DEMOCRATIC AND POPULAR ALGERIAN REPUBLIC
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
UNIVERSITE M'HAMED BOUGARA-BOUMERDES

Faculty of Hydrocarbons and Chemistry
Department: Automation and electrification of industrial processes
Branch: hydrocarbons
Major: industrial electricity

End of Study Thesis
In preparation for obtaining
the diploma: Master

Theme

Insights into Power Transformer: Analyzing Fault Scenarios, Protection system, and maintenance strategies .

Presented by:
Bouldjadj Oussama Abdenacer
Djafour Abdelkader

the supervisor
first and last name: Nadji Bouchra

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signature:

Favorable opinion of the jury President of the jury:

First and last name: BENDJEGHABA Omar

Stamp and signature.

بسم الله الرحمن الرحيم

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Yaa Menna San.

This project is a heartfelt dedication to my beloved parents, those who believe in me, my Loving mother and my inspiring father for their endless sacrifices and unconditional love and support and trust which was the fuel to every burning success light I have reached in my journey.

To my trusted right-hand friend and brother Adam cherishing all the joy, the sadness we celebrate and overcome together,

To my friends Khalil, Bobo, Yassine, Hamza, Islam, Keda, Ringo and all the Falcons high in the sky for the good old days and the better coming up,

thank y'all

To my beloved father, thank you for your love, guidance, and support, which paved the way for my success. I wish you were here to celebrate with me. I will continue to make you proud. May you rest in peace, knowing I will keep striving and achieving more, thanks to your teachings. -Dear mother, I dedicate this achievement to you for your unwavering love, support, and sacrifices. Without you, this wouldn't have been possible. My success reflects the values you instilled in me. Your encouragement and patience have been invaluable. -To my siblings and friends, your friendship, encouragement, and assistance made this journey enjoyable. Thank you for your support and advice.

TABLE OF CONTENT:

Abstract

A power transformer is a critical electrical device utilized in both transmission and distribution of electrical power to ensure the reliability, stability, and optimal performance of modern electricity networks.

Transformer safety plays a crucial role in the management and operation of electricity networks.

The main objective of transformer protection is to identify and isolate internal or external imperfections in order to reduce damage and preserve the integrity of the electrical system.

Transformer safety involves challenges such as handling high inrush currents during startup, accurate fault detection and coordination with other network protection devices.

To ensure safe and continuous power supply, it is necessary to have in-depth knowledge of electrical principles, protection technologies and maintenance strategies additional to fault detection, analyze and management to increase the efficiency and the reliability of power transformer.

The problematic addressed in this thesis focuses on understanding the fault mechanisms, evaluating the effectiveness of existing protection systems, and developing maintenance strategies to mitigate the risk of transformer failures. Through detailed simulations and analysis, the thesis seeks to provide actionable insights into enhancing the reliability and efficiency of power transformers within the operational framework of Electro-Industries.

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

A power transformer is a Fundamental electrical device in power network systems, utilized in both transmission and distribution processes. The efficient and reliable operation of power transformers is critical to the performance of electrical power systems. Power transformers, being essential components for voltage regulation, transmission, and distribution of electrical energy, must be maintained and protected to ensure uninterrupted service. This master's thesis aims to explore the intricacies of power transformer operations, their protection systems, and maintenance strategies, emphasizing the practical implications of these elements in a real-world industrial setting.

Given the centrality of power transformers in electrical grids, any malfunction or failure can lead to significant disruptions and economic losses. Despite advancements in technology, power transformers remain vulnerable to various faults, which can result from both internal and external factors. The problematic addressed in this thesis focuses on understanding the fault mechanisms, evaluating the effectiveness of existing protection systems, and developing maintenance strategies to mitigate the risk of transformer failures. Through detailed simulations and analysis, the thesis seeks to provide actionable insights into enhancing the reliability and efficiency of power transformers within the operational framework of Electro-Industries.

We can deduce our main problematic:

How can the reliability and efficiency of power transformers be enhanced through improved fault detection, protection systems, and maintenance strategies within the operational framework of Electro-Industries?

