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Design Improvements on Graded Insulation of Power Transformers Using Transient Electric Field Analysis and Visualization Technique

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Abstract— **This paper deals with design improvements on graded insulation of power transformers using transient electric field analysis and a visualization technique. The calculation method for transient electric field analysis inside a power transformer impressed with impulse voltage is presented: Initially, the concentrated electric network for the power transformer is constructed by dividing transformer windings into several blocks and by computing the electric circuit parameters. Next, the transient electric field analysis is performed. Using the results of the circuit analysis as boundary conditions, a 2D axisymmetrical electric field finite element analysis is performed. Finally, an animated display technique for the transient voltage, the electric field intensity and the tolerance rate of electric field intensity distributions is proposed as an extremely useful tool for design on graded insulation. A successful application of the proposed method for analysis of a model transformer for which the computed results agree very well with measured results is also presented.**

Keywords— **Power transformer, graded insulation, impulse voltage, transient electric field analysis, 2D axisymmetrical finite element method, scientific visualization.**

I. INTRODUCTION

Design problems of the graded insulation of transformers for impulse voltage already have been discussed at length [1]. With traditional methods, however, transformer windings have been treated as a concentrated electric network, and only transient voltage analysis has been carried out. Grasping the transient voltage distribution at the nodes of the electric network is possible, but estimating the electric field intensities between windings and coils from the voltage difference between the nodes is very difficult. This difficulty is because the electric field intensity distribution inside a transformer is highly affected by the geometrical shapes of windings and insulators.

In this paper, the authors propose a new method for calculating the transient electric field intensity distribution inside a model of power transformer impressed with impulse voltage. It is also shown that the visualization of this distribution is very useful for design problems of graded insulation. The proposed method has the following features:

1. A concentrated electric circuit is used for the analysis of transient voltage distribution inside transformer windings impressed with impulse voltage, making analysis very simple [2], [3]. The concentrated electric circuit is constructed of blocks, made by dividing transformer windings into appropriate parts.
2. The voltage, the electric field intensity and the tolerance rate of the electric field intensity distributions inside the transformer are calculated using 2D axisymmetrical finite element analysis.
3. Once the animated display of the obtained distributions mentioned above is realized, design improvements can be achieved easily by practice and the designer's own design sense.
4. Because finite element analysis is applied, the circuit constants of the blocks can be calculated with high accuracy.

II. CALCULATION PROCEDURE

A. Transient Electric Field Intensity Analysis

In the problem of graded insulation, it is important to construct an equivalent circuit considering all windings inside the transformer. The equivalent circuit is constructed by dividing windings into several blocks, each one made up of a number of coils as shown in Fig. 1. After block division is performed, transient electric field analysis is executed using the following procedure:

- *Step 1:* Using the finite element method, calculate the inductance L of each block, and the mutual inductance M between each set of two blocks [4] taking into account the existence of the transformer core and neglecting the ferrite losses. Calculate the parallel capacitance C_p between each of the two blocks and between each block and the earth [5], and the serial capacitance C_s inside each block [6].

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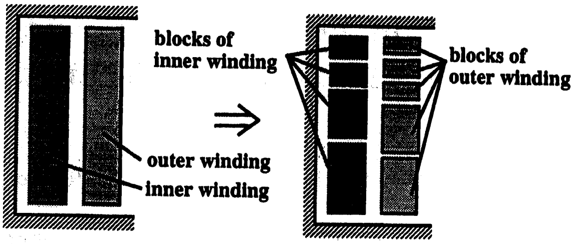


Fig. 1. Block subdivision of transformer windings.

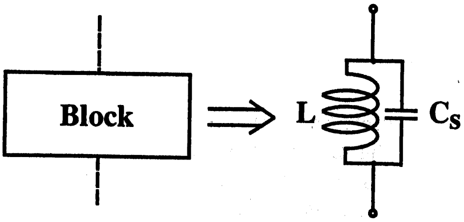


Fig. 2. Equivalent circuit for one block.

