Comparison of Analytical Method and Different Finite Element Models for the Calculation of Leakage Inductance in Zigzag Transformers

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***Abstract*—A zigzag transformer is a key segment of the electric power system. The optimal design of the zigzag transformer is important for transformer designers to provide a required return path for earth faults and to ensure proper operation of a power system. The two most important parameters of the zigzag transformers are no-load losses and leakage impedance. The accurate calculation of both factors helps to minimize the overall cost of the transformer. Therefore, the prediction of leakage reactance in the zigzag transformer using analytical or numerical methods is an essential part of the early designing stages of the transformer. This paper provides several two- and three-dimensional finite element models. The main purpose of these models is to evaluate the accuracy of the different models for the calculation of the leakage reactance. An analytical formula and a complete procedure for the calculation of the leakage reactance in the zigzag transformer are also provided, which will help the researchers and transformer designer to optimize this type of transformer. The prototype is also manufactured and tested to verify the accuracy of the analytical method and finite element models for the calculation of the leakage reactance. The simulation and experimental results show that the finite element calculation cannot only obtain accurate leakage reactance values (magnetostatic analysis), but also provides better accuracy in the no-load losses (transient analysis).**

***Index Terms*—Finite element method; Grounding transformer; Leakage reactance; Magnetostatics analysis; Transient analysis; Zigzag transformer.**

I. INTRODUCTION

Transient overvoltages, short-circuit withstands capability, basic insulation level, and other important factors of the power system depend on the neutral grounding. The impedance to ground faults can be decreased by using grounding transformers. The level of ground fault current can also be decreased by using the grounding transformers. Two main configurations of three-phase grounding transformers are:

– Interconnected star or zigzag connections;
– Wye-delta grounding transformer.

Zigzag transformers are preferred due to their lower cost and smaller size for the same value of the zero-sequence impedance in wye-delta grounding transformers. Zigzag transformers are found everywhere in the contemporary world. As their number increases, accurate calculation of leakage reactance becomes an important issue in maintaining the comfortable working of the zigzag transformer.

The zigzag transformer is built with copper windings, a soft magnetic material (silicon steel), and high-end insulation materials. Leakage reactance is one of the most important parameters of the zigzag transformer because the main purpose of the zigzag transformer is to provide a low leakage reactance to give a path for zero sequence components during the fault conditions. Using finite element models and analytical equations, a variety of changes can be made to the geometry and ampere-turns of the zigzag transformer to optimize the impact of leakage reactance and fulfilling the customer requirements. The voltage increase in the unfaulted phases is also prevented by the zigzag transformer.

Zigzag transformers are also known as interconnected star windings, and the zigzag transformer has some characteristics of the delta and the star connection, and the advantages of both delta and star connections.

Zigzag transformers are used as a grounding transformer; the main advantages of the zigzag transformer for the power systems are [1]–[5]:

– The zigzag transformer performs harmonic mitigation and terminates harmonics. The zigzag transformer can be used in a power system to trap triplet harmonic currents, i.e., 3rd, 9th, 15th, and 21st harmonics. Zigzag transformers are installed near the loads that produce higher triplet harmonic currents and minimize the undesirable effects of the triplet harmonic.

– Zigzag transformers provide cheaper grounding on the transformers. It helps components of the power system and decreases the stress of the voltage under the fault currents. The zigzag transformer also provides insulation

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between the power system components and the ground, so that the power system components may not be affected by the fault current.

– Due to the low internal winding impedance, zigzag transformers are more effective for grounding purposes and provide a better solution for grounding the power system. Zigzag transformers have a low leakage impedance value, which allows the triple-harmonics of the excitation current and the zero-sequence currents to flow through it because there is no opposition to their flow except the small value of the leakage reactance of the zigzag transformers.

The leakage reactance in the transformer can be calculated with analytical techniques, numerical methods, and experimental tests. The leakage reactance of the transformer can also be calculated by using the reluctance network modeling [6].

Numerical techniques are accurate, but this method is time-consuming. Reluctance network modeling is faster but less accurate as compared to the numerical method. Due to the higher accuracy, compared to the other analytical method, the Rogowski method is one of the efficient analytical techniques that can be used effectively to evaluate leakage reactance [7].

