# Experimental and Numerical Analyses of Leakage Flux Distribution in Core-type Voltage Transformers

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**Abstract**— This study is based on leakage magnetic flux analysis of a core type transformer. The distributions that obtained experimentally were compared with two-dimensional FDM and FEM calculation results to verify. The experiment set includes a voltage transformer and measurement coils that are used to determine leakage flux distribution around of transformer iron leg. With the solution of the matrix created by measuring the induced voltage, polynomial mathematical equations were obtained. Then flux values have been calculated in accordance with the numerical methods. In order to compare the results, plotting of the flux distribution is the best solution. For this purpose, total flux lines was determined. In addition, the difference between the smallest and largest value of the vector potential is also determined. The voltage (potential difference) vector is calculated by dividing the difference to flux lines. In the last step, the equipotential points were determined by adding to the minimum potential value. This process was repeated for eight different heights in the legs and two-dimensional coordinates of the equipotential point was determined at each height. By combining the same valuable points, flux distribution was obtained graphically. Finally, fluxes have been drawn in line with the measurement and calculation results, and have been compared with each other. As a result, leakage flux distribution of voltage transformer is obtained and it is observed that FEM calculates closer values to the measurements. According to the study results, the using of the measurements from several points taken with magnetic field probes in FEM model, can provide sufficient accuracy solutions.

## 1. INTRODUCTION

Magnetic flux measurement is a process that usually needs to be done during in service periods of machines. Especially in large power transformers, the measurement around the core during operation includes a variety of challenges. Since fluxes always complete their circuits by following the path of lowest magnetic resistance, refractions occur when the magnetic resistance of the path followed over the air becomes higher than the path over the metal sheet. Therefore, leakage fluxes are usually low, and they practically compose 5% of the useful flux. Despite their low value, leakage fluxes play a significant role in the operation of not only stationary-type machines but also rotating machines [1, 2]. Recognition of the flux distribution in machines is required for three reasons: 1) measurement of the inductances, 2) the forces applied to the coils, and 3) the additional losses that occur in the coils and steel parts. The finite different (FDM) and the finite element (FEM) methods [3–6] are the main approximation in this area. Among these methods, applications are the determination of losses [7, 8], magnetic flux, and circulating current analysis of new age amorphous modular transformers [9], superconducting high voltage transformers [10], and planar transformers [11] that are commonly used at low voltages, the computation of electromagnetic forces created by short-circuit faults [12], and in obtaining equivalent simulation models [13]. In addition, two-dimensional (2D) FEM is used in leakage flux analysis of electrical machines. In references [14–16], leakage flux analyses of mono-phase induction motor, transverse flux motor, and three-phase induction motor are realized with 2D FEM respectively. Reference [17] also investigates the effects of leakage fluxes on magnetic materials using 2D FEM. Khelil and Elleuch have proposed that the effects of the air gap on a magnetic-equivalent circuit can be determined by the FEM without the need for experimental measurements [18]. Similarly, in reference [19], the losses and distribution of current density in the conductors for a large air gap transformer were calculated by 3-D FEM. Hernandez et al. developed the Gaussian model for the magnetic flux analysis of transformers, using it to obtain the equivalent permeability and reluctance circuit, and compared the result with the FEM [20]. Hernandez and Arjona calculated efficiency, losses, impedance, magnetic flux density, and the magnetization current of a transformer using a hybrid FEM and knowledge-based system; the results are remarkably close to the values provided by the manufacturer [21]. Localized flux measurements in a wound core transformer are realized and extended by FEM to the point that values are unknown in reference [22]. Leakage flux distribution in large power transformers was examined by Me and Zhang with 3-D FEM [23].

In this study, leakage magnetic flux distributions that were obtained using FEMM software has been compared with the results obtained by measurements. In the next section, the method that is used for drawing the flux lines is described. The third section involves the introduction about the test set and also includes an analysis of the outputs and calculation results. The last section consists of analyzing the obtained output.