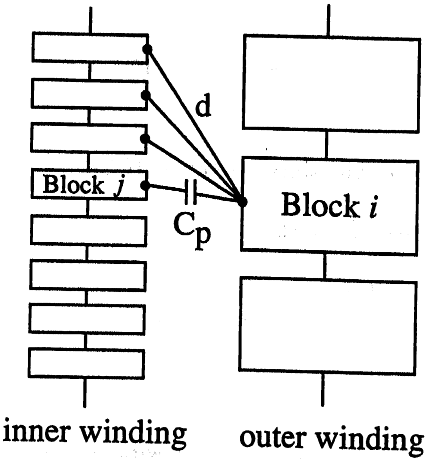


Fig. 3. Model for calculating the capacitance C_p.

- *Step 2:* Construct the equivalent circuit using L, M, C_p, and C_s.
- *Step 3:* Execute transient circuit analysis when an impulse voltage is impressed on the constructed equivalent circuit [2], [3].
- *Step 4:* Set time t equal to zero, in order to calculate transient electric field distribution.
- *Step 5:* Set the voltage boundary condition on block surfaces at time t from the voltage values calculated in *Step 3*, and execute electric field analysis using 2D axisymmetrical finite element method.
- *Step 6:* If t is less than t_{max} , the finishing time of analysis, set t to $t + \Delta t$, and go to *Step 5*.
- *Step 7:* Display still images or animate the distributions of voltage, the electric field intensity, and the tolerance rate of electric field intensity, by using the results of *Step 5*.

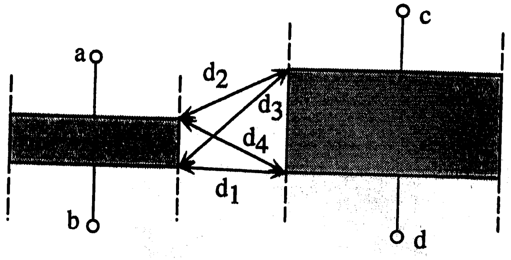
B. Construction of Equivalent Circuit

Next is described the method for construction of a concentrated equivalent circuit using the circuit parameters L, M, C_p and C_s, computed for each block separately. The equivalent circuit for one block is constructed as a parallel connection of a self-inductance L and a serial capacitance C_s as shown in Fig. 2. Mutual inductance M is set between each set of two blocks. As can be seen from Fig. 2, the effects of the circuit damping is neglected during analysis. Next, let us consider that a parallel capacitance C_p between any two blocks is composed of two capacitances; one is the parallel capacitance between the upper block and the lower block in the same winding; the other one is the capacitance between the blocks of inner and outer windings. The former one is considered a serial capacitance, while the latter one is a distributed capacitance on the block surface as it is shown in Fig. 3. In order to include the capacitance C_p into the concentrated equivalent circuit, the capacitance C_p must be connected to the circuit terminals. Here, the capacitance C_p is first divided into the capacitances C_{p1}, C_{p2}, C_{p3} and C_{p4}, as shown in Fig. 4*b*. Figure 5 shows the relationship between the parallel capacitance C_p and the distance d between block i of outer winding and any arbitrary block j of the inner winding, where d is the distance between the middle points on two block sides. It is clear from Fig. 5 that the capacitance C_p is the inverse proportion of distance d to the fourth power. Therefore, the capacitance C_p is distributed to the capacitances C_{p1}, C_{p2}, C_{p3} and C_{p4} in inverse proportion to the fourth power of the distances d_1, d_2, d_3 and d_4, respectively, where d_i, $(i = 1, 2, 3 \text{ or } 4)$ is the distance between block corners, as shown in Fig. 4*a*. If the distance d_i, $(i = 1, 2, 3 \text{ or } 4)$ is longer the $2 \cdot d_{min}$, where d_{min} is the $min\{d_1, d_2, d_3, d_4\}$, then the capacitance C_{pi} is neglected.