In the first chapter we begin with a presentation of the company ENEL discussing its main functions and the manufactured products more like a general view.

the second chapter contains overview of power transformers, outlining their crucial role in electrical power systems and highlighting the necessity of ensuring their reliable operation. Subsequently, the focus shifts to exploring various protection mechanisms employed to safeguard transformers against faults, encompassing both internal and external factors that can compromise their functionality. Additionally, an in-depth analysis of maintenance practices is provided, emphasizing the importance of proactive measures in enhancing transformer longevity and efficiency.

In the third chapter, this research delves into the simulation of current in both primary and secondary windings under normal operating conditions, providing valuable insights into the behavior of transformers during routine operation. Moreover, the study extends to the simulation of winding faults, examining the effects of abnormal conditions such as short circuits or open circuits on transformer performance. Additionally, the investigation includes simulations of core faults, shedding light on the implications of defects within the transformer core for its overall functionality.

Through rigorous analysis and simulation, and by observing and discussing the simulation obtained results this dissertation contributes in the fourth chapter to a deeper understanding of power transformer behavior under various scenarios, offering valuable insights for the design, operation, and maintenance of these critical components in electrical power systems.

Finally, we finish this study with a general conclusion.

CHAPTER.I. Company Presentation

I.1. Introduction

In this first chapter, a presentation of AZAZGA's national electro-industry company is recalled: its geographical location, history, and organization chart.

I.2. Presentation of the company

The electro-industry is a company specialized in the manufacture and marketing of distribution transformers and single-phase and three-phase electric motors and synchronous generators. Its headquarters are located in Algeria, in Tizi Ouzo (AZAZGA). This situation is ideal for export and import in Africa and the Mediterranean region.

Figure I-1 geographical location of the Electro-industry.

The electro-industry ranked among the large companies; has about 841 workers including 17% executives, 33% master and 50% execution who are divided into five units, all under the direction of the CEO.

The continuous improvement of the quality of products is the major concern of AZAZGA's electro-industry.

