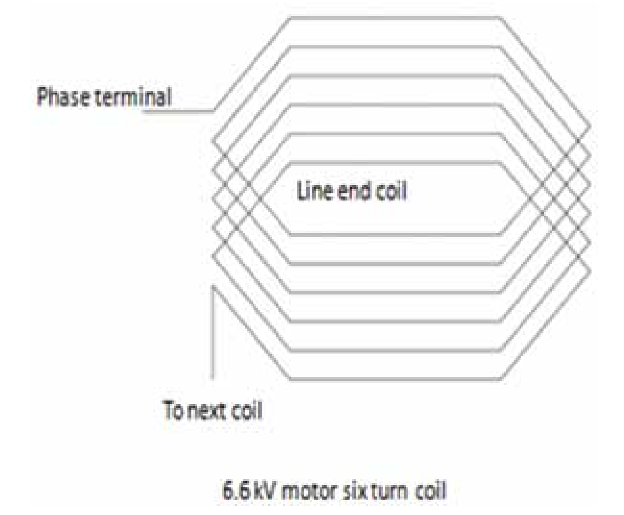

FIG 3. SCHEMATIC DIAGRAM OF A TYPICAL MOTOR COIL

Since the coil has insulation between each turn and major insulation on the combined six turns, hence it will contribute to capacitance between two turns and turn and ground. The six turns are modeled as inductances of individual turns and five mutual inductances with other remaining turns. The mutual inductance between turns and self inductance of individual turn are calculated by using available formulae [9]. The capacitance between any two turns and capacitance to ground are calculated using standard formula.

3.0 NETWORK FORMATION AND PARAMETER CALCULATION

The Electrical network is formulated using L and C parameters. The geometric specification of the coil is given in Table 1. To calculate self and mutual inductances equations (1) and (2) are used. Since the coil consists of six turns, the actual length of the conductor including overhang portion is considered for self inductance calculation using equation (1).

TABLE 1

GEOMETRIC SPECIFICATION OF 6.6 KV COIL

Length of mean turn	2600 mm
Main insulation	1.35 mm
Minor insulation	0.2 mm
Conductor height	1.5mm
Conductor width	3 mm
Core length	360 mm

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

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.

S= b×core length +2√p (p-a)² (p-b)

Where,

b is coil width

p=2a+b/s

where "a" is the length of overhang portion in mm.

s = L/6.

μ=1 of non magnetic materials

Φ can be expressed as a function of the ratio L/√S from the following tabulated data.

TABLE 2

Φ EXPRESSED AS A FUNCTION OF THE RATIO L/√S

L/√s	Φ
4.559	0.1629
4.000	0.0809
3.812	0.0354
3.722	0.0077
3.641	-0.0237
3.545	-0.0794

The mutual inductances are calculated using equation (2) as given below.

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

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 3.

TABLE 3

SELF AND MUTUAL INDUCTANCE OF COIL (MH)

$$\begin{pmatrix} 4.28 & 2.28 & 1.93 & 1.72 & 1.57 & 1.45 \\ 2.28 & 4.28 & 2.28 & 1.93 & 1.72 & 1.57 \\ 1.93 & 2.28 & 4.28 & 2.28 & 1.93 & 1.72 \\ 1.72 & 1.93 & 2.28 & 4.28 & 2.28 & 1.93 \\ 1.63 & 1.80 & 2.05 & 2.48 & 4.28 & 2.28 \\ 1.45 & 1.57 & 1.72 & 1.93 & 2.28 & 4.28 \end{pmatrix}$$

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

$$C_s = 8.854 \times 10^{-12} \times \epsilon_m \times w_c \times L/T \quad ...(3)$$

$$C_g = 8.854 \times 10^{-12} \times \epsilon_m \times L_{cr} \times H_c/T_m \quad ...... (4)$$

Where,

C_s = capacitance between turns(pF)

C_g = capacitance between turn and ground(pF)

ϵ_m is the Relative permittivity of minor insulating material

W_c is the width of conductor (mm)

T is the thickness of minor insulation (mm)

Tm is the thickness of major insulation (mm)

H_c= 2 × axial height of conductor (mm)

L_{cr}=2 × core length (mm)

For ground capacitance only slot region is considered where as for turn to turn capacitance total rectangular length is considered. The calculation yields

Turn to turn capacitance C_s=1450 pF.