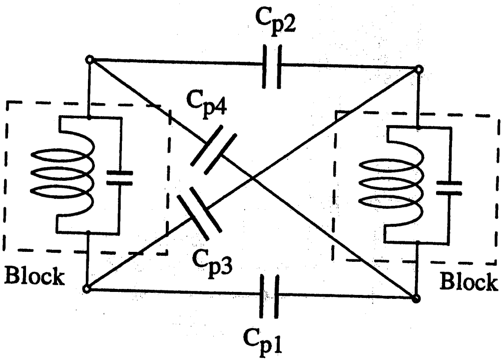
C. Setting the Boundary Conditions for the Finite Element Electric Field Analysis

From the transient analysis of the equivalent circuit constructed in the previous section, the voltage values at the connection points of each set of two blocks are obtained, and the electric field analysis is executed using 2D axisymmetrical finite element method. To perform the FEA, however, initially the appropriate boundary conditions on the parts of the finite element mesh must be set. Here, it must be pointed out that in case of the parallel capacitance parameter calculations, each block was treated as a conductor. However, as each block is composed of a large number of coils, voltage distribution on the block surfaces is not constant. Therefore, in order to calculate electric field distribution with high accuracy, it is necessary to set boundary conditions so that the voltage on the block surface varies depending upon position.

In this paper, it is assumed that voltage distribution on the block surfaces is linear, and the method for setting



a) block corner area



b) concentrated electric circuit

Fig. 4. Definition of capacitances C_{p1}, C_{p2}, C_{p3} and C_{p4}.

such boundary conditions is developed as follows: First, we assumed that the voltages at points a and b are V_a and V_b respectively, and the coils inside each block are uniformly wound (Fig. 6). Then, the boundary conditions on the block surfaces for the finite element electric field analysis are set as shown in Fig. 6: The voltages on the boundaries $1-2$ and $3-4$ vary from V_a to V_b linearly, and the voltages on the boundaries $1-4$ and $2-3$ are constant and equal to V_a and V_b, respectively.

III. VISUALIZATION

As mentioned above, it is very important to grasp the physical phenomena in the analysis region during the design stage for graded insulation. As a result of finite element analysis, physical values for voltage and electric field intensity at each node of the finite element mesh are obtained as numerical information. It is very difficult, therefore, to grasp the distribution and the physical meaning of the obtained results directly from these numerical data. On the other hand, observers may sometimes miss important data or may even misunderstand the obtained results. In order to solve these problems and to aid in the design process, the authors have developed a post-processor that display electric and magnetic field distributions on a color *CRT* [7]. This technique is utilized in this paper, but in order to grasp the transient phenomena for impulse voltage, observation of time-varying processes is more important than still-images. Therefore, the time-series of transient distributions are recorded on *VTR* and observed as animation. This procedure, makes it easier to grasp the time progress of the analyzed physical phenomena which is very useful for design on graded insulation of power transformers.

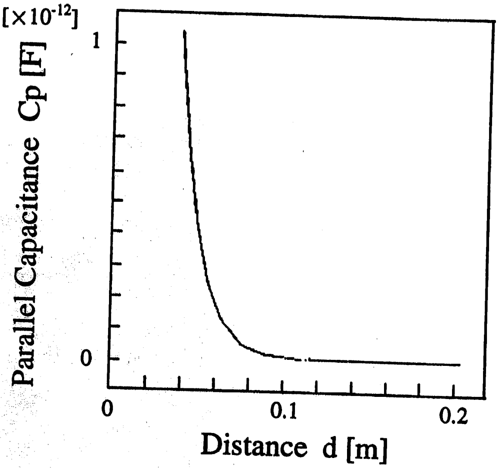


Fig. 5. Parallel capacitance C_p vs. distance d.

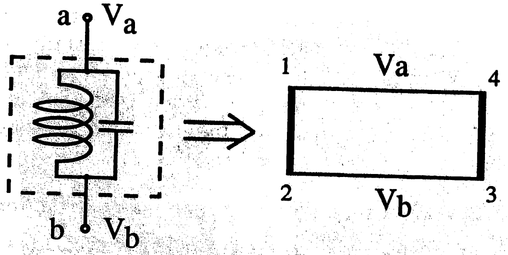


Fig. 6. Assignment of boundary conditions.