## 2. DRAWING THE FLUX LINES

Taking the potential difference between the flux lines is a basis: If the differences between the flux lines, that is to say the increases (or decreases), are requested to be a certain value, the drawing starts from the lowest or highest value. The value of the next flux line is different from the previous flux line at a value equal to the amount of increase (or decrease). In this method, the total number of lines is equal to the amount of increase (or decrease) in the difference between the highest value and the lowest value. The potential value of the line, which will be drawn, is compared with the potential value of the two adjacent nodes of each element. After this comparison, the coordinate of the equipotent point can be calculated by utilizing the coordinates of the adjacent nodes. In this study, an equipotent line crossing over a triangular element was considered as in reference [24].

## 3. EXPERIMENTAL STUDIES

In experimental studies, the primary coil of transformer was supplied from a synchronous generator. Measurements have been performed at eight different heights (55 mm–125 mm) starting from the inner corner of the leg and at two different primary currents (2.1 A–4.1 A). There is not any device which measures the magnetic flux distribution directly. For this reason, measuring coils are used to realize this process. The magnetic field of a coil induced a voltage ($U_{ind}$) that can be expressed as:

$$U_{ind} = \frac{\omega \cdot B \cdot A \cdot N}{\sqrt{2}} \tag{1}$$

In this equation, $B$, $A$ and $N$ represent magnetic flux density (T), cross-section of the coil ($m^2$) and number of turns, respectively. $\omega$ is also angular velocity (Rad/s). Thus, flux density ($B$) can be calculated by measuring the induced coil voltage [25]. Figure 1 shows the perspective view of the transformer with measuring coils and the photo of experimental set.

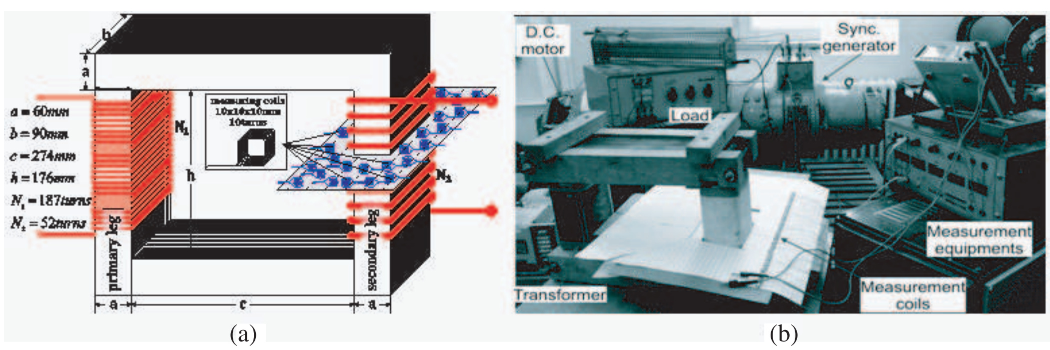


Figure 1: (a) Appearance of the transformer and measuring coils. (b) The photograph of the test set.

Superficial flux distribution in the secondary leg of the transformer has been drawn for eight different heights using FEMM software. For the drawing process, first the surface on which the flux distribution was divided into 3232 elements is shown in Figure 2. Then, equipotent points were calculated and superficial flux distributions were obtained by FEMM software and are also shown in Figure 2. Flux values and coordinates of a, b, c, and d points are given in Table 1.

Lastly, the flux distributions in the secondary leg of the experiment voltage transformer were drawn using these superficial flux distributions. A rectangular-lined central domain shown in the figures is the section where the secondary leg crosses. The flux distributions within this domain are the beneficial flux distributions. As for the flux distributions outside this domain, they show the leakage flux distributions. The coordinates of any point on the flux lines and the magnitudes belonging to the flux on that point can be determined using the computer program. Boundary