Turn to ground capacitance C_g=26.73 pF.

Using the inductive and capacitive parameters the equivalent circuit is derived as shown in figure 4.

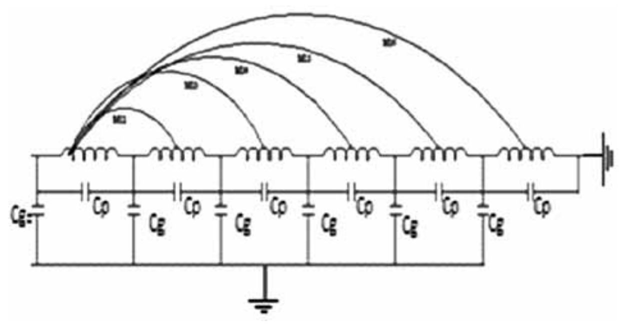

FIG 4. EQUIVALENT ELECTRIC CIRCUIT FOR 6 TURN COIL

4.0 APPLICATION OF EMTP TO CALCULATE VOLTAGE DISTRIBUTION

Input parameter to the EMTP™ data sheet for inductances is taken from Table 3. Similarly series and ground capacitances are distributed along the coil and entered as input to EMTP™. Surge voltage to the line end of motor is applied in accordance with IEC 34-15, 1995 [1].

At the line end a voltage of 22.5 kV with 0.2/2 μs surge is applied and voltage distribution along the coil is calculated. Surge magnitude of 24.5 kV and 20.7 kV are used for surge of 0.3/3 μs and 0.1/5 μs respectively. For impulse lightning voltage of 31 kV is applied. The different voltage magnitudes are calculated using equation (5)

$$V_{out} = V_o\left[e^{-\propto t} - e^{\beta t}\right] \qquad ...(5)$$

Where: α and β control rise and fall time for a given pulse.

5.0 RESULT AND DISCUSSIONS

The simulation results shown in figure 5 and 6 depict non linear nature of voltage distribution among the coil and turns of motor winding. Distribution of peak nodes to ground voltages for fast surges is shown in Table 4.

TABLE 4			
NODE TO GROUND VOLTAGES FOR FAST SURGES (0.2/2, 0.3/3) AND (0.1/5MS)			
Node number	**Peak node to ground voltage(kV) (0.2/2 μs)**	**Peak node to ground voltage(kV) (0.3/3 μs)**	**Peak node to ground voltage(kV) (0.1/5 μs)**
1	18.3	19.9	20
2	15.7	16.6	17.2
3	12.8	13.3	14.2
4	9.67	10	10.6
5	6.36	6.63	6.99
6	3.09	3.26	3.39

It is observed from Table 4 that rise and fall time of applied voltage determines the turn to ground voltage at each node. Superimposed minor oscillation as seen in figure 5 is found to be small. However it has been calculated that for still faster surge having 0.1 μs rise time the superimposed oscillations are more pronounced.

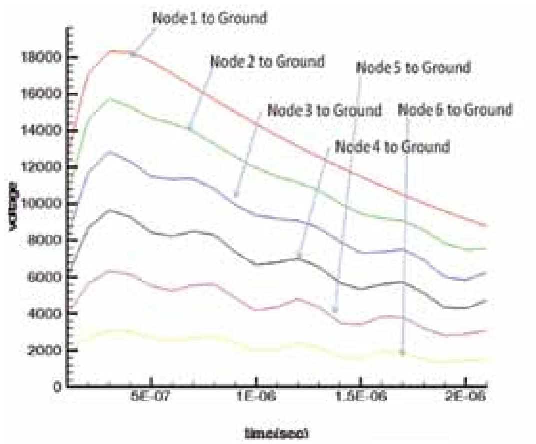

FIG 5. VOLTAGE DISTRIBUTION IN COIL WITH REFERENCE TO GROUND (0.2/2 MS)

Inter turn voltages for fast surges with a rise time of 0.2/2 µs and 0.1/5 µs are given in Table 5. The inter turn voltage distribution in the coil is shown in figure 6.