To easily understand the physical phenomena, it is important to directly visualize the physical values which are of the main analyst's interest. If voltage distribution is final information needed by the analyst, its depiction is preferred. In the design of graded insulation, the electric field intensity distribution between insulation materials or windings is very important. Therefore, the visualization of the electric field intensity distribution makes understanding of the observed phenomena easier. In the case of the investigation of dielectric breakdown of power transformers during impulse voltage impression, it is important that the obtained electric field intensity values of each material inside the transformer should be less or equal to the maximum permissible value of each material for its dielectric breakdown. It is extremely difficult to determine the exact values for the maximum permissible electric field stresses since they depend on a large number of parameters such as geometrical structure, type of transformer insulators, age of transformer and its working conditions such as contamination, overload and overheat history. Therefore, in this analysis we used the prescribed values for each dielectric material inside the transformer. The proposed method for display of the tolerance rate distribution of electric field intensity gives extremely important information to a designer, especially when several insulators are considered at the same time, as the designer can directly observe the information of interest. For calculating the tolerance rate T_i at arbitrary point i, the following equation is proposed:

$$T_i = \left(1 - \frac{E_i}{EP_i}\right) \cdot 100 \ [\%] , \qquad (1)$$

where E_i is the electric field intensity at point i, and EP_i is the prescribed maximum permissible electric field intensity of the insulation material including point i.

IV. INVESTIGATION USING A MODEL TRANSFORMER

In order to verify the correctness of the calculation method, an impulse voltage is impressed to the model transformer shown in Fig. 7*a*. Figure 7*b* shows the developed concentrated electric circuit for the model transformer. The calculated values of transient voltage distribution in the primary winding were initially compared with measured values. Afterwards, the transient electric field intensity distributions are visualized, thereby demonstrating the method's usefulness in solving design problems with regard to graded insulation.

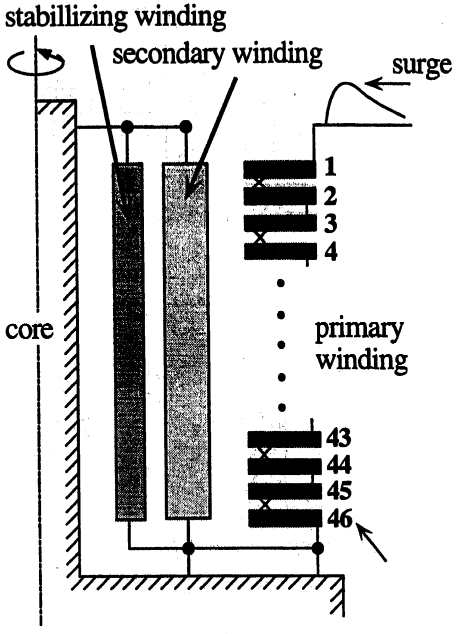
A. Comparison of Transient Voltage Distributions

Figure 8 shows a comparison between analysis results and measured values of transient voltages when 1/40 μs impulse voltage is impressed to the primary winding. One hundred steps of the transient electric circuit analysis were performed using constant time step of 1 μs, and the voltage distribution at several measuring points along primary winding (see Fig. 8a) was monitored. As evident from Fig. 8, both measured and computed voltage wave-forms from 0 μs to 45 μs coincide almost completely. However, after 45 μs, the differences between the wave-forms become gradually larger. The reason for this discrepancy is hypothesized to be twofold: (1) because the distributed constant circuit is treated as a concentrated constant circuit, and (2) because the effect of circuit dumping was neglected during transient electric circuit analysis. Fortunately, in the problem of graded insulation, the transient phenomenon during several cycles just after the inroad of impulse voltage is especially important.