The change in the dimension of the transformer winding can significantly affect the leakage reactance, resulting in the change in the short-circuit current and the short-circuit impedance of the transformer [8]. The size of the internal winding can also be determined by leakage reactance [9]. Magnetic traps to harmonics are also affected by the leakage reactance [10]. In [11]–[18], different analytical methods and finite element models are presented to evaluate leakage reactance in the different types of winding connections. However, a comparison of the different methods for evaluating leakage reactance applied to zigzag configuration transformers for determining the accuracy of these methods is still missing. Hence, this work explains the determination of the leakage reactance in the zigzag transformer in detail, i.e., the calculation of the leakage reactance by analytical methods and the finite element method. Furthermore, several finite element models are compared for the accurate calculation of the leakage reactance.

Different magnetostatic analysis and transient analysis are performed to evaluate the accuracy of the finite element analysis for values of the leakage reactance and no-load losses in the zigzag transformers. For the estimation of the leakage reactance four different models are used, namely, three-phase three-dimensional, single-phase three-dimensional, three-phase two-dimensional, and single-phase two-dimensional. The analytical method is derived from the available analytical equations and the results of the analytical method are also compared and investigated by finite element simulations and experimental tests.

II. Reactance in Zigzag Transformers

As a consequence of international standards and manufacturing tolerances, leakage reactance calculation is one of the important subjects for transformer designers. One important question for transformer designers is how different parameters affect the overall leakage reactance of the zigzag transformer. In this paper, a comparative study of a leakage reactance calculation for the zigzag transformer is presented.

The short-circuit performance of the transformer is also related to the leakage reactance. The leakage reactance depends on the ampere-turns and geometry of the transformer, all of which can be analysed by using an analytical method or numerical method. Evaluating leakage reactance in the zigzag transformer using analytical and numerical techniques saves time, reduces the number of experiments, and prototypes. These methods can accurately predict the leakage reactance within the zigzag transformer, which contributes to optimization of the overall zigzag transformer design.

For the flow of the positive and negative sequence currents, zigzag connections pose a high magnetization impedance. However, to improve the flow of triple-harmonics and zero-sequence currents, zigzag transformers have a lower leakage reactance because they provide a path for zero-sequence currents coming from ground faults. Zero-sequence currents in the power system come mainly from unbalanced loads and faults involving grounding. That is why it is in the greater interest of the zigzag transformer designers to give an accurate value of the leakage reactance and guarantee leakage inductance levels in the range of the international standards. The IEC 60076–1 standard mandates tolerance of ±10 % for zigzag transformers. Equation (1) shows the Rogowski method for the evaluation of leakage reactance [13]:

$$X = 2\pi \times f\,\frac{\pi N^2 \mu_o}{H_{eq}} \times \sum ATD, \tag{1}$$

$$\sum ATD = \frac{1}{3}\left(B_{HV} \times D_{HV}\right) + \left(B_{HL} + D_{HL}\right) + \frac{1}{3}\left(B_{LV} \times D_{LV}\right), \tag{2}$$

where N, f, ATD, μ_o, B_{HV}, B_{HL}, and B_{LV} are the number of turns in the high voltage winding, frequency, ampere-turn density, free space permeability, radial depth of the high voltage winding, the gap between low voltage (LV) and high voltage (HV) windings, and LV winding. D_{HV}, D_{HL}, and D_{LV} are the mean diameter of the HV winding, the gap between the LV and HV windings, and the LV winding. The equivalent height of the winding can be represented as H_{eq}

$$H_{eq} = \frac{H_w}{K_R}. \tag{3}$$

H_w is the average height of the windings, and K_R is the Rogowski factor

$$K_R = 1 - \frac{1 - e^{\left(\frac{-\pi \times H_w}{B_{LV} + B_{HL} + B_{HV}}\right)}}{\frac{\pi \times H_w}{B_{LV} + B_{HL} + B_{HV}}}. \tag{4}$$