TABLE 5				
INTER TURN VOLTAGE DISTRIBUTION DUE TO FAST SURGES				
Between turns	**Peak Inter turn voltage for 0.2/2 µs (kV)**	**Stress kV/mm**	**Peak Inter turn voltage 0.1/5 µs (kV)**	**Stress kV/mm**
1-2	3.11	15.55	3.51	17.55
2-3	3.21	16.05	3.62	18.1
3-4	3.19	15.95	3.57	17.85
4-5	3.32	16.6	3.7	18.5
5-6	3.28	16.4	3.59	17.95
6-7	3.09	15.45	3.35	16.75

Table 5 suggested that inter turn voltage up to coil 4 increases in order of turn number and beyond that it decreases up to last turn. This phenomenon is in conformity with Oraee and McLaren [10].

Node to ground and inter turn voltage distribution for impulse is given in Table 6 and related wave shapes are shown in figure 7 and figure 8. The electric voltage stress is calculated on the basis of formula given in equation (6)

$$\text{Stress (kV/mm)} = \frac{\text{Peak inter turn voltage}}{\text{Inter turn insulation thickness}} \quad ..(6)$$

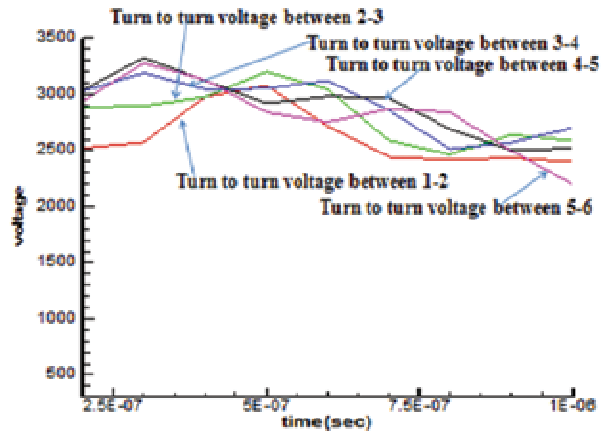

FIG 6. INTER TURN VOLTAGES DUE TO FAST SURGE (0.2/2 MS)

For example : stress at turn1 and turn 2 is calculated as

$$\frac{\text{Stress kV}}{\text{mm}} = \frac{3.51(\text{peak intter turn voltage})}{0.2(\text{inter turn insulation thickness})} = 17.55$$

From Table 6 it is observed that stress is more at turn 4 and less in all other turns.

TABLE 6				
VOLTAGE DISTRIBUTION AND STRESS FOR IMPULSE VOLTAGE				
Node number	**Peak node to Ground Voltage (kV)**	**Between turns**	**Peakinter turn voltages**	**Stress (kV/ mm)**
1-G	30.9	1-2	4.8	24
2-G	26.1	2-3	5.1	25.5
3-G	21.	3-4	5.4	27
4-G	15.6	4-5	5.3	26.5
5-G	10.3	5-6	5.28	26.4
6-G	5.02	6-7	5.02	25.1

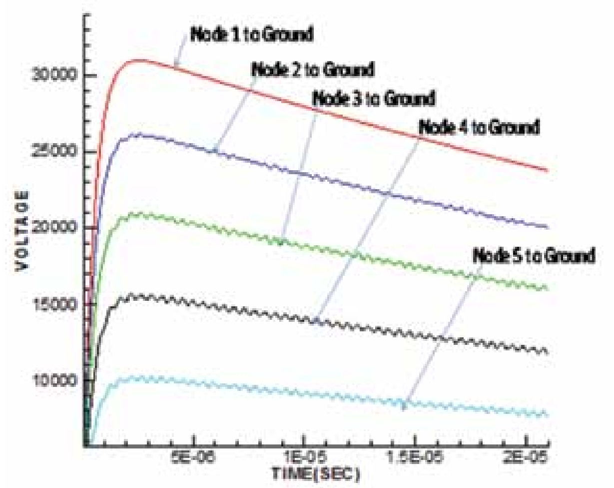

FIG 7. NODE TO GROUND VOLTAGE DISTRIBUTION IN COIL DUE TO IMPULSE VOLTAGE

Since the impulse voltage has high rate of rise the distribution of voltage between various turns is non-linear as shown in Figure 8. Superimposed minor oscillation on each voltage is due to combined effect of both inductance and capacitances.