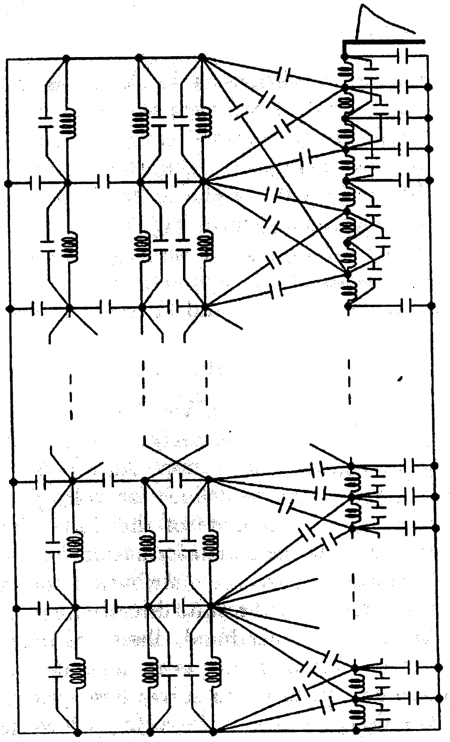
B. Visualization of Transient Electric Field Distribution

Voltage and electric field distributions are displayed if the peak value of impulse voltage reaches 1 $p.u.$ Tolerance rate distribution of the electric field intensity is visualized when the peak value of impulse voltage is 550 kV, the normal test voltage of the model transformer.

The transient voltage distributions, electric field intensity distributions, and the tolerance rate distributions of the electric field intensity from 0 μs to 40 μs are recorded by *VTR*, so the physical phenomena inside the transformer can be observed easily as animation. The animated

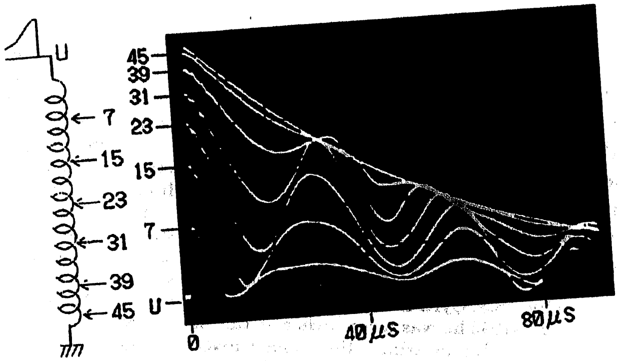


a) block representation

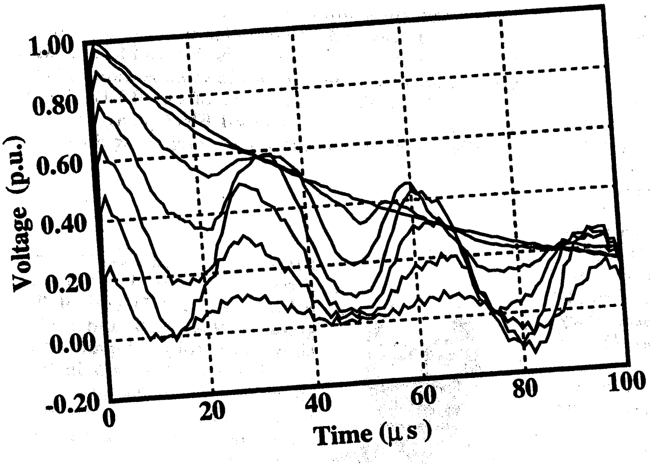


b) concentrated electric circuit

Fig. 7. Model transformer.



a) Measured values



b) Computed values

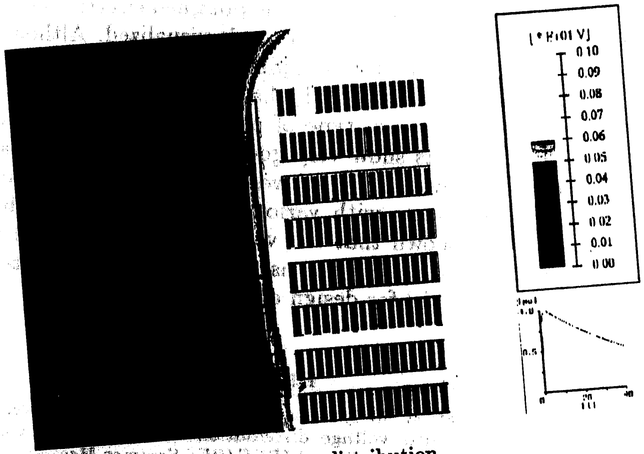
Fig. 8. Comparison between measured and computed results.

