Study of Transient Impulse Voltage Distribution and Evaluation of Tap-lead Insulation of A Power Distribution Transformer

By

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirementes
for the degree of

Master of Science

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STUDY OF TRANSIENT IMPULSE VOLTAGE DISTRIBUTION AND EVALUATION OF TAP-LEAD INSULATION OF A POWER DISTRIBUTION TRANSFORMER

BY

WEI CUI

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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To My Parents

献给我的父母

ABSTRACT

This work is concerned with the evaluation of present and new designs of tap-lead insulation of a distribution transformer with barrel-type coils. To accomplish this, simulations, based on lumped parameter equivalent circuits, and test measurements were carried out to investigate transient impulse voltage distribution in a distribution transformer coils, and coils with new tap-lead insulation designs. In order to establish the equivalent circuit models, an accurate and flexible technique was proposed to calculate lumped inductive parameters. The models were validated by a good agreement between the simulation results and test measurements through investigating the capacitive effects of core and tank, the effect of various equivalent circuits and the effect of tap connections under impulse voltage application. By using the simulation results of transient over-voltage distribution as boundary conditions, electric field stresses on insulation near the input end and tap-leads were evaluated through quasi-static field analysis based on Finite Element Method. With conservative factors already built in, the field analysis results show that the present tap-lead insulation design of three layers of paper is conservative and it can be reduced to two layers of paper or even one layer of paper without any problem in electrical point of view.

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The author wants to dedicate this thesis to his parents for their love and encourgement.

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1. INTRODUCTION

Accumulation of knowledge from research work and practical experience has resulted in transformer designs which are increasingly optimal in functionality and economy. With increasing transmission voltage levels, in the past many years, researchers concentrated their attention on the optimal design of large capacity power transformers. Nowdays, because of stiff competition in the marketplace, manufacturers are interested in the optimal design of distribution transformers. Even though the improvement may only be very limited, the gains to be made in the long term is appreciable. Among present designs of various types of distribution transformers, improvements are possible in the high-low barrier and tap-lead insulation. The objective of this project is to evaluate the design of tap-lead insulation of a distribution transformer and suggest optimal designs. Fig. 1.1 shows the arrangement of tap leads and associated insulation of a coil which belongs to a 10 kVA, 14,400/240 distribution transformer.

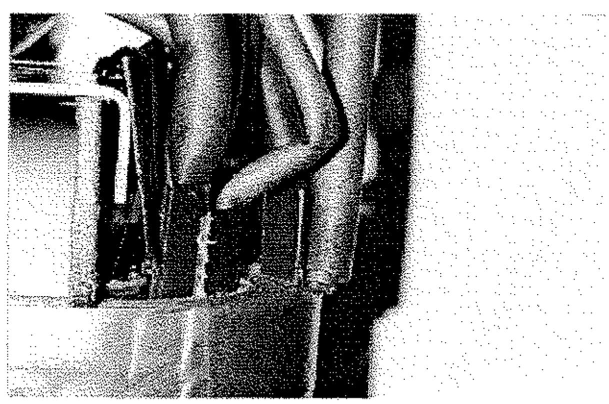


Fig. 1.1 Tap leads and insulation of a coil of a 10 kVA, 14,400 / 240 distribution transformer

Generally speaking, under normal operation in the steady state, the voltage is linearly distributed along the winding; therefore, insulating the tap leads presents no difficulty. However, during operation, the transformer may suffer many types of abnormal voltages. The resulting non-linear distribution of these voltages along the transformer winding can cause high stress at certain portions of the winding. Some extra insulation is normally used to reinforce the insulation structure. This is the reason why extra insulation is present around the input end and tap leads. Therefore, accurate simulation of transient abnormal voltage distribution along a transformer winding is crucial for the evaluation of it's insulation structure at these locations.

In the early 1950s, Abetti [1] suggested a scaled transformer model in conjunction with a capacitance network to model the transient distribution of impulse voltage in transformer winding. Though the simulation results are sufficiently accurate for design purposes, the method suffers the disadvantage that it requires the construction of a special model for each transformer design.

Almost at the same time, Lewis [2] proposed that the transient behavior of a transformer winding can be studied with an equivalent ladder-type network composed of a finite number of uniform sections. Each section is composed of lumped capacitive and inductive components which represent the distributed parameters of actual winding. The transient behavior of the equivalent network when subjected to an impulse surge can be readily evaluated by numerical computation. Lewis's model is applicable only to a uniform winding. Furthermore, the representation of inductive coupling effect was included by modifying the self inductance value.

McWhirter et al [3], studied the same problem based on an equivalent circuit approach. They derived from the circuits a set of equations which were solved by using an analog computer. Their model still suffers the restrictions arising from the size and symmetry of the equivalent circuit used to represent the winding.

Dent [4] used an equivalent circuit of the same general form as that proposed by Lewis, but with certain differences. Dent's model can represent a non-uniform winding and the effect of inductive coupling between sections are taken into account. The differential equations of the equivalent circuit were solved numerically by a digital computer. Besides, any form of applied waveshape may be used. Because almost all the simulation work can be done on a digital computer, it is very convenient to change parameters of the equivalent circuits to simulate different winding designs, different test connections and change parameters to simulate various types of input voltages. Because of it's speed and economy, this method is widely used in transformer design work.

After Dent's paper was published, most of the researchers in this area, concentrated their attention on the calculation of parameters of the equivalent circuits.

Okuyama [6] calculated the self and mutual inductances of transformer winding through introduction of some correction factors obtained from experiment.

Stein [5] and Kawaguchi [7] proposed a method to calculate equivalent series capacitance by computing the electrostatic energy stored in the coils.

Fergestad [9],[10] calculated self and mutual inductance of sections of windings by taking certain effects of iron-core into account.

Wilcox [14],[15] derived a set of formulae from Maxwell's equations to calculate self and mutual inductive parameters. He also did some work to incorporate in his formulae the effect of induced eddy currents in the iron-core.

Leon and Semlyen [17] used the image method to calculate turn to turn leakage inductance and the charge simulation method to calculate the capacitance between turns and from turn to ground.

All of the above methods to calculate self and mutual inductance can only be applied to coils with circular shape, which is the general case for power transformer. But, for distribution transformers, the shape of coils is not circular and can not be represented by a simple geometric shape. Therefore, the above methods and formulae can not be applied directly.

Kazibwe [25] used some simple geometric shapes composed of straight line segments to represent the coils of a barrel-type distribution transformer. The self and mutual inductance values were calculated by a proper summation of the inductance values calculated for the single line segments and line segment pairs using the formulae given by Grover [19]. Because the number of segments used by Kazibwe to model the shape of barrel-type coil is only 4 ~ 6, the calculation results are not accurate enough to show the effect of small changes of coil shapes caused by modification of insulation design.

Based on Kazibwe's idea, a more accurate and flexible technique for the calculation of self and mutual inductive parameters of equivalent circuits of barrel-type coils has been developed in the present work. Each turn of the winding is represented by 24, 40 or even more straight line segments. Therefore, the calculation results are more accurate and can approximately show the small difference caused by various tap-lead insulation designs.

The present research work covers the following aspects:

- Establishment of equivalent circuits to model transformer winding transient response

  Several equivalent circuit models were established to simulate transient impulse voltage distribution in the sample transformer winding. The models are composed of non-uniform sections; the layers of the winding near tap leads are divided into more sections than other layers of the same coil. Therefore, the impulse voltage distribution near the tap leads can be simulated in more detail.

- Calculation of capacitive, inductive and resistive parameters of equivalent circuits

  Series capacitance of one section was obtained through calculation of the total electrostatic energy stored in that section. Parallel capacitances between two sections and section to ground were calculated by utilizing simplified models. The self inductance of each section and the mutual inductance between two sections were calculated by the new technique mentioned above. Resistance of each section was calculated by taking skin effect into account.

- Transient Voltage Distribution Simulation and RSG measurement

  Transient response of equivalent circuits to full lightning wave and chopped lightning wave application were solved by using a transient analysis program written by the author which utilizes the trapezoidal integration technique. In order to validate the simulation methods, the transient impulse voltage distribution in the transformer winding was measured by using Recurrent Surge Generator technique.

- Evaluation of present insulation design through field analyses

  Transient impulse voltage distribution in the sample transformer winding with present tap lead insulation design was simulated under actual working conditions. The simulation results were used as boundary conditions to carry out field analysis of insulation near the input end and tap leads of the transformer coils by employing the Finite Element Method.

- Evaluation of modified tap lead insulation designs through field analyses

  The design of tap lead insulation considered in this work includes three layers of paper, A modified design reduces the insulation by one layer of paper; another design uses only one layer of paper. All the parameters of the equivalent circuits were recalculated because of the changes caused by the tap lead insulation modification. Following the steps described above, field analyses were carried out by using the transient simulation results as boundary conditions and the new designs are evaluated. Based on the field analysis results, suggestions were made for alternative designs of tap lead insulation.

2. METHODOLOGY

2.1 Equivalent circuit of transformer winding

During an impulse voltage test, an impulse of known waveshape is applied at one end of a transformer winding, the other end of the winding being grounded or isolated, while all the associated windings are effectively grounded and fully or partially short-circuited. If the grounding and short-circuiting of all windings except that under test are completely effective, the condition would be equivalent to the application of an impulse voltage to an isolated winding. An equivalent circuit may be used to simulate the behavior of a single distributed winding subjected to an applied voltage impulse. A distributed winding is generally modeled by a ladder-type network, each section of the network only represents a part of winding which can be regarded as having individual self-inductance, mutual indutance with all other sections, capacitance to adjacent sections, series capacitance, and resistance. A general ladder-type network is shown in Fig. 2.1.

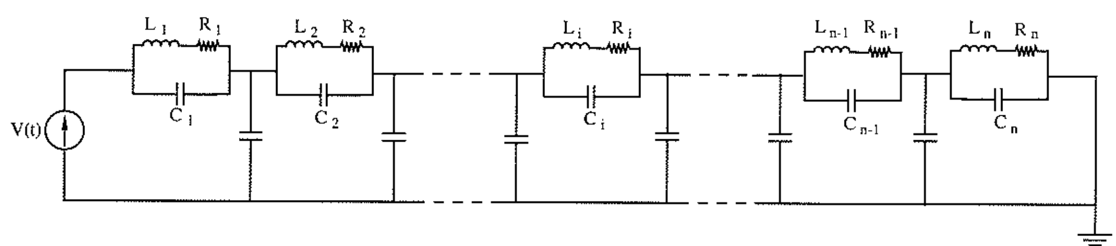


Fig. 2.1 A general ladder-type equivalent network of a transformer winding

This equivalent circuit can be used to model non-uniform windings. A section of the equivalent circuit, therefore, may represent a layer, layers or part of a layer of winding. The manner in which the equivalent circuit is constructed can be varied according to specific need, so that significant portions of the winding (e.g. near the input end or tap leads) can be examined in detail while less significant portions are grouped together.

In this study, the primary concern is tap-lead insulation. Therefore, the layers of winding which are adjacent to tap leads are divided into several sections, while the other layers are represented by one section per layer. Three equivalent circuits with different sectionalizations of layers of winding near tap leads are shown in Fig. 2.2. Each section of the equivalent circuits contains a self inductor, a series capacitor and a resistor. Besides, each inductor is coupled with all other inductors and parallel capacitors exist between section to section and section to ground. With the fine sectionalization of the transformer winding near the tap leads, the effect of nonlinear distribution of impulse voltage on tap lead insulation can be analysed in more detail.

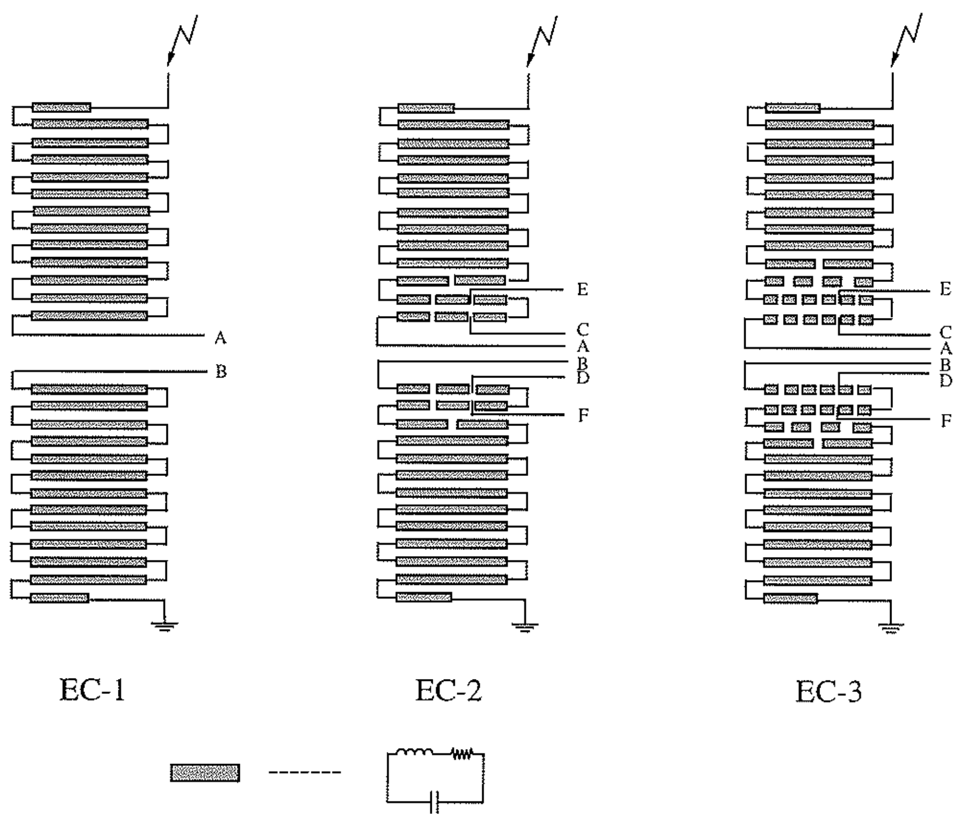
2.2 Calculation of parameters

2.2.1 Inductance

As mentioned in the last chapter, considerable work has been done on the calculation of inductance of coils. The methods used, however, can only be applied to a circular coil configuration, which is the general case for a power transformer. For distribution transformers, the coils usually have non-circular shape, as shown in Fig. 2.3. It is evident that this non-circular shape can not be represented by simple geometrical shapes such as a circle or a rectangle. Therefore, another approach has to be found to calculate the inductive parameters of coils with non-circular shape. The method used in the present work comprises of the following steps.

- Accurately measure the geometrical dimensions of the coils, or for new designs, calculate the geometrical dimensions according to winding design specifications;
- Simulate the coil shape through a curve fitting technique. Represent the con-

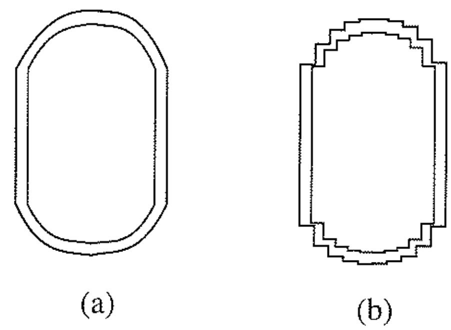
tinuous fitting curve with straight lines which intersect at right angles, as shown in Fig. 2.3;



EC-1 ------- Equivalent circuit No. 1;
EC-2 ------- Equivalent circuit No. 2;
EC-3 ------- Equivalent circuit No. 3.

Fig. 2.2 Three equivalent circuits of a two coil transformer winding

- Calculate the self inductance of one section and the mutual inductance between two sections by first calculating the self inductance of all line segments and the mutual inductance between all possible line segment pairs, then properly sum the calculated values. The formula for self inductance of a straight conductor with round cross section is given by [19]:



(a) ------ Shape of barrel-type transformer winding;
(b) ------ Line segmental representation.

Fig. 2.3 Non-circular shape of barrel-type transformer winding and it's line segmental representation

$$L = 0.002l[\ln\frac{2l}{\rho} - \frac{3}{4}] \tag{1}$$

L ---- Inductance value in microhenry;

l ---- Length of winding in cm;

ρ ---- Radius of wire in cm.

The formula for mutual inductance of two straight line segments placed as shown in Fig. 2.4 is given by [19];

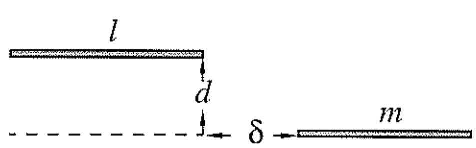


Fig. 2.4 Two straight line segments position

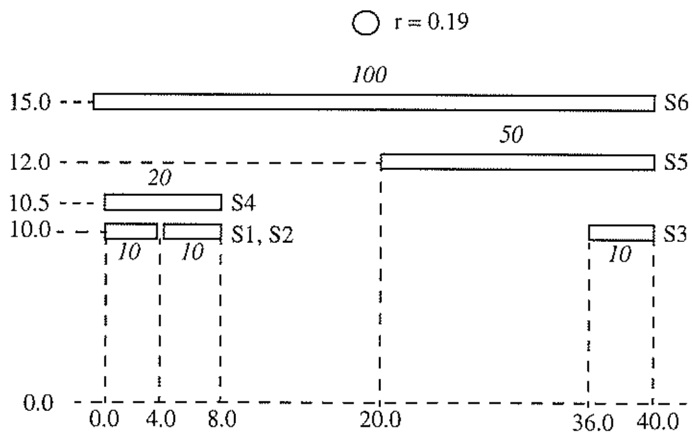
$$L = 0.001[\alpha \sinh^{-1}\frac{\alpha}{d} - \beta \sinh^{-1}\frac{\beta}{d} - \gamma \sinh^{-1}\frac{\gamma}{d} + \delta \sinh^{-1}\frac{\delta}{d}$$

$$- \sqrt{\alpha^2 + d^2} + \sqrt{\beta^2 + d^2} + \sqrt{\gamma^2 + d^2} - \sqrt{\delta^2 + d^2} \quad (2)$$

where:

$\alpha = l + m + \delta;$
$\beta = l + \delta;$
$\gamma = m + \delta;$
If two filaments overlap, δ is to be used with negative sign.

In order to validate this new technique, two ways were used to calculate the self inductances and mutual inductances of several simple solenoids. These solenoids are circular concentric coils, with dimensions shown in Fig. 2.5. In the first approach, the formulae for self and mutual inductance of circular solenoids given in [19] were used. In the second approach, the circular coils were modeled by many straight line segments and the self and mutual inductance values were obtained by proper summation of the self inductance of each segment and the mutual inductance between each segment pair. The circular coils were represented by 24, 40, 80 and 160 segments as shown in Fig. 2.6. The results are listed in Tables 2.1 and 2.2. By comparison of the results yielded by the two ways, it is seen that the new approach yields quite accurate results. One disadvantage of the new approach is the limitation on the number of segments used to represent the circular coils. When the number of segments used is too large, the calculations are very time consuming. The other disadvantage is that the effect of the iron core is not taken into account. However, under transient conditions, the effect of iron core is not significant and the coils can be treated as if they are wound on an air core.



01234 ---- geometrical dimension (cm);
01234 ---- number of turns in a section;
S1 ~ S6 ---- solenoid No.1 to No. 6

Fig. 2.5 Circular concentric solenoids used to validate the calculation method of self and mutual inductance

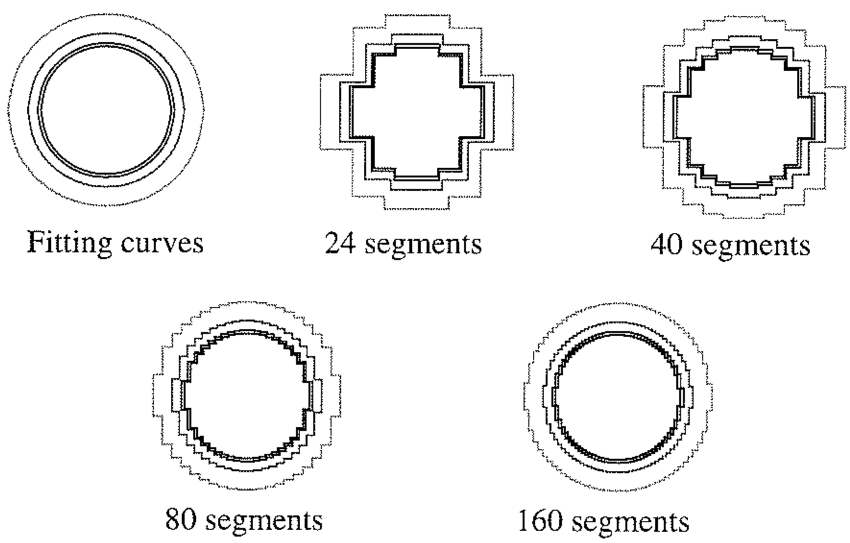


Fig. 2.6 Segmental representations of the circular coils

2.2.2 Capacitance

2.2.2.1 Series Capacitance

The lumped series capacitance in the equivalent circuit is used to represent the series capacitive effect of the corresponding section of the transformer winding. Consequently, under uniform voltage distribution conditions, the electrostatic energy stored in the section of winding should be equal to the energy stored in the lumped series capacitance. By calculating the total electrostatic energy stored in that section, we can obtain the corresponding series capacitance value. This method has been frequently used in previous research. The development of the formula, given below, can be found in [25].

$$C_s = \frac{C_u (n-1) L}{n^2} \tag{3}$$

$$C_u = \frac{\varepsilon_0 \varepsilon_r W}{d} \tag{4}$$

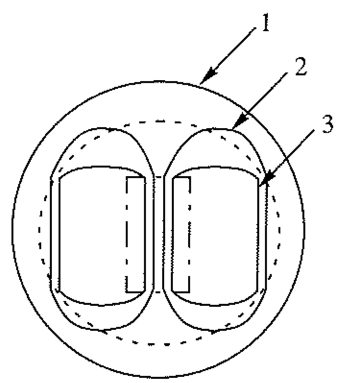
ε_0 ------- Dielectric constant of free space;
ε_r ------- Relative dielectric constant of formel coating on the conductor;
W ------- Conductor thickness;
d ------- Thickness of formel coating between two consecutive turns;
n ------- The number of turns of the section;
L ------- Perimeter of a turn.