The leakage reactance in the zigzag and delta (or star) transformers can be calculated by using (5) [18]. As shown in (5), the leakage reactance in the zigzag transformer can be calculated in three pairs of winding (three steps), i.e., between the high voltage and zig winding, the high voltage and zag winding, and the zig and zag winding

$$X_{star-zigzag} = \frac{1}{2}\left[X_{HV-zig} + X_{HV-zag}\right] + \frac{1}{6}\left[X_{zig-zag}\right]. \tag{5}$$

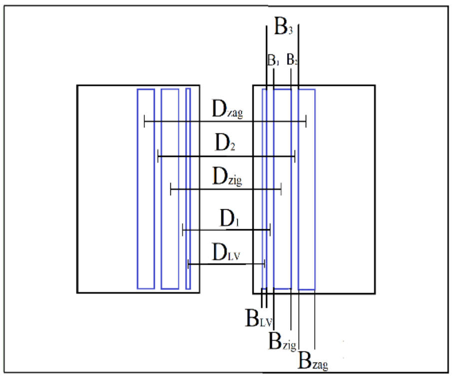

Fig. 1. Geometric dimensions.

When the zig-zag is on the high voltage side, (5) can be rewritten as

$$X_{zigzag-star} = \frac{1}{2}\left[X_{LV-zig} + X_{LV-zag}\right] + \frac{1}{6}\left[X_{zig-zag}\right]. \tag{6}$$

The leakage reactance between the pair of low voltage and zig winding can be calculated by using (7)

$$X_{LV-zig} = 2\pi f \times \frac{\pi N^2 \mu_o}{H_{LV-zig}} \times \sum ATD_{LV-Zig}, \tag{7}$$

where $\sum ATD_{LV-zig}$ and H_{LV-zig} are the ampere-turn density and the equivalent height of the LV and zig winding. Equations (8) and (9) can be used to calculate $\sum ATD_{LV-zig}$ and H_{LV-zig}:

$$\sum ATD_{LV-Zig} = \frac{1}{3}\left(B_{zig} \times D_{zig}\right) + \\ + \left(B_1 + D_1\right) + \frac{1}{3}\left(B_{LV} \times D_{LV}\right), \tag{8}$$

$$H_{LV-Zig} = \frac{H_{w1}}{K_{R1}}. \tag{9}$$

H_{w1} is the average height of the low voltage and zig winding. B_{zig}, D_{zig}, and B_1, D_1 are the radial depth and mean diameter of the zig winding and the radial depth and mean diameter of the gap between LV and zig winding. Figure 1 shows the geometrical dimension of the equations from (8) to (18).

The Rogowski factor of the LV and the zig winding can be calculated by using (10)

$$K_{R1} = 1 - \frac{1 - e^{\left(\frac{-\pi \times H_w}{B_{zig} + B_1 + B_{LV}}\right)}}{\frac{\pi \times H_w}{B_{zig} + B_1 + B_{LV}}}. \tag{10}$$

The leakage reactance between the pair of the low voltage and the zag winding can be calculated using (11)

$$X_{LV-zag} = 2\pi f \times \frac{\pi N^2 \mu_o}{H_{LV-zag}} \times \sum ATD_{LV-Zag}, \tag{11}$$

where $\sum ATD_{LV-zag}$ and H_{LV-zag} are ampere-turn density and equivalent height of the LV and zag winding. Equations (12) and (13) can be used to calculate $\sum ATD_{LV-zag}$ and H_{LV-zag}:

$$\sum ATD_{LV-Zag} = \frac{1}{3}\left(B_{zag} \times D_{zag}\right) + \\ + \left(B_3 + D_3\right) + \frac{1}{3}\left(B_{LV} \times D_{LV}\right), \tag{12}$$

$$H_{LV-Zag} = \frac{H_{w2}}{K_{R2}}. \tag{13}$$

H_{w2} is the average height of the low voltage and zag winding. B_{zag}, D_{zag}, and B_3, D_3 are the radial depth and mean diameter of the zag winding, and the radial depth and mean diameter of the gap between the LV and zag winding.

