Early Detection of Short Circuit Faults Between Windings in Distribution Transformers Using Finite Element Method

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***Abstract*—The primary aim and contribution of this study is the presentation of a non-intrusive early diagnosis method based on finite element simulation (FEM). The focus was on a 1000 kVA distribution transformer based on manufacturing data and field tests conducted in Mosul, Iraq. An accurate two-dimensional model of the transformer was developed using ANSYS Maxwell software, simulating normal operation and various internal fault scenarios (such as single-phase or double-phase short-circuits and ground faults) at varying rates. The resulting changes in magnetic flux distribution, core losses, currents, and voltages were analyzed as indicators to determine the presence, type, and severity of faults. A representation of internal faults in the three-phase transformer windings was performed to detect and diagnose faults early. The results clearly show that small short-circuit faults (up to 1.2% of the windings) are distinguishable by specific changes in transformer parameters. These faults lead to a localized temperature increase and the onset of insulation deterioration. It was also observed that an increase in the fault percentage (5% to 25%) causes a significant increase in magnetic flux and total losses. These effects are significantly exacerbated by ground faults or faults involving two phases. These results confirm that computational analysis provides a powerful tool for proactive monitoring, enabling preventive maintenance scheduling based on initial fault indications. This contributes to extending transformer life, enhancing network reliability, and avoiding costly catastrophic failures. Continuous monitoring and effective ground protection remain critical elements for maintaining transformer safety and efficiency.**

Keywords*—Distribution Transformers; Internal Short Circuit Fault Simulation; Finite Element Method (FEM); ANSYS Maxwell Software; Magnetic Flux Distribution Analysis; Predictive Fault Diagnosis.

I. Introduction

Electrical transformers are vital components of modern power transmission and distribution networks, playing a pivotal role in regulating voltage levels to ensure efficient transmission and safe use of electricity for various loads [1]-[3]. With their ability to step up and step down voltage, these devices form the backbone of the energy infrastructure, ensuring the stability and efficiency of the electrical grid [4][5]. However, ensuring the reliable and continuous operation of these valuable assets is a significant challenge. During their operation, transformers are exposed to constant electrical, thermal, and mechanical stresses, as well as harsh environmental conditions such as lightning and humidity, which lead to the gradual deterioration of their components and expose them to the risk of failure [6]-[8].The main problem addressed in this research is internal faults within transformers, specifically winding failures, which are among the most common and serious causes of transformer failure. These faults cover a wide range, from short circuits between a few adjacent turns (Turn-to-Turn Faults), to short circuits between different phases (Inter-Phase Faults), to ground faults (Winding-to-Ground Faults) and deterioration of the overall insulation system [9]-[12]. These faults pose a serious threat to the safety of the transformer and the continuity of electrical service.

This deterioration over time increases the risk of catastrophic failures, causing significant financial losses and long-term power outages. In addition to the high cost of repair or replacement, replacing a damaged transformer can be time-consuming, increasing operational and financial impacts. Therefore, a deep understanding of the causes of failures and developing effective early detection and prevention strategies is critical to ensuring service continuity and reducing risks. Internal faults in the electrical transformer, the most important of which are winding faults, are among the most prominent problems facing three-phase transformers, which greatly affect their performance and reliability. These faults vary, starting from short circuits between windings (Turn-to-Turn Faults) [13]. Up to more complex faults such as ground faults and insulation deterioration. And inter-phase faults (Inter-Phase Faults) [14]. These faults cause a rise in local temperature and the generation of flammable gases, which may lead to catastrophic failure of the transformer [15][16]. The causes of these faults include the previously explained reasons such as electrical, thermal, and mechanical stress, in addition to moisture contamination [17]-[20].

The main objective of the work is to simulate a 1000 kVA three-phase transformer, which means simulation of the high-voltage and low-voltage windings with all their details and number of turns, in addition to the iron core and the tank filled with transformer oil. This simulation is modeled by using ANSYS MAXWELL SOFTWARE that takes into account a wide range of different operating conditions, which helps to better understand the fault behavior in transformers. Furthermore, to conduct additional experiments in which the loads drawn from the transformer are varied, starting with operating the transformer at 100% full load and 50% of the total load. This variety of experiments provides an increase in accuracy and visualization when observing the fault representation on different loads. The additional experiments also aim to validate the models, theories, and simulations, which enhances the reliability of the results extracted from the research.

The research contribution of this study:

- Develop a detailed electromagnetic simulation model using ANSYS Maxwell that accurately reflects the operational behaviour of a real distribution transformer under normal conditions and various internal fault conditions.
- Identify measurable indicators (such as flux distribution variations, iron core losses, and induced currents) that are sensitive to the presence of minute internal short-circuit faults (up to 1.2% of windings) in single-phase or dual-phase circuits or ground faults.
- Provide a quantitative analysis demonstrating the relationship between the internal fault ratio (severity) and the extent of deviation in transformer performance and efficiency, providing valuable insights that can be used as a basis for developing transformer condition monitoring systems and predictive maintenance strategies.

II. METHOD AND TOOLS

This study aims to simulate the behavior of a 1000 kVA distribution transformer using ANSYS Maxwell and the finite element method (FEM). The methodology is based on a series of integrated steps, illustrated in Fig. 1, which begins with collecting detailed manufacturing data of the transformer, then building an accurate simulation model in ANSYS Maxwell, followed by analyzing the behavior of the transformer under different operating conditions. The various electrical results are then obtained.

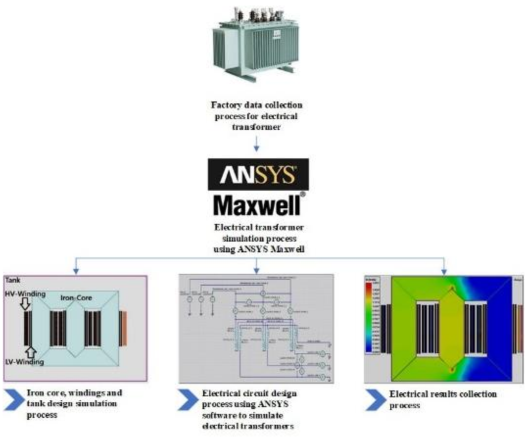

Fig. 1. Flowchart illustrating the methodology of this research paper

This study followed a computer simulation methodology using the finite element method (FEM) to investigate the impact of internal faults on the performance of a three-phase distribution transformer. The main steps include:

1) Determining transformer specifications and collecting data:

Actual manufacturing data for a 1000 KVA distribution transformer with all its specifications and basic characteristics of the components of this transformer, which are the manufacturing materials and design of the iron core, coils, and oil immersing the coils, were obtained. Fig. 2 shows a real model of the electrical transformer from the outside, which was obtained at the transformer maintenance center in Mosul, Iraq. Routine tests were conducted at the maintenance center to take the data and specifications of the transformer and compare them first with the manufacturing data.

Fig. 2. Shows a real model of the exterior of a 1000 kVA transformer at the maintenance center in Mosul, Iraq

Table I shows the specifications and ratings of the electrical transformer according to the manufacturer's data that were used in the computer representation. The transformer's capacity, as well as the voltage, frequency, weight, and other important details in the design illustrated in this table. All these characteristics and specifications were used in the ANSYS software for the purpose of representing this transformer.

TABLE I. ELECTRICAL TRANSFORMER RATINGS OF FREQUENCY, CORE LOSSES, AND COOLING METHOD FOR THREE-PHASE TRANSFORMER

Name	Value	Units
Power rated	1000	KVA
Voltage	11/0.433	KV
Frequency	50	Hz
Core loss	1496	Watt
Weight	1185	Kg
Material (CRGO)	M5	------
Flux Density	1.584	Tesla
Cooling Type	ONAN	------
Core dimensions	1030 (width) × 910 (high) × 133 (depth)	mm
Leg length	480	mm
Phase	3	

The basic electrical dimensions used in this design are that the transformer core is made of cold-rolled grain-oriented silicon steel with 97% iron and 3% silicon Table II shows the dimensions of the iron core of the three-phase transformer that will be adopted in the design in the simulation program. This data was used in the two-dimensional design in the ANSYS software [17][21]. As for the design of the files, it was based on the manufacturing data and the properties of the copper material used in manufacturing the files. This data is explained in Table II, which will show the basic manufacturing dimensions of the files, which were relied upon in the computer representation in the ANSYS program [22][23].