2.2.2.2 Parallel Capacitance

Because the segmental representation of coils, as shown in Fig. 2.3, is exactly the same for each turn on the same layer, the surface of a layer of winding can be approximated by several planes intersecting with each other at right angles. The capacitance between two layers of winding is obtained from summing the capacitance calculated for each pair of adjacent parallel planes. When the number of straight line segments used is large enough, the obtained capacitance value should be close to the exact value. Because the capacitance calculations are not time consuming, the continuous curve can be represented by a very large number of straight lines, i.e several hundred segments.

2.2.2.3 Capacitive effect of core and tank

In order to calculate the capacitance between the outer layer of transformer windings and the tank, the two coils were modeled by a cylinder which is concentric with the circular tank as shown in Fig. 2.7. The capacitance formula for coaxial cylinders configuration was used in the calculation. The perimeter of the central cylinder is approximately equal to the peripheral length of the two coils in their assembled position. A copper foil is used to simulate the capacitive effect of core. The capacitance of the core to the end turn of each layer of winding was calculated by utilizing a parallel plane model.



1 ---- Tank;
2 ---- Outer layer of H.V. winding;
3 ---- Outer layer of L.V. winding;
---- Coaxial cylinder used to calculate the capacitance between outer layer of winding and tank;
---- Copper foil sheet used to simulate the capacitive effect of core.

Fig. 2.7 Simulation of capacitive effect of core and tank

2.2.3 Resistance

Because the applied voltage impulse contain many high order harmonics, skin effect should be taken into account when the resistance of each section is calculated. For a rough estimation, 750 kHz was chosen as the frequency used to calculated the skin depth of the conductor wires. The resistance was then calculated according to the skin depth and the length of wire.

2.3 Transient Voltage Distribution Simulation [21]

The time responses of equivalent circuits to applied impulse voltage were solved by an electromagnetic transient analysis program based on the trapezoidal integration rule. The development of the node-voltage equations used in the program is described in the following sections.

2.3.1 Inductor Model

The voltage-current relationship for an inductor of value L is

$$i(t) = \frac{1}{L}\int_{t'=0}^{t} v(t')\,dt' + i(0) \tag{5}$$

where $i(0)$ is the current at time $t = 0$ in the inductor. In computing the inductor voltage values, a series of values will be calculated at equally spaced time intervals $t_0, t_1, \ldots\ldots, t_{k-1}, t_k, \ldots\ldots$, the current in the inductor at the end of the k th interval is

$$i_k = \frac{1}{L}\int_{t_{k-1}}^{t_k} v(t)dt + i_{k-1} \tag{6}$$

The integration is replaced by trapezoid approximation.

$$i_k = i_{k-1} + \frac{1}{2}\frac{\Delta t}{L}(v_{k-1} + v_k) \tag{7}$$

$$= \frac{\Delta t}{2L}v_k + \left(\frac{\Delta t}{2L}v_{k-1} + i_{k-1}\right) \tag{8}$$

This last expression is of the form

$$i = gv + I \tag{9}$$

and thus represents a parallel combination of a current source and conductance as shown in Fig. 2.8.

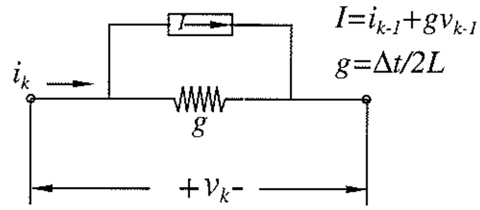


Fig. 2.8 Inductor model

The symbol g represents the conductance which is determined by L and the time interval Δt. I is determined by the value of i and v at the previous time instant.

2.3.2 Capacitor Model

The voltage current relationship for a capacitor of value C is

$$i(t) = C\frac{d}{dt}v(t) \tag{10}$$

The slope of voltage versus time curve can be approximated only from a knowledge of some past values of v. The simplest such approximation is:

$$\left.\frac{dv}{dt}\right|_{t_k} = \frac{1}{\Delta t}(v_k - v_{k-1}) \tag{11}$$

Hence the capacitance current at the end of the kth interval is approximated by

$$i_k = \frac{C}{\Delta t}(v_k - v_{k-1})$$

$$i_k = \frac{C}{\Delta t}v_k - \frac{C}{\Delta t}v_{k-1} \tag{12}$$

Again, this relationship can be described as a parallel combination of a current source and a conductance as shown in Fig. 2.9.

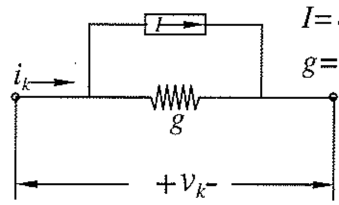


Fig. 2.9 Capacitor model

The conductance g is determined by capacitance value C and time interval. The current source is determined by conductance value g and the value of voltage at last time interval instant.

2.3.3 Node-voltage Equation

The lumped parameter equivalent network of the transformer winding contains only passive elements, such as resistors, capacitors and inductors, each inductor may be coupled with other inductors. Suppose each branch contains only one component. Based on the inductor and capacitor model mentioned above, the element currents I_e and element voltages V_e can be expressed as follows:

$$I_e = \begin{bmatrix} I_L \\ I_R \\ I_C \end{bmatrix} \tag{13}$$

$$V_e = \begin{bmatrix} V_L \\ V_R \\ V_C \end{bmatrix} \tag{14}$$

Where I_L and V_L refer to the currents and voltages of the inductor elements, I_R and V_R to those of resistors, I_C and V_C to those of capacitors.

The voltages and currents of various types of elements at kth time interval are related as follows.

For resistors

$$I_{R_k} = \left[\frac{1}{R}\right] V_{R_k} \tag{15}$$

Where [*1/R*] is a diagonal matrix of the conductances of resistive elements.

For capacitors

$$I_{C_k} = [C]\frac{1}{\Delta t}(V_{C_k} - V_{C_{k-1}}) \tag{16}$$

Where [*C*] is a diagonal matrix of capacitance values, Δt is the time step, and V_{c_k} are the capacitor voltages at $t = t_k$.

For inductors

$$I_{L_k} = [L]^{-1}\frac{\Delta t}{2}V_{L_k} + [L]^{-1}\frac{\Delta t}{2}V_{L_{k-1}} + I_{L_{k-1}} \tag{17}$$

Where [*L*] is a matrix of inductance values including mutual inductances, I_{L_k} and V_{L_k} are the inductor currents and voltages at $t = t_k$.

Hence the element currents at time t_k are given by

$$I_{e_k} = \begin{bmatrix} \frac{\Delta t}{2}[L]^{-1} & 0 & 0 \\ 0 & \left[\frac{1}{R}\right] & 0 \\ 0 & 0 & \frac{1}{\Delta t}[C] \end{bmatrix} \begin{bmatrix} V_{L_k} \\ V_{R_k} \\ V_{C_k} \end{bmatrix} + \begin{bmatrix} \frac{\Delta t}{2}[L]^{-1}V_{L_{k-1}} + I_{L_{k-1}} \\ 0 \\ -\frac{1}{\Delta t}[C]\,V_{C_{k-1}} \end{bmatrix}$$

$$= Y_e V_{e_k} + I_{p_{k-1}} \tag{18}$$

The above equation defines the element-admittance matrix Y_e and the vector $I_{p_{k-1}}$ which incorporates all the "past history" of the inductors and capacitors in the network. Since there is no dependent current source and independant current source in the equivalent network, the branch current is equal to element current.

$$I_b = I_e \tag{19}$$

The applied impulse voltage is treated as an independant voltage source, and there is no other independant voltage source or dependant voltage source in the equivalent network. The general expression for the branch voltage is:

$$V_b + V_g = V_e \tag{20}$$

V_b ---- Branch voltage;

V_g ---- Source voltage;

V_e ---- Element voltage.

By Kirchhoff's current law, $\boldsymbol{AI_b = 0}$ at all instants of time.

$$A\,(Y_e V_{e_k} + I_{p_{k-1}}) = 0 \tag{21}$$

Rearranging (21) we have:

$$A Y_e V_{e_k} + A I_{p_{k-1}} = 0$$

The element voltages are related to the branch voltages from Eq. (20).

$$A Y_e (V_{b_k} + V_{g_k}) + A I_{p_{k-1}} = 0 \tag{22}$$

$$A Y_e V_{b_k} + A (Y_e V_{g_k} + I_{p_{k-1}}) = 0$$

The network node equation is obtained as follows.

$$A Y_e A^T V_{n_k} = -A (Y_e V_{g_k} + I_{p_{k-1}}) \tag{23}$$

The above equation is now solved for V_{n_k}. The entire transient analysis consists of stepping k from 1 to K so that t_k equals or exceeds the final time for which the analysis is to be performed. The $I_{p_{k-1}}$ term incorporates the voltages and currents for each inductor calculated at the previous time step and the previously calculated voltages across the capacitors.

2.3.4 Transient Analysis Program

Although some very powerful and user-friendly commercial programs are available, such as EMTDC and ATP, they are mainly designed for system simulation. Through their user interfaces, a large number of mutual inductances can not be inputted directly. Therefore, a transient calculation program suitable for analysis of circuits with large number of mutual inductances was written in FORTRAN, as shown in Appendix C. This program is based on the principles discussed in section 2.3.3 and it was verified by comparing the simulation results with that obtained by use of EMTDC program.

2.4 Field Analysis

2.4.1 Quasi-static Field Approximation

From the simulation results, the distribution of impulse voltage in the transformer coils at various locations can be obtained in the time domain. The harmonic content of a full lightning impulse is small in the frequency range of 0.5 ~ 1.0 MHz [26]. Though the chopping of lightning impulse introduces an increase in the harmonic content, significant harmonic components are still below 10 MHz. For a rough estimation, suppose the relative dielectric constant of insulating media between the layers of winding is 3.4. The speed of transmission of an electromagnetic wave in insulating media is $v = c/\varepsilon_r,$ which is about 1.0 x 10^8 m/sec, therefore the wave-length v/f, is about 10 m. The geometric dimensions between the tap lead and adjacent layers is less than 0.01 m, which is much less than 10 m. Therefore, it is accurate enough to approximate the exact field problem through quasi-static field analysis. For quasi-static fields, the physical characteristics of the electric field is the same as that of static electric field. At any chosen time, the magnitude of impulse voltage distributed along the winding can be taken as boundary conditions for field analysis.

2.4.2 Finite Element Method and ANSYS Program [24]

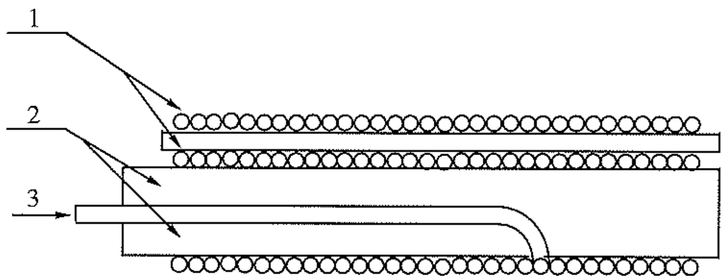
In the Finite Element Method, the boundary and interior of the solution domain are subdivided into a finite number of subregions or finite elements. A discrete number of nodal points are established with an imaginary mesh that divides the region. The variables of interest can be uniquely specified throughout the solution domain by nodal parameters associated with the nodal points of the system. These nodal parameters are the unknown parameters of the problem. It is assumed that the parameters at a particular node influence only the values of the quantity of interest within the elements that are connected to that particular node. Next, an interpolation function is assumed for the purpose of relating the quantity of interest within the element in terms of the values of the nodal parameters at the nodes that are connected to that particular element. The interpolation functions are then substituted into the governing integral form. By the minimization of a functional or by employing the method of weighted residuals, element matrices are formulated. Once the element equations have been established, the contribution of each element is added to form the system equations. Next, the boundary constraints are incorporated into the system equation. After the system equations are solved, the nodal potentials are known, from which other nodal parameters of interest are calculated.

ANSYS is a computer program for various type field analyses based on Finite Element Method. In this research work, ANSYS is used as the field analysis tool.

2.4.3 Field Analysis Configuration

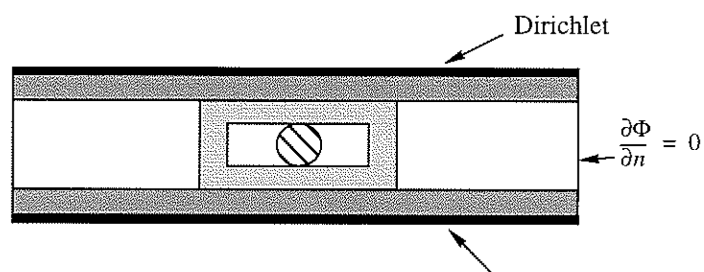
Theoretically, the Finite Element Method can be used to analyse a geometry with arbitrary shape. Because of the limitation of storage space and computer speed, a practical field region is usually simplified to a simple configuration according to the physical characteristics of actual field problem.

The field analysis of tap lead insulation is actually a three dimensional problem. Fig. 2.10. shows a cross section of the layer of winding which is tapped. Though the distribution of impulse voltage in a transformer winding is not linear, the potential difference between adjacent turns in the same layer is very small. From the equivalent circuits, shown in figure 2.2, the potential difference between the outer most turns is larger than that between adjacent inner turns. Therefore, maximum stress should occur in the location near the edge of winding. Because of this characteristic, the three dimensional field problem can be simplified to a two dimensional problem. The potentials of the end turns of corresponding layers are applied as boundary conditions. Two dimensional analysis, therefore, incorporates an element of conservativeness. A two dimensional representation of the tap lead insultation is shown in fig. 2.11.



1 ------ Winding;
2 ------ Tap lead insulation;
3 ------ Tap lead.

Fig. 2.10 Cross section of winding showing tap lead insulation



------ Tube;
------ Tap lead;
------ Lead pad (comprises of three layers of paper)
------ Winding.

Fig. 2.11 Two dimensional representation of tap lead insulation

Table 2.1 Self Inductance of simple solenoids unit : μH

	REF-F	L-24	L-40	L-80	L-160
CPU Time*	1 secs	3 mins	8 mins	22 mins	90 mins
S-1	30.6	29.1	29.6	29.8	29.8
S-2	30.6	29.1	29.6	29.8	29.8
S-3	30.6	29.1	29.6	29.8	29.8
S-4	97.9	92.4	94.7	95.97	96.27
S-5	453.9	424.4	438.1	445.83	447.90
S-6	1644.8	1534.1	1588.4	1618.45	1626.86

Note:

REF-F ---- Reference formula from [19];
L-24 ---- 24 segments representation;
L-40 ---- 40 segments representation;
L-80 ---- 80 segments representation;
L-160 ---- 160 segments representation;
S-1 ~ S-6 ---- Solenoid 1 ~ Solenoid 6, see Fig. 2.5;
* CPU time is the time taken to calculate the inductance of all 6 solenoids;
Machine type : Sparc station 10.

Table 2.2 Mutual inductance of simple solenoids unit : μH

	REF-F	L-24	L-40	L-80	L-160
CPU Time	1 sec	4 min	9 min	28 min	115 min
S-1 & S-2	14.97	13.80	14.40	14.75	14.87
S-1 & S-3	0.201	0.302	0.326	0.339	0.343
S-1 & S-4	37.15	42.14	42.99	43.45	43.57
S-1 & S-5	4.20	4.57	4.91	5.09	5.15
S-1 & S-6	47.41	50.40	52.33	53.27	53.55
S-2 & S-3	0.54	0.41	0.44	0.46	0.47
S-2 & S-4	37.15	42.14	42.99	43.45	43.57
S-2 & S-5	6.02	6.76	7.24	7.50	7.57
S-2 & S-6	59.43	62.21	64.41	65.48	65.81
S-3 & S-4	1.24	0.78	0.84	0.87	0.88
S-3 & S-5	47.63	50.26	51.70	52.49	52.71
S-3 & S-6	47.41	50.39	52.33	53.27	53.55
S-4 & S-5	12.07	12.29	13.17	13.65	13.79
S-4 & S-6	124.83	125.32	129.35	131.53	132.18
S-5 & S-6	502.35	485.02	499.73	509.7	512.38

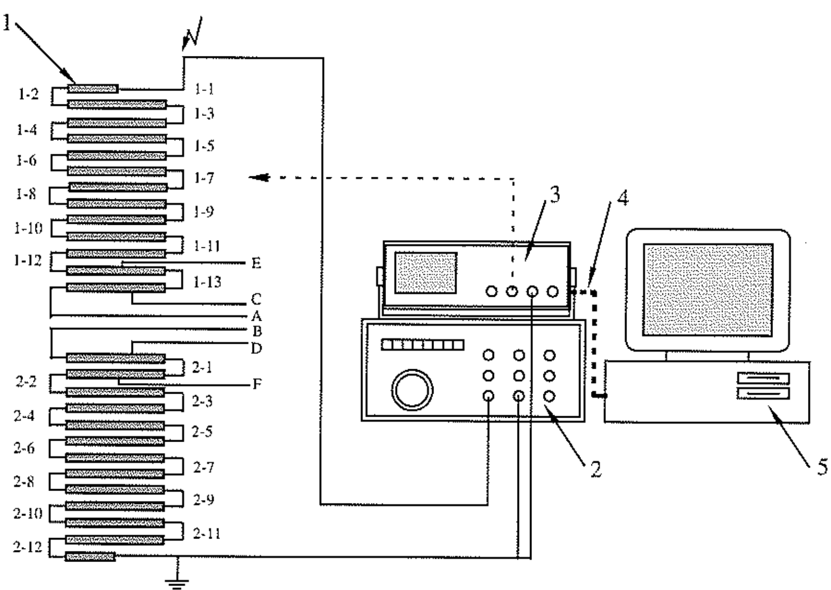
Note:

Expressions see Table 2.1

3. RESULTS AND ANALYSES

3.1 RSG Test set-up and measurement results

In order to validate the simulation method used, a distribution transformer (10 kVA, 14,400/240) winding assembly with two coils without iron core were used. Recurrent Surge Generator (RSG) tests were carried out on these coils. The chosen applied waveforms were full lightning wave (1.2 X 50 μS) and chopped lightning wave (chopped at about 1.16 μS). The transient voltage distribution of the coils were measured by probing the end turns of each layer and recorded by using a digital oscilloscope. The data was transfered to a PC through a GPIB cable. Finally, DOCUWAVE, a software installed in the PC, transformed the data to a text file. The set-up of the RSG test is shown in Fig. 3.1. The measured results are shown in Figs. 3.2 to 3.5.