The Rogowski factor of the LV and zag winding can be calculated using (14)

$$K_{R2} = 1 - \frac{1 - e^{\left(\frac{-\pi \times H_w}{B_{zag} + B_3 + B_{LV}}\right)}}{\frac{\pi \times H_w}{B_{zag} + B_3 + B_{LV}}}. \tag{14}$$

The leakage reactance between the pair of zig and zag windings can be calculated by using (15)

$$X_{zig-zag} = 2\pi f \times \frac{\pi N^2 \mu_o}{H_{zig-zag}} \times \sum ATD_{zig-zag}, \tag{15}$$

where $\sum ATD_{zig-zag}$ and $H_{zig-zag}$ are the ampere-turn density and the equivalent height of the zig and zag windings. Equations (16) and (17) can be used to calculate the $\sum ATD_{zig-zag}$ and $H_{zig-zag}$:

$$\sum ATD_{zig-Zag} = \frac{1}{3}\left(B_{zig} \times D_{zig}\right) + \\ + \left(B_2 + D_2\right) + \frac{1}{3}\left(B_{zag} \times D_{zag}\right), \tag{16}$$

$$H_{zig-Zag} = \frac{H_{w3}}{K_{R3}}. \tag{17}$$

H_{w3} is the average height of the zig and zag windings. B_2, D_2 are the radial depth and mean diameter of the gap between the zig and zag windings. The Rogowski factor of the zig and zag windings can be calculated using (18)

$$K_{R3} = 1 - \frac{1 - e^{\left(\frac{-\pi \times H_w}{B_{zig} + B_2 + B_{zag}}\right)}}{\frac{\pi \times H_w}{B_{zig} + B_2 + B_{zag}}}. \tag{18}$$

III. NUMERICAL TECHNIQUES

Due to the limitations of analytical methods, the use of numerical techniques for the solution of electromagnetic, magnetic, and electrostatic field problems is increasing day by day [19]–[21]. Numerical analysis can solve the irregular and complex geometrie and non-linear electric machine materials more appropriately as compared to the analytical method.

Finite element analysis is one of the most commonly used numerical techniques for solving magnetostatic problems. The finite element method can be used for the solution of differential equations in engineering fields such as magnetostatic analysis, thermal analysis, electromagnetic analysis, acoustics and vibration analysis, mechanics and structural analysis, fluid mechanic analysis, and transient analysis. In the finite element method, the solution mainly depends on the type of problem (mechanical, electromagnetic, linear, nonlinear, and thermal) and the type of software used for the computation. Nevertheless, the general structure is common to all finite element methods and can be divided into the three steps:

– Pre-processing;
– Processing;
– Post-processing.

In the pre-processing, the problem is defined. The first process of the pre-processing is to draw the geometry of the structure or problem which is needed to be solved and assign the suitable material properties for each of the objects. The finite element methods subdivide a geometry into simpler and smaller parts that are called "finite elements" and the main objective of the pre-processing in the finite element method is to discretize the structure into smaller elements and develop an appropriate finite element mesh. After mesh operation, the implementation of the boundary conditions and required contacts between the different objects and model components is needed. For the two-dimensional problems, triangle- or rectangle-based meshes can be used, and for the three-dimensional problem, tetrahedron meshes are preferred.

Figure 2 shows the steps of the pre-processing.

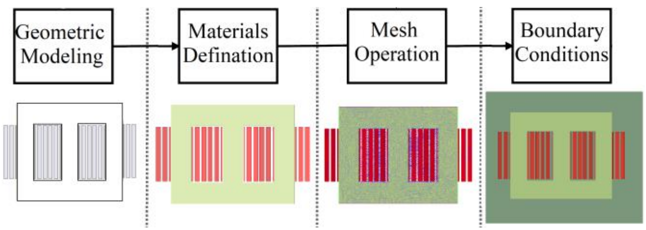

Fig. 2. Pre-processing.

In the processing step, the problem is assembled into the system equations using computational resources and an appropriate solution to the physical problem can be obtained.