TABLE II. Dimensions and Number of Copper Coils for the Three-Phase Transformer that Will be Adopted in the Design in the Simulation Program

Name	High-voltage windings for each phase of three-phase windings	Low-voltage windings for each phase of three-phase windings
Type of Connection	Delta	Star
No. of Turns	739 Turn	16 Turn
No. of Disk	57 Disk	--------
Dimensions of turn	6.5×2.4 mm	430×1.3 mm
Thickness of isolation between turn to turn	0.25 mm	0.15 mm

It was necessary to conduct tests on the electrical transformer before representing and simulating it in the simulation program ANSYS because the program needs the values of the coil resistance in the case of the transformer operating in its normal state without faults [24]-[26]. The value on the high voltage side when the test was conducted was 827.7 milliohms in the windings of the high voltage coils. As for the resistance of the coils on the low voltage side, the value obtained during the test was 675.4 micro-ohms in the windings of the low voltage coils. This test is shown in Fig. 3, which shows the test conducted on the 1000 kilo-volt-ampere electrical transformer.

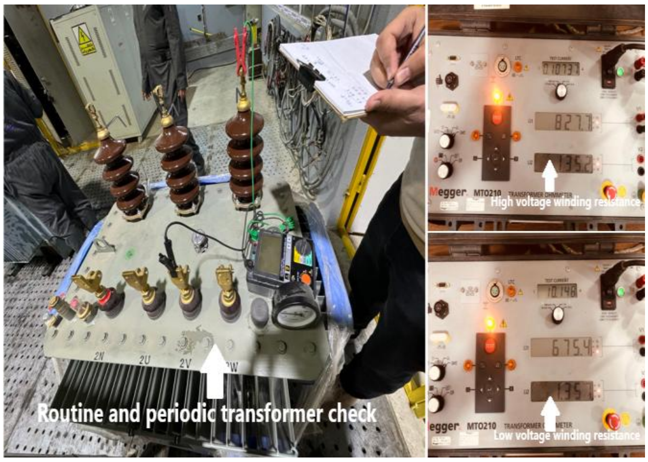

Fig. 3. Shows part of the tests conducted on a real model of a 1000 kVA transformer to determine the resistance values of the coils

These practical measurements are necessary for two main reasons: First, to provide accurate values for the input parameters required by the simulation software. Second, and more importantly, to enable validation of the underlying simulation model (in normal operation) by comparing simulation results (such as calculated resistances or currents) with experimentally measured values. This test is illustrated in Fig. 3, which shows a test performed on a 1000 kVA transformer.

2) Developing the engineering model and simulation using ANSYS Maxwell

The finite element method for two-dimensional geometric designs of three-phase transformers is a current issue worldwide [27]-[29]. The ANSYS Maxwell software was used for simulation, and the model will be simplified for modelling purposes as necessary. For modelling distribution transformers, the insulation components can be considered as air only, considering that the core, windings, and metallic parts will be important. Furthermore, a complete model of the above-mentioned components in fine detail is almost impossible in practice [30]-[34]. The model must be modified according to the intended purposes and simulation needs. The simulation related to the two-dimensional design was designed using ANSYS Maxwell software based on the geometric diagram of the three-phase transformer [35]. The two-dimensional (2D) model was adopted in this study primarily to achieve a balance between accuracy of results and computational efficiency. The two-dimensional model allows for adequate capture of the basic electromagnetic phenomena and the magnetic flux distribution in the core and windings for the analysis of common internal faults, and it is an accepted approach in many similar studies [36]-[39]. However, it is important to recognize that this simplification ignores some three-dimensional effects, such as the spurious flux at the ends of the windings (end-winding flux) and the complex field distribution at the junctions, which may lead to slight inaccuracies in the calculation of some losses or mechanical forces [40][49]. Fig. 4 shows the two-dimensional design of a transformer with an iron core, high-voltage windings, low-voltage windings, and the surrounding tank.

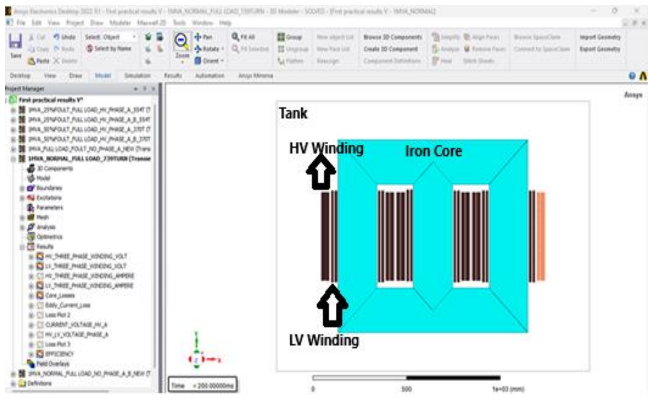

Fig. 4. Three-phase transformer geometry in 2D after drawing in ANSYS software

To further clarify the windings in the manufacturing data, the three-phase windings for the high voltage side (11000 volts) consist of copper windings, the number of which in the normal state is (739 windings) divided into discs, the number of which is (57) discs; each disc contains (13 windings) with dimensions of (2.4×6.5 mm) for each winding. As for the low-voltage windings (433 volts), the number of which is 16 and their dimensions are (1.3×430 mm), and they are shown in Fig. 5. Therefore, the closer the simulation is to the reality of the real transformer, the better the results will be. From this point of view, the simulation procedure in this study took a long time to find a stable way to simulate transformers, especially for the windings part, and the reason for this is that the transformer energy comes from injecting the windings with voltage or currents [50]-[56].

Three levels of mesh resolution were considered for the transformer geometry (core, windings, and boundary region) to increase the accuracy of the results. A high-resolution mesh was assigned to the problem regions for all windings and different T-connection designs in the primary transformer. Fig. 6 shows the mesh analysis of the core and windings used in this work. The convergence of the solution was checked with improved mesh resolution to ensure that the results were not overly sensitive to the chosen mesh density. Time-domain electromagnetic field simulation (transient analysis) was performed to calculate the magnetic flux distribution, losses in the iron core (hysteresis and vorticity), and induced currents and voltages in the windings [56]-[65].

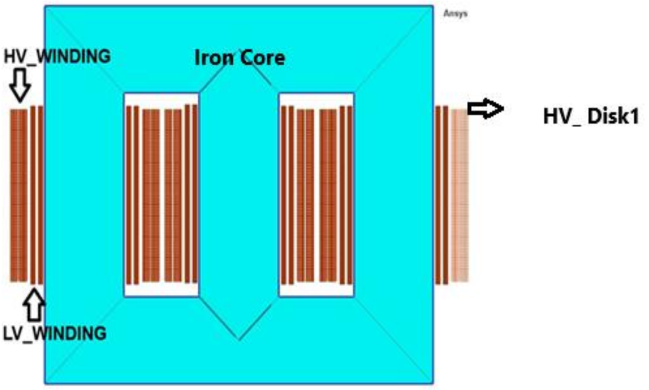

Fig. 5. 2D design approximation showing the windings of three-phase high and low voltage coils (ANSYS)

