CALCULATION OF ELECTRICAL PARAMETERS FOR LARGE A.C. MACHINE WINDINGS WITH REFERENCE TO STEEP-FRONTED SURGE TRANSIENTS

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1. INTRODUCTION

This paper represents the method of calculation of electrical parameters of large A.C. machine windings for an analytical model being developed for prediciting voltage stresses in interturn insulation of motor winding coils due to incident of steep-fronted surges.

Parameters of the model are derived from physical considerations of coil geometry. The parameters are subsequently transformed into a form suitable for input to ElectroMagnetic Transient Program (EMTP), in order to determine the time domain response to an applied surge.

2. STRUCTURE OF WINDING MODEL

Windings of large A.C. motors consists of several multiturn coils connected in series electrically. Each coil is positioned around the stator core iron frame, such that it is embedded in iron over two distinict regions (termed slot regions), and is suspended in air over two another regions on either side of the stator frame (termed end-winding or overhang regions).

The proposed winding model treats turn conductor within each such coil section as mutually coupled transmission lines.
Electromagnetic coupling between coil sections is neglected since presence of stator iron between sections provided effective shielding at high frequencies. As a result each coil section may be modelled independently. The model for complete coil is obtained by stablishing boundary conditions on individual section models such that a series electrical connection is achieved. The model for the complete winding is formed similarly, by connecting individual coils in series. With this framework established, the modelling task reduces to one of developing suitable analytical representation for overhang, and the slot section of winding coils.

3. MULTICONDUCTOR REPRESENTATION OF COIL WINDINGS

The basis of the model being developed is the representation of winding coil sections as mutually coupled multiconductor transmission lines. The governing equations for voltage and current on a uniform n-conductor transmission line may be written in matrix form as :

$$\frac{d^2V}{dx^2} = ZYV \qquad (1.a)$$

$$\frac{d^2I}{dx^2} = YZI \qquad (1.b)$$

where V and I are phasors representing voltages and currents respectively at a given point x on the line. V and I are the vector matrices of n elements representing, respectively, the voltage and current on the n conductors and the current flowing in them. Z and Y are nxn matrices which are representing series impedance matrix and shunt admittance matrix respectively.

Each of these equations represents n simultaneous differential equation.

Since ZY are nondiagonal square matrices of order nxn, a direct solution of these equations is not self evident. The problem may be solved by making use of linear transformation defined by :

$$V = SVm \qquad (2)$$

Where S is a nonsingular matrix of order nxn and V the transformed vector matrix of voltage, and substituting in equation 1.a gives

$$\frac{d^2V_m}{dx^2} = S^{-1}(ZY)SVm \qquad (3)$$

and letting

$$\gamma^2 = S^{-1}(ZY)S \qquad (4)$$

then

$$\frac{d^2V_m}{dx^2} = \gamma^2 V_m \qquad (5)$$

Wedepohl(1) shows that if the matrix S is chosen such that γ^2 diagonal matrix of the form

$$\gamma^2 = \begin{bmatrix} \gamma_1^2 & 0 & \dots & 0 \\ 0 & \gamma_2^2 & \dots & 0 \\ \vdots & & & \\ 0 & 0 & \dots & \gamma_n^2 \end{bmatrix} \qquad (6)$$

Then equation 3 separates into n single second order differential equations with no mutual effect between them. Each value of γ_i defines the propagation characteristics of the hypothetical single conductor lines and is, in fact, the propagation constant for each of the so-called natural modes of multiconductor system.

In effect a transformation may be made from the real domain to modal domain, a solution obtained for each modal component and then a reverse transformation made from modal domain to real domain.

It is further shown that γ_i^2 are the eigenvalues of the matrix ZY and the columns of the matrix S are the eigenvectors.

The values of γ_i are the propagation constants of the individual modes, and are complex quantities of the form $(\alpha - j\beta)$, where α is the attenuation and the velocity of propagation v is given by

$$v = \omega / \beta \qquad (7)$$

where ω is the angular frequency

4. DETERMINATION OF MODEL PARAMETERS

In the slot region it is assumed that the slot walls act as flux barriers at the frequencies of interest and are at the ground potential. The resisitivity of the core iron and copper conductors is low and the propagation modes are assumed to be TEM. Under such conditions it is only necessary to calculate the capacitance matrix and the inductance matrix can be calculated using the property that :

$$L = C_*^{-1} / c^2 \qquad (8)$$

where L is the inductance matrix, C_* is the capacitance matrix with all $\varepsilon_r = 1$, and c is the propagation velocity of light

In the overhang region the ground return path is assumed to be in the immediately adjacent coil sides in the same layer.