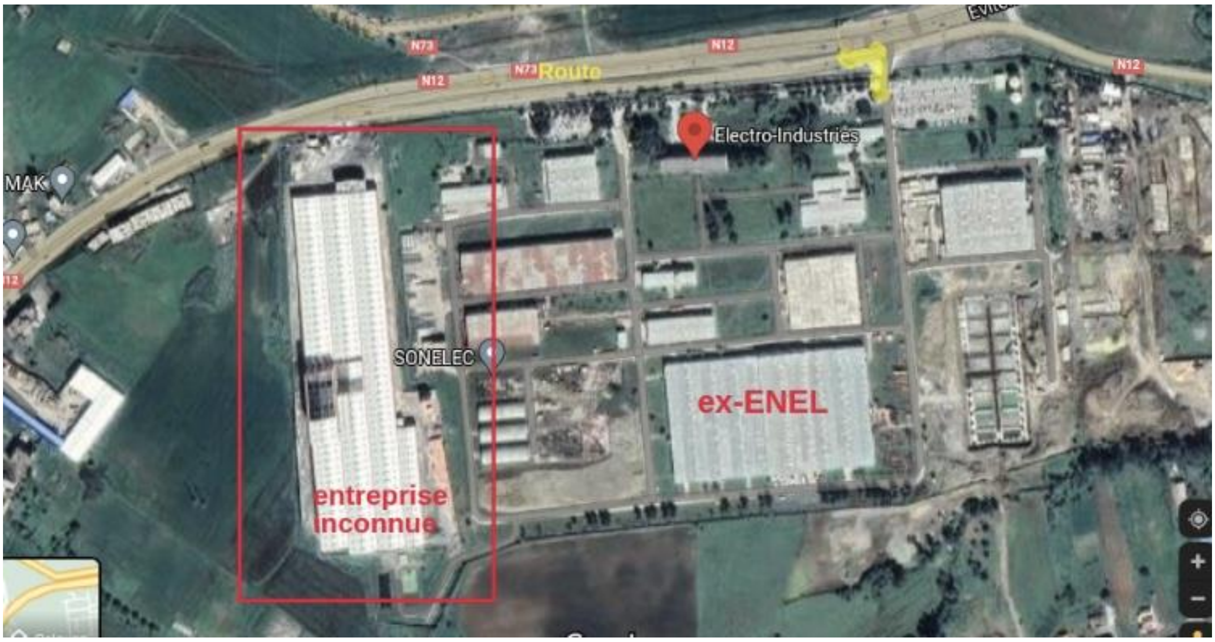

Figure I-2Electro-industry satellite image.

I.3. History and evaluation of the company Electro-Industries

has its origins in the restriction of SONELEC's electrotechnical company (National Society of Electronics).

In 1971, SONELEC signed an agreement on the construction of a complex composed of three production units in TIZI-OUZOU, the most important of which is electronic equipment (MEL) due to the extension of market needs and the need to increase the autonomy of national production.

In 1985, the plant was created by an agreement that was signed between SONELEC and the German partners in this case:

- SIEMENS: for alternator products, generators, and generator sets
- TRAFO-UNION: for the transformer product.
- FRITZ-WERNER: for the engineering part of the project As for Construction and infrastructure, they are carried out by Algerian companies ECOTEC, COSIDER and BATIMETAL.

The entry into production and launch of the products took place in January 1985 for transformers, and in January 1986 for engines/alternators, these products were manufactured under the SIEMENS license until 1992.

After the restructuring of SONELEC, the company became under the name ENEL (Enterprise Nationale des Industries Electro techniques) composed of seven subsidiaries including the MEL complex, which is considered the most important, given the importance of its turnover.

Finally, the electro-industry resulted from the reorganization of the industrial sector carried out in Algeria between 1980 and 2000, which led in 1999 to the restructuring concretized by the division of the former ENEL (National Enterprise of Electrotechnical Industries) into a number of EPE/SPAs, including ELECTRO-INDUSTRIES. The products manufactured by ELECTRO-INDUSTIEL comply with IEC recommendations and GERMAN DIN/VDE standards. The current production of ELECTRO-INDUSTIES is sold on the Algerian market and generates a turnover of 1.8 billion dinars.

The production capacity of transformers of this Company covers the needs of the market at about 70%. Engine sales represent about 30% of its production capacity. It is reported that ELECTRO-INDUSTRIES is the only manufacturer of these products in Algeria. In terms of quality ELECTRO-INDUSTRIES has its own laboratories for testing and measuring these products as well as for the control of the main materials used in its manufacture. When it comes to a documentary system, we use 252 internal standards in addition to DIN/VDE and CEL standards.

The different test and measurement values are recorded on minutes and maps from Canada on 24.7.2004, IS09001 version 2000. Canada Rice set up its quality system in 2002 and was ratified by QMI.

I.4. Organization chart of the company

The management of the company is administered by a CEO whose mission is to ensure coordination between various departments and the good management of the company, he makes strategic decisions from an organizational point of view, he is supported in his tasks by assistants in charge of management control, assistant in charge of legal litigation and recovery legal affairs and a head of IT department.

The ELECTRO-INDUSTRIE company contains six 06 departments that ensure the proper functioning of the entity's production process and well to achieve the objective, they are represented in the following organization chart:

Table I-1 Enel main departments

Executive management
Technical sales management (DTC)
Human resources and organization department (HRD)
Procure ment Departement (DAP)
Finance and accounting department (DFC)
Transformer unit management (UTR)
Transformer unit management (UTR)

- Quality and development department
- Management control and planning assistant
- Communication and social relations assistant
- Legal Assistant
- Informatic service

I.5. Conclusion

AZAZGA's national Electro-industry company can play an important role in the industry sector in Algeria and Africa.

Industrial machinery and the Technology of Construction and manufacture of transformers can be considered as a real model that the company must use, to develop other models that meet market requirements.