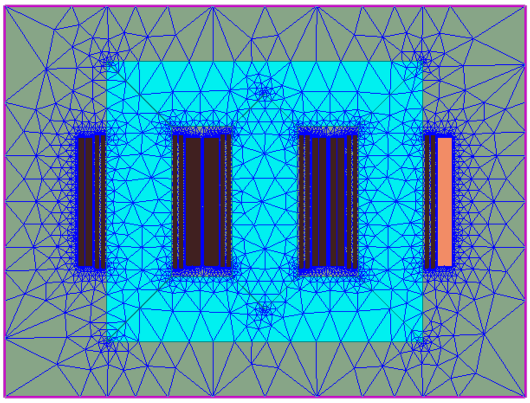

Fig. 6. Network analysis for 2D design of a transformer in ANSYS Maxwell

3) Coupling the design with ANSYS network circuit, simulating faults, and determining operating conditions

After completing the design phase and matching the design simulation to the real model of the 1000 kVA transformer, the data and factory standards are linked, as well as the data taken from the transformer testing center in Mosul, Iraq. This data includes the injected voltages on the high voltage side with the hertz, phase difference, and resistance values for the turns on the high and low voltage sides with the number of turns and the load resistance value. All this data will be linked through the electrical circuit design program for ANSYS because this program is one of the branches of ANSYS programs and has the ability to link with the design that was done in ANSYS Maxwell [66]-[69]. In Fig. 7, there is a model for designing a circuit in the ANSYS circuit design program, and this design simulates the normal operation of the 1000 kVA transformer.

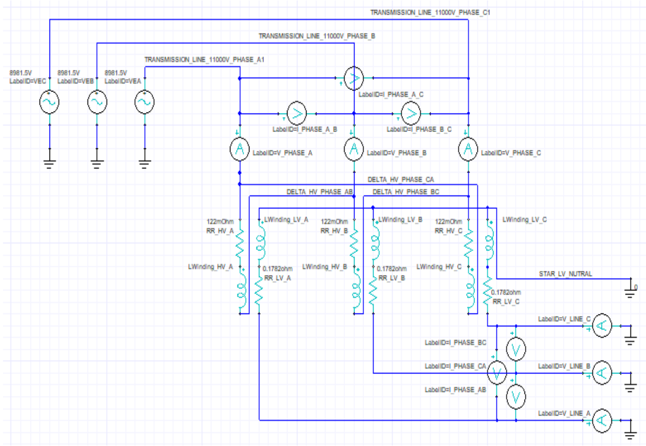

Fig. 7. Design of electrical network circuit in ANSYS circuit design program to be linked with the transformer design in ANSYS Maxwell

The windings were unified in the ANSYS simulation program so that each phase and each side would have one cost with the possibility of entering the number of windings in it, but when representing the faults, this unification was opened in the location where the fault was and divided into several windings, and the fault was made in it while keeping the healthy part with one cost, as Fig. 8 shows this design for the short circuit fault that occurs inside the first disc in a number of 13 windings, which will be at a rate of 1.2% of the number of windings. This process will be repeated when the percentages of faults increase, as it turns from between the windings of the first disc to faults between the lending with an increase in the number of windings; for example, a fault in two discs means 26 windings and is equivalent to 3.5% of the number of windings.

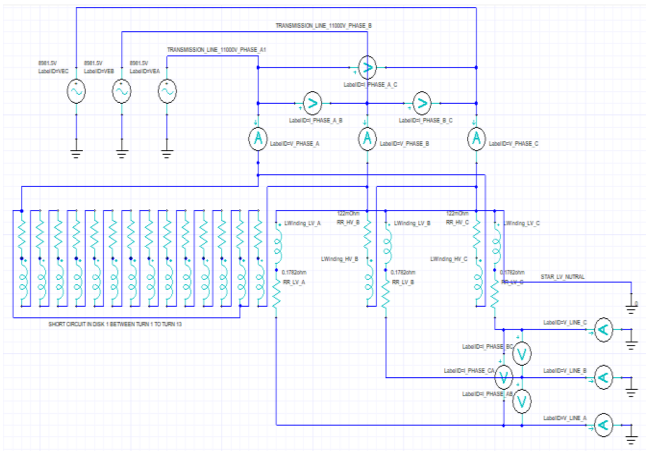

Fig. 8. Design of an electrical network circuit in the ANSYS circuit design program to create a short circuit fault in one of the phases of the high voltage coils

The fault of the coils to the ground was also represented through the electrical circuit design program ANSYS [70]-[73]. This was done by taking a percentage of the coils and connecting them to the ground, as shown in Fig. 9, where the unification of the coils was divided to take a percentage of the coils and connect them to the ground and achieve the fault of the coils to the ground.

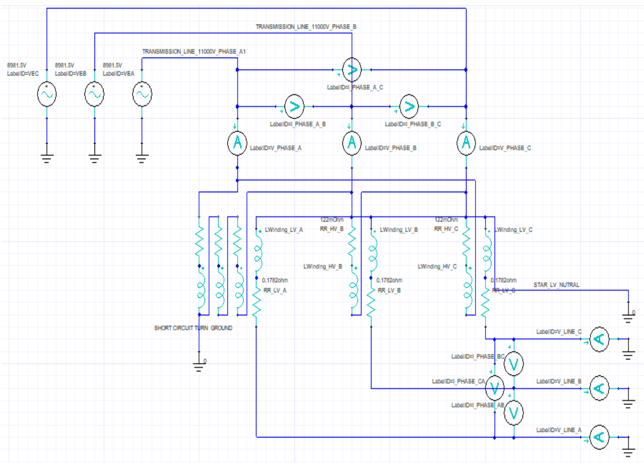

Fig. 9. Design of electrical network circuit in ANSYS circuit design program to perform short circuit fault of windings to ground

All simulations (normal operation and various fault conditions) were conducted under two load conditions: full load (100%) and 50% load, to study the effect of load level on fault behavior and transformer parameters. The resulting simulation data (flux, losses, currents, voltages, and efficiency) were then extracted and analyzed for each condition to compare and identify fault indicators. To validate the initial model, the normal operation simulation results (such as secondary-side induced voltages and currents and core losses) were compared with values predicted from manufacturing data and experimentally measured values to ensure that the basic model accurately reflects the actual transformer behavior before starting fault simulations.

III. Results and Discussion

In the computer simulation using ANSYS Maxwell, a 1000 kVA transformer was operated under normal operating conditions, i.e., without any faults or distortions in the windings. Short-circuit and open-circuit tests were first performed. These tests aim to obtain basic reference values for the transformer's normal operating characteristics, against which the transformer's performance can be compared under various fault conditions. The data measured under normal conditions include magnetic flux and iron core losses in two parts: hysteresis losses and eddy current losses; induced voltage in the high-voltage windings and voltage in the low-voltage windings for all phases; current in the high-voltage windings and the low-voltage windings for all phases; and efficiency. These results serve as a basis for comparison against various fault conditions that may occur in a transformer, such as internal faults between windings or short circuits between windings and ground. To illustrate the faults analyzed, the following points illustrate the types of faults worked on to understand their impact on transformer efficiency, magnetic flux distribution, iron core losses, and current and voltage values in high and low voltage windings. Types of faults analyzed:

1) Internal faults between coil turns: These faults occur when a short circuit occurs between a certain number of turns within the same phase. Since each phase contains 739 turns divided into 57 discs, each disc containing 13 turns, the fault is represented by a single disc, i.e., 13 turns. This fault within disc 1 is called a 13-turn short circuit fault, which represents 1.7% of the total number of 739 turns, resulting in a change in magnetic flux distribution and a local increase in currents and losses.