The required solutions to the problem can be obtained in the post-processing step. The required solution and desired quantities (e.g., electromagnetic field, transient analysis, electrostatic field, stress, forces, temperature) can be represented by using plots, graphs, and tables. One of the most benefits of using the finite element method is to include the visual representation by using graphs, plots, and tables. Figure 3 shows the different types of representation during post-processing.

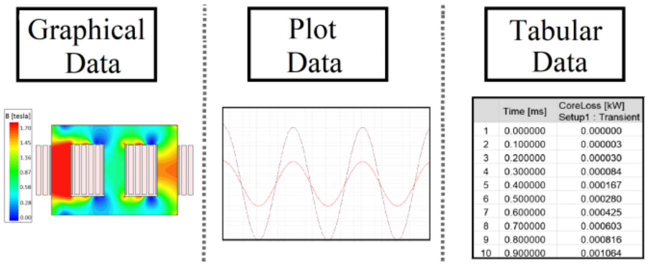

Fig. 3. Post-processing.

The use of finite element analysis is increasing rapidly due to its ability to solve real-world problems in a simple way. In transformer design, finite element analysis can be used to evaluate iron losses, copper losses, inrush current, vibration, stress, temperature, and electromagnetic forces.

The main aim of transformer designers is to construct a high-quality transformer at the lowest possible cost. In the zigzag transformer, the working of the transformer is mainly based on the leakage reactance. Designers of zigzag transformer can find the ideal value of the leakage reactance by changing the dimensions of the windings, the space between the windings, and the height of the windings.

Magnetostatic Problems. In transformers, leakage reactance, electromagnetic forces, inductance, capacitance, and other important factors involve magnetostatic problems. The analysis of the magnetostatics problem for the evaluation of the leakage reactance can be divided into four main parts:

– Modelling and materials definition;
– Generating and refining mesh;
– Current excitation and boundary conditions;
– Analysing the results.

Optimization of the transformer design for performance and efficiency can be achieved by performing all the steps of the analysis properly.

The two Maxwell equations given below in differential form can be applied to magnetostatic problems:

$$\nabla . B = 0, \quad (19)$$

$$\nabla \times H = J, \quad (20)$$

where J, H, and B are the electric current density, magnetic field intensity, and magnetic flux density. The relationship between H and B in magnetic materials is given below

$$B = \mu . H. \quad (21)$$

In the equation above, μ is the permeability. The ferromagnetic materials, which are used in the manufacturing of the transformer and reactor magnetic circuits, possess a nonlinear B-H characteristic curve, and magnetic flux density is a function of the permeability and magnetic field intensity of the magnetic material. For the calculation of the leakage reactance, the permeability of the magnetic material must be kept high, and during the simulation, adding non-linear characteristics properties to the core is not compulsory. However, during the evaluation of the no-load and load losses, one must assign non-linear properties to the core of the transformer.

Using finite element methods, the leakage reactance of the zigzag transformer can be evaluated using the energy method. Equation (22) shows the formula for the calculation of the magnetic energy in the different parts of the transformer

$$W_{\text{mag}} = \int_{vol} \frac{1}{2} B.HdV. \qquad (22)$$

The calculated stored energy from the finite element method software can easily be converted to the inductance using (23)

$$L = \frac{2W_m}{I^2}. \qquad (23)$$

IV. ACCURACY OF ANALYTICAL METHOD AND FINITE ELEMENT MODELS FOR THE LEAKAGE REACTANCE

This section will compare the experimental results of the prototype transformer with the finite element method and analytical approach. The finite element results presented in this paper were obtained using the program ANSYS Maxwell. For the evaluation of the leakage reactance by the finite element method, four different models are used, namely three-phase three-dimensional, one-phase three-dimensional, three-phase two-dimensional, and single-phase two-dimensional. Figures 4 and 5 show the mesh operation of the three-phase and single-phase two-dimensional models. The total number of mesh elements of three-phase two-dimensional and single-phase two-dimensional models are 40396 and 5950, respectively.

To validate the analytical method and numerical models, experiments were performed on the prototype transformer. Experimental measurements of the analysed transformer were performed in the test laboratory of the Astor Transformer Turkey, which is equipped with state-of-the-art testing devices.