Small and medium-sized private sector companies can play an important role in the development of electro- Industry.

CHAPTER.II.Literature overview

II.1. Overview of the power transformer

II.1.1. Introduction

Power transformers are fundamental devices in electrical engineering, designed to transfer electrical energy between circuits through electromagnetic induction. They are critical in electricity transmission and distribution systems, ensuring efficient and safe power transfer across various voltage levels. The basic principle of a power transformer involves the use of wire coils, or windings, wound around a ferromagnetic core. These windings are typically made from insulated copper or aluminum wires and are configured in specific patterns to optimize performance. The core is usually constructed from laminated steel, which minimizes energy losses and enhances magnetic flux conductivity. Windings and Electromagnetic Induction. A power transformer comprises two main types of windings: the primary winding and the secondary winding. The primary winding connects to the input voltage source, and the secondary winding connects to the output load. When an alternating current (AC) flows through the primary winding, it generates a varying magnetic flux within the core. This changing magnetic flux induces a voltage in the secondary winding, adhering to the principles of electromagnetic induction. Power transformers are available in various sizes and ratings to meet diverse power requirements and applications. Common uses include electrical substations, power plants, industrial facilities, and distribution networks. Transformer ratings typically encompass power capacity (measured in kilovolt-amperes, or kVA), voltage ratings, frequency, and efficiency. The design, construction, and operation of power transformers are governed by industry standards and regulations to ensure performance, durability, and safety. These standards address various aspects of transformer functionality, including material quality, insulation, cooling, and protective measures.

In this part of the thesis, we are going to get a general idea about power transformer types, function and importance .

II.1.2. Definition

Figure II-1A transformer Outsider view.

A power transformer is a specific type of transformer designed for use in high-voltage applications within electric power transmission and distribution systems. Here's a breakdown of the definition:

A power transformer is an essential device used in electrical power systems to transfer electrical energy between circuits through electromagnetic induction. It consists of primary and secondary windings made of insulated copper or aluminum wire, wound around a laminated ferromagnetic core. When alternating current (AC) flows through the primary winding, it generates a varying magnetic flux in the core, which induces a voltage in the secondary winding.

The voltage transformation ratio is determined by the ratio of turns between the primary and secondary windings, allowing the transformer to step up or step-down voltage levels. This capability is crucial for efficient long-distance electricity transmission and safe distribution to end-users. Power transformers also provide electrical isolation between circuits, enhancing safety and system reliability. They are designed to meet specific power capacity, voltage, frequency, and efficiency requirements, and are subject to rigorous industry standards to ensure performance and durability. [1]

II.1.3. Characteristics and Symbol

II.1.3.1. Nameplate

A permanent metal or plastic label (figure 1.2), usually seen on the side or close to the top of the transformer, is called a nameplate. It shows vital technical information for secure and effective operation. It indicates the following parameters:

Figure II-2 NAMEPLATE.

Manufacturer and model: Indicates whose business manufactured the transformer and which model it is.

Rated capacity: This indicates the most power that a transformer can continually take without overheating or going above its design limitations. It is typically expressed in kVA or MVA.Voltage ratings: The transformer's primary and secondary voltage levels.

Cooling system: To maintain acceptable operating temperatures.

Safety: By operating the transformer within its intended voltage and current limits, according to the nameplate specifications helps to prevent potential damage and safety issues.

Selection and Installation: To ensure that the transformer is suitable for the intended use and grid voltage levels, technicians during installation rely on the nameplate data.

Operation and Maintenance: To guarantee effective performance and prolong the life of the nameplate, appropriate operation and maintenance procedures are guided by the information. [2]

II.1.3.2.Symbolization:

The following transformer symbols, showing some standard electrical transformer symbols for industrial control systems such as magnetic core and inductor symbol. Electrical transformer symbols for industrial control systems. The following transformer symbols showing some standard electrical transformer symbols for industrial control systems like magnetic core symbol, inductor symbol, choke symbol, barometer symbol, transducer, induction, induction voltage, transformer current, linear coupler symbol, etc.