2) Multiple faults between coils of different discs: In this case, the fault spreads across multiple discs within the coil, resulting in gradual changes in voltage, current, and efficiency. These failures begin in two discs, or 26 windings. This two-disc failure is called a 26-winding short circuit, accounting for 3.5% of the total number of 739 windings. As the number of damaged discs' increases, magnetic and thermal losses become more pronounced, potentially causing the transformer to overheat and negatively impacting its lifespan. The percentage of damaged windings increases as the short circuit increases across more discs. Experiments were conducted, and results were obtained with five disc failures, equivalent to a 65-winding short circuit failure, or 8.8% of the total windings. The experiments were repeated at a rate of 17.6%, corresponding to 10 disc failures. They were also repeated at a rate of 26.6%, corresponding to 15 disc failures. They were also repeated at a rate of 35.2%, corresponding to 20 disc failures. They were also repeated at a rate of 44%, corresponding to 25 disc failures. It was also repeated at a rate of 52.8%, meaning 30 discs failed, or 390 coils failed due to a short circuit. All of these experiments were conducted when the transformer was operating at full load and at 50% of full load. They were also conducted when the short circuit between the coils occurred in only one phase and when the fault occurred in both phases simultaneously.

3) Wind-to-ground faults: This is considered one of the most serious faults that can affect a transformer, as a direct connection occurs between the windings and ground, resulting in very high short-circuit currents. This type of fault significantly affects the stability of the electrical system and can cause a complete shutdown of the transformer if not detected and addressed quickly. This fault was represented by dividing the windings of one phase, which totalled 739 turns, into three sections, each containing 247 turns. A short circuit occurred in one section, which totalled 247 turns, resulting in 247 turns being lost to ground. The process was then repeated with two sections, which totalled 494 turns being lost to ground. The results obtained after the failure were monitored. This process was repeated at two different load levels: the first at 100% load and the second at 50% load.

The effect of faults on the performance of the transformer:

- As the severity of the fault increases, losses in the iron core increase due to the increase in eddy currents and hysteresis losses.
- Efficiency decreases significantly as the percentage of damaged windings increases.
- Voltages and currents change in different phases, which may lead to an imbalance in the electrical system.
- In extreme cases, faults may lead to permanent damage to the transformer unless they are detected and treated in a timely manner.

Through this study, the extent of the impact of different faults on the performance of the transformer can be determined, which helps in developing preventive maintenance strategies and improving protection techniques to ensure more stable and reliable operation. In this study, the performance of the electrical transformer was analyzed at two different load conditions, the first at full load (100%) and the second at half load (50%), in order to understand the effect of load changes on the operational properties of the transformer. When the transformer is loaded at 100%, it operates at its full design capacity, which leads to stable voltages and currents but with high losses in the iron core and eddy currents. The efficiency of the transformer is also at its highest levels in the normal state, but it is affected when there are internal faults. When the transformer is loaded at 50%, the currents are lower, which reduces the total losses and leads to a slight improvement in operating efficiency.

However, internal faults may lead to unexpected effects, such as high currents in some phases and voltage imbalance, which may increase the severity of faults despite the reduced load. This analysis allows the performance of the transformer to be compared under different operating conditions, which helps in determining the best maintenance and operation methods to ensure its stability and efficiency in the long term.

A. Main Findings of the Present in Operating the Electrical Transformer at 100% Full Load and in Normal Condition

1) Magnetic flux, its value and distribution

The electrical transformer was operated with a capacity of 1000 kVA in the normal state, i.e., without faults, and at full load (100%) to study its electrical and magnetic behavior under ideal operating conditions. The aim of this analysis is to determine the performance of the transformer in its optimal state, where the efficiency is high and the losses are within the design limits. One of the most important results analyzed is the magnetic flux inside the iron core of the transformer. Fig. 10 shows the magnetic distribution inside the transformer, showing the flux gradient between the different regions, which helps in understanding the saturation regions and the possibility of the appearance of magnetic losses.

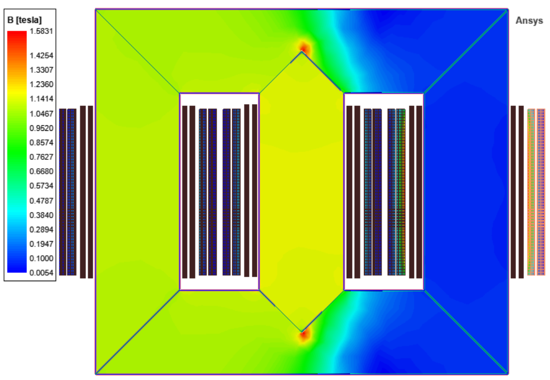

Fig. 10. Simulation of the distribution of magnetic flux in the 1000 kVA transformer in the normal state and at full load

To analyze the magnetic distribution, the iron core areas of the transformer are the areas that carry most of the magnetic flux, with values ranging between 0.8 and 1.5 Tesla, indicating that the transformer operates within the natural limits of magnetic saturation, as there are no areas of excess saturation that may lead to high magnetic losses. As for the areas of the iron core corners, an accumulation of magnetic flux appears with higher values reaching about 1.58 Tesla, indicating that these areas are more susceptible to saturation, which may lead to increased losses of hysteresis and eddy currents. As for the area of the coil, the magnetic flux inside the coils is relatively low compared to the iron core, and this is normal because the coils depend on the magnetic field generated around them to stimulate the voltage and current, and a clear gradation appears from dark blue (very low values close to zero) to light green, which reflects the efficiency of magnetic energy transfer inside the transformer.

As for the areas of the outer edges of the iron core, the magnetic flux is almost non-existent, which indicates a good design of the iron core that prevents magnetic leakage, which maintains the efficiency of the transformer's operation and reduces magnetic losses. Let us give another pictorial model of the distribution of magnetic flux in the transformer, but this time in the event of a fault. For example, in the event of a fault in the coils due to an electrical short circuit to the ground a shown in Fig. 11. A significant change in the distribution with a significant increase in the values of magnetic flux in the flux when an electrical short circuit occurs between more than half of the coils of one phase and the ground.

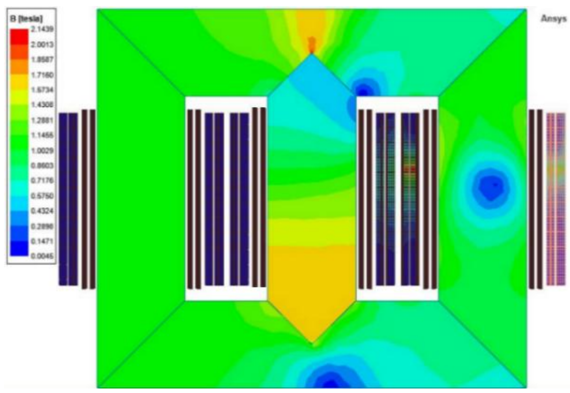

Fig. 11. Simulation of the distribution of magnetic flux in a 1000 kVA transformer in the event of a fault and at full load

This image shows that the transformer may be in an abnormal operating condition, where there is an inhomogeneity in the distribution of the flux, with areas of very high magnetic flux (saturation) and others with low or no flux. High saturation may lead to increased magnetic losses and high temperatures in some areas, which may affect the transformer's life and operational efficiency. From the study and the results tables, it will be clear that this distribution is the result of an internal fault, such as a short circuit in the coils with the ground.

2) Iron core losses

When operating the 1000 kVA electrical transformer under normal operating conditions and at 100% full load, losses occur in the iron core as a result of the magnetic flux generated inside the core during operation. These losses consist of two main types: The first type is hysteresis losses. They result from the rearrangement of the magnetic material particles in the iron core during the reversal of the magnetic field at each cycle. They depend on the operating frequency, magnetic flux density, and the properties of the magnetic material. Its value is 851.8 watts, and its shape is shown in Fig. 12.