1 ---- Coils;
2 ---- Recurrent surge generator;
3 ---- TDS 540 digital oscilloscope;
4 ---- GPIB cable;
5 ---- PC with DOCUWAVE installed

Fig. 3.1 Set-up of RSG test

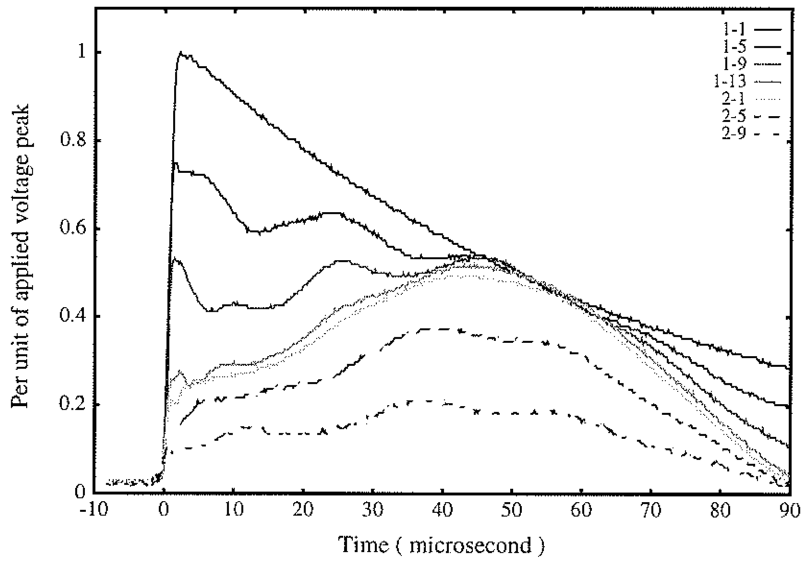


Fig. 3.2 RSG test results, standard lightning wave, measured waveforms at locations 1-1 to 2-9 (see Fig. 3.1)

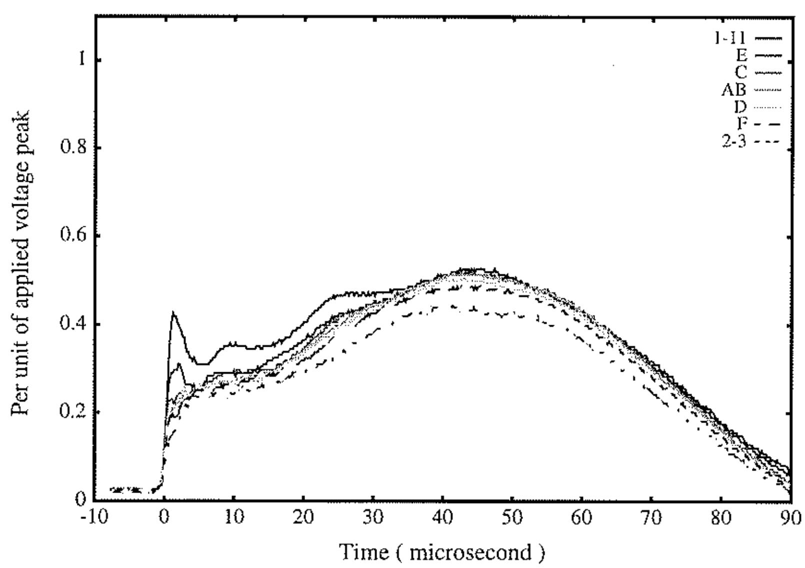


Fig. 3.3 RSG test results, standard lightning wave, measured waveforms at locations 1-11 to 2-3 near the tap leads (see Fig. 3.1)

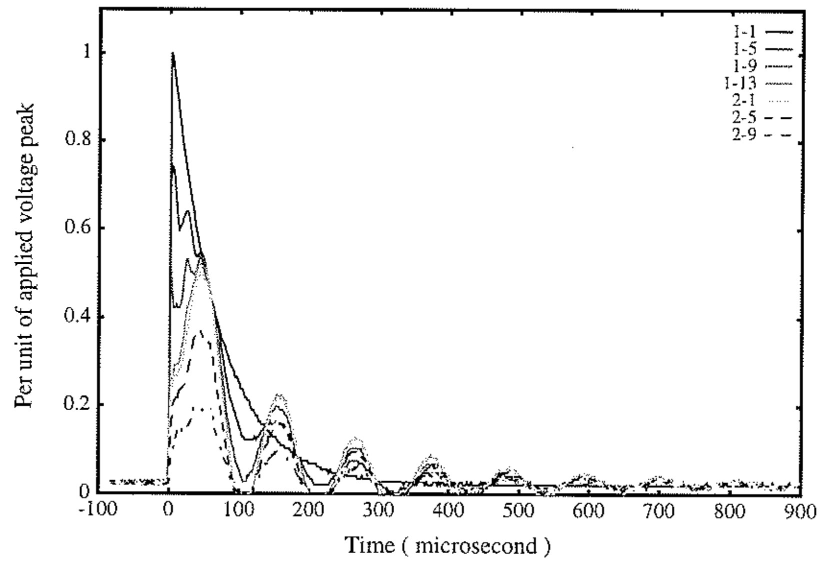


Fig. 3.4 RSG test results, standard lightning wave, measured wave-form (long time range) at locations 1-1 to 2-9 (see Fig. 3.1)

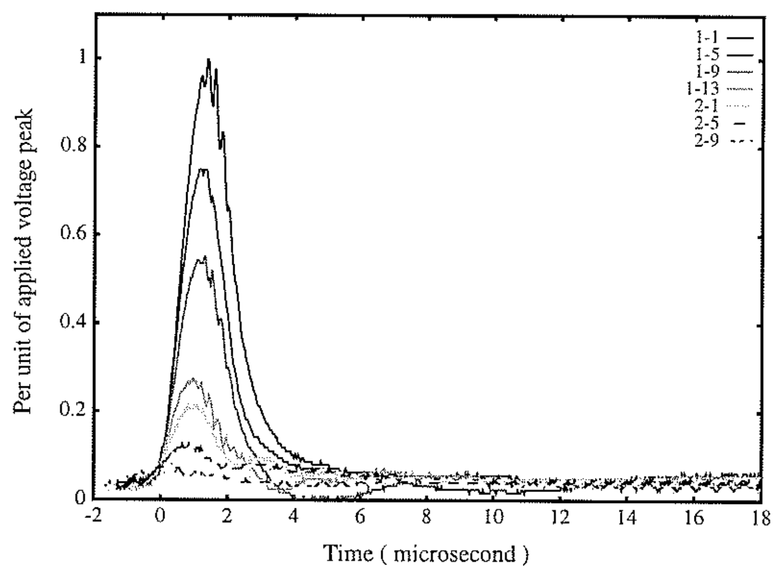


Fig. 3.5 RSG test results, chopped lightning wave, measured waveform at locations 1-1 to 2-9 (see Fig. 3.1)

From the measured results, it can be seen that the transient voltage distributions of full and chopped lightning wave have following characteristics.

- Impulse voltage input causes oscillations in the transformer winding. These oscillations attenuate significantly after about 100 microseconds.
- During the first 100 microseconds, the transient voltage distribution in transformer winding is very non-uniform, that is, in the first 2 ~ 3 microseconds, the windings of coil No. 1 near the input end experience a relatively large voltage drop, while at about 45 microseconds after application of the lightning impulse voltage, the oscillations in the coils cause high stress inside coil No. 2.
- The potentials of tap leads and adjacent layers are almost equal, except that there is some potential difference between taps E, F and their adjacent layers.
- In coil No.1, the transient voltage distribution of the chopped lightning wave is even more non-uniform than that of the standard lightning wave.

3.2 Full lightning wave distribution simulation

In order to simulate the transient impulse voltage distribution in transformer windings, the lumped parameter equivalent circuits shown in Fig. 2.2 were used. The values of the lumped inductive, capacitive and resistive components of the equivalent circuits were calculated by the methods introduced in the last chapter. The forty segments representation was used to calculate the self and mutual inductances of sections in a coil, the twenty four segments representation was used to calculate the mutual coupling between two coils. The capacitive components were calculated using a eight hundred segment repersentation. The transient impulse voltage distributions in these equivalent networks were calculated using the developed transient analysis program. In order to validate the simulation method, the calculation results of several cases are compared with the RSG measurement results in the following sections.

3.2.1 Capacitive effect of core, tank and mutual inductive coupling effect between two coils

It has been stated in the last chapter that as far as transient voltage distribution is concerned, transformer coils with iron core can be treated as though they are wound on air core. Though the inductive effect of iron core can be neglected, it is not clear whether the capacitive effect of the iron core can be ignored. In this section, the capacitive effect of the iron core and tank, and the effect of mutual inductive coupling between two coils are investigated.

The values of the capacitive components which represent the capacitive effect of the core, tank and the mutual inductances between two coils are calculated by the methods outlined in chapter 2. The RSG measurement results and simulation results are shown in Figs. 3.6.1 to 3.6.6.

In Figs. 3.6.1 to 3.6.6, the abbreviations ref, cor, tak, gap and ab represent the following cases:

ab ------ two coils with core and tank simulated, with mutual coupling in between;
ref ------ two coils without core and tank simulated, with mutual coupling in between;
cor ------ two coils with only core simulated, with mutual coupling in between;
tak ------ two coils with only tank simulated, with mutual coupling in between;
gap ------ two coils with 20 cm gap, without mutual coupling.

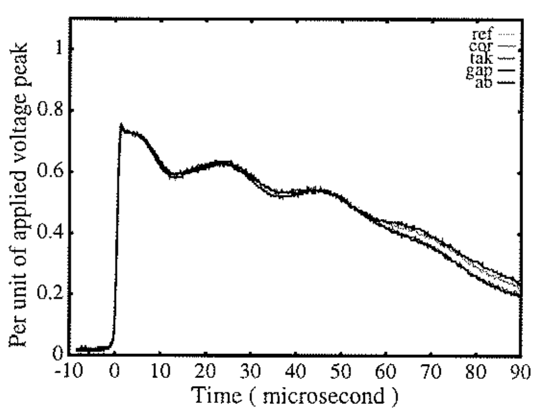


Fig. 3.6.1 RSG result, waveforms at location 1-5 (see Fig. 3.1)

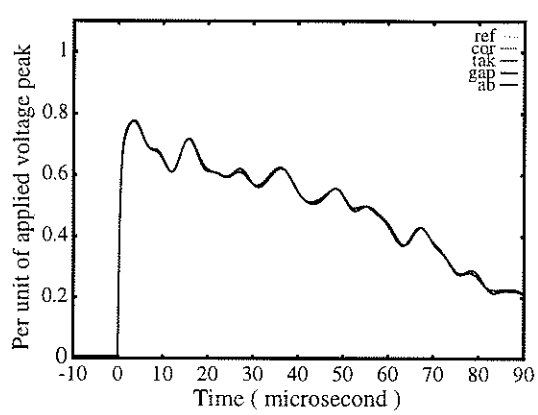


Fig. 3.6.2 Simulation result, waveforms at location 1-5 (see Fig. 3.1)

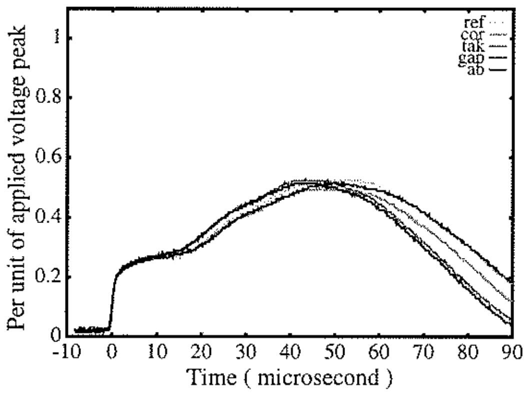


Fig. 3.6.3 RSG result, waveforms at location AB (see Fig. 3.1)

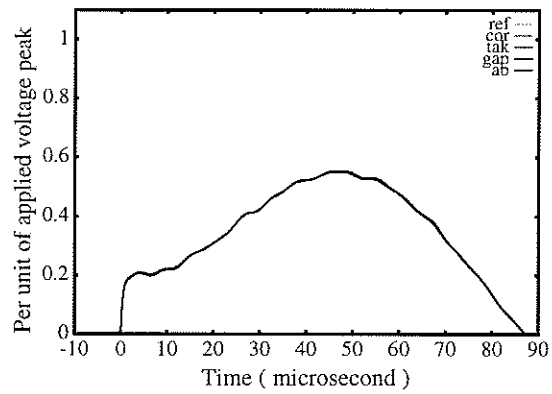


Fig. 3.6.4 Simulation result, waveforms at location AB (see Fig. 3.1)

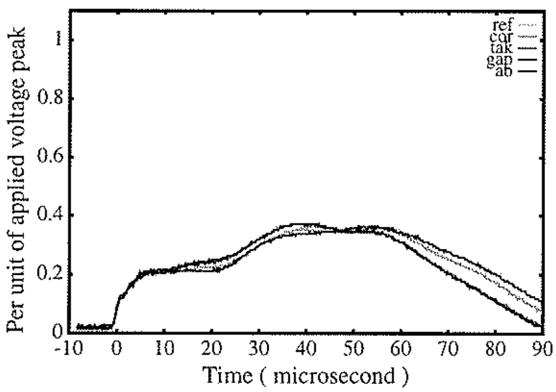


Fig. 3.6.5 RSG result, waveforms at location 2-5 (see Fig. 3.1)

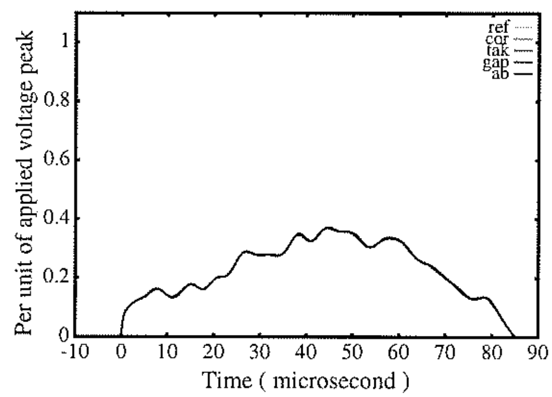


Fig. 3.6.6 Simulation result, waveforms at location 2-5 (see Fig. 3.1)

As Figs. 3.6.1 ~ 3.6.6 shown, for RSG test results, in the first 50 microseconds, the results almost overlap; differences appear after 50 microseconds. The "ab" and "tank" curves are almost identical. The same can be said for the "ref" and "gap" curves. The "cor" curve lies in between. This implies that the tank has a relatively larger effect than the core and that the mutual inductive coupling between two coils has no evident effect. From the simulation results, the effects of core, tank and mutual coupling between two coils are not evident because the curves corresponding to all fives cases overlap. However, the simulation results are still meaningful when one is mainly concerned with the initial values and maximum values of impulse voltage distribution.

3.2.2 RSG and simulation results for AB tap connection

Figs. 3.7.1 to 3.7.8 compare the RSG measurement results and the corresponding simulation results of transient full lightning wave distribution. The simulaiton employed the EC-1 equivalent circuit (see Fig. 2.2). The coils are connected in AB tap position and both core and tank were simulated. Fig. 3.8 shows the distribution of full lightning wave along the winding at 1.2 and 45 microseconds.

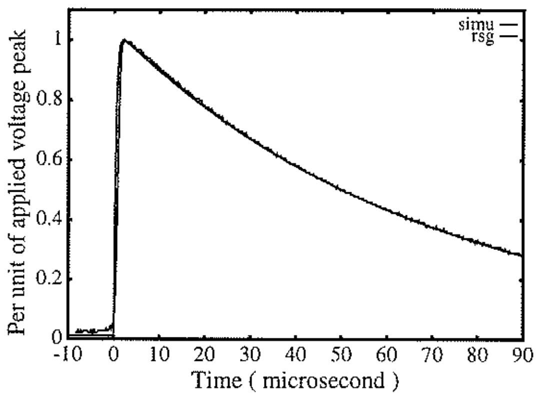


Fig. 3.7.1 Simulation & RSG results at location 1-1 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

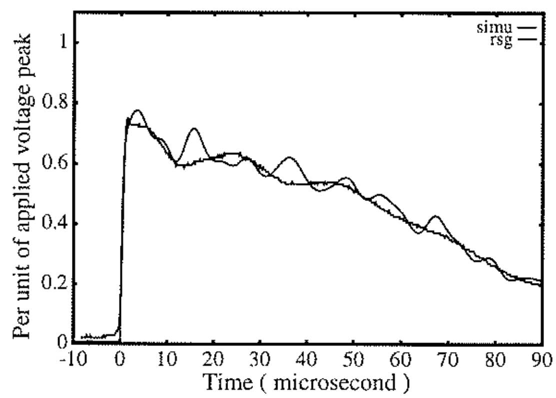


Fig. 3.7.2 Simulation & RSG results at location 1-5 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

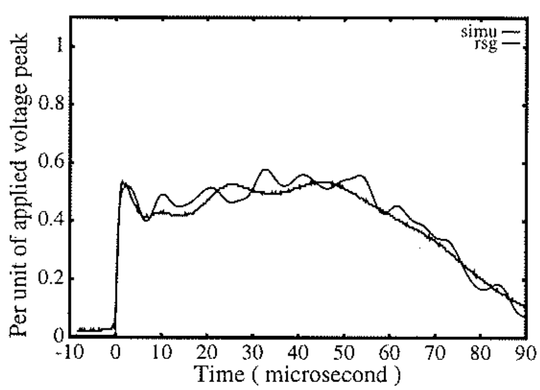


Fig. 3.7.3 Simulation & RSG results at location 1-9 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

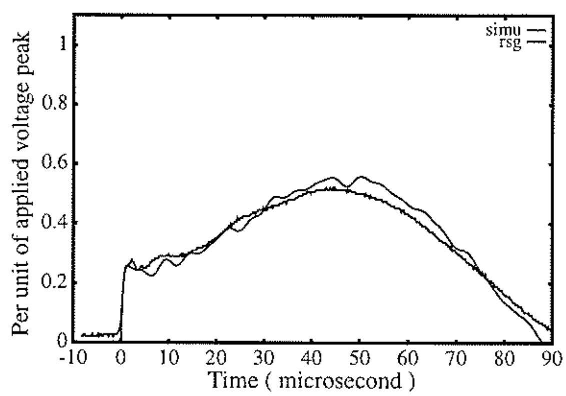


Fig. 3.7.4 Simulation & RSG results at location 1-13 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

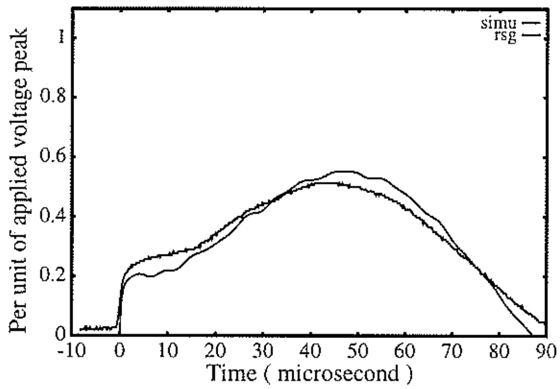


Fig. 3.7.5 Simulation & RSG results at location AB (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

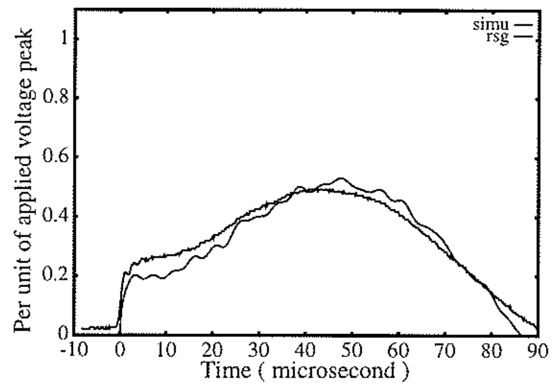


Fig. 3.7.6 Simulation & RSG results at location 2-1 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

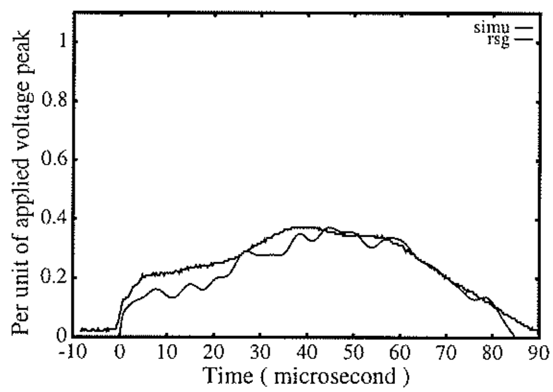


Fig. 3.7.7 Simulation & RSG results at location 2-5 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

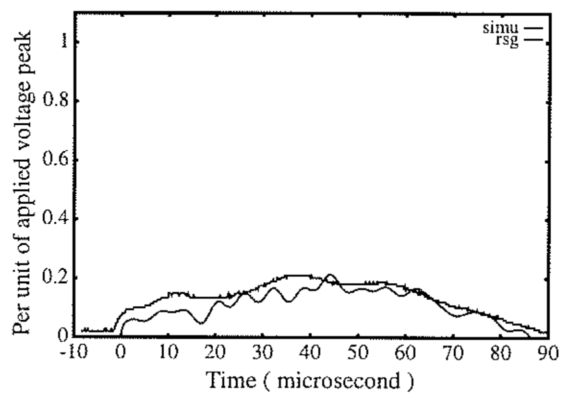


Fig. 3.7.8 Simulation & RSG results at location 2-9 (see Fig. 3.1), winding excited with lightning wave (1.2 X 50)

It can be seen that the RSG measurement and simulation results are in good agreement, especially for coil 1. For coil 2, there are differences in the RSG and simulation results during the initial 20 microseconds, the maximum values are still in good agreement.

3.2.3 Comparison of simulation results using various equivalent circuits

The objective of this research work is to evaluate the tap lead insulation design and make suggestions for more economic designs. Therefore, detailed information about the transient impulse voltage distribution in windings near the tap leads is

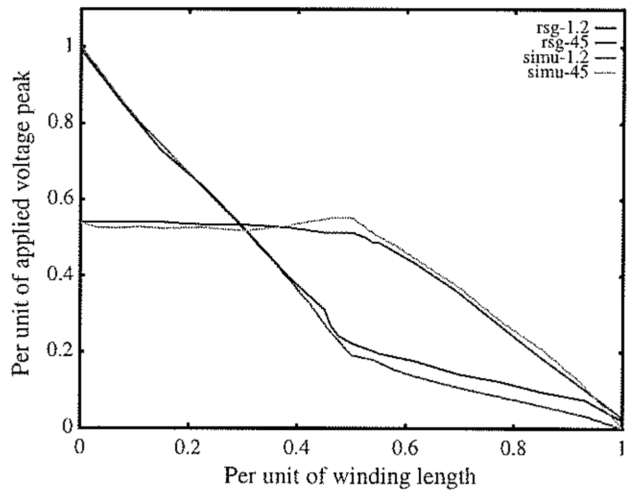


Fig. 3.8 Simulation & RSG results of full lightning wave distribution along winding at 1.2 and 45 microseconds

needed. Theoretically, the more the number of sections in the layers near the tap leads, the more detailed the information to be had about the transient impulse voltage distribution near that location. The comparison of simulation results obtained by consideration of the three equivalent circuits EC-1, EC-2 and EC-3 (shown in Fig. 2.2) are shown in Figs. 3.9.1 to 3.9.6 and Table 3.1. It is shown that the simulation results are quite close except that a finer division i.e. more sections per layer seems to result in small oscillations, especially near the low-voltage winding. The reason for this is probably associated with the relatively high natural frequency of this type of winding depiction. Fig. 3.10 shows the simulated voltage distribution along the winding at 1.2 and 45 microseconds.