Fig. 1 shows the coil sides. Since wavelength is comparable with the coil side adjacent coil must be closed to allow currents to flow as in an infinite plane. The C matrix and hence L matrix are calculated as explained in equation 8.

The losses can be added to the L and C matrices but previous work has shown that such effects are not significant in short time span within which the peak interturn voltages appear [2, 3].

For the calculation of the admittance matrix Y, the capacitance is evaluated by approximating the winding to parallel plate capacitors as shown in Fig. 2 and 3 for slot region and overhang region respectively. Knowing the dielectric constant value of each insulating layer, capacitaces are calculated from the equation

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (9)$$

where A is the area normal to the electric field and d is the thickness of insulation. The conductivity of each insulating region is given by :

$$\sigma = w \varepsilon_0 \varepsilon_r \tan\delta \qquad (10)$$

where δ is the loss angle. Having determined the conductivity of each insulating region at agiven frequency, conductances are calculated from

$$G = \sigma \frac{A}{d} \qquad (11)$$

The values of conductances are extremely low which may be ignored.

5. SUMMARY OF THE DIGITAL COMPUTER PROGRAM

(i) The input data are read in. This includes the physical geometry of the winding of each section, length, conductor cross section dimensions, isulation thicknesses, and dielectric relative permittivities.
(ii) The matrix C is formed from the geometry of the coil
(iii) The matrix L is formed from the equation 8.
(iv) Calculate the value of λ and the eigenvector matrix S of LC.
(v) Form the diagonal matrix $\gamma^2 = \lambda$
(vi) Form the characteristic impedance $Z = S^{-1}\gamma SL$.
(vii) Print Z in ohms.
(viii) Print S the real-to-modal and S^{-1} modal-to-real transformation matrices and the modal velocities in per unit of velocity of light.

6. APPLICATION OF THE PROGRAM TO A PRACTICAL CALCULATION

In order to demonstrate a practical application of the program, calculations were done for 3.3.-KV, 1-MW, 4-pole induction motor. The coil configuration is shown in Fig. 4.a The following constants were assumed in the calculations for insulating materials used in the coil.

(a) Ground insulation (slot region): 8 turns of GM23 sheet wrapped hot processed, dielectric constant=4.2,
(b) Ground insulation (overhang region): flexible TGMT tape, dielectric constant = 2,

(c) Interturn insulation: 3 layers of aromatic polymide paper (nomex), dielctric constant = 2.6.

6.1 CALCULATED RESULTS

Table (1) shows the surge impedence matrix (upper triangle), real-to-modal transformation matrix, and modal velocities for overhang, bottom of slot and top of slot regions respectively. Because of the airgap in the overhang region the first mode has a propagation velocity of 0.9 per unit. In general, the modal propagation velocities depend entirely on the insulation dielectric constants, and the higher the dielectric constants, the lower the propagation velocities.

6.2 VERIFICATION OF RESULTS

The data obtained in section 6.1 were used to calculate the interturn voltages between turns 2-1, and 10-9 for a line end coil fed from a matched and the coil was on open circuit. It can be seen that there is close agreement between the calculated waveforms and the corresponding measured waveforms as shown in Fig.4.

7. CONCLUSIONS

A method has been described for solving the wave equations in machine windings. The modal parameters may be used to calculate the interturn voltage distribution in machine windings.

A practical example has shown close agreement between calculated voltage waveforms and the corresponding measured waveforms.

8. ACKNOWLEDGEMENTS

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Table 1: Coil parameters.

$Z^{s}_{o.h}$ = (ohms)

81	73	66	61	56	52	50	47	46	45
74	67	62	57	53	51	49	47	46	
71	66	59	55	52	50	48	47		
67	62	57	54	52	51	50			
69	61	57	55	53	52				
69	62	58	57	56					
67	64	62	61						
71	67	64							
76	73								
81									

S =

0.316	0.442	-0.425	-0.399	-0.362	-0.316	-0.263	0.203	0.138	-0.070
0.316	0.399	-0.263	-0.070	0.138	0.316	0.425	-0.442	-0.362	0.203
0.316	0.316	0.000	0.316	0.447	0.316	0.000	0.316	0.447	-0.316
0.316	0.203	0.263	0.442	0.138	-0.316	-0.425	0.070	-0.362	0.399
0.316	0.070	0.425	0.203	-0.362	-0.316	0.263	-0.399	0.138	-0.442
0.316	-0.070	0.425	-0.203	-0.362	0.316	0.263	0.399	0.138	0.442
0.316	-0.203	0.263	-0.442	0.138	0.316	-0.425	-0.070	-0.362	-0.399
0.316	-0.316	0.000	-0.316	0.447	-0.316	0.000	-0.316	0.447	0.316
0.316	-0.399	-0.263	0.070	0.138	-0.316	0.425	0.442	-0.362	-0.203
0.316	-0.442	-0.425	0.399	-0.362	0.316	-0.263	-0.203	0.138	0.070

V_{modal} = [0.906 0.655 0.630 0.625 0.623 0.622 0.622 0.621 0.621 0.621] (p.u.