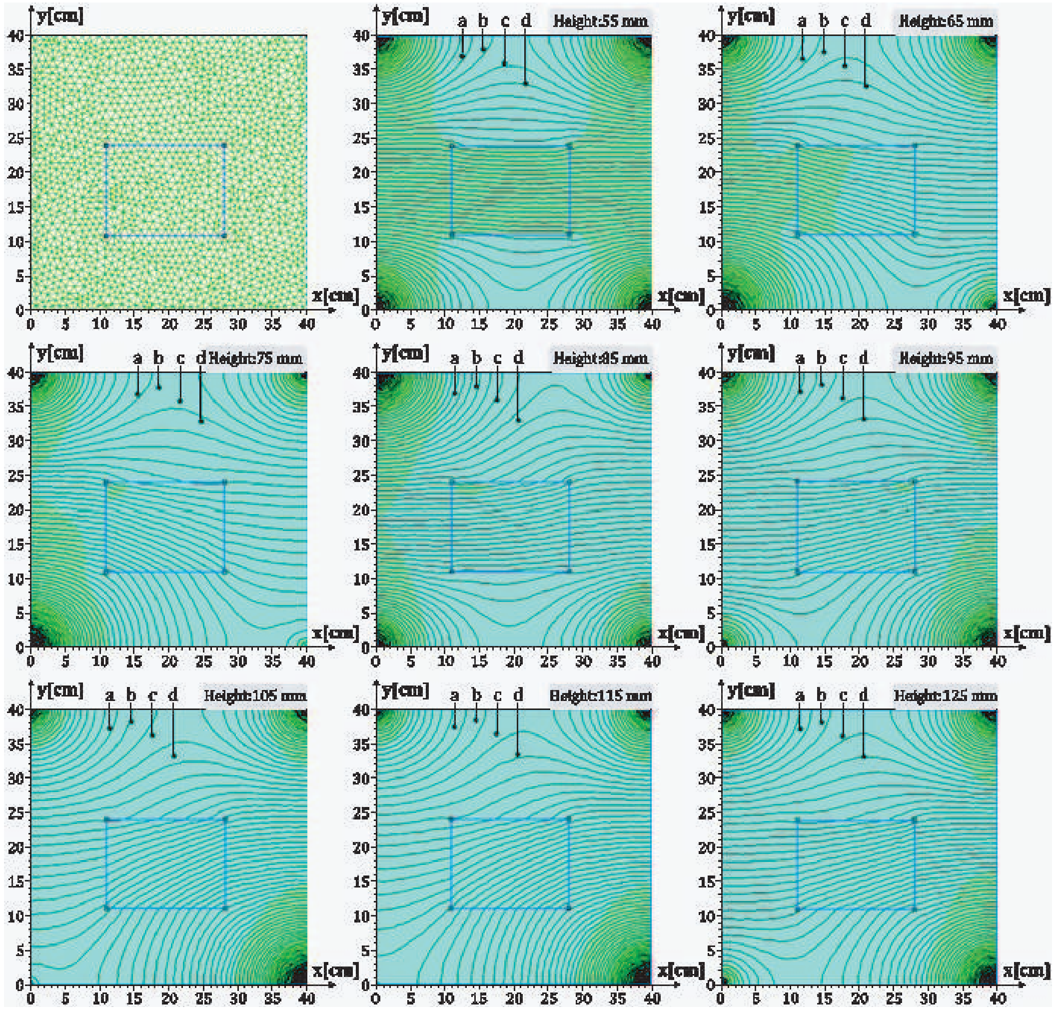


Figure 2: 3232 triangle finite elements for flux distribution measurement (top left) and surface flux distributions at eight different heights on the secondary leg.

Table 1: Flux values and coordinates of measurement points.

| Point | Coordinates $(x, y)$ | Flux values [x10$^{-7}$ Wb] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 55 mm | 65 mm | 75 mm | 85 mm | 95 mm | 105 mm | 115 mm | 125 mm |
| a | (13.9-37.8) | 0.2773 | 0.3516 | 0.4914 | 0.3679 | 0.2605 | 0.2225 | 0.2323 | 0.2141 |
| b | (15.0-36.5) | 0.2800 | 0.3556 | 0.4976 | 0.3724 | 0.2628 | 0.2244 | 0.2343 | 0.2158 |
| c | (20.0-36.5) | 0.2826 | 0.3578 | 0.5050 | 0.3816 | 0.2661 | 0.2276 | 0.2370 | 0.2186 |