Table 7 shows a consolidated list of inter turn voltages for impulse as well as fast surges. The magnitudes of applied voltages as per the standard [1] for different rise time pulses are not the same.

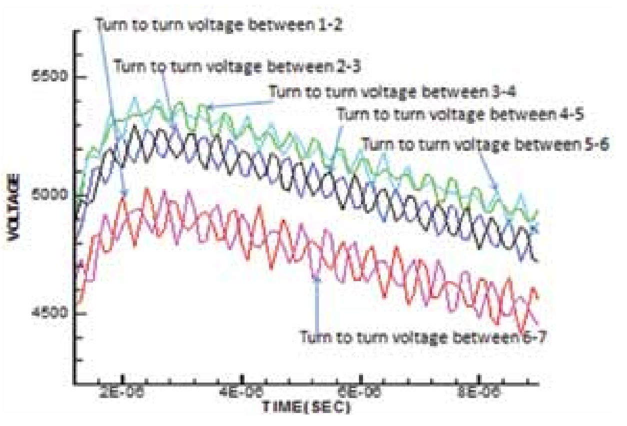

FIG 8. INTER TURN VOLTAGES DUE TO IMPULSE VOLTAGE

Figure 9 shows the voltage stress among the turns at different rise times with reference to turn number. The result show that stress is more at middle turns for impulse voltage and whereas it is more at turn 4-5 of the line end coil for the fast surge 0.1/5 µs. As the rate of rise decreases the voltage stress decreases (Table 5). This phenomenon is not applicable for impulse voltage, probably due to higher tail time. The results are presented for various wave shapes. For a given shape of pulse the inter turn voltage increases till 4^{th} -5^{th} turn (Table 7) and decreases beyond it. For the comparison of turn to turn or turn to ground voltages, 6.6 kV coils of different geometric parameters may need to be analyzed.

TABLE 7

INTER TURN VOLTAGES FOR IMPULSE AND FAST SURGES.

Between turns	Peak Inter turn voltage 1.2/50 µs (kV)	Peak Inter turn voltage 0.1//5 µs (kV)	Peak Inter turn voltage 0.2/2 µs (kV)	Peak Inter turn voltage 0.3/3 µs (kV)
1-2	4.8	2.8	2.6	3.3
2-3	5.1	3	2.9	3.3
3-4	5.4	3.6	3.13	3.3
4-5	5.3	3.61	3.31	3.37
5-6	5.28	3	3.27	3.37
6-7	5.02	3.39	3.09	3.26

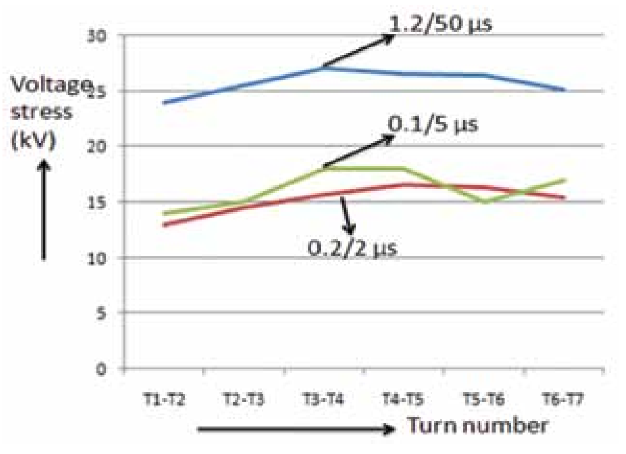

FIG 9. VOLTAGE STRESS DUE TO DIFFERENT RISE TIMES

6.0 CONCLUSIONS

The results are concluded as follows:

1. Surge voltage impinging on motor terminal propagates internally and causes non-linear distribution in turns.
2. The front time and tail time of surges have a bearing on the voltage to ground at each node representing turns.
3. The surge of rise time 0.1 µs induces higher oscilations in the winding compared to 0.2 µs or 0.3 µs rise time.
4. The result associated with impulse and other fast surges suggest that inter-turn voltage due to impulse is higher compared to that of other surges for all turns. However, for 0.1 µs rise time the last turn have relatively higher voltage drop compared to other surges. Hence it can be inferred that stress due to 0.1/5 µs and 1.2/50 µs is more onerous for the coil.

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