3.2.4 Effect of tap connections, Comparison of RSG and simulated waveforms at chosen locations

In practice, transformer may operate under various tap connections. The effect of tap connections on the transient impulse voltage distribution was studied using

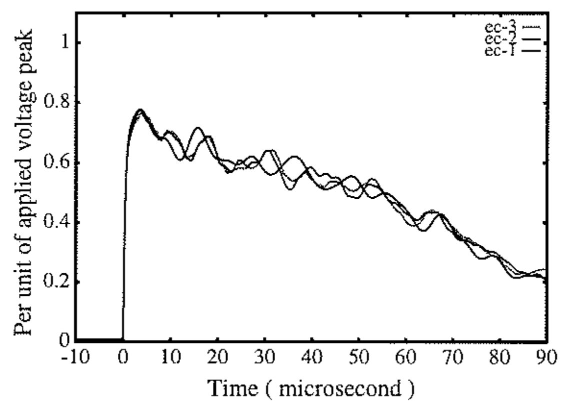


Fig. 3.9.1 Simulation results at location 1-5 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

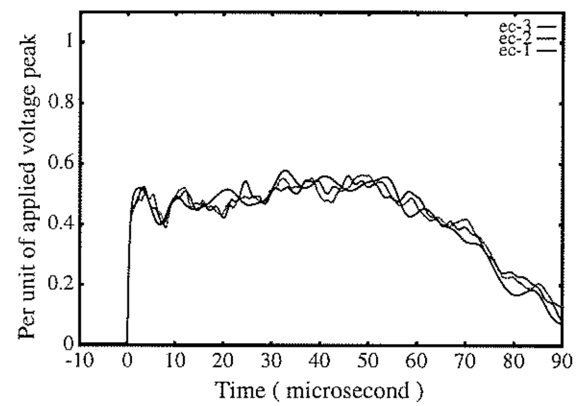


Fig. 3.9.2 Simulation results at location 1-9 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

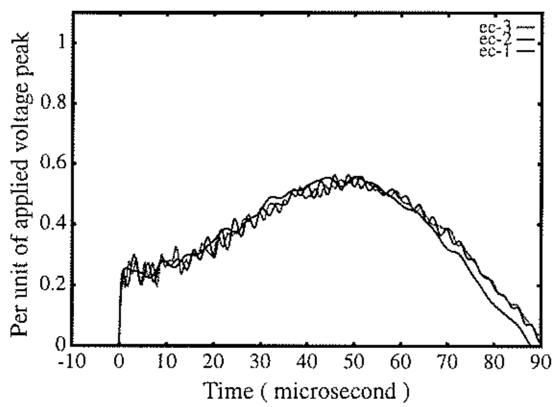


Fig. 3.9.3 Simulation results at location 1-13 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

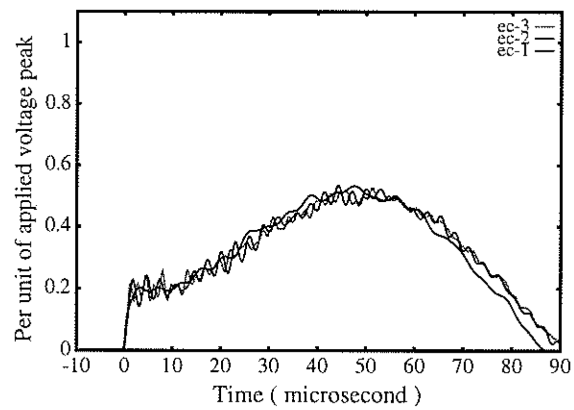


Fig. 3.9.4 Simulation results at location 2-1 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

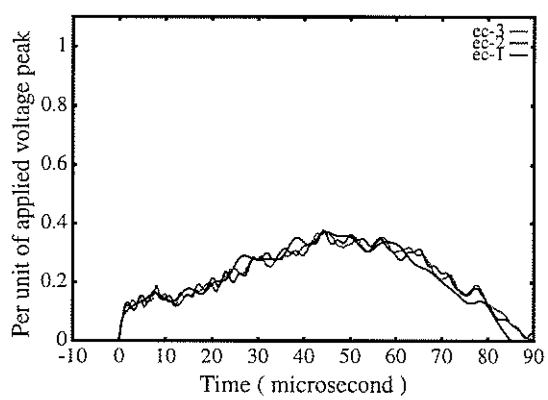


Fig. 3.9.5 Simulation results at location 2-5 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

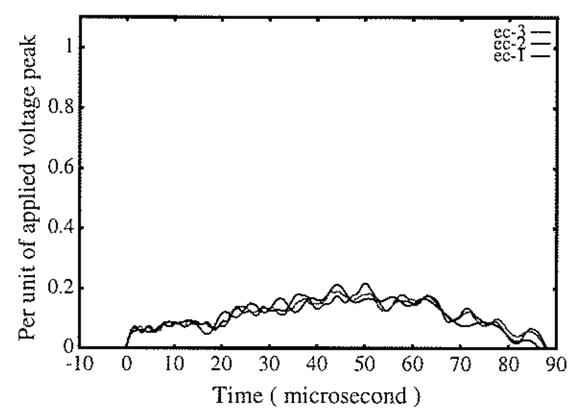


Fig. 3.9.6 Simulation results at location 2-9 (see Fig. 3.1), winding excited with lighning wave (1.2 X 50)

equivalent circuits EC-2 and EC-3. The RSG and Simulation results are shown in Figs. 3.11.1 to 3.11.12 and Table 3.1. These figures show that tap connections influence transient impulse voltage distribution at the initial time. Tap connection EF results in a relatively large voltage drop in the winding near the input end at initial time than do tap connections AB and CD.

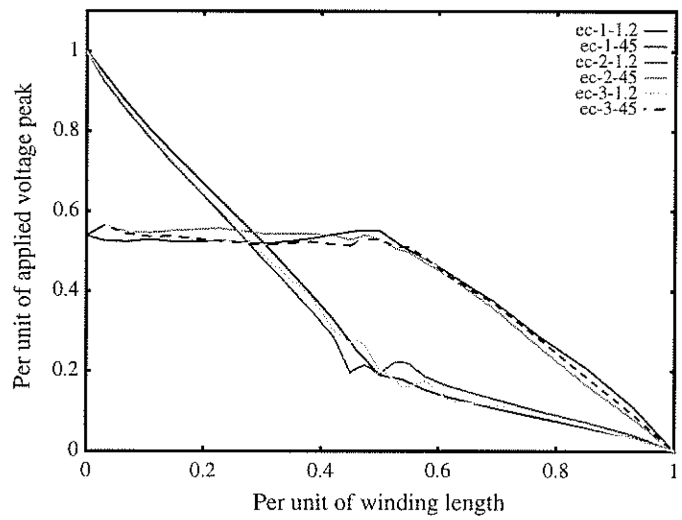


Fig. 3.10 Simulated results of voltage distribution along winding with various tap connections at 1.2 and 45 microseconds, winding excited with full lightning wave

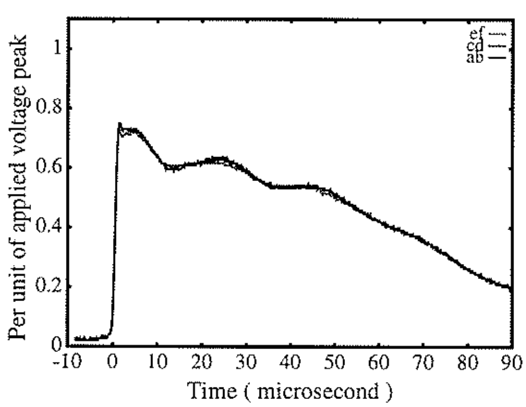


Fig. 3.11.1 RSG results at location 1-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

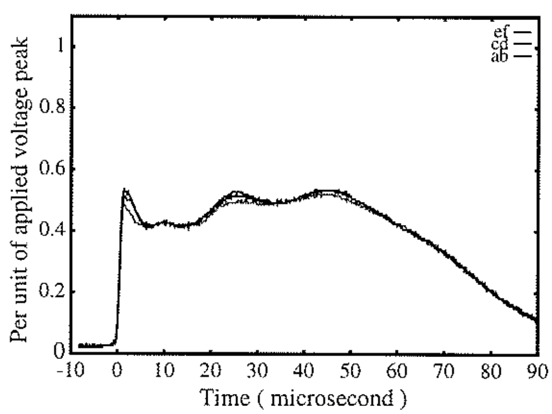


Fig. 3.11.2 RSG results at location 1-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

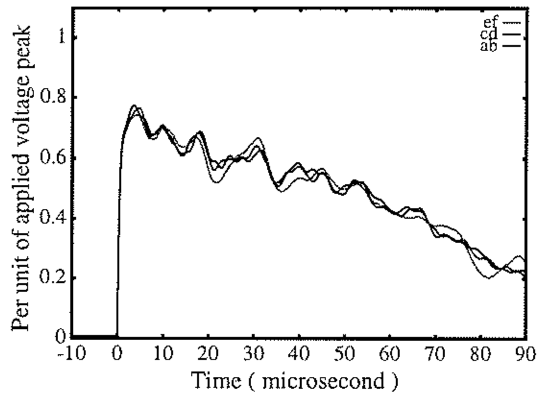


Fig. 3.11.3 Simulation results of EC-2 at location 1-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

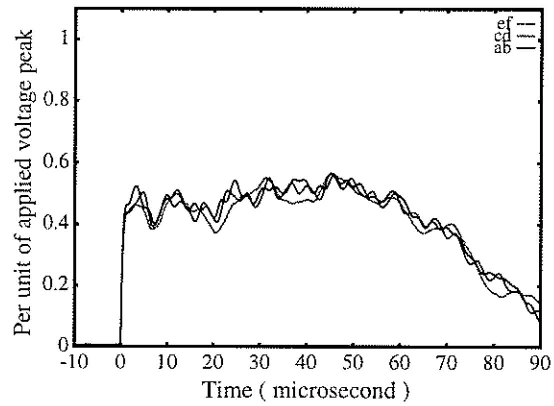


Fig. 3.11.4 Simulation results of EC-2 at location 1-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

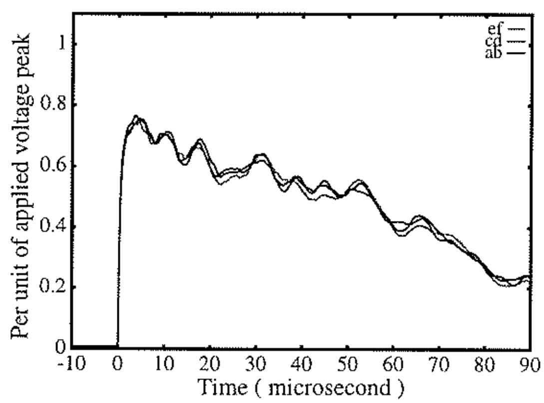


Fig. 3.11.5 Simulation results of EC-3 at location 1-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

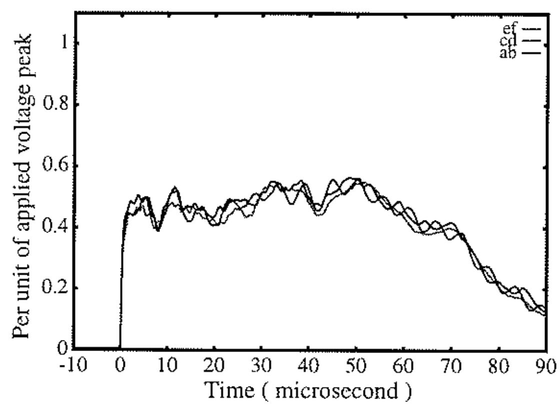


Fig. 3.11.6 Simulation results of EC-3 at location 1-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

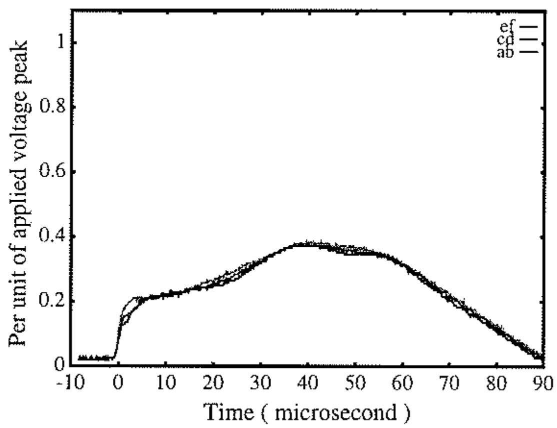


Fig. 3.11.7 RSG results at location 2-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

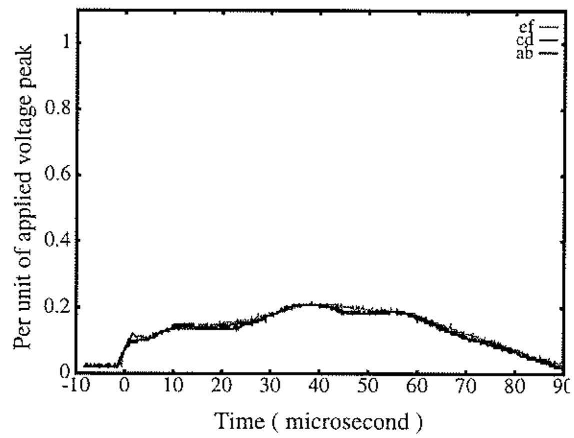


Fig. 3.11.8 RSG results at location 2-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

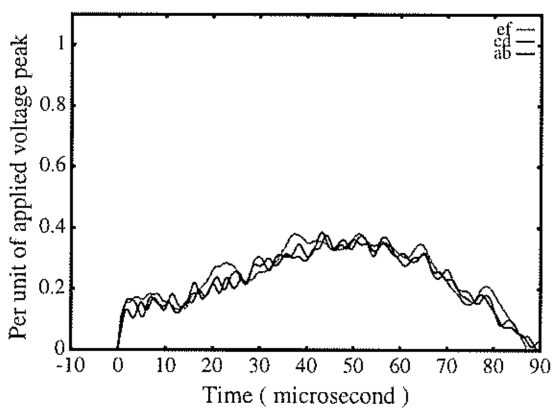


Fig. 3.11.9 Simulation results of EC-2 at location 2-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

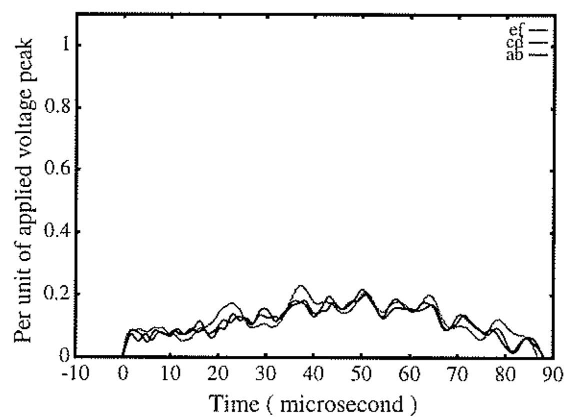


Fig. 3.11.10 Simulation results of EC-2 at location 2-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

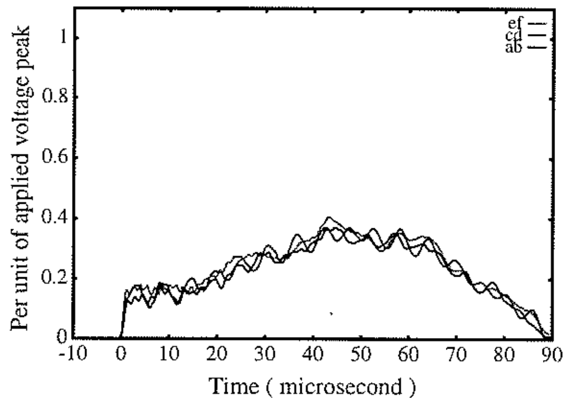


Fig. 3.11.11 Simulation results of EC-3 at location 2-5 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

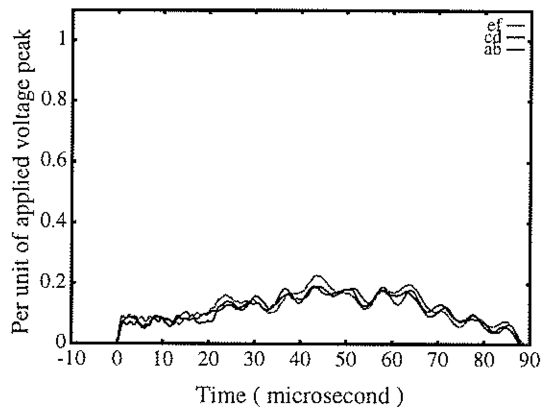


Fig. 3.11.12 Simulation results of EC-3 at location 2-9 (see Fig. 3.1), tap connection ab, cd and ef, winding excited with lightning wave

3.3 Chopped lightning wave distribution

Under operating conditions, a transformer sometimes may experience a chopped lightning wave which can stress the transformer insulation because of the highly non-linear distribution of the impulse voltage. Therefore, it is meaningful to investigate the non-linear distribution of the chopped lightning wave in transformer winding. RSG measurements and simulation results of the transient chopped lightning wave distribution are shown in Figs. 3.12.1 to 3.12.8 and Table 3.2. Fig. 3.13 shows RSG measurements and simulation results of chopped lightning wave distribution along the transformer winding at the chop time about 1.16 μS.

It is seen that the simulation results of the chopped lightning wave distribution agree well with RSG measurement results. The simulation results show a worse non-linear transient voltage distribution than the practical case. Therefore, when the insulation design is evaluated based on the simulation results, a factor of safety is built in the analysis.

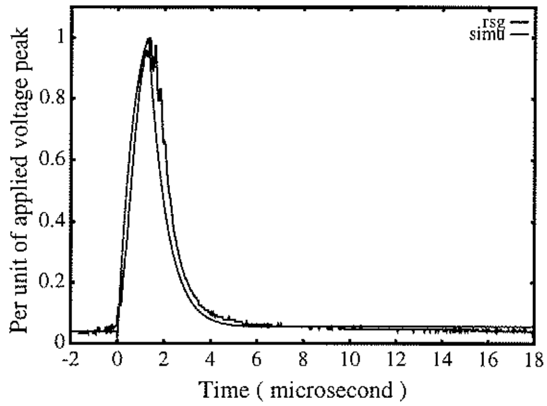


Fig. 3.12.1 RSG and simulation results at location 1-1 (see Fig. 3.1), winding excited with chopped lightning wave

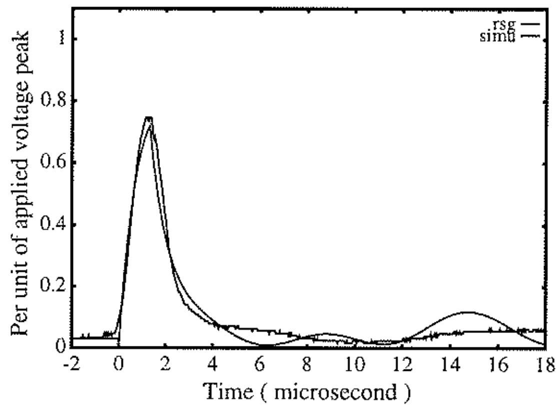


Fig. 3.12.2 RSG and simulation results at location 1-5 (see Fig. 3.1), winding excited with chopped lightning wave

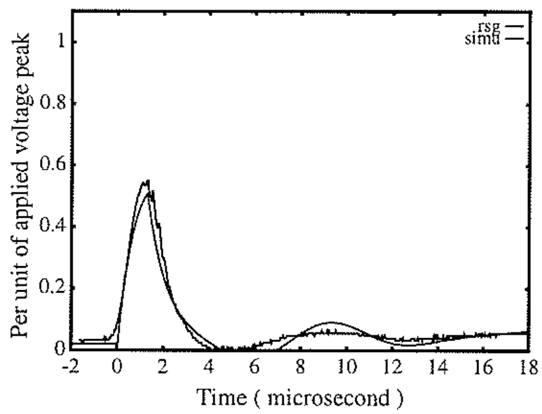


Fig. 3.12.3 RSG and simulation results at location 1-9 (see Fig. 3.1), winding excited with chopped lightning wave

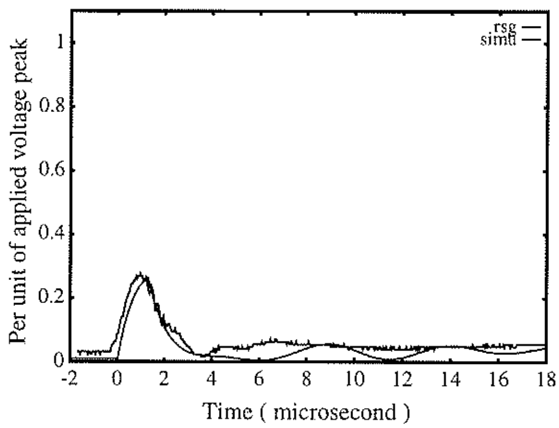


Fig. 3.12.4 RSG and simulation results at location 1-13 (see Fig. 3.1), winding excited with chopped lightning wave