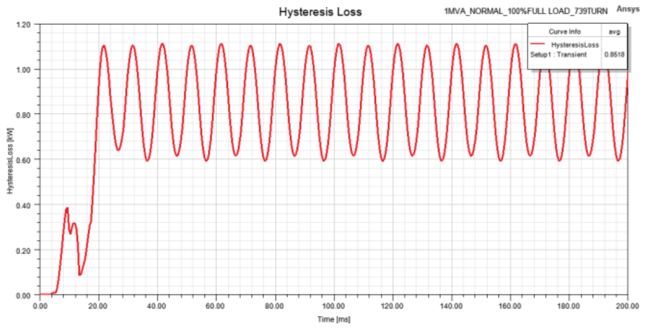

Fig. 12. Simulation of hysteresis losses in a 1000 kVA transformer in normal condition and at full load

The second type is eddy current losses. These are caused by eddy currents generated inside the iron core due to changes in magnetic flux. These losses are reduced by using thin electrically insulated iron plates to reduce the path of the eddy currents and reduce their thermal effects. Its value is 255.2835 watts, and its shape is shown in Fig. 13.

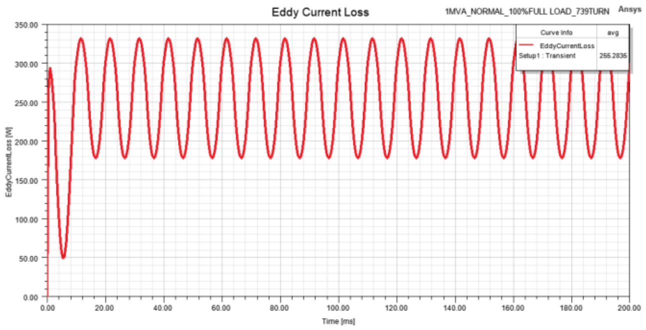

Fig. 13. Simulation of eddy current losses in a 1000 kVA transformer in normal condition and at full load

So from these two basic types, the iron core losses shown to us in Fig. 14, which in the normal condition and at full load are 1107.1 watts. In the results and tables that will be mentioned, the increases that will occur in these values as a result of the faults that will be discussed.

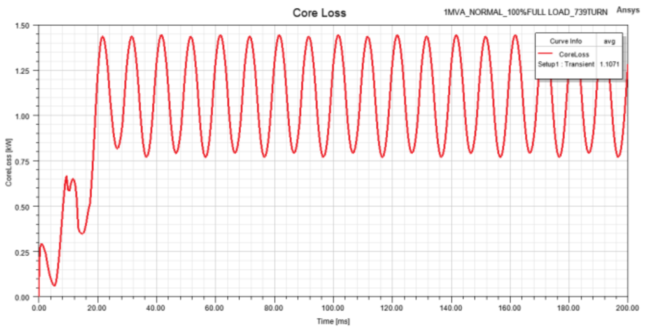

Fig. 14. Simulation of the distribution of iron core losses in a 1000 kVA transformer in normal condition and at full load

Thus, at full load (100%), the maximum values of magnetic flux are reached, which leads to increased losses in the iron core due to the high flux density. The distribution of losses shows that the areas near the corners and joints in the iron core are most exposed to hysteresis and eddy current losses. In order to control these losses, it helps in improving the efficiency of the transformer and reducing the temperature rise in the iron core.

3) Induced voltages in high voltage and low voltage windings

When operating a 1000 kVA transformer under normal operating conditions and at 100% full load, the voltage on the high voltage side is analyzed to ensure the stability of performance and to ensure that the results are consistent with the engineering design of the transformer. In this study, it was found that the voltage of the high-voltage windings is about 11000 V, which is in line with the design specifications of the transformer and is shown in Fig. 15.

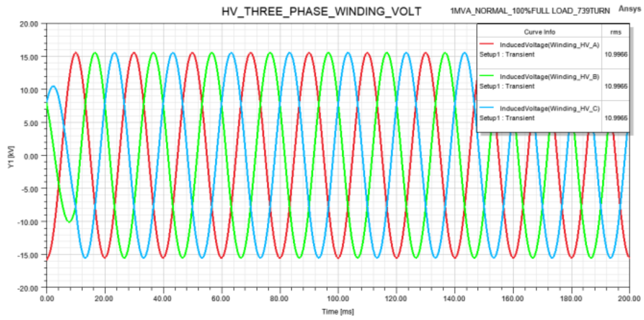

Fig. 15. Simulation of induced voltage in high voltage windings of 1000 kVA transformer under normal operating conditions and at full load

The measured values of 11000 volts are consistent with the triangular connection method, where the phase and line voltages are equal. The triangular connection helps in achieving a balanced distribution of currents inside the transformer, reduces eddy currents, and ensures more stable operation under high loads. The voltage is then measured on the low voltage side to ensure stable performance and verify the extent to which the results match the engineering design of the transformer. Since the connection method in the secondary windings (low voltage) is star, the voltage measured between each phase and the neutral point represents the phase voltage, while the voltage between any two lines represents the line voltage.

At full load, the actual value of the low voltage is about 410 to 433 volts as a line voltage, which is consistent with the standard designs of transformers used in distribution networks. Thus, the phase voltage is about 237 to 249.9 volts. In order to achieve and match the result of the simulation model, the real model is shown in Fig. 16, which showed that the voltage values in the phases are equal at a value of approximately 238 volts.

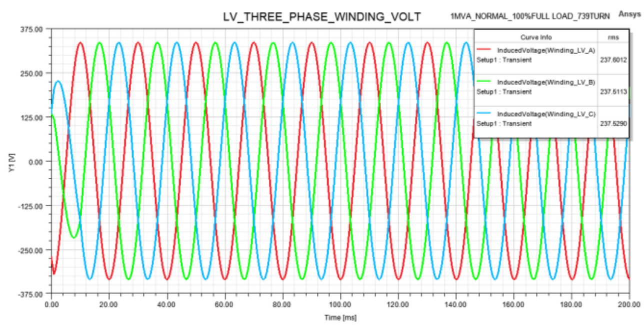

Fig. 16. Simulation of induced voltage in the step-down windings of a 1000 kVA transformer under normal operating conditions and at full load

The voltage on the low voltage side is 412 volts as a line voltage and 237.8 volts as a phase voltage at full load. This star connection method led to this result due to the relationship between the phase and line voltage in this type of connection. These values are in line with the standard design of transformers used in electrical networks to ensure efficient operation and voltage stability at different loads.

4) Currents in High Voltage and Low Voltage Windings

The currents in high and low voltage windings play a major role in the performance of electrical transformers, as they depend on different operating conditions such as load and possible faults in the windings. At full load (100%), the maximum power transfer between the primary (high voltage) and secondary (low voltage) windings is achieved, resulting in specific current characteristics. The currents in high-voltage windings are shown in Fig. 17.

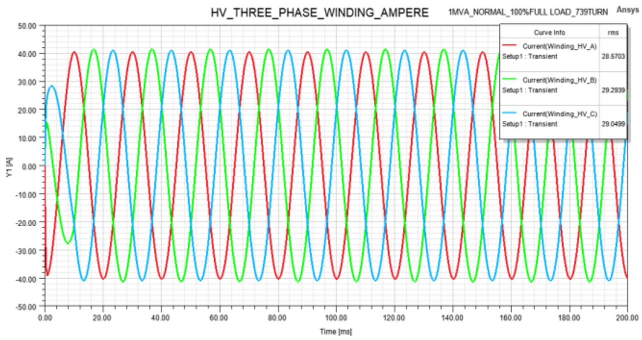

Fig. 17. Simulation of currents generated in the high-voltage windings of a 1000 kVA transformer under normal operating conditions and at full load

Under normal full load operation, the currents in the primary windings are 52.488 amperes per line, or 30 amperes per phase, because the windings are triangular in connection and in proportion to the electrical capacity of the transformer. The current in each of the three phases is determined based on the voltage and internal design of the transformer. The currents increase in the event of internal faults such as missing coils or short circuits. As for the low-voltage windings, the currents generated in them are shown in Fig. 18.