values must be determined in order to calculate the potential value in each measuring coil in Figure 1 and to compare the measurement results. The measurement values and flux distributions drawn according to the two different flux values ($1.74 \cdot 10^{-7}$ Wb and $2.14 \cdot 10^{-7}$ Wb) using FEM and FDM are given in Figure 3 in order to compare them to one another. It suggests that at a height of 55 mm (from the leg), 0.4746 mV (or $2.14 \cdot 10^{-7}$ Wb flux value) is observed at a horizontal distance of 83 mm, 77 mm and 92 mm according to the measurement results, FDM, and FEM calculations, respectively. At a height of 95 mm, the same potential value is observed at a horizontal distance of 92 mm. Similarly, for $1.74 \cdot 10^{-7}$ Wb flux value, these results are measured as 55 mm, 110.24 mm, and 169.44 mm respectively.

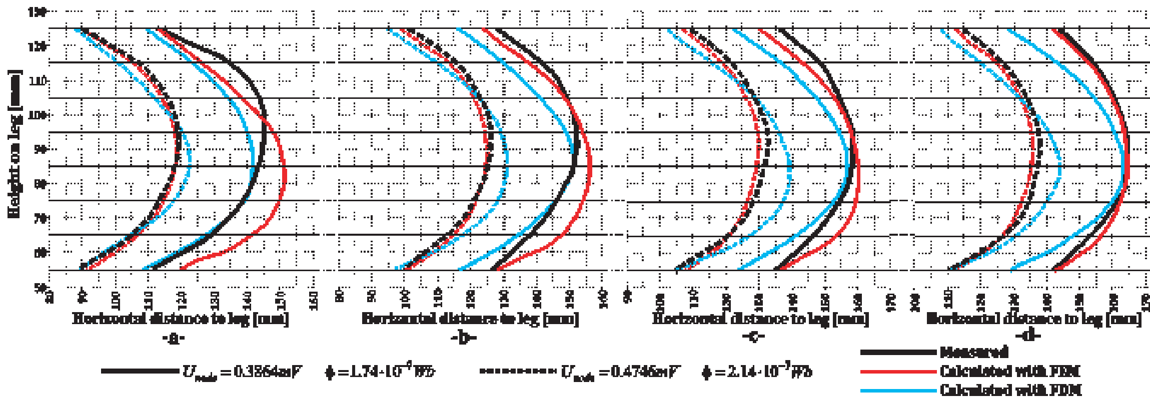


Figure 3: Comparison of the flux distributions for different horizontal distances from secondary leg of transformer.

## 4. CONCLUSION

This study is based on a comparison of flux distributions of a core type voltage transformer. The experimental set was established to measure real time flux components. Results of measurements and calculations obtained from the most useful numerical methods (FEM and FDM) were compared with each other. It shows that if a good imitation and definition is in place, numerical methods are superior in terms of accuracy in the detection of flux distributions.

As seen in Figure 3, FEM and FDM offer very close results for a network that contains an equal number of unknowns. Moreover, the numerical methods provide adequate close results in terms of the flux distributions compared to experimental measurements. Furthermore, flux distributions that were calculated using FEM and obtained from the measurement results were shown to be very close to each other (slopes nearly overlap). In the study, the results obtained using triangular elements and the approximation function of the first degree were found to be adequate, but the degree of the polynomial has not been increased accordingly. The accuracy rate can be increased by increasing the polynomial used in FEM. FEM can be more reliable depending on the sizes of the finite elements and the flexibility of the figures. Boundary conditions can be easily implemented, and an unlimited number and boundary conditions can be obtained. Thanks to the multifaceted and flexible structure of these methods, environment and field relations in complex structures as well as cause-effect relationships in different problems can be constantly calculated efficiently. The results obtained show that both numerical methods can be applied effectively and easily in determining leakage flux of voltage transformers. These methods can also be used for different transformer model in future investigations.

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