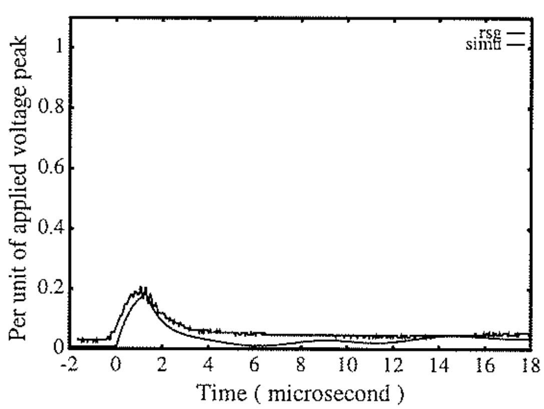


Fig. 3.12.5 RSG and simulation results at location AB (see Fig. 3.1), winding excited with chopped lightning wave

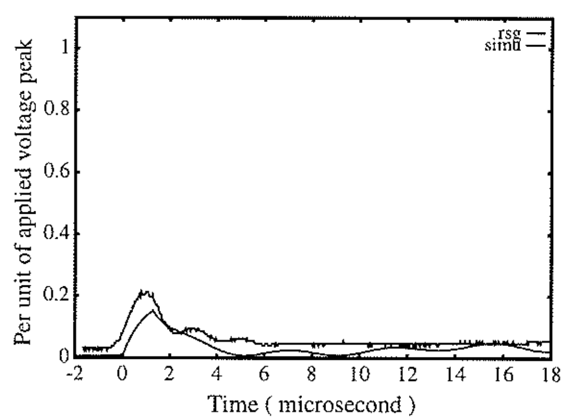


Fig. 3.12.6 RSG and simulation results at location 2-1 (see Fig. 3.1), winding excited with chopped lightning wave

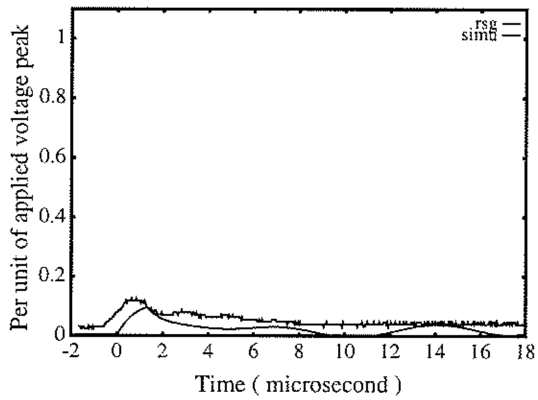


Fig. 3.12.7 RSG and simulation results at location 2-5 (see Fig. 3.1), winding excited with chopped lightning wave

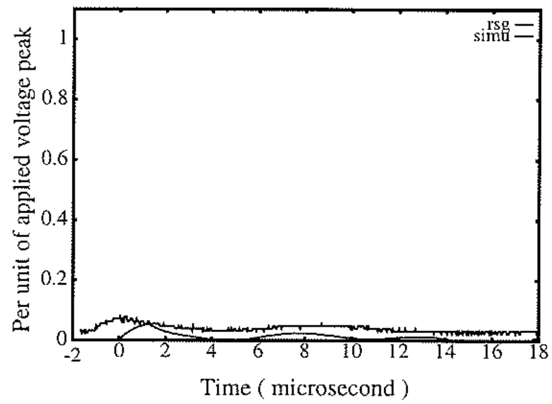


Fig. 3.12.8 RSG and simulation results at location 2-9 (see Fig. 3.1), winding excited with chopped lightning wave

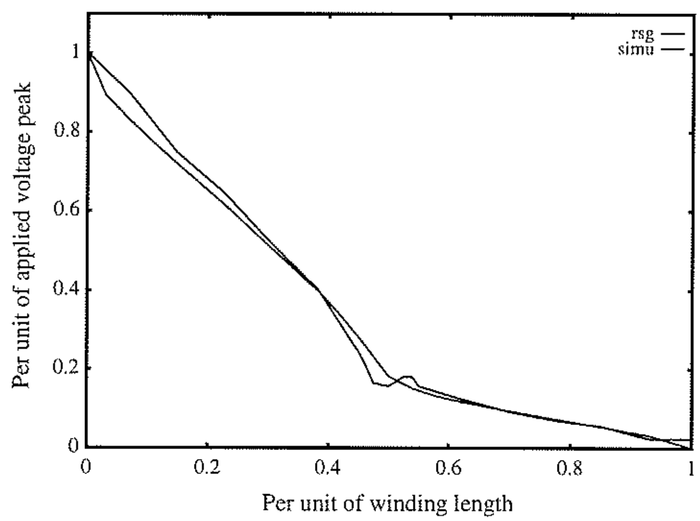


Fig. 3.13 RSG and simulation results of voltage distribution along winding at time (1.16 μS), winding excited with chopped lightning wave, simulation carried out using EC-1

From the results of sections 3.2 and 3.3, it can be concluded that:

- For both full lightning wave (at about 1.2 μS) and chopped lightning wave (at chop time, about 1.16 μS), no matter what tap connection is chosen, the insulation near the input end of transformer coil, such as the insulation between points 1-1 and 1-3, between points 1-2 and 1-4 (see figure 3.1), experience larger stress than the insulation of the other parts. This non-linear voltage distribution becomes worse for the E-F tap connection.

- Among the several tap leads, the insulation aound E (between point 1-11 and E) is stressed more than the insulation around other tap leads.

The good agreement between RSG measurement results and simulation results justify the methods which are used to calculate self and mutual inductive parameters, series and parallel capacitive parameters and the method of lumped parameter equivalent networks which are used to simulate the transient impulse voltage distribution. Furthermore, it suggests that we can use these methods to simulate transient voltage distribution in transformer coils under actual conditions and to predict transient voltage distribution in transformer coils with modified insulation design.

3.4 Present insulation design evaluation

In order to evaluate the insulation design, the transient voltage distribution in transformer windings must be known. In actual working conditions, the transformer coils are assembled on an iron-core and impregnated with transformer oil. It has already been mentioned in Chapter 2 that as far as transient impulse voltage distribution is concerned, the effect of iron core on the inductive parameters can be ignored. The capacitive effects of core and tank can be simulated by adding several lumped capacitors to the equivalent circuit networks. The effect of oil impregnation can be included by using a larger relative dielectric constant when the series and parallel lumped capacitances are calculated. Therefore, the equivalent circuit networks with these additional and modified parameters can be used to simulate the transient voltage distribution in transformer windings under actual working condition.

From simulation results, we can know the transient impulse voltage distribution in transformer coils. In order to evaluate the insulation design, we need to carry out quasi-static field analysis which utilizes appropriate simulation results at chosen time as boundary conditions. The RSG measurement and simulation results show that at 1.2 microseconds for the full lightning wave and at the chop time of about 1.16 microsecond for chopped lightning wave, the voltage distributions are the most non-linear. Therefore, field analyses were carried out using simulation results at these times as boundary conditions. The simulation results of transient lightning wave distribution at chosen points of transformer coils at 1.2 microseconds are listed in Table 3.3. The results of chopped lightning wave distribution are listed in Table 3.4. The field evaluation results of present coil insulation design under over-voltage of magnitude 125 kV for full lightning wave and 145 kV for chopped lightning wave [27] are shown in Table 3.5. According to the analysis results, the maximum stress on the insulation around the input end is about 26.4 kV/mm and the maximum stress on tap lead insulation around location E (see Fig. 3.1) is about 13.5 kV/mm. Generally speaking, the impulse strength of paper oil combination is about 35 kV/mm. Since a factor of safety is already built into the analyses, therefore, it may be concluded that the present insulation design can withstand the full and chopped lightning over-voltage it is supposed to withstand. Fig. 3.14 and Fig. 3.15 show potential contours around points 1-1 and E respectively.

3.5 Modified insulation design evaluation

Field analyses of the present design in the last section shows that the maximum stress in the tap lead insulation is lower than the maximum stress value near the input end of the coil. For the most economic design, the maximum stress of every part of the coil should be approximately the same value. However, this condition is not possible to attain in practice. The results obtained in the last section suggest that the present tap lead insulation design is conservative and may be modified to obtain economic designs.

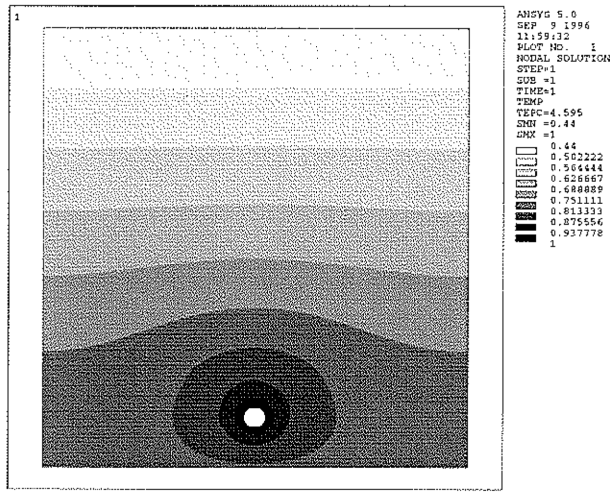


Fig. 3.14 An example of potential contour plot at point 1-1

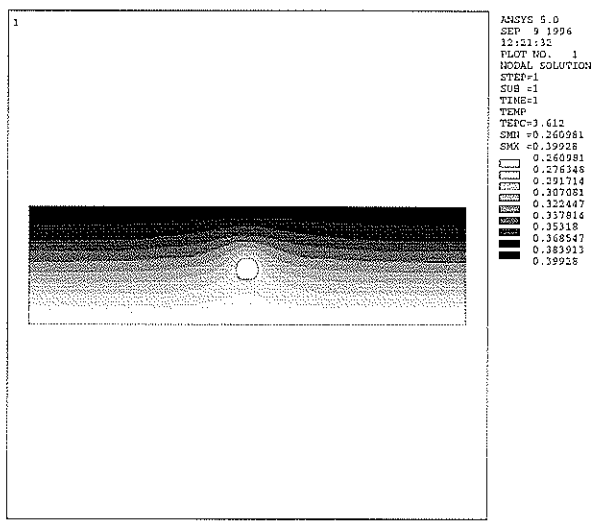


Fig. 3.15 An example of potential contour plot at point E

The present design of tap lead insulation comprises of three layers of paper above and three layers of paper below the tap lead (see Fig. 2.11). In the first modified design (design A), the tap leads are insulated with two layers of paper above and two layers of paper below. In another modified design (design B), only one layer of paper insulates both sides of the tap lead. For these modified tap lead insulation designs, the geometric dimensions of the coils were calculated. The values of all inductive, capacitive and resistive parameters of the equivalent networks were calculated according to the new coil dimensions. Following the procedure described previously, the transient impulse voltage distributions were simulated and the stresses in coil insulation were evaluated based on the transient simulation results. The simulation results of transient full lightning wave distribution in transformer coils with modified tap lead insulation are listed in Table 3.6 for design A and in Table 3.9 for design B. The simulation results of transient chopped lightning wave distribution in transformer coils with modified tap lead insulation design are listed in Table 3.7 for design A and Table 3.10 for design B. The field evaluation results are listed in Table 3.8 for design A and in Table 3.11 for design B.

The simulation results show that, the transient impulse voltage distributions do not change significantly after tap lead insulation design is modified. The field analysis results show that maximum field stress near the input end remains almost the same as in the unmodified design. The maximum stress on the tap lead insulation increases to about 14.7 kV/mm for design A and to about 16.3 kV/mm for design B. Although, the maximum stress on the tap lead insulation of the new designs are a little bit higher than that in the present design, it is still in the safe range and well below the maximum stress on the insulation near the input end.

Table 3.1 RSG measurement and simulation results of transient lightning wave distribution in transformer coils without oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. difference at 1.2 μS				Volt. difference at 45 μS			
		RSG	EC-1	EC-2	EC-3	RSG	EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.128	0.129	0.149	0.141	0.000	0.015	0.009	0.005
	1-3 & 1-5	0.135	0.125	0.131	0.132	0.000	0.000	0.004	0.007
	1-11 & E	0.088	0.120	0.155	0.116	0.014	0.017	0.015	0.010
	1-13 & C	0.027	0.022	0.010	0.014	0.000	0.000	0.007	0.008
	1-13 & A	0.047	0.062	0.013	0.074	0.000	0.000	0.004	0.006
	B & 2-1	0.020	0.011	0.030	0.040	0.027	0.040	0.029	0.020
	D & 2-1	0.007	0.004	0.002	0.019	0.014	0.014	0.007	0.004
	F & 2-3	0.020	0.037	0.057	0.035	0.054	0.058	0.059	0.074
	2-1 & 2-3	0.027	0.044	0.060	0.035	0.054	0.067	0.064	0.073
	2-3 & 2-5	0.034	0.028	0.032	0.011	0.074	0.073	0.083	0.069
CD	1-1 & 1-3	0.135	----	0.153	0.151	0.000	----	0.009	0.006
	1-3 & 1-5	0.135	----	0.143	0.144	0.007	----	0.005	0.007
	1-11 & E	0.081	----	0.135	0.093	0.014	----	0.000	0.005
	1-13 & C	0.020	----	0.010	0.007	0.007	----	0.023	0.021
	1-13 & A	----	----	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----	----	----
	D & 2-1	0.000	----	0.001	0.003	0.007	----	0.036	0.030
	F & 2-3	0.027	----	0.036	0.012	0.054	----	0.043	0.070
	2-1 & 2-3	0.034	----	0.017	0.024	0.061	----	0.077	0.099
	2-3 & 2-5	0.027	----	0.037	0.042	0.074	----	0.076	0.065

Tap cons.	Volt. diff. between	Volt. difference at 1.2 μS				Volt. difference at 45 μS			
		RSG	EC-1	EC-2	EC-3	RSG	EC-1	EC-2	EC-3
EF	1-1 & 1-3	0.149	----	0.161	0.157	0.007	----	0.011	0.018
	1-3 & 1-5	0.149	----	0.136	0.140	0.000	----	0.015	0.016
	1-11 & E	0.074	----	0.119	0.118	0.014	----	0.046	0.000
	1-13 & C	----	----	----	----	----	----	----	----
	1-13 & A	----	----	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----	----	----
	D & 2-1	----	----	----	----	----	----	----	----
	F & 2-3	0.014	----	0.019	0.037	0.047	----	0.089	0.068
	2-1 & 2-3	----	----	----	----	----	----	----	----
	2-3 & 2-5	0.041	----	0.036	0.026	0.081	----	0.091	0.058

Note:

RSG ---- RSG measurement results;

EC-1 ---- Simulation results of equivalent circuit No. 1, see Fig. 2.2;

EC-2 ---- Simulation results of equivalent circuit No. 2, see Fig. 2.2;

EC-3 ---- Simulation results of equivalent circuit No. 3, see Fig. 2.2;

Table 3.2 RSG measurement and simulation results of transient chopped lightning wave distribution in transformer coils without oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. difference at 1.16 μS			
		RSG	EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.102	0.168	0.179	0.183
	1-3 & 1-5	0.150	0.111	0.116	0.120
	1-11 & E	0.157	0.118	0.124	0.119
	1-13 & C	0.047	0.028	0.016	0.025
	1-13 & A	0.055	0.078	0.056	0.030
	B & 2-1	0.024	0.030	0.006	0.019
	D & 2-1	0.000	0.011	0.002	0.002
	F & 2-3	0.031	0.028	0.040	0.043
	2-1 & 2-3	0.055	0.033	0.040	0.054
	2-3 & 2-5	0.031	0.023	0.026	0.030
CD	1-1 & 1-3	0.135	----	0.185	0.187
	1-3 & 1-5	0.143	----	0.123	0.124
	1-11 & E	0.095	----	0.094	0.103
	1-13 & C	0.034	----	0.021	0.031
	1-13 & A	----	----	----	----
	B & 2-1	----	----	----	----
	D & 2-1	0.032	----	0.007	0.009
	F & 2-3	0.024	----	0.010	0.028
	2-1 & 2-3	0.016	----	0.032	0.027
	2-3 & 2-5	0.048	----	0.027	0.026

Tap cons.	Volt. diff. between	Volt. difference at 1.16 μS			
		RSG	EC-1	EC-2	EC-3
EF	1-1 & 1-3	0.103	----	0.193	0.198
	1-3 & 1-5	0.167	----	0.123	0.129
	1-11 & E	0.087	----	0.121	0.101
	1-13 & C	----	----	----	----
	1-13 & A	----	----	----	----
	B & 2-1	----	----	----	----
	D & 2-1	----	----	----	----
	F & 2-3	0.048	----	0.037	0.025
	2-1 & 2-3	----	----	----	----
	2-3 & 2-5	0.056	----	0.030	0.029

Note:

Expressions are the same as Table 3-1.

Table 3.3 Simulation results of transient lightning wave distribution in transformer coils with present tap lead insulation design, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 μS			Volt. diff. at 45 μS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.133	0.154	0.145	0.035	0.008	0.008
	1-2 & 1-4	0.138	0.141	0.142	0.032	0.024	0.005
	1-11 & E	0.120	0.156	0.115	0.010	0.016	0.031
	1-13 & C	0.023	0.009	0.017	0.004	0.007	0.017
	1-13 & A	0.064	0.009	0.072	0.011	0.009	0.008
	B & 2-1	0.013	0.035	0.037	0.032	0.044	0.028
	D & 2-1	0.005	0.001	0.022	0.011	0.002	0.030
	F & 2-3	0.036	0.058	0.034	0.067	0.050	0.017
	B & 2-2	0.039	0.003	0.025	0.077	0.061	0.047
	2-3 & 2-5	0.028	0.033	0.011	0.068	0.089	0.079
CD	1-1 & 1-3	----	0.157	0.155	----	0.014	0.013
	1-2 & 1-4	----	0.153	0.154	----	0.006	0.006
	1-11 & E	----	0.131	0.092	----	0.010	0.001
	1-13 & C	----	0.008	0.009	----	0.022	0.006
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	0.000	0.006	----	0.015	0.007
	F & 2-3	----	0.032	0.012	----	0.080	0.044
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.036	0.042	----	0.082	0.086

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 µS			Volt. diff. at 45 µS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.164	0.160	----	0.013	0.024
	1-2 & 1-4	----	0.144	0.149	----	0.026	0.027
	1-11 & E	----	0.118	0.121	----	0.001	0.026
	1-13 & C	----	----	----	----	----	----
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	----	----	----	----	----
	F & 2-3	----	0.019	0.040	----	0.069	0.021
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.035	0.025	----	0.085	0.067

Note:

Expressions are the same as Table 3.1

Table 3.4 Simulation results of transient chopped lightning wave distribution in transformer coils with present tap lead insulation design, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 μS		
		EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.169	0.181	0.185
	1-2 & 1-4	0.118	0.121	0.125
	1-11 & E	0.118	0.122	0.119
	1-13 & C	0.029	0.017	0.025
	1-13 & A	0.079	0.061	0.030
	B & 2-1	0.031	0.011	0.018
	D & 2-1	0.011	0.002	0.002
	F & 2-3	0.028	0.038	0.043
	B & 2-2	0.050	0.038	0.029
	2-3 & 2-5	0.022	0.025	0.030
CD	1-1 & 1-3	----	0.187	0.189
	1-2 & 1-4	----	0.128	0.130
	1-11 & E	----	0.093	0.102
	1-13 & C	----	0.023	0.032
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	0.008	0.008
	F & 2-3	----	0.010	0.027
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.027	0.025

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 μS		
		EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.195	0.200
	1-2 & 1-4	----	0.128	0.135
	1-11 & E	----	0.121	0.099
	1-13 & C	----	----	----
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	----	----
	F & 2-3	----	0.038	0.024
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.030	0.030

Note:

Expressions are the same as Table 3.1

Table 3.5 Field magnitude (kV/mm) at various locations of the coils with present tap lead insulation design, when the winding is subjected to full lightning wave (peak value 125 kV) and chopped lightning wave (peak value 145 kV), coils impregnated with oil

Tap cons.	Stress between	At 1.2 μS, full wave				At 1.16 μS, chopped wave			
		EC-1	EC-2	EC-3	Avg.	EC-1	EC-2	EC-3	Avg.
AB	1-1 & 1-3	19.34	17.85	16.89	18.03	22.74	24.19	24.73	23.89
	1-2 & 1-4	15.68	16.02	16.14	15.95	15.56	15.94	16.47	15.99
	1-11 & E	11.17	15.51	11.38	12.68	13.26	13.88	13.30	13.48
CD	1-1 & 1-3	----	18.23	17.97	18.10	----	24.99	25.24	25.11
	1-2 & 1-4	----	17.39	17.50	17.44	----	16.87	17.13	17.00
	1-11 & E	----	13.20	9.03	11.11	----	10.31	11.51	10.91
EF	1-1 & 1-3	----	19.04	18.59	18.81	----	26.04	26.78	26.41
	1-2 & 1-4	----	16.36	16.93	16.64	----	16.87	17.80	17.33
	1-11 & E	----	11.82	11.96	11.89	----	14.01	11.37	12.69

Note:

Expressions are the same as Table 3.1

Table 3.6 Simulation results of transient lightning wave distribution in transformer coils with design A of tap lead insulation, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 μS			Volt. diff. at 45 μS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.133	0.154	0.145	0.034	0.005	0.005
	1-2 & 1-4	0.138	0.141	0.142	0.030	0.020	0.004
	1-11 & E	0.120	0.155	0.114	0.007	0.010	0.033
	1-13 & C	0.023	0.009	0.016	0.004	0.007	0.015
	1-13 & A	0.063	0.010	0.073	0.011	0.005	0.005
	B & 2-1	0.012	0.034	0.038	0.033	0.030	0.042
	D & 2-1	0.004	0.001	0.021	0.012	0.000	0.029
	F & 2-3	0.036	0.057	0.034	0.066	0.053	0.013
	B & 2-2	0.038	0.004	0.026	0.076	0.051	0.058
	2-3 & 2-5	0.028	0.033	0.011	0.067	0.091	0.080
CD	1-1 & 1-3	----	0.157	0.155	----	0.013	0.012
	1-2 & 1-4	----	0.154	0.154	----	0.005	0.005
	1-11 & E	----	0.131	0.092	----	0.016	0.001
	1-13 & C	----	0.008	0.008	----	0.023	0.007
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	0.000	0.005	----	0.016	0.008
	F & 2-3	----	0.032	0.011	----	0.081	0.043
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.036	0.042	----	0.081	0.088

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 μS			Volt. diff. at 45 μS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.164	0.160	----	0.013	0.023
	1-2 & 1-4	----	0.145	0.149	----	0.024	0.026
	1-11 & E	----	0.118	0.120	----	0.003	0.019
	1-13 & C	----	----	----	----	----	----
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	----	----	----	----	----
	F & 2-3	----	0.019	0.040	----	0.068	0.026
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.035	0.025	----	0.085	0.067

Note:

Expressions are the same as Table 3.1

Table 3.7 Simulation results of chopped lightning wave distribution in transformer coils with design A of tap lead insulation, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 μS		
		EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.170	0.181	0.185
	1-2 & 1-4	0.118	0.121	0.126
	1-11 & E	0.117	0.122	0.118
	1-13 & C	0.028	0.017	0.025
	1-13 & A	0.078	0.059	0.029
	B & 2-1	0.030	0.009	0.018
	D & 2-1	0.011	0.002	0.002
	F & 2-3	0.028	0.038	0.043
	B & 2-2	0.049	0.037	0.028
	2-3 & 2-5	0.022	0.025	0.030
CD	1-1 & 1-3	----	0.187	0.189
	1-2 & 1-4	----	0.128	0.130
	1-11 & E	----	0.092	0.102
	1-13 & C	----	0.023	0.031
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	0.008	0.008
	F & 2-3	----	0.010	0.027
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.027	0.025

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 μS		
		EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.195	0.200
	1-2 & 1-4	----	0.128	0.135
	1-11 & E	----	0.121	0.099
	1-13 & C	----	----	----
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	----	----
	F & 2-3	----	0.038	0.024
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.030	0.030

Note:

Expressions are the same as Table 3.1

Table 3.8 Field magnitude (kV/mm) at various locations of the coils with design A, when the winding is subjected to full lightning wave (peak value 125 kV) and chopped lightning wave (peak value 145 kV), with oil impregnation

Tap cons.	Stress between	At 1.2 μS, full wave				At 1.16 μS, chopped wave			
		EC-1	EC-2	EC-3	Avg.	EC-1	EC-2	EC-3	Avg.
AB	1-1 & 1-3	19.36	17.81	16.84	18.00	22.76	24.24	24.76	23.92
	1-2 & 1-4	15.68	16.02	16.14	15.95	15.56	15.94	16.61	16.04
	1-11 & E	12.19	16.80	12.33	13.77	14.46	15.13	14.50	14.70
CD	1-1 & 1-3	----	18.19	17.95	18.07	----	25.00	25.25	25.12
	1-2 & 1-4	----	17.50	17.50	17.50	----	16.87	17.13	17.00
	1-11 & E	----	14.29	9.78	12.03	----	11.25	12.55	11.90
EF	1-1 & 1-3	----	19.01	18.59	18.80	----	26.03	26.78	26.40
	1-2 & 1-4	----	16.48	16.93	16.70	----	16.87	17.80	17.33
	1-11 & E	----	12.81	12.96	12.88	----	15.14	12.33	13.73

Note:

Expressions are the same as Table 3.1

Table 3.9 Simulation results of lightning wave distribution in transformer coils with design B of tap lead insulation, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 μS			Volt. diff. at 45 μS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.133	0.153	0.144	0.033	0.003	0.005
	1-2 & 1-4	0.139	0.142	0.143	0.027	0.017	0.003
	1-11 & E	0.119	0.154	0.113	0.005	0.003	0.034
	1-13 & C	0.022	0.009	0.016	0.004	0.006	0.013
	1-13 & A	0.062	0.010	0.075	0.012	0.020	0.010
	B & 2-1	0.011	0.033	0.040	0.037	0.017	0.047
	D & 2-1	0.004	0.001	0.021	0.013	0.002	0.028
	F & 2-3	0.036	0.057	0.034	0.063	0.056	0.010
	B & 2-2	0.038	0.004	0.027	0.076	0.042	0.064
	2-3 & 2-5	0.028	0.033	0.011	0.066	0.093	0.083
CD	1-1 & 1-3	----	0.157	0.155	----	0.011	0.011
	1-2 & 1-4	----	0.154	0.155	----	0.004	0.003
	1-11 & E	----	0.130	0.090	----	0.025	0.000
	1-13 & C	----	0.008	0.007	----	0.023	0.008
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	0.000	0.004	----	0.015	0.009
	F & 2-3	----	0.032	0.010	----	0.086	0.043
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.036	0.041	----	0.079	0.090

Tap cons.	Volt. diff. between	Volt. diff. at 1.2 µS			Volt. diff. at 45 µS		
		EC-1	EC-2	EC-3	EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.164	0.160	----	0.012	0.023
	1-2 & 1-4	----	0.145	0.150	----	0.022	0.026
	1-11 & E	----	0.117	0.119	----	0.007	0.015
	1-13 & C	----	----	----	----	----	----
	1-13 & A	----	----	----	----	----	----
	B & 2-1	----	----	----	----	----	----
	D & 2-1	----	----	----	----	----	----
	F & 2-3	----	0.019	0.039	----	0.067	0.027
	B & 2-2	----	----	----	----	----	----
	2-3 & 2-5	----	0.035	0.025	----	0.084	0.067

Note:

Expressions are the same as Table 3.1

Table 3.10 Simulation results of chopped lightning wave distribution in transformer coils with design B of tap lead insulation, with oil impregnation, entries in the table are in per unit of peak value of applied voltage

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 µS		
		EC-1	EC-2	EC-3
AB	1-1 & 1-3	0.170	0.181	0.185
	1-2 & 1-4	0.119	0.122	0.126
	1-11 & E	0.117	0.121	0.117
	1-13 & C	0.028	0.016	0.025
	1-13 & A	0.077	0.058	0.028
	B & 2-1	0.030	0.008	0.019
	D & 2-1	0.011	0.002	0.002
	F & 2-3	0.028	0.039	0.042
	B & 2-2	0.049	0.036	0.027
	2-3 & 2-5	0.022	0.025	0.030
CD	1-1 & 1-3	----	0.187	0.189
	1-2 & 1-4	----	0.129	0.131
	1-11 & E	----	0.092	0.101
	1-13 & C	----	0.022	0.031
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	0.008	0.008
	F & 2-3	----	0.009	0.027
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.027	0.025

Tap cons.	Volt. diff. between	Volt. diff. at 1.16 μS		
		EC-1	EC-2	EC-3
EF	1-1 & 1-3	----	0.195	0.200
	1-2 & 1-4	----	0.129	0.135
	1-11 & E	----	0.119	0.098
	1-13 & C	----	----	----
	1-13 & A	----	----	----
	B & 2-1	----	----	----
	D & 2-1	----	----	----
	F & 2-3	----	0.037	0.024
	B & 2-2	----	----	----
	2-3 & 2-5	----	0.030	0.029

Note:

Expressions are the same as Table 3.1

Table 3.11 Field magnitude (kV/mm) at various locations of the coils with design B, when the winding is subjected to full lightning wave (peak value 125 kV) and chopped lightning wave (peak value 145 kV), with oil impregnation

Tap cons.	Stress between	At 1.2 μS, full wave				At 1.16 μS, chopped wave			
		EC-1	EC-2	EC-3	Avg.	EC-1	EC-2	EC-3	Avg.
AB	1-1 & 1-3	19.40	17.77	16.79	17.99	22.80	24.30	24.81	23.97
	1-2 & 1-4	15.79	16.14	16.25	16.06	15.69	16.07	16.61	16.12
	1-11 & E	13.51	18.47	13.57	15.18	16.03	16.73	16.03	16.26
CD	1-1 & 1-3	----	18.15	17.92	18.03	----	25.04	25.27	25.15
	1-2 & 1-4	----	17.50	17.61	17.55	----	17.00	17.27	17.13
	1-11 & E	----	15.70	10.75	13.22	----	12.48	13.92	13.20
EF	1-1 & 1-3	----	19.00	18.59	18.79	----	26.07	26.80	26.43
	1-2 & 1-4	----	16.48	17.04	16.76	----	17.00	17.80	17.40
	1-11 & E	----	14.11	14.27	14.19	----	16.64	13.58	15.11

Note:

Expressions are the same as Table 3.1

4. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

In order to evaluate the present design of tap lead insulation of a distribution transformer with barrel-type coils and suggest more economic designs, it is necessary to simulate the transient impulse voltage distribution. Simulations were carried out by using the equivalent circuit method proposed by Lewis and Dent. A new accurate and flexible technique has been proposed to calculate lumped inductive components of the equivalent circuits. This technique is suitable for the application to transformers with barrel-type coils. The simulation results of transient voltage distribution have been validated by comparison with test measurement results. The effect of various equivalent circuit models and the effect of tap connections to transient voltage distribution have been examined. According to the RSG measurement and simulation results, the transient impulse voltage distribution have following characteristics:

- Impulse voltage input causes oscillations in transformer coils. These oscillations attenuate significantly after about 100 microseconds.
- During the first 100 microseconds period, the transient voltage distribution in transformer winding is very non-uniform, that is, in the first 2 ~ 3 microseconds, the windings of the coil No. 1 near the input end experience relatively large voltage drop, while at about 45 microseconds, the oscillations in the coils cause high voltage drop inside the coil No.2.
- The potentials of the tap leads and the adjacent layers are almost identical, except that there is some potential difference between taps E, F and their adjacent layers.
- The transient voltage distribution of chopped lightning wave is even more non-uniform than that of full lightning wave in coil No. 1.

By modification of the capacitive components in the equivalent networks to reflect the effect of oil impregnation, the transient impulse voltage distribution under actual working condition were simulated. By using the simulation results as boundary conditions, field stress in the insulation near the input end and tap lead insulation were evaluated under over-voltage condition by quasi-static field analysis. The results show that the insulation design of the transformer coils is safe; tap lead insulation design with three layers of paper is conservative and it can be improved. Two modified designs have been suggested. One includes two layers of paper around the tap leads, the other includes only one layer of paper. The simulation results show that the transient impulse voltage distributions do not change significantly when the tap lead insulation design is modified. The field stress analysis shows that the field stress in the insulation of the modified designs at the location of the tap lead is still well below the stress at the input end. In view of the factor of safety built into the field analysis. Therefore, the tap lead insulation can be reduced to two layers of paper or only one layer of paper without any problem from an electrical point of view.

Although, the conclusions are drawn based upon consideration of a specific distribution transformer, all the methods used in this research work are general in the sense that they may be used to evaluate insulation levels in other types of transformer with barrel type coils.

For future research, the effect of iron core on the lumped inductive components of the equivalent circuit of transformer with barrel-type coils should be investigated. The transient impulse voltage distribution caused by the current surge entering the low voltage side and corresponding tap lead insulation stress evaluation are worth ascertaining by both test measurement and simulation method [18].

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APPENDIX A.

Curve Fitting and Sectionalization Programs (Partial)

```
*
* PROGRAM read
*
* USE TO READ MEASURING DATA POINTS AND OUTPUT STEPPED
* LINE END POINTS AND SHOWING CURVE DATA POINTS
*
      PROGRAM read
*
*
      PARAMETER(C1X=0.0)
*
      INTEGER DIV,M,NUM
      PARAMETER (M=4,NUM=5)
      DOUBLE PRECISION T1X(NUM),T1Y(NUM),T2X(NUM),T2Y(NUM)
      DOUBLE PRECISION T3X(NUM),T3Y(NUM),T4X(NUM),T4Y(NUM)
      DOUBLE PRECISION A1(M),A2(M),A3(M),A4(M)
      DOUBLE PRECISION STX(1000),STY(1000),SHX(1000),SHY(1000)
      REAL SHXX(1000),SHYY(1000)
      REAL STXX(1000),STYY(1000)
      DOUBLE PRECISION XAVG(4)
      DOUBLE PRECISION WID
      DOUBLE PRECISION TMLEN, TTLEN
*
      PRINT *,'INPUT LINE DIVISION VALUE'
      READ(*,10) DIV
   10 FORMAT(I3)
*
      OPEN(UNIT=10,FILE='input1/length.txt')
*        2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678 90
************************************************ LAYER No.1
      OPEN(UNIT=11,FILE='input1/md11.txt')
      OPEN(UNIT=12,FILE='input1/md12.txt')
      OPEN(UNIT=13,FILE='input1/md13.txt')
      OPEN(UNIT=14,FILE='input1/md14.txt')
*
      OPEN(UNIT=21,FILE='input2/stp1.txt')
      OPEN(UNIT=22,FILE='input31/c1stp1.txt')
*
      OPEN(UNIT=31,FILE='output/shc1.txt')
      OPEN(UNIT=32,FILE='output/sttp1.txt')
*
      XX=0
      DO 100 I=1,NUM
         READ(11,110) T1X(I),T1Y(I)
  110    FORMAT(D12.4,5X,D12.4)
         XX=XX+T1X(I)
  100 CONTINUE
      XAVG(1)=XX/NUM
```

```
*
*
      XX=0
      DO 120 I=1,NUM
         READ(12,130) T2X(I),T2Y(I)
 130     FORMAT(D12.4,5X,D12.4)
         WID=T2X(NUM)
         XX=XX+T2X(I)
 120  CONTINUE
      XAVG(2)=XX/NUM
*
*
      XX=0
      DO 140 I=1,NUM
         READ(13,150) T3X(I),T3Y(I)
 150     FORMAT(D12.4,5X,D12.4)
         XX=XX+T3X(I)
 140  CONTINUE
      XAVG(3)=XX/NUM
*
*
      XX=0
      DO 160 I=1,NUM
         READ(14,170) T4X(I),T4Y(I)
 170     FORMAT(D12.4,5X,D12.4)
         XX=XX+T4X(I)
 160  CONTINUE
      XAVG(4)=XX/NUM
*
      CALL fit(T1X,T1Y,T2X,T2Y,T3X,T3Y,T4X,T4Y,
     $NUM,M,STX,STY,SHX,SHY,XAVG,DIV,WID,A1,A2,A3,A4)
      DO 180 I=1,8*DIV+6
         STXX(I)=STX(I)
         STYY(I)=STY(I)
         WRITE(32,182) STXX(I)+C1X,STYY(I)
 182     FORMAT(E10.4,5X,E10.4)
         WRITE(21,184) STX(I),STY(I)
         WRITE(22,184) STX(I)+C1X,STY(I)
 184     FORMAT(D16.10,5X,D16.10)
 180  CONTINUE
      DO 186 I=1,803
         SHXX(I)=SHX(I)
         SHYY(I)=SHY(I)
         WRITE(31,188) SHXX(I),SHYY(I)
 188     FORMAT(E10.4,5X,E10.4)
 186  CONTINUE
*
      TTLEN=0.0
      DO 190 I=1,803-1
         TMLEN=0.0
         TMLEN=SQRT((SHX(I+1)-SHX(I))*(SHX(I+1)-SHX(I))+
     $(SHY(I+1)-SHY(I))*(SHY(I+1)-SHY(I)))
         TTLEN=TTLEN+TMLEN
 190  CONTINUE
```

```
      WRITE(10,*) 1, TTLEN
*
      CLOSE(11)
      CLOSE(12)
      CLOSE(13)
      CLOSE(14)
*
      CLOSE(21)
      CLOSE(22)
*
      CLOSE(31)
      CLOSE(32)
****************************************** END OF LAYER No.1
      CLOSE(10)
      STOP
      END


*
* SUBROUTINE fit
*
      SUBROUTINE fit(M1X,M1Y,M2X,M2Y,M3X,M3Y,M4X,M4Y,
     $NUM,M,STX,STY,SHX,SHY,XAVG,DIV,WID,A1,A2,A3,A4)
*
      DOUBLE PRECISION M1X(NUM),M2X(NUM),M3X(NUM),M4X(NUM)
      DOUBLE PRECISION M1Y(NUM),M2Y(NUM),M3Y(NUM),M4Y(NUM)
      DOUBLE PRECISION STXX(1000),STYY(1000)
      DOUBLE PRECISION STX(1000),STY(1000)
      DOUBLE PRECISION SHX(1000),SHY(1000)
      DOUBLE PRECISION XAVG(4),WID
      DOUBLE PRECISION X,Y,Y1,Y2
      DOUBLE PRECISION A1(M),A2(M),A3(M),A4(M)
      INTEGER I,J,NUM,DIV,TNUM
*
* CALL SUBROUTINE pcir TO DETERMINE THE COEFFICIENTS
* OF FITTING FUNCTION
*
*        2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      CALL pcir(M1X,M1Y,A1,NUM,M)
      CALL pcir(M2X,M2Y,A2,NUM,M)
      CALL pcir(M3X,M3Y,A3,NUM,M)
      CALL pcir(M4X,M4Y,A4,NUM,M)
*
*        2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      DO 10 I=1,201
      X=WID*(I-201)/200
      SHX(I)=X
      Y1=1
      Y=A1(1)
      DO 20 J=2,M
         Y1=Y1*(X-XAVG(1))
         Y2=A1(J)*Y1
```

```
         Y=Y+Y2
   20 CONTINUE
      SHY(I)=Y
   10 CONTINUE
*
*          2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678
      DO 30 I=202,401
      X=WID*(I-201)/200
      SHX(I)=X
      Y1=1
      Y=A2(1)
      DO 40 J=2,M
         Y1=Y1*(X-XAVG(2))
         Y2=A2(J)*Y1
         Y=Y+Y2
   40 CONTINUE
      SHY(I)=Y
   30 CONTINUE
*
*          2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678
      DO 50 I=402,602
      X=WID*(602-I)/200
      SHX(I)=X
      Y1=1
      Y=A3(1)
      DO 60 J=2,M
         Y1=Y1*(X-XAVG(3))
         Y2=A3(J)*Y1
         Y=Y+Y2
   60 CONTINUE
      SHY(I)=Y
   50 CONTINUE
*
*          2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678
      DO 70 I=603,802
      X=WID*(602-I)/200
      SHX(I)=X
      Y1=1
      Y=A4(1)
      DO 80 J=2,M
         Y1=Y1*(X-XAVG(4))
         Y2=A4(J)*Y1
         Y=Y+Y2
   80 CONTINUE
      SHY(I)=Y
   70 CONTINUE
*
* CONNECTION POINT
      SHX(803)=SHX(1)
      SHY(803)=SHY(1)
*
```

```
**
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      DO 100 I=1,(DIV+1)
      X=WID*(I-(DIV+1))/DIV
      STXX(I)=X
      Y1=1
      Y=A1(1)
      DO 110 J=2,M
         Y1=Y1*(X-XAVG(1))
         Y2=A1(J)*Y1
         Y=Y+Y2
  110 CONTINUE
      STYY(I)=Y
  100 CONTINUE
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      DO 120 I=(DIV+2),(2*DIV+1)
      X=WID*(I-(DIV+1))/DIV
      STXX(I)=X
      Y1=1
      Y=A2(1)
      DO 130 J=2,M
         Y1=Y1*(X-XAVG(2))
         Y2=A2(J)*Y1
         Y=Y+Y2
  130 CONTINUE
      STYY(I)=Y
  120 CONTINUE
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      DO 140 I=(2*DIV+2),(3*DIV+2)
      X=WID*((3*DIV+2)-I)/DIV
      STXX(I)=X
      Y1=1
      Y=A3(1)
      DO 150 J=2,M
         Y1=Y1*(X-XAVG(3))
         Y2=A3(J)*Y1
         Y=Y+Y2
  150 CONTINUE
      STYY(I)=Y
  140 CONTINUE
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      DO 160 I=(3*DIV+3),(4*DIV+2)
      X=WID*((3*DIV+2)-I)/DIV
      STXX(I)=X
      Y1=1
      Y=A4(1)
      DO 170 J=2,M
```

```
          Y1=Y1*(X-XAVG(4))
          Y2=A4(J)*Y1
          Y=Y+Y2
  170 CONTINUE
      STYY(I)=Y
  160 CONTINUE
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      STXX(4*DIV+3)=STXX(1)
      STYY(4*DIV+3)=STYY(1)
*
* TOTAL NUMBER OF STEP POINTS
      TNUM=4*DIV+3
*
      CALL step(STXX,STYY,TNUM,STX,STY)
      RETURN
      END


*
* SUBROUTINE pcir
*
*      CURVE FITTING USING LEAST SQUARE METHOD TO N DATA POINTS
*      WITH POLYNOMINAL FUNCTION
*      SUBROUTINE NAME: PCIR
*
*
*      SUBROUTINE pcir(X,Y,A,N,M,DT1,DT2,DT3)
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      SUBROUTINE pcir(X,Y,A,N,M)
      DIMENSION X(N),Y(N),A(M),S(20),T(20),B(20)
      DOUBLE PRECISION X,Y,A,S,T,B,DT1,DT2,DT3,Z,D1,P,C,D2,G,
     $Q,DT
      Z=0.0
      DO 10 I=1,N
 10   Z=Z+X(I)/N
      B(1)=1.0
      D1=N
      P=0.0
      C=0.0
      DO 20 I=1,N
         P=P+(X(I)-Z)
         C=C+Y(I)
 20   CONTINUE
      C=C/D1
      P=P/D1
      A(1)=C*B(1)
      IF ( M.GT.1 ) THEN
         T(2)=1.0
         T(1)=-P
         D2=0.0
         C=0.0
```

```
         G=0.0
         DO 30 I=1,N
            Q=X(I)-Z-P
            D2=D2+Q*Q
            C=Y(I)*Q+C
            G=(X(I)-Z)*Q*Q+G
30       CONTINUE
         C=C/D2
         P=G/D2
         Q=D2/D1
         D1=D2
         A(2)=C*T(2)
         A(1)=C*T(1)+A(1)
      END IF
      DO 100  J=3,M
         S(J)=T(J-1)
         S(J-1)=-P*T(J-1)+T(J-2)
         IF ( J.GE.4 ) THEN
            DO 40 K=J-2,2,-1
40             S(K)=-P*T(K)+T(K-1)-Q*B(K)
         END IF
         S(1)=-P*T(1)-Q*B(1)
         D2=0.0
         C=0.0
         G=0.0
         DO 70 I=1,N
            Q=S(J)
            DO 60 K=J-1,1,-1
60          Q=Q*(X(I)-Z)+S(K)
            D2=D2+Q*Q
            C=Y(I)*Q+C
            G=(X(I)-Z)*Q*Q+G
70       CONTINUE
         C=C/D2
         P=G/D2
         Q=D2/D1
         D1=D2
         A(J)=C*S(J)
         T(J)=S(J)
         DO 80 K=J-1,1,-1
            A(K)=C*S(K)+A(K)
            B(K)=T(K)
            T(K)=S(K)
80       CONTINUE
100   CONTINUE
      DT1=0.0
      DT2=0.0
      DT3=0.0
      DO 120 I=1,N
        Q=A(M)
        DO 110 K=M-1,1,-1
110        Q=Q*(X(I)-Z)+A(K)
        DT=Q-Y(I)
        IF ( ABS(DT).GT.DT3 ) DT3=ABS(DT)
```

```
          DT1=DT1+DT*DT
          DT2=DT2+ABS(DT)
 120  CONTINUE
      RETURN
      END


*
*
* SUBROUTINE step
*
      SUBROUTINE step(XX,YY,NUM,SXX,SYY)
*
      DIMENSION XX(NUM), YY(NUM), SXX(1000), SYY(1000)
      DOUBLE PRECISION XX,YY,SXX,SYY
      INTEGER NUM, I
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
      SXX(1)=XX(1)
      SYY(1)=YY(1)
      SXX(2)=XX(1)
      SYY(2)=0.5*(YY(1)+YY(2))
      DO 100 I=2,NUM-1
         SXX(2*I-1)=XX(I)
         SYY(2*I-1)=0.5*(YY(I-1)+YY(I))
         SXX(2*I)=XX(I)
         SYY(2*I)=0.5*(YY(I)+YY(I+1))
 100  CONTINUE
      SXX(2*NUM-1)=XX(NUM)
      SYY(2*NUM-1)=0.5*(YY(NUM-1)+YY(NUM))
      SXX(2*NUM)=XX(NUM)
      SYY(2*NUM)=YY(NUM)
      RETURN
      END
*
```