display is extremely effective for the direct visual grasping of the time-varying nature of the physical phenomena. As the presentation of animation is impossible here, some still images are depicted in Fig. 9; the distribution of voltage, the electric field intensity, and the tolerance rate in the upper part of the transformer at 2 μs are shown. Although the obtained animation is color, the still images presented in this paper are gray-scale due to the publication problems.

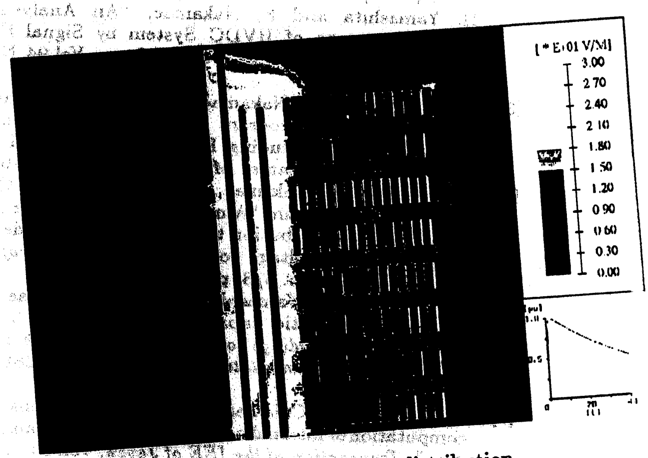
It must be mentioned that, in addition, the insulation oil in the model transformer is removed for measuring. The tolerance rate distribution of the electric field intensity shows that dielectric breakdown happens in the air region between the primary and the secondary windings.

V. CONCLUSION

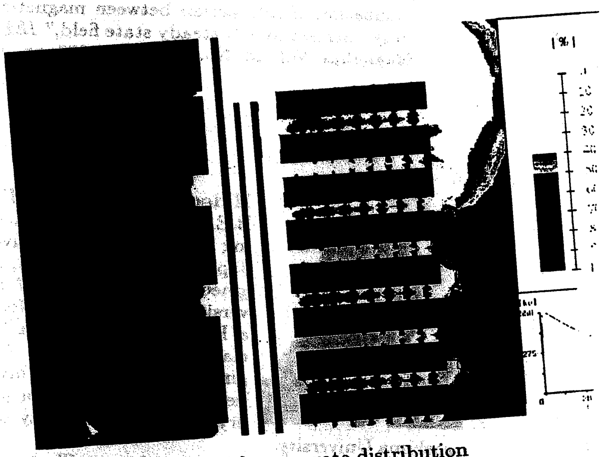
In this paper, a calculation method of transient electric field distribution inside a power transformer impressed with impulse voltage as a contribution to the design of graded insulation of power transformers is proposed. The transient electric field analysis is executed using previously developed electric circuit with electric parame-



a) Voltage distribution



b) Electric field intensity distribution



c) Tolerance rate distribution

Fig. 9. Obtained distributions.

ters computed accurately by means of the finite element method. The obtained voltage values from circuit analysis are set as boundary conditions for a 2D axisymmetrical electric field analysis and the obtained electric field distribution inside the transformer is visualized. Although the proposed method was applied only to one type of transformer used as a model, the method is general and it is applicable for any type of power transformer. The presented results show very good agreement with measured ones, however, further investigation using different type of transformers with various insulators is advisable. It was also shown that the visualization of physical values such as electric field intensity and its tolerance rate is extremely useful for design on graded insulation.

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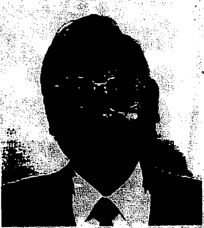

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