A Design Method for Graded Insulation of Transformers by Transient Electric Field Intensity Analysis

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ABSTRACT—In this paper, a calculation method for transient electric field distribution inside a transformer impressed with inpulse voltage is proposed: The concentrated electric network for the transformer is constructed by dividing transformer windings into several blocks, and the transient voltage and electric field intensity distributions inside the transformer are calculated by using the axisymmetrical finite element method. Moreover, an animated display of the distributions is realized: The visualization of physical values, such as electric field intensity, is extremely useful for the design of graded insulation.

INTRODUCTION

The design problems of the graded insulation of transformers for impulse voltage already have been discussed at length. With traditional methods, however, transformer windings have been treated as a concentrated electric network, and only transient voltage oscillation analyses have been carried out. Grasping the transient voltage oscillation 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 is because the electric field intensity distribution inside a transformer is highly affected by the geometrical shapes of windings and insulations.

In this paper, a method for calculating the transient electric field intensity distribution inside a transformer impressed with impulse voltage is proposed, and it is shown that the visualization of this distribution is very useful for the design problems of graded insulation. The proposed method has the following characteristics:

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

CALCULATION PROCEDURE FOR TRANSIENT ELECTRIC FIELD INTENSITY DISTRIBUTION

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 (see Fig. 1). After block division is performed, transient electric field analysis is executed by the following procedures:

- *Step 1:* Using the finite element method, calculate the inductance L of each block, the mutual inductance M between each of the two blocks [1], the parallel capacitance C_p between each of the two blocks and between each block and the earth [2], and the serial capacitance C_s inside each block [3].
- *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 equivalent circuit.
- *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 with the 2-D 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*.

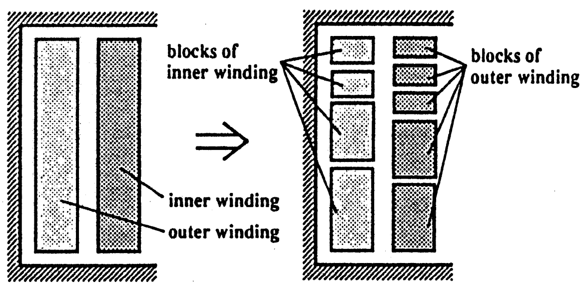


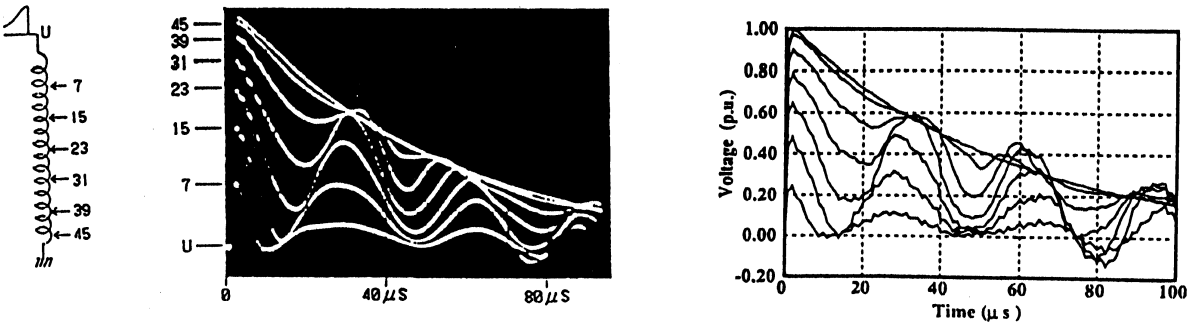
Fig. 1. Block subdivision of transformer windings.

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. 2, and the calculated values of transient voltage distribution in the primary winding was 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.

Comparison of Transient Voltage Distributions

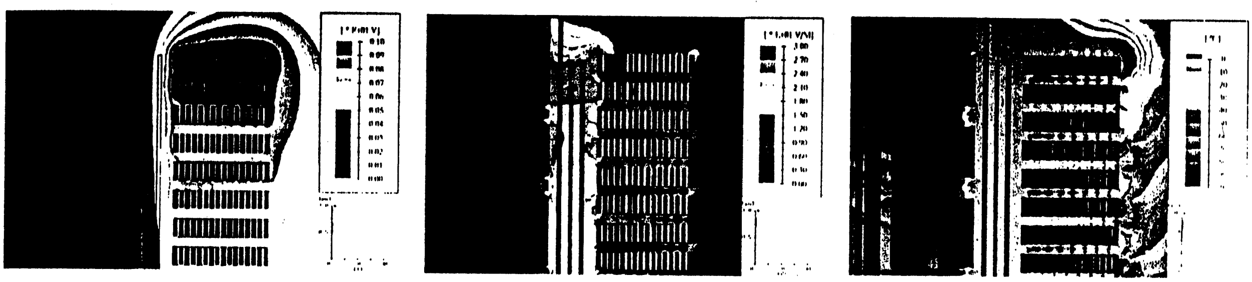
Figure 3 shows a comparison between analysis results and measured values of transient voltages when 1/40 [μs]



a) Measured values

b) Computed values

Fig. 3. Comparison between measured and computed results.



a) Voltage distribution b) Electric field intensity distribution c) Tolerance rate distribution

Fig. 4. Obtained distributions.

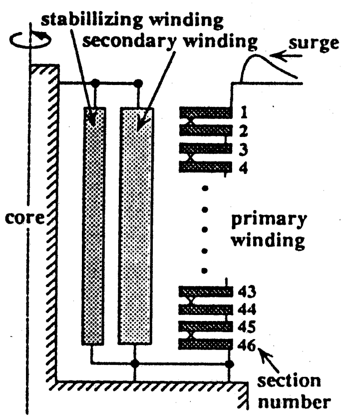


Fig. 2. Model transformer.

impulse voltage is impressed to the primary winding. As evident from the figure, both voltage wave forms from 0 to 45 [μs] coincide almost completely. But after 45 [μs], the differences between the wave forms become gradually larger. The reason for this discrepancy is hypothesized to be because the distributed constant circuit is treated as a concentrated constant circuit. In the problem of graded insulation, the transient phenomenon during several cycles just after the inroad of impulse voltage is especially important.

Visualization of Transient Electric Field Distribution

Voltage and electric field distribution 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], which is 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 to 40 [μs] are recorded by *VTR*, so the physical phenomena inside the transformer can be observed easily as animation. The animated 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. 4; the distribution of voltage, the electric field intensity, and the tolerance rate in the upper part of the transformer at 2 [μs] are shown. It must be mentioned that, in addition, the insulation oil in the model transformer is removed for measuring. The tolerance rate distribution shows that dielectric breakdown happens in the air region between the primary and the secondary windings.

Conclusion

In this paper, a method for calculating transient electric field intensity distribution inside a transformer impressed with impulse voltage was proposed, and it was shown that the visualization of physical values, such as electric field intensity, is extremely useful for graded insulation design.

References

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