APPENDIX B.

Equivalent Circuit Parameters Calculation Programs (Partial)

```
* PROGRAM call
*
* USE TO CALCULATE THE SELF INDUCTANCE, CAPACITANCE AND
* RESISTANCE OF DIFFERENT LAYER/SUB-LAYER
*
      PROGRAM call
*
      COMMON /COM1/ PI,E0,ER,MU
      COMMON /COM2/ SIGMA,FREQ
      COMMON /COM3/ RADIUS,PITCH
*
      PARAMETER(DIV=5,NS=13)
*
      DOUBLE PRECISION PI,E0,ER,MU,SIGMA,FREQ,RADIUS,PITCH
      DOUBLE PRECISION DX(1000),DY(1000),DZ(1000)
      DOUBLE PRECISION TL,TC,TR
      INTEGER NUM,TMP,I
      INTEGER NUMZ(50)
*
      NUM=8*DIV+6
*
*  INPUT THE NUMBER OF TURNS IN EACH SECTION
*
       OPEN(UNIT=5,FILE='input1/section.txt')
       DO 50 I=1,NS
          READ(5,*) NUMZ(I)
 50    CONTINUE
       CLOSE(5)
*
* INPUT THE NUMBER OF TURNS IN EACH LAYER
*
      OPEN(UNIT=10,FILE='output/p2s1sl1-5.txt')
****************************************** START LAYER No.1
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
*
      TL=0.0
      TC=0.0
      TR=0.0
*
      OPEN(UNIT=11,FILE='input1/mz1.txt')
      DO 100 I=1,NUMZ(1)
         READ(11,110) DZ(I)
 110     FORMAT(D12.4)
 100  CONTINUE
      CLOSE(11)
*
      OPEN(UNIT=12,FILE='input2/stp1.txt')
      DO 120 I=1,NUM
```

```
         READ(12,130) DX(I),DY(I)
 130     FORMAT(D16.10,5X,D16.10)
 120  CONTINUE
      CLOSE(12)
*
      CALL slcr(DX,DY,DZ,TL,TC,TR,NUM,NUMZ(1))
*
      TMP=1
      WRITE(10,140) TMP,TL,TC,TR
 140  FORMAT(I3,5X,D16.10,5X,D16.10,5X,D16.10)
********************************************* END LAYER No.1
*
      CLOSE(10)
      STOP
      END
* END OF PROGRAM cal1


* PROGRAM cal2
* USE TO CALCULATE MUTUAL INDUCTANCE BETWEEN TWO DIFFERENT SECTIONS
*
*        2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234567890
      PROGRAM cal2
*
      PARAMETER(DIV=5,NS=13)
      DOUBLE PRECISION DX(50,200),DY(50,200),DZ(50,300)
      DOUBLE PRECISION ML(50,50)
      DOUBLE PRECISION LLL,LL
      INTEGER I,J,K,L,M,N
      INTEGER NUM
      INTEGER NUMZ(50)
*
      NUM=8*DIV+6
*
       OPEN(UNIT=5,FILE='input1/section.txt')
       DO 1000 I=1,NS
       READ(5,*) NUMZ(I)
 1000  CONTINUE
       CLOSE(5)
*
      OPEN(UNIT=10,FILE='output/p2s1ml1-5.txt')
*
      OPEN(UNIT=11,FILE='input2/stp1.txt')
      OPEN(UNIT=12,FILE='input2/stp2.txt')
      OPEN(UNIT=13,FILE='input2/stp3.txt')
      OPEN(UNIT=14,FILE='input2/stp4.txt')
      OPEN(UNIT=15,FILE='input2/stp5.txt')
      OPEN(UNIT=16,FILE='input2/stp6.txt')
      OPEN(UNIT=17,FILE='input2/stp7.txt')
      OPEN(UNIT=18,FILE='input2/stp8.txt')
      OPEN(UNIT=19,FILE='input2/stp9.txt')
      OPEN(UNIT=20,FILE='input2/stp10.txt')
      OPEN(UNIT=21,FILE='input2/stp11.txt')
```

```
      OPEN(UNIT=22,FILE='input2/stp12.txt')
      OPEN(UNIT=23,FILE='input2/stp13.txt')
*
*        2         3         4         5         6
*23456789012345678901234567890123456789012345678901234567890
      DO 1010 I=1,NS
         DO 1020 J=1,NUM
            II=I+10
            READ(II,1030) DX(I,J),DY(I,J)
 1030       FORMAT(D16.10,5X,D16.10)
 1020    CONTINUE
 1010 CONTINUE
      CLOSE(11)
      CLOSE(12)
      CLOSE(13)
      CLOSE(14)
      CLOSE(15)
      CLOSE(16)
      CLOSE(17)
      CLOSE(18)
      CLOSE(19)
      CLOSE(20)
      CLOSE(21)
      CLOSE(22)
      CLOSE(23)
*
      OPEN(UNIT=11,FILE='input1/mz1.txt')
      OPEN(UNIT=12,FILE='input1/mz2.txt')
      OPEN(UNIT=13,FILE='input1/mz3.txt')
      OPEN(UNIT=14,FILE='input1/mz4.txt')
      OPEN(UNIT=15,FILE='input1/mz5.txt')
      OPEN(UNIT=16,FILE='input1/mz6.txt')
      OPEN(UNIT=17,FILE='input1/mz7.txt')
      OPEN(UNIT=18,FILE='input1/mz8.txt')
      OPEN(UNIT=19,FILE='input1/mz9.txt')
      OPEN(UNIT=20,FILE='input1/mz10.txt')
      OPEN(UNIT=21,FILE='input1/mz11.txt')
      OPEN(UNIT=22,FILE='input1/mz12.txt')
      OPEN(UNIT=23,FILE='input1/mz13.txt')
*
*        2         3         4         5         6
*23456789012345678901234567890123456789012345678901234567890
*
      DO 1040 I=1,NS
         DO 1050 J=1,NUMZ(I)
            II=I+10
            READ(II,1060) DZ(I,J)
 1060       FORMAT(D12.4)
 1050    CONTINUE
 1040 CONTINUE
      CLOSE(11)
      CLOSE(12)
      CLOSE(13)
      CLOSE(14)
```

```
      CLOSE(15)
      CLOSE(16)
      CLOSE(17)
      CLOSE(18)
      CLOSE(19)
      CLOSE(20)
      CLOSE(21)
      CLOSE(22)
      CLOSE(23)
*
*        2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234567890
      DO 1100 I=1,NS-1
         DO 1110 L=(I+1),NS
            LL=0.0
            DO 1120 N=1,NUMZ(L)
               DO 1130 M=1,NUM-1
                  DO 1140 K=1,NUMZ(I)
                     DO 1150 J=1,NUM-1
                        LLL=0.0
                        CALL mutual(DX(I,J),DY(I,J),DZ(I,K),
     $DX(I,J+1),DY(I,J+1),DZ(I,K),DX(L,M),DY(L,M),DZ(L,N),
     $DX(L,M+1),DY(L,M+1),DZ(L,N),LLL)
                        LL=LL+LLL
 1150                CONTINUE
 1140             CONTINUE
 1130          CONTINUE
 1120       CONTINUE
*        2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234567890
         ML(I,L)=LL
 1110    CONTINUE
 1100 CONTINUE
*
*        2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234567890
      DO 1200 I=1,NS-1
         DO 1210 J=I+1,NS
            WRITE(10,1220) I, J, ML(I,J)
 1220       FORMAT(I3,5X,I3,5X,D16.10)
 1210    CONTINUE
 1200 CONTINUE
*
      CLOSE(10)
      STOP
      END
*

* SUBROUTINE slcr
*
* USE TO CALCULATE THE SELF INDUCTANCE, CAPACITANCE AND
* RESISTANCE OF A LAYER/SECTION
*
      SUBROUTINE slcr(DX,DY,DZ,TL,TC,TR,NUM,NUMZ)
```

```
*
*
      COMMON /COM1/ PI,E0,ER,MU
      COMMON /COM2/ SIGMA,FREQ
      COMMON /COM3/ RADIUS,PITCH
*
      DOUBLE PRECISION PI,E0,ER,MU,SIGMA,FREQ,RADIUS,PITCH
      DOUBLE PRECISION DX(NUM),DY(NUM),DZ(NUMZ)
      DOUBLE PRECISION TL,TC,TR
      DOUBLE PRECISION SL,SLL,SELFL,ML,MLL
      DOUBLE PRECISION CC,TLEN,LEN
      DOUBLE PRECISION RR,TTR
      INTEGER I,J,K,L,NUM,NUMZ
*
      TL=0.0
      TR=0.0
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
      SLL=0.0
      DO 500 I=1,NUM-1
         CALL self(DX(I),DY(I),DZ(1),DX(I+1),DY(I+1),DZ(1),SL)
         SLL=SLL+SL
 500  CONTINUE
      SELFL=SLL*NUMZ
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
      ML=0.0
      MLL=0.0
      DO 510 K=1,NUMZ
         DO 520 I=1,NUM-1
            DO 530 L=1,NUMZ
               DO 540 J=1,NUM-1
          CALL mutual(DX(I),DY(I),DZ(K),DX(I+1),DY(I+1),DZ(K),
     $DX(J),DY(J),DZ(L),DX(J+1),DY(J+1),DZ(L),ML)
                  MLL=MLL+ML
 540           CONTINUE
 530        CONTINUE
 520     CONTINUE
 510  CONTINUE
*
      TL=SELFL+MLL
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
      LEN=0.0
      CC=0.0
      TC=0.0
      DO 550 I=1,NUM-1
         TLEN=SQRT((DX(I)-DX(I+1))*(DX(I)-DX(I+1))+
     $(DY(I)-DY(I+1))*(DY(I)-DY(I+1)))
         LEN=LEN+TLEN
 550  CONTINUE
```

```
      CALL cap1(NUMZ,LEN,CC)
      TC=CC
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      TTR=0.0
      DO 600 I=1,NUM-1
         CALL res(DX(I),DY(I),DZ(1),DX(I+1),DY(I+1),DZ(1),RR)
         TTR=TTR+RR
 600  CONTINUE
      TR=NUMZ*TTR
*      WRITE(8,610) TL, TC, TR
* 610  FORMAT(D16.10,5X,D16.10,5X,D16.10)
*
      RETURN
      END


* SUBROUTINE self
*
      SUBROUTINE self(DX1,DY1,DZ1,DX2,DY2,DZ2,L)
*
*
      COMMON /COM1/ PI,E0,ER,MU
      COMMON /COM2/ SIGMA,FREQ
      COMMON /COM3/ RADIUS,PITCH
*
      DOUBLE PRECISION PI,E0,ER,MU,SIGMA,FREQ,RADIUS,PITCH
      DOUBLE PRECISION L,LEN,DX1,DY1,DZ1,DX2,DY2,DZ2
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
*
      IF ((DX1 .EQ. DX2) .AND. (DY1 .EQ. DY2)) THEN
         L=0.
      ELSE
         LEN=SQRT((DX2-DX1)*(DX2-DX1)+(DY2-DY1)*(DY2-DY1)+
     $(DZ2-DZ1)*(DZ2-DZ1))
         L=0.002*LEN*(LOG(2*LEN/RADIUS)-0.75)
      END IF
      RETURN
      END


* SUBROUTINE mutual
*
* USE TO CALCULATE THE MUTUAL INDUCTANCE
* OF TWO STRAIGHT LINE SEGMENTS
*
      SUBROUTINE mutual(DX11, DY11, DZ11, DX12, DY12, DZ12,
     $DX21, DY21, DZ21, DX22, DY22, DZ22, MUTL)
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
```

```
      DOUBLE PRECISION DX11, DY11, DZ11, DX12, DY12, DZ12
      DOUBLE PRECISION DX21, DY21, DZ21, DX22, DY22, DZ22
      DOUBLE PRECISION LEN1, LEN2, DIS, DELTA
      DOUBLE PRECISION MUTL, ALPH, BELTA, GARMA
      DOUBLE PRECISION BIGX1, BIGY1, BIGX2, BIGY2
      DOUBLE PRECISION SMAX1, SMAY1, SMAX2, SMAY2
      DOUBLE PRECISION SIGN
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      IF (( DX11 .EQ. DX12) .AND. ( DX21 .EQ. DX22 )) THEN
*
         IF ((DX11*DX21) .GT. 0 ) THEN
            SIGN=1.0
         ELSE
            SIGN=-1.0
         END IF
         LEN1=ABS(DY11-DY12)
         LEN2=ABS(DY21-DY22)
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
           IF ( DZ11 .EQ. DZ21 ) THEN
              DIS=ABS(DX11-DX21)
           ELSE
              DIS=SQRT((DX11-DX21)*(DX11-DX21)+(DZ11-DZ21)*
     $(DZ11-DZ21))
           END IF
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
           IF ( DIS .EQ. 0. ) THEN
              MUTL=0.0
              RETURN
           ELSE
              CONTINUE
           END IF
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
           IF ( DY11 .GT. DY12 ) THEN
              BIGY1=DY11
              SMAY1=DY12
           ELSE
              BIGY1=DY12
              SMAY1=DY11
           END IF
           IF ( DY21 .GT. DY22 ) THEN
              BIGY2=DY21
              SMAY2=DY22
           ELSE
              BIGY2=DY22
              SMAY2=DY21
           END IF
```

```
*
           IF ( BIGY1 .GT. BIGY2 ) THEN
              DELTA=SMAY1-BIGY2
*
           ELSE IF ( BIGY2 .GT. BIGY1 ) THEN
                   DELTA=SMAY2-BIGY1
*
           ELSE IF ( SMAY1 .GT. SMAY2 ) THEN
                   DELTA=-LEN1
           ELSE
                   DELTA=-LEN2
           END IF
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
       ALPH=LEN1+LEN2+DELTA
      BELTA=LEN1+DELTA
      GARMA=LEN2+DELTA
       MUTL=0.001*(ALPH*LOG((ALPH/DIS)+SQRT((ALPH/DIS)*(ALPH/
     $DIS)+1))-BELTA*LOG((BELTA/DIS)+SQRT((BELTA/DIS)*(BELTA/
     $DIS)+1))-GARMA*LOG((GARMA/DIS)+SQRT((GARMA/DIS)*(GARMA/
     $DIS)+1))+DELTA*LOG((DELTA/DIS)+SQRT((DELTA/DIS)*(DELTA/
     $DIS)+1))-
     $SQRT(ALPH*ALPH+DIS*DIS)+
     $SQRT(BELTA*BELTA+DIS*DIS)+
     $SQRT(GARMA*GARMA+DIS*DIS)-
     $SQRT(DELTA*DELTA+DIS*DIS))*SIGN
      RETURN
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
      ELSE IF (( DY11.EQ.DY12).AND.( DY21.EQ.DY22 )) THEN
*
              IF ((DY11*DY21) .GT. 0 ) THEN
                 SIGN=1.0
              ELSE
                 SIGN=-1.0
              END IF
              LEN1=ABS(DX11-DX12)
              LEN2=ABS(DX21-DX22)
*
*         2         3         4         5         6
*23456789012345678901234567890123456789912345678901234567890
             IF ( DZ11 .EQ. DZ21 ) THEN
                DIS=ABS(DY11-DY21)
             ELSE
                DIS=SQRT((DY11-DY21)*(DY11-DY21)+(DZ11-DZ21)*
     $(DZ11-DZ21))
             END IF
*
           IF ( DIS .EQ. 0. ) THEN
              MUTL=0.0
              RETURN
           ELSE
```

```
            CONTINUE
         END IF
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
         IF ( DX11 .GT. DX12 ) THEN
            BIGX1=DX11
            SMAX1=DX12
         ELSE
            BIGX1=DX12
            SMAX1=DX11
         END IF
         IF ( DX21 .GT. DX22 ) THEN
            BIGX2=DX21
            SMAX2=DX22
         ELSE
            BIGX2=DX22
            SMAX2=DX21
         END IF
*
         IF ( BIGX1 .GT. BIGX2 ) THEN
            DELTA=SMAX1-BIGX2
*
         ELSE IF ( BIGX2 .GT. BIGX1 ) THEN
                 DELTA=SMAX2-BIGX1
*
         ELSE IF ( SMAX1 .GT. SMAX2 ) THEN
                 DELTA=-LEN1
         ELSE
                 DELTA=-LEN2
         END IF
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
       ALPH=LEN1+LEN2+DELTA
      BELTA=LEN1+DELTA
      GARMA=LEN2+DELTA
       MUTL=0.001*(ALPH*LOG((ALPH/DIS)+SQRT((ALPH/DIS)*(ALPH/
     $DIS)+1))-BELTA*LOG((BELTA/DIS)+SQRT((BELTA/DIS)*(BELTA/
     $DIS)+1))-GARMA*LOG((GARMA/DIS)+SQRT((GARMA/DIS)*(GARMA/
     $DIS)+1))+DELTA*LOG((DELTA/DIS)+SQRT((DELTA/DIS)*(DELTA/
     $DIS)+1))-
     $SQRT(ALPH*ALPH+DIS*DIS)+
     $SQRT(BELTA*BELTA+DIS*DIS)+
     $SQRT(GARMA*GARMA+DIS*DIS)-
     $SQRT(DELTA*DELTA+DIS*DIS))*SIGN
      RETURN
*
      ELSE
         MUTL=0.0
      END IF
      RETURN
      END
```

```
* SUBROUTINE cap1
*
* USED TO CALCULATE THE SELF-CAPACITANCE OF A LAYER/SUB-LAYER
*
*         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234567890
      SUBROUTINE cap1(NUMZ,LEN,SC)
*
      COMMON /COM1/ PI,E0,ER,MU
      COMMON /COM2/ SIGMA,FREQ
      COMMON /COM3/ RADIUS,PITCH
*
      DOUBLE PRECISION PI,E0,ER,MU,SIGMA,FREQ,RADIUS,PITCH
      DOUBLE PRECISION LEN,SC
      INTEGER NUMZ
*
      SC=(E0*ER*2*(RADIUS/100))/((PITCH/100)-2*(RADIUS/100))*
     $((NUMZ-1.0)/(NUMZ*NUMZ))*(LEN/100)
*
      RETURN
      END


*  SUBROUTINE  res
*
*  USED TO CALCULATE HIGH FREQUENCY RESISTANCE OF A LINE
SEGMENT                                                    *
      SUBROUTINE res(DX1,DY1,DZ1,DX2,DY2,DZ2,SR)
*
      COMMON /COM1/ PI,E0,ER,MU
      COMMON /COM2/ SIGMA,FREQ
      COMMON /COM3/ RADIUS,PITCH
*
      DOUBLE PRECISION PI,E0,ER,MU,SIGMA,FREQ,RADIUS,PITCH
      DOUBLE PRECISION DX1,DY1,DZ1,DX2,DY2,DZ2,SR
      DOUBLE PRECISION OMEGA,DEEP,AREA,LEN
*
*         2         3         4         5         6
*234567890123456789012345678901234567899123456789012345678901234567890
*
      OMEGA=2.0*PI*FREQ
*
      DEEP=SQRT(2.0/(OMEGA*MU*SIGMA))
*
      AREA=2*PI*((RADIUS/100)*(RADIUS/100)-((RADIUS/100)-DEEP)*
     $((RADIUS/100)-DEEP))
*
      LEN=0.01*SQRT((DX1-DX2)*(DX1-DX2)+(DY1-DY2)*(DY1-DY2)+(DZ1-
     $DZ2)*(DZ1-DZ2))
*
      SR=LEN/(SIGMA*AREA)
*
      RETURN
      END
```

APPENDIX C.