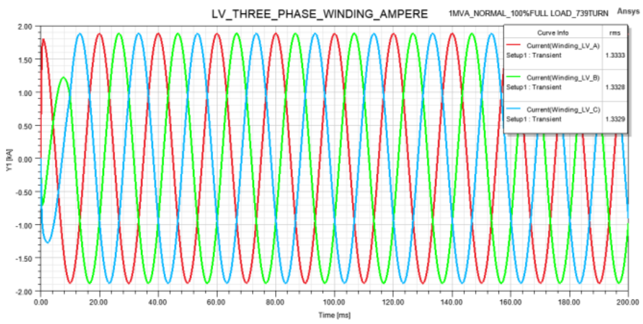

Fig. 18. Simulation of currents generated in the low-voltage windings of a 1000 kVA transformer under normal operating conditions and at full load

At full load, the currents in the low voltage windings are much larger than their high voltage counterparts, due to the inverse relationship between voltage and current according to the transformation equation, and the transformer operates at a maximum load of 1333.3 A. The current flow in these windings depends on the voltage stability and efficiency of the transformer, where the power loss is minimal in the normal case. In normal operation the currents are evenly distributed between the three phases, with acceptable power loss levels and high efficiency.

However, in the case of partial damage to the windings due to a short circuit, the current increases in some phases due to the natural compensation of the transformer, but with high power losses and low efficiency. In the case of severe faults such as a short circuit or a ground fault, the current increases significantly in the affected phase, which leads to a reduction in the efficiency of the transformer and the possibility of serious faults.

5) Efficiency

The efficiency of the electrical transformer is one of the most important factors that determine the quality and performance of the transformer during operation, especially at full load (100%). Efficiency expresses the ratio of the output power to the input power and takes into account the losses that occur inside the transformer during the conversion of electrical energy from high voltage to low voltage or vice versa. In Fig. 19, a simulation in the ANSYS program of the efficiency at normal operating conditions without faults and at full load.

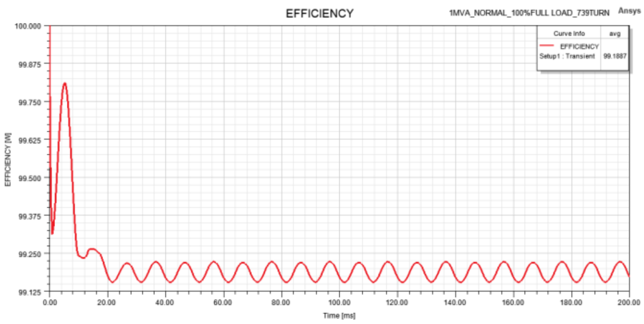

Fig. 19. Efficiency simulation of a 1000 kVA transformer under normal operating conditions and at full load

It is clear that the transformer operates with high efficiency at full load, as the efficiency under normal conditions reaches approximately 99.1887%, indicating effective performance and low energy loss. However, when faults or damage occur in some coils, the efficiency gradually decreases until it reaches a small amount at severe faults, as will be shown later in the tables. The factors affecting the efficiency of the transformer at full operation include losses in the iron core, which include hysteresis and eddy current losses, and increase with the increase in magnetic flux.

Losses in the coils, which result from the electrical resistance of the coils, increase with the increase in electric current. Overloading or faults, where a fault or damage in some coils increases the losses and reduces the efficiency significantly. When faults occur, such as a short circuit in some coils or a short circuit in the coils to ground, the losses increase, leading to a decrease in efficiency. For example, when 30 coil discs are damaged, the efficiency decreases to approximately 52%, all within 200 milliseconds of the test, indicating the impact of major faults on the performance of the transformer.

The following results in Table III show the performance of the transformer when operating at full load (100%). The data includes the measured values of voltages and currents in both high and low voltage windings, in addition to the losses in the iron core and copper windings.

The results also show the overall efficiency of the transformer under normal operating conditions and when there are different faults in the windings. The Table III highlights the effect of partial and progressive faults on the performance of the transformer, starting from the normal condition, passing through minor faults in a limited number of turns, up to severe faults that greatly affect the efficiency of the transformer. This data is used to analyze the performance of the transformer and take the necessary measures to maintain its efficiency and ensure its continued operation with high efficiency.

The transformer operating data at full load (100%) reflects its electrical behavior under normal conditions and in various fault conditions. The efficiency and performance of the transformer depend on several factors, including currents, voltages, and magnetic and copper losses. By analyzing the three tables in the attached file, a set of important conclusions can be drawn that highlight the impact of faults on the performance and efficiency of the transformer. In the normal condition (without faults), the transformer operates at an efficiency of 99.19%, which is a high percentage indicating stable performance and limited losses. The performance of the transformer in this case shows the maximum possible efficiency with the lowest loss ratio, reflecting the good design and accurate calibration of the transformer. With the occurrence of partial faults in the windings (such as a short circuit in a few turns), the efficiency begins to gradually decline, but the effect is limited at first. The short circuit between the windings creates a low-resistance internal current path within the faulty coil. This circulating current generates additional magnetic flux that opposes the main flux in some areas and augments it in others, resulting in a slight redistribution of flux within the core and a local increase in its density. This local increase, in turn, causes a slight increase in the hysteresis and eddy losses in that area. The circulating current itself also causes additional copper losses (I^2R) in the faulty windings, contributing to the reduced efficiency and localized temperature rise (which was not directly analyzed thermally in this study but is inferred from the increased losses). Partial faults do not lead to a rapid deterioration in the performance of the transformer, but they cause a gradual increase in losses, which affects long-term sustainability. When the fault ratio exceeds 20% of the windings, the transformer begins to lose its thermal stability, and the risk of catastrophic faults increases significantly.

With major faults, more than 35% of the windings are damaged, the efficiency drops to less than 95%, and with the damage increasing to 52.8%, the efficiency drops to 78.76%, which means that more than 20% of the input power is lost as heat and losses. The magnetic flux is almost doubled, which increases the level of eddy currents inside the iron core. Iron losses exceed 2300 watts, which is more than twice the normal value, which increases the temperature of the iron core. The currents in the high-voltage windings reach 340 amperes, which is more than 10 times the normal values, which means a huge increase in the temperature of the windings. The voltages begin to fluctuate and become unstable, which negatively affects the performance of the loads connected to the transformer. When the fault rate exceeds 40%–50% of the windings, the transformer loses the ability to operate stably and becomes unsafe for use, which requires immediate shutdown to prevent complete breakdown or fire hazard. The very large circulating current in the shorted windings generates a strong opposing magnetic field (MMF), which forces the primary flux to alternate paths within or even outside the core (leakage flux). This large distortion in the flux distribution causes severe saturation in some parts of the core, resulting in a dramatic increase in hysteresis losses (due to the widening hysteresis loop) and eddy losses (due to the high flux density). The very high currents in the faulted phase result from the source's attempt to compensate for the voltage drop caused by the short, causing enormous copper losses and dangerous temperature rises. This temperature rises and high short-circuit currents generate large mechanical forces that can lead to permanent damage to the windings and insulation. All this when the fault occurs in the single-phase coils but when it occurs in two phases at the same time.