Z_{bottom} = (ohms)

22	15	11	8	5	4	3	2	1	1
17	12	9	6	4	3	2	2	1	
15	11	7	5	4	3	2	2		
14	10	7	5	4	3	2			
13	12	7	5	4	3				
13	10	7	6	5					
14	13	8	7						
14	11	9							
16	13								
19									

S =

0.316	0.433	-0.436	-0.408	-0.377	0.326	-0.271	-0.213	0.141	0.071
0.316	0.412	-0.282	-0.092	0.119	-0.306	0.425	0.450	-0.372	-0.210
0.316	0.335	-0.026	0.297	0.453	-0.343	0.031	-0.352	0.433	0.326
0.316	0.227	0.238	0.435	0.109	0.286	-0.443	-0.105	-0.332	-0.409
0.316	0.099	0.416	0.281	-0.323	0.363	0.219	0.422	0.110	0.449
0.316	-0.038	0.449	-0.136	-0.430	-0.261	0.319	-0.376	0.075	-0.444
0.316	-0.171	0.323	-0.427	0.046	-0.379	-0.400	0.007	-0.391	0.395
0.316	-0.269	0.083	-0.387	0.441	0.238	-0.093	0.348	0.450	-0.301
0.316	-0.381	-0.187	-0.047	0.253	0.394	0.452	-0.427	-0.329	0.178
0.316	-0.439	-0.391	0.330	-0.269	-0.213	-0.163	0.118	0.077	-0.038

V_{modal} = [0.688 0.658 0.636 0.629 0.626 0.624 0.623 0.623 0.622 0.622] (p.u.

Z_{top} = (ohms)

19	11	9	7	5	3	2	1	1	1
16	11	8	5	4	3	2	1	1	
14	12	7	5	3	2	2	1		
13	9	7	5	3	2	2			
13	9	8	4	3	2				
13	9	8	5	3					
13	9	7	5						
13	9	7							
13	12								
16									

S =

0.316	0.481	-0.428	-0.356	-0.289	0.229	-0.174	-0.126	0.081	0.040
0.316	0.433	-0.244	-0.005	0.220	-0.383	0.459	0.443	-0.347	-0.189
0.316	0.335	0.005	0.349	0.466	-0.298	-0.041	-0.351	0.462	0.316
0.316	0.234	0.232	0.470	0.155	0.328	-0.440	-0.066	-0.377	-0.410
0.316	0.133	0.427	0.273	-0.342	0.358	0.266	0.422	0.130	0.457
0.316	0.002	0.480	-0.104	-0.430	-0.263	0.324	-0.387	0.174	-0.436
0.316	-0.121	0.394	-0.413	-0.003	-0.406	-0.398	-0.006	-0.402	0.399
0.316	-0.249	0.195	-0.446	0.427	0.189	-0.158	0.393	0.437	-0.300
0.316	-0.345	-0.059	-0.129	0.346	0.441	0.463	-0.417	-0.314	0.166
0.316	-0.425	-0.297	0.207	-0.149	-0.109	-0.079	0.055	0.033	-0.017

V_{modal} = [0.683 0.662 0.637 0.630 0.626 0.624 0.623 0.623 0.622 0.622] (p.u.

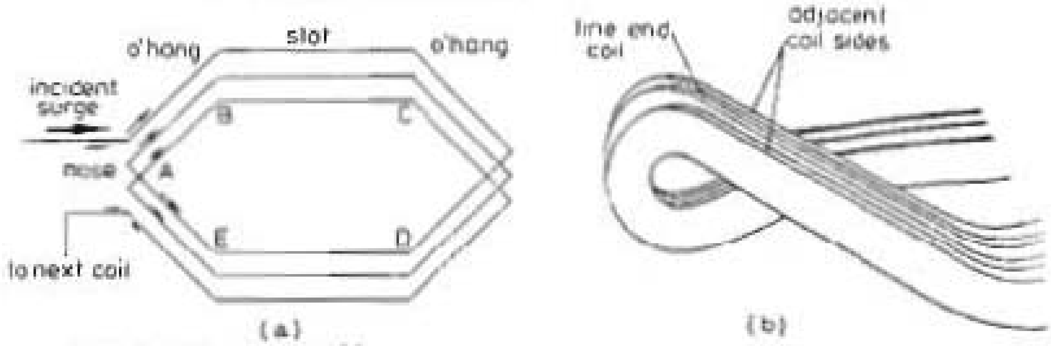


Fig.1 Line end coil
(a) Initial surge distribution at nose of coil.
(b) Overhang enviroment of line end coil.