For measuring voltage, current, power, and short-circuit impedance, the Yokogawa Electric WT500 power analyzer was used. All the tests are carried out on the transformer following the IEC-60076-1 standards. For the calculation of the no-load losses, the rated voltage was applied to the primary winding and other windings were open-circuited. A short-circuit test on the transformer was performed to determine the leakage reactance of the transformer.

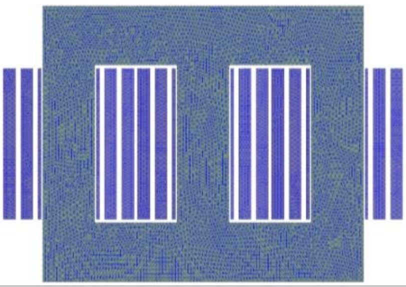

Fig. 4. Mesh operation of 3-phase two-dimensional.

In this study, leakage inductance and core losses were evaluated with the help of the numerical technique for the zigzag transformer with a power of 250 kVA and a voltage level of 33/0.4 kV with Znyn1 connections. After finding the leakage reactance results satisfactory, the zigzag transformer was manufactured with the same geometric dimensions. Figure 6 shows the image of the transformer during routine tests.

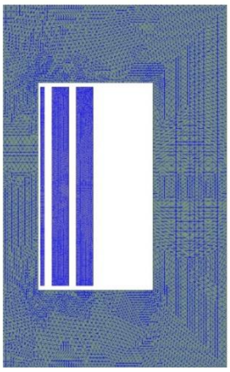

Fig. 5. Mesh operation of 1-phase two-dimensional.

Fig. 6. Transformer during routine tests.

The basic design data of the prototype zigzag transformer are shown in Table I.

TABLE I. DESIGN DATA OF THE ZIGZAG TRANSFORMER.

Connection	ZNyn 1
Power	250 kVA
HV Voltage	33 kV
LV Voltage	0.4 kV
Zig + Zag turns	1048 + 1048 turns
HV Current	4.38 A
Core Material	M5 cold rolled grain-oriented Steel
Magnetic flux density	1.651 T

Table II compares the calculation of the leakage reactance of the analytical method and finite element models with the experimental test.

TABLE II. CALCULATION OF LEAKAGE REACTANCE.

Method	Leakage reactance %	Difference %
3-phase 3-D	4.25	1.19
1-phase 3-D	4.39	4.52
3-phase 2-D	4.26	1.42
1-phase 2-D	4.40	4.76
Analytical	3.92	6.67
Experimental	4.2	-

Figures 7 and 8 show the B-H and power loss curve of the core material of the zigzag transformer [11].

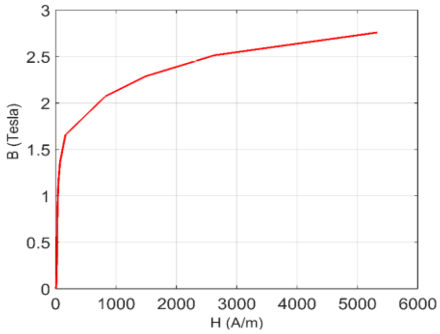

Fig. 7. B-H curve.

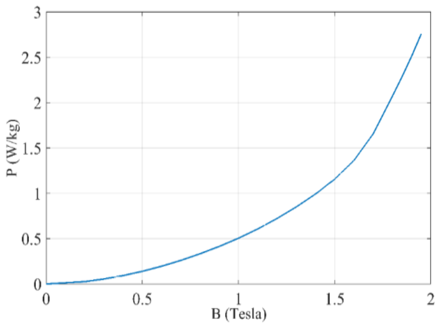

Fig. 8. Power loss curve.

The results clearly show a higher accuracy for the finite element method. The accuracy of the 3-phase three-dimensional model is higher than that of the other models. The difference between the 3-phase 3-D and the experimental test is 1.19 %. The difference between the single-phase 3-D model and the experimental method is 4.5 %. As shown in Table II, the difference between the two- and three-dimensional models is very small or negligible, i.e., the results of the 3-phase 3-D and 3-phase 2-D are very similar, and the results of the 1-phase 3-D and 1-phase 2-D are also almost the same. The difference between the prototype transformer and the analytical method is 6.67 %. The difference between the 3-phase models and the analytical method is greater than 7.76 %, and the difference between the 1-phase models and the analytical method is greater than 10.70 %.