TABLE III. SUMMARY OF ALL VALUES RECORDED DURING THE TEST AT 100% FULL LOAD OF THE TRANSFORMER

STATUS OF TRANSFORMER	*Magnetic flux (TESLA)*	*Core Loss (WATT)*	*Hysteresis Loss (WATT)*	*Eddy current loss (WATT)*	*Efficiency*
Normal test	1.5831	1107.1	851.8	255.2835	99.1887
Short circuit in 1.7% of one phase turns	1.5827	1122.4	863.6	258.7265	99.1726
Short circuit in 3.5% of one phase turns	1.5824	1137.7	875.4	262.3479	99.1508
Short circuit in 8.8% of one phase turns	1.5806	1188.4	914.0	277.3994	99.0425
Short circuit in 17.6% of one phase turns	1.5779	1293.3	994.0	299.3333	98.6413
Short circuit in 26.6% of one phase turns	1.5756	1434.1	1101.1	333.0218	97.716
Short circuit in 35.2% of one phase turns	1.5838	1628.6	1248.9	379.7015	95.6441
Short circuit in 44% of one phase turns	1.6614	1911.4	1464.0	447.3752	90.8449
Short circuit in 52.8% of one phase turns	2.3755	2354.5	1801.1	553.4	78.7603
Short circuit in 1.7% of two phase turns	1.5853	1132.1	871.1	261.0201	99.1583
Short circuit in 3.5% of two phase turns	1.5874	1157.8	890.8	267.0619	99.1209
Short circuit in 8.8% of two phase turns	1.5938	1243.5	956.3	287.1961	98.9545
Short circuit in 17.6% of two phase turns	1.6064	1422.9	1093.5	329.4084	98.3842
Short circuit in 26.6% of two phase turns	1.6202	1622.8	1246.0	376.8682	97.3517
Short circuit in 35.2% of two phase turns	1.8059	2001.3	1533.2	468.0712	94.0348
Short circuit in 44% of two phase turns	2.5105	3296.7	2513.4	783.3	67.0381
Short circuit in 52.8% of two phase turns	2.7045	3718.4	2830.3	888.1	52.5823
Short circuit in 33% of turns to ground in one phase	1.8860	1428.0	1096.4	331.5433	80.2403
Short circuit in 66% of turns to ground in one phase	2.1405	1425.7	1093.4	332.2918	24.9628

Operating the transformer at full load with faults occurring in two phases instead of one phase. This table allows a broader understanding of the impact of faults on the overall performance of the transformer, as faults in more than one phase lead to more complex effects on the distribution of currents, voltages, and losses, which negatively affect efficiency. Faults that affect two phases instead of one phase cause efficiency to decrease faster and more significantly, as they affect the distribution of energy between the phases and increase losses in the coils and iron core. The presence of a fault in two phases instead of one phase leads to a significant increase in magnetic flux, which leads to greater losses in iron and a faster rise in temperature. Also, the effect of faults on two phases leads to greater fluctuations in voltages across different phases, which may lead to problems in the loads connected to the transformer. When a fault occurs in two phases, circulating currents and magnetic flux distortion affect a larger magnetic and electrical system within the transformer. A greater phase imbalance occurs, resulting in uneven flux distribution across the three core legs and an overall increase in core and copper losses.

The table shows the effect of a fault between the windings and ground in a transformer at full load (100%). This type of fault differs from single-phase or two-phase faults, as it leads to unbalanced changes in voltages and currents and may cause high leakage currents, which increases operational risks. Here the effect of this type of fault is analyzed and compared to cases of partial faults in one phase or two phases. The fault between the windings and ground leads to the greatest reduction in efficiency compared to all other faults, as the efficiency deteriorates more rapidly than partial faults or two-phase faults. The fault between the windings and ground causes a significant increase in magnetic losses but does not lead to a flux rise as rapidly as two-phase faults. However, the unbalance of magnetic flux increases the possibility of dielectric breakdown. The fault between the windings and ground leads to sharp voltage drops in the affected phase, making the system very unstable and increasing the operating risks compared to partial faults in one or two phases. The fault between the windings and ground increases the currents in the affected phase enormously, which can lead to rapid breakdown of the dielectric and overheating, which is more dangerous than partial faults in one or two phases. A ground fault provides a low-impedance path for fault current to flow directly from the coil to ground (usually through the tank). This current is not limited to circulating within the coil as in a short circuit; rather, it is a large fault current that passes through a large portion of the coil. This results in an almost complete collapse of the voltage in the faulted phase, severe unbalance in the three-phase system, and very high currents that cause enormous thermal and mechanical stress.

Comparing the occurrence of a fault in one phase or two phases:

- Two-phase faults lead to a faster and greater decrease in efficiency compared to a single phase.
- Magnetic losses are almost doubled when a fault occurs in two phases, which increases the temperature of the transformer.
- Currents rise dangerously in some phases, which exposes the transformer to the risk of rapid breakdown.
- In the event of two-phase faults, the transformer becomes unsafe for use and may require immediate shutdown or complete replacement.

Compared to the previous cases:

- The fault between the windings and ground is the most dangerous, as it leads to a sharp decrease in efficiency, an unbalanced rise in currents, and a huge increase in iron losses.
- While partial faults lead to a gradual decrease in performance, a fault to ground causes a rapid and serious breakdown.
- A two-phase fault has a greater impact on voltage and magnetic flux imbalance than a single-phase fault but does not reach the level of severity found in a fault to ground.
- A fault to ground results in significantly unbalanced currents, which can lead to complete breakdown of the transformer if immediate protective measures are not taken.

B. Main Findings of the Present in Operating the Electrical Transformer at 50% of the Full Load

To increase reliability and verify the results, the experiments were repeated with a change in the load level to 50% of the full load, and the results were read in Table IV, which will show a repetition of all the results, but this time at half the load.

The lower severity of the fault effect at low load is due to lower primary currents flowing in the transformer, which results in less severe interaction of the circuit fault current with the system. The lower primary current also reduces the overall thermal stress on the transformer.

When comparing the last three tables representing the transformer operation at 50% of full load with the previous tables at 100% of load, it becomes clear that there is a noticeable effect on the transformer efficiency, losses, currents, and magnetic flux. In general, when the load is reduced to 50%, the efficiency improves relatively compared to cases that include major faults at full load, as the efficiency in the normal case remains very high, exceeding 99.7%, which is a higher percentage than it was at 100% of load, reflecting the decrease in relative losses in the coils and iron core. Also, the magnetic losses and eddy currents decrease, as the iron losses are less than they were at full load, as the load ratio on the iron core is reduced, which leads to a reduction in internal heating and an improvement in the stability of the magnetic flux. In terms of voltages, the values remain at acceptable levels without significant decreases as in the case of full load, as the voltage difference is less affected by the increase in faults, but some decreases appear at severe faults, but at a lower rate than their counterpart at full load.

TABLE IV. SUMMARY OF ALL VALUES RECORDED DURING THE TEST AT 50% OF THE FULL LOAD OF THE TRANSFORMER

STATUS OF TRANSFORMER	*Magnetic flux (TESLA)*	*Core Loss (WATT)*	*Hysteresis Loss (WATT)*	*Eddy current loss (WATT)*	*Efficiency*
Normal test	1.5831	1107.1	851.8	255.2835	99.1887
Short circuit in 1.7% of one phase turns	1.5833	1123.9	864.8	259.1023	99.7062
Short circuit in 3.5% of one phase turns	1.5829	1139.2	876.5	262.7320	99.6948
Short circuit in 8.8% of one phase turns	1.5811	1190.0	915.2	274.8070	99.6238
Short circuit in 17.6% of one phase turns	1.5785	1295.1	995.3	299.8038	99.3147
Short circuit in 26.6% of one phase turns	1.5759	1411.3	1083.6	327.6462	98.7130
Short circuit in 35.2% of one phase turns	1.5834	1631.1	1250.7	380.3730	96.7566
Short circuit in 44% of one phase turns	1.6604	1914.4	1466.2	448.2299	92.5158
Short circuit in 52.8% of one phase turns	2.3744	2359.0	1804.3	554.8	81.6613
Short circuit in 1.7% of two phase turns	1.5858	1133.7	872.3	261.4005	99.7014
Short circuit in 3.5% of two phase turns	1.5880	1159.5	892.0	267.4559	99.6848
Short circuit in 8.8% of two phase turns	1.5943	1245.3	957.7	287.6334	99.5923
Short circuit in 17.6% of two phase turns	1.6070	1425.2	1095.2	329.9435	99.2008
Short circuit in 26.6% of two phase turns	1.6208	1625.6	1248.0	377.5300	98.4085
Short circuit in 35.2% of two phase turns	1.8176	2004.9	1535.9	468.9933	95.6760
Short circuit in 44% of two phase turns	2.1125	2505.4	1915.1	590.2686	89.3081
Short circuit in 52.8% of two phase turns	2.5228	3305.2	2519.7	785.5	71.9116
Short circuit in 33% of turns to ground in one phase	1.8930	1429.7	1097.8	331.8953	81.8411
Short circuit in 66% of turns to ground in one phase	2.1439	1427.4	1094.7	332.6952	28.0730

The currents in the high and low voltage coils are lower at 50% load compared to full load, which is expected due to the lower required power, but when there are faults in the coils, these currents begin to fluctuate and become unbalanced, especially in the case of ground faults or faults that include more than one phase, which is clearly noticeable when the percentage of faults increases, as the problem gradually worsens and leads to an unbalanced increase in currents in some phases, which may lead to additional stress on the electrical insulation. Compared to the results at 100% load, faults at 50% affect performance but at a less severe rate, as the magnetic flux remains relatively lower than it was at full load, which reduces the stress on the iron core.