Electromagnetic Transient Analysis Program (Partial)

```
* PROGRAM emtp
* USED TO CALCULATE THE TRANSIENT RESPONSE OF A R-L-C NETWORK
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
      PROGRAM emtp
*
* INPUT DATA
      PARAMETER (IBN=185)
      PARAMETER (INN=54)
      PARAMETER (IRRN=29)
      PARAMETER (ICCN=130)
      PARAMETER (ILLN=26)
      PARAMETER (IMLN=325)
*
      DOUBLE PRECISION AA(INN,IBN),AAT(IBN,INN)
      DOUBLE PRECISION AMR(IRRN,IRRN),AMC(ICCN,ICCN),AML(ILLN,ILLN)
      INTEGER ADR(IRRN),ADC(ICCN),ADL(ILLN)
      DOUBLE PRECISION DELTT
      INTEGER TIS,SN
      DOUBLE PRECISION ZE(IBN,IBN),YB(IBN,IBN)
      DOUBLE PRECISION MR(IRRN,IRRN),MC(ICCN,ICCN),ML(ILLN,ILLN)
      DOUBLE PRECISION TYN(INN,IBN),YN(INN,INN),YNI(INN,INN)
      DOUBLE PRECISION TML(ILLN,ILLN)
      DOUBLE PRECISION TT,SVAL,VG(IBN)
      DOUBLE PRECISION VN(INN),VB(IBN),VE(IBN),CE(IBN),ECS(IBN)
      DOUBLE PRECISION CN1(IBN),CN2(IBN),CN3(IBN),CN4(IBN)
      INTEGER ERROR,TEMPIS(IBN),TEMPJS(IBN)
      DOUBLE PRECISION TVAL1,TVAL2
      DOUBLE PRECISION VCE(ICCN),TCCE(ICCN)
      DOUBLE PRECISION VLE(ILLN),ILE(ILLN),TCL1E(ILLN),TCL2E(ILLN)
      DOUBLE PRECISION VRI(IRRN),VCI(ICCN),VLI(ILLN)
      DOUBLE PRECISION TCRI(IRRN),TCCI(ICCN),TCLI(ILLN)
*
* INPUT TIME STEP, ITERATION TIMES AND SOURCE TYPE
* SN=1  -----  LIGHTNING WAVE
* SN=2  -----  LIGHTNING CHOPPED WAVE
* SN=3  -----  SINE WAVE
*
      DELTT=1.0D-8
      TIS=2000
      SN=2
*
      CALL input(ZE,AA,MR,MC,ML,ADR,ADC,ADL,DELTT,IBN,INN,IRRN,
     $ICCN,ILLN,IMLN)
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
*
```

```
* (1) SETTING ZERO
      DO 100 I=1,INN
         DO 110 J=1,INN
            YNI(I,J)=0.0
 110     CONTINUE
 100  CONTINUE
*
      DO 200 I=1,IRRN
         DO 210 J=1,IRRN
            AMR(I,J)=0.0
 210     CONTINUE
 200  CONTINUE
*
      DO 300 I=1,ICCN
         DO 310 J=1,ICCN
            AMC(I,J)=0.0
 310     CONTINUE
 300  CONTINUE
*
      DO 400 I=1,ILLN
         DO 410 J=1,ILLN
            AML(I,J)=0.0
 410     CONTINUE
 400  CONTINUE
*
      DO 500 I=1,INN
         VN(I)=0.0
 500  CONTINUE
*
      DO 510 I=1,IBN
         VB(I)=0.0
 510  CONTINUE
*
      DO 520 I=1,IBN
         VE(I)=0.0
 520  CONTINUE
*
      DO 530 I=1,IBN
         CE(I)=0.0
 530  CONTINUE
*
      DO 540 I=1,IBN
         VG(I)=0.0
 540  CONTINUE
*
* END OF (1)
*
      DO 600 I=1,IBN
         DO 610 J=1,IBN
            YB(I,J)=ZE(I,J)
 610     CONTINUE
 600  CONTINUE
*
      CALL inv(YB,IBN,ERROR,TEMPIS,TEMPJS)
```

```
      CALL tran(AA,AAT,INN,IBN)
      CALL mul(AA,YB,INN,IBN,IBN,TYN)
      CALL mul(TYN,AAT,INN,IBN,INN,YN)
*
      DO 620 I=1,INN
         DO 630 J=1,INN
            YNI(I,J)=YN(I,J)
 630     CONTINUE
 620  CONTINUE
*
      CALL inv(YNI,INN,ERROR,TEMPIS,TEMPJS)
*
      DO 700 I=1,IRRN
            AMR(I,I)=1.0/MR(I,I)
 700  CONTINUE
*
      DO 800 I=1,ICCN
            AMC(I,I)=(1.0/DELTT)*MC(I,I)
 800  CONTINUE
*
      DO 900 I=1,ILLN
         DO 910 J=1,ILLN
            TML(I,J)=ML(I,J)
 910     CONTINUE
 900  CONTINUE
      CALL inv(TML,ILLN,ERROR,TEMPIS,TEMPJS)
      TVAL1=DELTT/2.0
      CALL smul(TVAL1,TML,AML,ILLN,ILLN)
*
* END OF (2)
*
      OPEN(UNIT=21,FILE='s-oil/c1-ab-p3/node1.txt')
      OPEN(UNIT=22,FILE='s-oil/c1-ab-p3/node3.txt')
      OPEN(UNIT=23,FILE='s-oil/c1-ab-p3/node5.txt')
      OPEN(UNIT=24,FILE='s-oil/c1-ab-p3/node7.txt')
      OPEN(UNIT=25,FILE='s-oil/c1-ab-p3/node9.txt')
      OPEN(UNIT=26,FILE='s-oil/c1-ab-p3/node13.txt')
      OPEN(UNIT=27,FILE='s-oil/c1-ab-p3/node17.txt')
      OPEN(UNIT=28,FILE='s-oil/c1-ab-p3/node21.txt')
      OPEN(UNIT=29,FILE='s-oil/c1-ab-p3/node23.txt')
      OPEN(UNIT=30,FILE='s-oil/c1-ab-p3/node25.txt')
      OPEN(UNIT=31,FILE='s-oil/c1-ab-p3/node27.txt')
      OPEN(UNIT=32,FILE='s-oil/c1-ab-p3/node28.txt')
      OPEN(UNIT=33,FILE='s-oil/c1-ab-p3/node30.txt')
      OPEN(UNIT=34,FILE='s-oil/c1-ab-p3/node32.txt')
      OPEN(UNIT=35,FILE='s-oil/c1-ab-p3/node34.txt')
      OPEN(UNIT=36,FILE='s-oil/c1-ab-p3/node38.txt')
      OPEN(UNIT=37,FILE='s-oil/c1-ab-p3/node42.txt')
      OPEN(UNIT=38,FILE='s-oil/c1-ab-p3/node46.txt')
      OPEN(UNIT=39,FILE='s-oil/c1-ab-p3/node50.txt')
      OPEN(UNIT=40,FILE='s-oil/c1-ab-p3/node54.txt')
*
      JJ=1
*
```

```
      DO 1000 I=1,TIS
         TT=DELTT*(I-200)
*
      IF (TT .LT. 0.0) THEN
*         SVAL=0.01
         SVAL=0.04
         VG(1)=SVAL
      ELSE
         CALL source(TT,SVAL,SN)
         VG(1)=SVAL
      END IF
*
         CALL add(VB,VG,IBN,1,VE)
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
      CALL eqi(VE,CE,ECS,AMC,AML,ADC,ADL,VCE,TCCE,VLE,ILE,
     $TCL1E,TCL2E,IBN,INN,IRRN,ICCN,ILLN)
*
         CALL mul(YB,VG,IBN,IBN,1,CN1)
         CALL add(CN1,ECS,IBN,1,CN2)
         TVAL2=-1.0
         CALL smul(TVAL2,CN2,CN3,IBN,1)
         CALL mul(AA,CN3,INN,IBN,1,CN4)
         CALL mul(YNI,CN4,INN,INN,1,VN)
*
         JJ=JJ-1
         IF (JJ .EQ. 0) THEN
*
            WRITE(21,1100) TT,VN(1)
            WRITE(22,1100) TT,VN(3)
            WRITE(23,1100) TT,VN(5)
            WRITE(24,1100) TT,VN(7)
            WRITE(25,1100) TT,VN(9)
            WRITE(26,1100) TT,VN(13)
            WRITE(27,1100) TT,VN(17)
            WRITE(28,1100) TT,VN(21)
            WRITE(29,1100) TT,VN(23)
            WRITE(30,1100) TT,VN(25)
            WRITE(31,1100) TT,VN(27)
            WRITE(32,1100) TT,VN(28)
            WRITE(33,1100) TT,VN(30)
            WRITE(34,1100) TT,VN(32)
            WRITE(35,1100) TT,VN(34)
            WRITE(36,1100) TT,VN(38)
            WRITE(37,1100) TT,VN(42)
            WRITE(38,1100) TT,VN(46)
            WRITE(39,1100) TT,VN(50)
            WRITE(40,1100) TT,VN(54)
 1100       FORMAT(E12.6,5X,E12.6)
*
            JJ=4
         ELSE
            CONTINUE
```

```
         END IF
*
         CALL mul(AAT,VN,IBN,INN,1,VB)
         CALL add(VB,VG,IBN,1,VE)
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
      CALL ic(VE,ECS,CE,AMR,AMC,AML,ADR,ADC,ADL,VRI,VCI,VLI,
     $TCRI,TCCI,TCLI,IBN,INN,IRRN,ICCN,ILLN)
*
 1000 CONTINUE
      CLOSE(21)
      CLOSE(22)
      CLOSE(23)
      CLOSE(24)
      CLOSE(25)
      CLOSE(26)
      CLOSE(27)
      CLOSE(28)
      CLOSE(29)
      CLOSE(30)
      CLOSE(31)
      CLOSE(32)
      CLOSE(33)
      CLOSE(34)
      CLOSE(35)
      CLOSE(36)
      CLOSE(37)
      CLOSE(38)
      CLOSE(39)
      CLOSE(40)
*
      STOP
      END

* SUBROUTINE input
* USE TO FORM THE IMPEDANCE MATRIX, INCIDENCE MATRIX OF THE NETWORK
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
      SUBROUTINE input(ZE,AA,MR,MC,ML,ADR,ADC,ADL,DELTT,IBN,INN,
     $IRRN,ICCN,ILLN,IMLN)
*
      DOUBLE PRECISION ZE(IBN,IBN),AA(INN,IBN)
      DOUBLE PRECISION MR(IRRN,IRRN),MC(ICCN,ICCN),ML(ILLN,ILLN)
      INTEGER ADR(IRRN),ADC(ICCN),ADL(ILLN)
      DOUBLE PRECISION DELTT
      INTEGER IBN,INN,IRRN,ICCN,ILLN,IMLN
*
      INTEGER I1,I2,I3,I4
      DOUBLE PRECISION VAL
      INTEGER II1,II2,II3,IT1,IT2
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
```

```
*
      DO 100 I=1,IBN
         DO 110 J=1,IBN
            ZE(I,J)=0.0
 110     CONTINUE
 100  CONTINUE
*
      DO 120 I=1,INN
         DO 130 J=1,IBN
            AA(I,J)=0.0
 130     CONTINUE
 120  CONTINUE
*
      DO 140 I=1,IRRN
         DO 150 J=1,IRRN
            MR(I,J)=0.0
 150     CONTINUE
 140  CONTINUE
*
      DO 160 I=1,ICCN
         DO 170 J=1,ICCN
            MC(I,J)=0.0
 170     CONTINUE
 160  CONTINUE
*
      DO 180 I=1,ILLN
         DO 190 J=1,ILLN
            ML(I,J)=0.0
 190     CONTINUE
 180  CONTINUE
*
      DO 200 I=1,IRRN
         ADR(I)=0
 200  CONTINUE
*
      DO 210 I=1,ICCN
         ADC(I)=0
 210  CONTINUE
*
      DO 220 I=1,ILLN
         ADL(I)=0
 220  CONTINUE
*
      II1=0
      II2=0
      II3=0
      IT1=0
      IT2=0
*
*        1         2         3         4         5         6
*2345678901234567890123456789012345678901234567890123456789012345
      OPEN(UNIT=10,FILE='input/s-oil/ab-s1-p3')
*
      DO 500 I=1,IBN+IMLN
```

```
         READ(10,*) I1,I2,I3,I4,VAL
*
* IF COMPONENT IS RESISTOR
         IF (I4 .EQ. 1) THEN
            II1=II1+1
            ADR(II1)=I1
            MR(II1,II1)=VAL
            ZE(I1,I1)=VAL
*
            IF (I2 .EQ. 0) THEN
               AA(I3,I1)=-1.0
            ELSE
               CONTINUE
            END IF
            IF (I3 .EQ. 0) THEN
               AA(I2,I1)=1.0
            ELSE
               CONTINUE
            END IF
            IF ((I2 .NE. 0) .AND. (I3 .NE. 0)) THEN
               AA(I2,I1)=1.0
               AA(I3,I1)=-1.0
            ELSE
               CONTINUE
            END IF
*
         ELSE
            CONTINUE
         END IF
* IF COMPONENT IS CAPACITOR
         IF (I4 .EQ. 2) THEN
            I1=I1-IMLN
            II2=II2+1
            ADC(II2)=I1
            MC(II2,II2)=VAL
            ZE(I1,I1)=DELTT/VAL
*
            IF ((I2 .NE. 0) .AND. (I3. NE. 0)) THEN
               AA(I2,I1)=1.0
               AA(I3,I1)=-1.0
            ELSE
               CONTINUE
            END IF
            IF (I2 .EQ. 0) THEN
               AA(I3,I1)=-1.0
            ELSE
               CONTINUE
            END IF
            IF (I3 .EQ. 0) THEN
               AA(I2,I1)=1.0
            ELSE
               CONTINUE
            END IF
*
```

```
          ELSE
             CONTINUE
          END IF
* IF COMPONENT IS INDUCTOR
          IF (I4 .EQ. 3) THEN
             II3=II3+1
             ADL(II3)=I1
             ML(II3,II3)=VAL
             ZE(I1,I1)=2.0*VAL/DELTT
*
             IF (I2 .EQ. 0) THEN
                AA(I3,I1)=-1.0
             ELSE
                CONTINUE
             END IF
             IF (I3 .EQ. 0) THEN
                AA(I2,I1)=1.0
             ELSE
                CONTINUE
             END IF
             IF ((I2 .NE. 0) .AND. (I3 .NE. 0)) THEN
                AA(I2,I1)=1.0
                AA(I3,I1)=-1.0
             ELSE
                CONTINUE
             END IF
*
          ELSE
             CONTINUE
          END IF
* IF COMPONENT IS MUTUAL INDUCTANCE
          IF (I4 .EQ. 10) THEN
             ZE(I2,I3)=2.0*VAL/DELTT
             ZE(I3,I2)=2.0*VAL/DELTT
             DO 510 J=1,ILLN
                IF (I2 .EQ. ADL(J)) THEN
                   IT1=J
                ELSE
                   CONTINUE
                END IF
 510         CONTINUE
             DO 520 J=1,ILLN
                IF (I3 .EQ. ADL(J)) THEN
                   IT2=J
                ELSE
                   CONTINUE
                END IF
 520         CONTINUE
             ML(IT1,IT2)=VAL
             ML(IT2,IT1)=VAL
          ELSE
             CONTINUE
          END IF
* END (4)
```

```
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234 5
*
 500  CONTINUE
      CLOSE(10)
      CLOSE(20)
*
      RETURN
      END

* SUBROUTINE eqi
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234 5
      SUBROUTINE eqi(VE,CE,ECS,AMC,AML,ADC,ADL,VCE,TCCE,VLE,ILE,
     $TCL1E,TCL2E,IBN,INN,IRRN,ICCN,ILLN)
*
      DOUBLE PRECISION VE(IBN),CE(IBN),ECS(IBN)
      DOUBLE PRECISION AMC(ICCN,ICCN),AML(ILLN,ILLN)
      INTEGER ADC(ICCN),ADL(ILLN)
      DOUBLE PRECISION VCE(ICCN),TCCE(ICCN)
      DOUBLE PRECISION VLE(ILLN),ILE(ILLN),TCL1E(ILLN),TCL2E(ILLN)
      INTEGER IBN,INN,IRRN,ICCN,ILLN
*
      DO 100 I=1,IBN
         ECS(I)=0.0
 100  CONTINUE
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234 5
      DO 200 I=1,ICCN
         VCE(I)=VE(ADC(I))
 200  CONTINUE
      CALL mul(AMC,VCE,ICCN,ICCN,1,TCCE)
*
      DO 300 I=1,ICCN
         ECS(ADC(I))=-1.0*TCCE(I)
 300  CONTINUE
*
* (2) CALCULATE ECS DUE TO INDUCTOR
*
      DO 400 I=1,ILLN
         VLE(I)=VE(ADL(I))
         ILE(I)=CE(ADL(I))
 400  CONTINUE
      CALL mul(AML,VLE,ILLN,ILLN,1,TCL1E)
      CALL add(TCL1E,ILE,ILLN,1,TCL2E)
*
      DO 500 I=1,ILLN
         ECS(ADL(I))=TCL2E(I)
 500  CONTINUE
*
      RETURN
      END
```

```
* SUBROUTINE ic
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
      SUBROUTINE ic(VE,ECS,CE,AMR,AMC,AML,ADR,ADC,ADL,VRI,VCI,VLI,
     $TCRI,TCCI,TCLI,IBN,INN,IRRN,ICCN,ILLN)
*
      DOUBLE PRECISION VE(IBN),ECS(IBN),CE(IBN)
      DOUBLE PRECISION AMR(IRRN,IRRN),AMC(ICCN,ICCN),AML(ILLN,ILLN)
      INTEGER ADR(IRRN),ADC(ICCN),ADL(ILLN)
      DOUBLE PRECISION VRI(IRRN),VCI(ICCN),VLI(ILLN)
      DOUBLE PRECISION TCRI(IRRN),TCCI(ICCN),TCLI(ILLN)
      INTEGER IBN,INN,IRRN,ICCN,ILLN
*
      DO 100 I=1,IBN
         CE(I)=0.0
 100  CONTINUE
*
*         1         2         3         4         5         6
*234567890123456789012345678901234567890123456789012345678901234
*
      DO 200 I=1,IRRN
         VRI(I)=VE(ADR(I))
 200  CONTINUE
      CALL mul(AMR,VRI,IRRN,IRRN,1,TCRI)
      DO 250 I=1,IRRN
         CE(ADR(I))=TCRI(I)
 250  CONTINUE
*
      DO 300 I=1,ICCN
         VCI(I)=VE(ADC(I))
 300  CONTINUE
      CALL mul(AMC,VCI,ICCN,ICCN,1,TCCI)
      DO 350 I=1,ICCN
         CE(ADC(I))=TCCI(I)
 350  CONTINUE
*
      DO 400 I=1,ILLN
         VLI(I)=VE(ADL(I))
 400  CONTINUE
*
      CALL mul(AML,VLI,ILLN,ILLN,1,TCLI)
      DO 450 I=1,ILLN
         CE(ADL(I))=TCLI(I)
 450  CONTINUE
*
      DO 500 I=1,IBN
         CE(I)=CE(I)+ECS(I)
 500  CONTINUE
*
      RETURN
      END
```