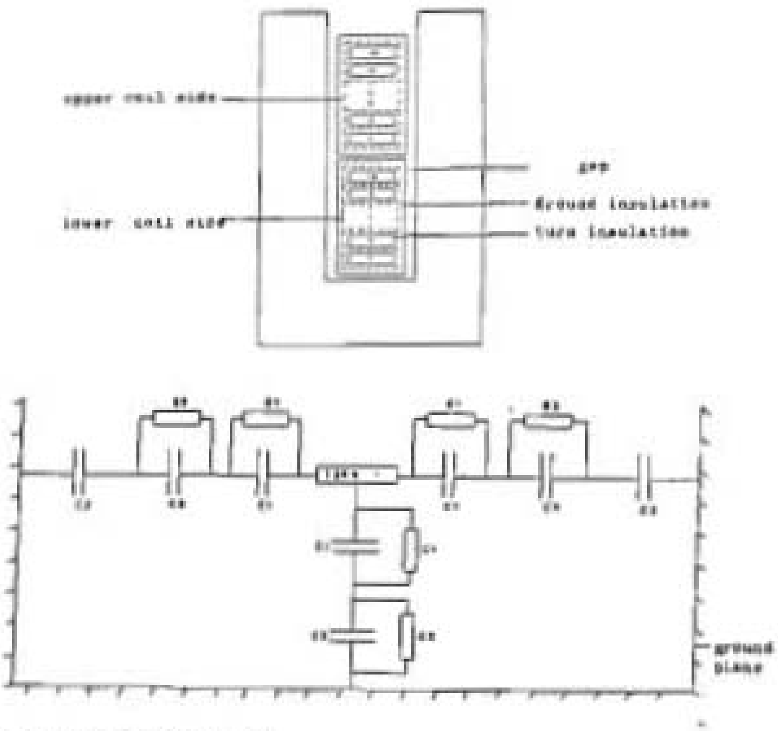


Fig.2 Slot arrangement

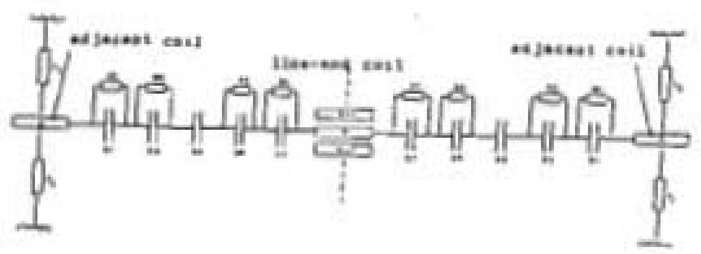
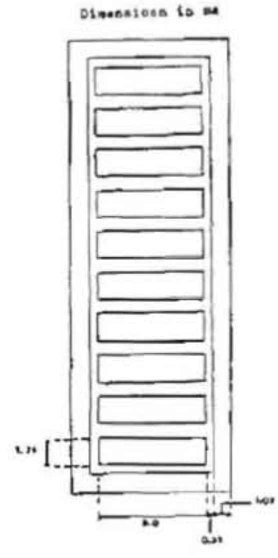
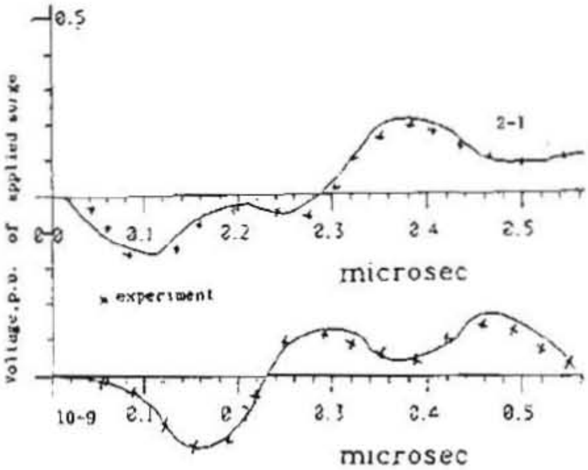


Fig.3 Overhang arrangement



(a)



(b)

Fig.4 Transient interturn voltage.
(a) Slot dimension
(b) Voltage waveforms