Transient analysis is also performed for the evaluation of the magnetic flux density and core losses. Figures 9 and 10 show the magnetic flux density and core losses of the zigzag transformer using 3-phase two-dimensional model.

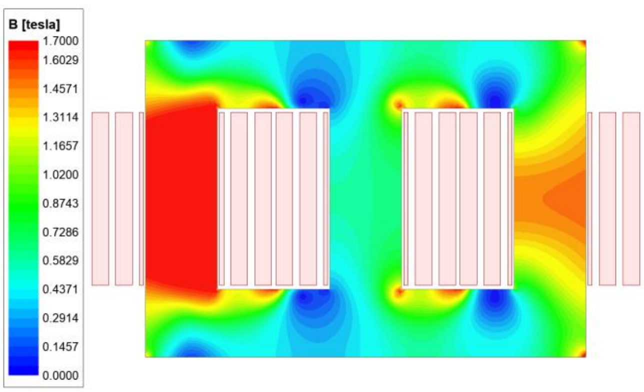

Fig. 9. Magnetic flux distribution of the analysed zigzag transformer.

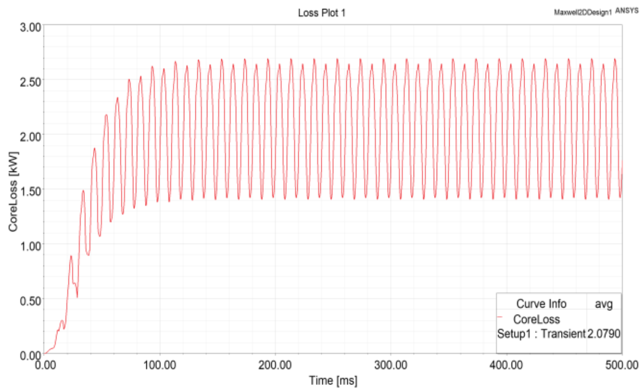

Fig. 10. Core losses of the analysed zigzag transformer.

Table III compares the results of the no-load losses using finite element 2-D three-phase model and experimental test.

TABLE III. CORE LOSS CALCULATION.

Method	**Core loss (kW)**
FEM 2D	2079
Experimental	2020

The difference between the finite element 2-D three-phase model and the experimental method is less than 3 %.

During the manufacturing of the transformer, an accurate calculation of short-circuit reactance is crucial because it increases the credibility of the manufacturer and the reliability of the transformer. It also helps to reduce the cost and size of the material, since a smaller leakage impedance design margin can be used [22]. Transformer designers mainly rely on analytical formulas. However, the results show that the finite element method is more reliable for calculating the leakage reactance in the zigzag transformer.

The accurate calculation of the leakage reactance and core losses using the finite element method not only helps to evaluate these parameters, but can also be used to optimize the design of the zigzag transformer, which will also help to fulfil the customer requirements and international standards.

V. Conclusions

Appropriate calculation of the leakage reactance is vital for transformer designers because the short-circuit current of the transformer is mainly dependent on the leakage reactance. The overall cost of the transformer can also be minimized by appropriately calculating the leakage reactance.

In this study, the leakage reactance is calculated using experimental tests, numerical techniques, and the analytical method. Several finite element models, namely 3-phase 3D, 1-phase 3D, 3-phase 2D, and 1-phase 2D, are examined for leakage reactance, and these models have been compared with the experimental test and analytical method. Among the analytical techniques, the Rogowski method is used for the evaluation of the leakage reactance. On the other hand, prototype experiment tests are performed to find the exact solution. By using analytical techniques, the leakage reactance can be calculated in a short time and without any financial problems as most of the finite element method software is expensive and time-consuming. However, the accuracy of the finite element models is much higher than that of the analytical method.

This work will help researchers and transformer designers evaluate and understand different parameters of the leakage reactance by using analytical formulas and finite element models.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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