However, ground faults, although less dangerous at 50% load compared to full load, remain the most dangerous of all types of faults, as they lead to unbalanced currents and significant voltage variations. Therefore, it can be concluded that operating the transformer at half load reduces losses and improves efficiency, but it does not prevent the impact of faults, as major faults, especially those affecting two phases or those involving contact with the ground, still have a significant impact on the transformer's performance, even if their impact is less severe than their counterparts at full load. In the end, it remains necessary to monitor the transformer's performance periodically, whether at full load or at half load, to ensure stable operation and high efficiency and prevent faults that affect the transformer's service life.

Limitations of the Study is important to acknowledge the inherent limitations of this study. First, its reliance on a two-dimensional (2D) simulation model inherently ignores some three-dimensional effects that may affect the accuracy of leakage flux or mechanical forces calculations. Second, a direct thermal analysis was not included to evaluate temperature rise and its effect on insulation degradation. Third, direct experimental validation was limited to winding resistance and comparison with overall performance specifications. Conducting detailed experimental measurements under simulated fault conditions (if possible) would further enhance the reliability of the results. Fourth, the focus was on a single type and rating of transformer (1000 kVA), and quantitative results may vary for transformers of different designs or capacities.

The results of this study are consistent with the general trends observed in other research that used simulation or experimental methods to analyze transformer faults [74][75]. Previous studies also emphasized the increased core losses and high fault currents resulting from shorted windings or ground faults. The study provided similar results regarding the magnetic flux distribution in transformers. The factory value is 1.584 Tesla. Fig. 20 shows a similar result obtained in this study [76]-[78].

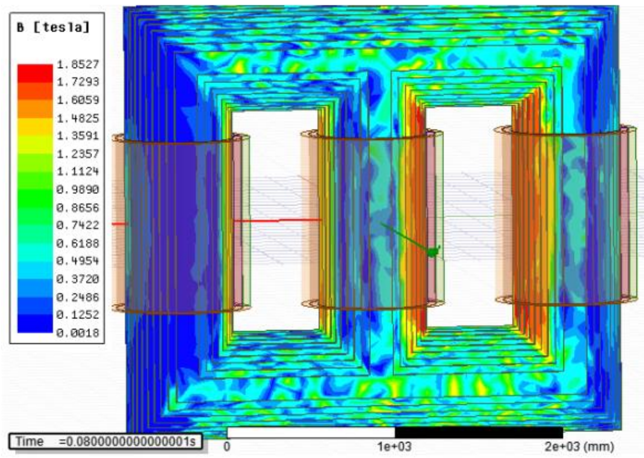

Fig. 20. Is the result of a previous study comparing the factory value of the magnetic flux distribution

Study confirmed the validity of the iron core loss values obtained from this study [79][80]. These values are due to hysteresis and eddy current losses. They were performed on a transformer similar to the one used in this research. The results shown in Fig. 21 were obtained. This comparison enhances confidence in the validity and reliability of the simulation results.

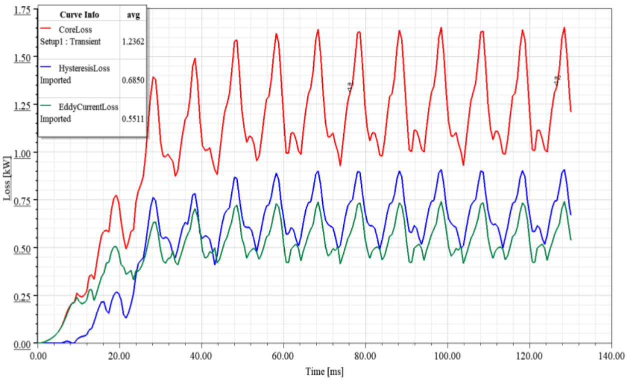

Fig. 21. The result of a previous study of the value of iron core losses

IV. Conclusion

This study presented a comprehensive computational analysis using the finite element method (FEM) in ANSYS Maxwell to identify the primary internal faults in a 1000 kVA three-phase distribution transformer. A detailed electromagnetic model was constructed and initially validated by comparing its normal performance with operating data and reference specifications. The effect of short-winding faults of varying magnitudes (starting at 1.2%) in single-phase and two-phase models, in addition to ground faults, was then simulated under different load conditions (100% and 50%).

The most important conclusions:

1. The simulation demonstrated that changes in transformer operational parameters, such as magnetic flux distribution, iron core losses (hysteresis and eddy currents), induced currents, and overall efficiency, are sensitive to the presence of internal faults, even at very small magnitudes (1.2% of the windings). This sensitivity suggests that these parameters can be used as indicators for early detection of faults.
2. The results showed a clear quantitative relationship between fault severity (percentage of affected turns) and the level of deterioration in transformer performance. Losses increase, currents rise, and efficiency decreases significantly as the fault percentage increases, emphasizing the progressive and dangerous nature of these faults if left undetected and untreated.
3. It was confirmed that ground faults and faults involving two phases are the most influential and dangerous, leading to a faster and more severe breakdown in transformer performance than single-phase short circuits of the same magnitude.
4. While reducing the load (to 50%) improves efficiency under normal conditions and reduces the severity of the fault, it does not eliminate the fault's existence or potential long-term severity.

Theoretical and Practical Contributions:

1. This study contributes to an enhanced understanding of the electromagnetic mechanisms underlying the development of primary internal faults and their quantitative impact on key transformer parameters.
2. The study provides a theoretical and methodological basis for developing transformer condition monitoring systems based on computational analysis and non-intrusive indicators. The identified relationships between fault severity and parameter changes can be used to establish thresholds for early detection of faults in predictive maintenance applications.
3. On a practical level, the results indicate that investing in advanced monitoring technologies that can track subtle changes in transformer performance may be cost-effective, as it can enable maintenance scheduling based on actual conditions, avoid catastrophic failures, and extend the operational life of transformers.

In conclusion, this study emphasizes the great potential of computational analysis as a powerful tool for early detection of internal faults in electrical transformers. Through careful monitoring of electromagnetic indicators, predictive maintenance strategies can be enhanced, transformer reliability increased, and power grid stability ensured.

Future Research Prospects

Based on this study and its limitations, future research can be directed in several directions:

1. Developing three-dimensional (3D) simulation models to more accurately assess field distribution and mechanical forces.
2. Incorporating coupled electro-thermal analysis to directly model temperature rise and its effect on insulation life.
3. Conduct practical experiments on test transformers or use field data from in-service transformers to more comprehensively validate simulation results and determine practical alarm thresholds.
4. Expand the scope of the study to include different types and classifications of transformers (larger transformers, transformers with different core or winding designs) to assess the generalizability of the results.
5. Explore and apply advanced diagnostic techniques based on artificial intelligence and machine learning (AI/ML) to analyze simulation or operational data and develop more intelligent and robust fault detection systems.
6. Analyze the impact of other types of internal faults, such as mechanical winding distortion or tap changer problems.

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