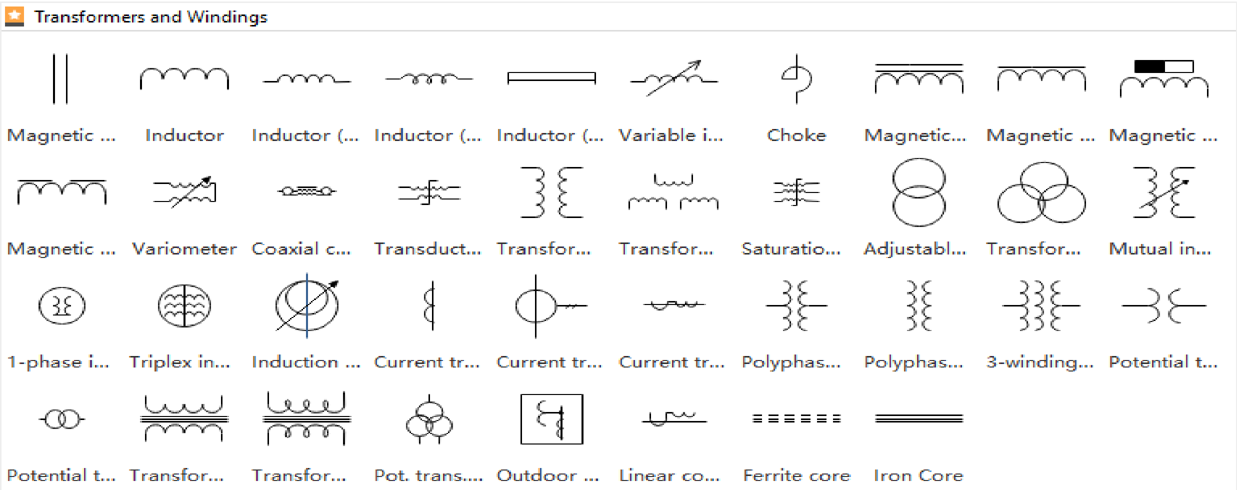

Figure II-3 transformer different electrical symbols

II.1.4. The role of transformer

Transformers are major players in the field of electrical power systems. Below is a summary of their main roles:

II.1.4.1.Adjusters of Voltage

Altering the voltage of AC (alternating current) electricity is a transformer's primary function.

step-up transformers, the voltage is raised. Utilized to efficiently transport electricity over long distances close to power plants (high voltage results in reduced current and less energy loss during transmission). **step down transformers:** Reduce the voltage so that appliances and residences may utilize them safely and practically.

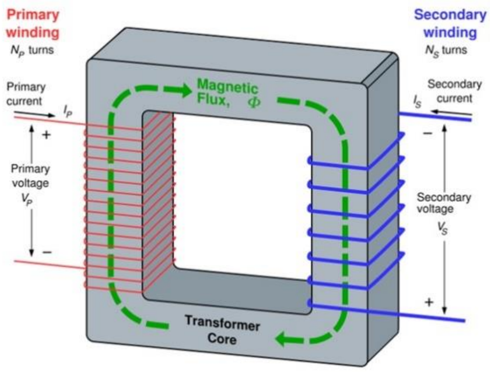

Figure I.4

II.1.4.2. Transmission and Distribution of Power:

The entire process of transporting electricity from generation plants to final consumers depends on power transformers:
Transmission: Transformers boost the high-voltage electricity produced at power plants so that it can be efficiently transmitted over large distances via power lines.

Distribution: Transformers scale down the voltage to gradually lower levels for distribution networks servicing neighborhoods and individual buildings once they reach substations. Separation Transformers can occasionally offer electrical separation between circuits. For safety purposes or to avoid undesired electrical interference between circuits, this may be advantageous.[3]

II.1.4.3.Matching Impedance:

Transformers can also be used to match the impedance between circuits; however, they are less prevalent in power systems. Transformers can help optimize power transfer by maintaining a good match between source and load impedance. Impedance is the resistance to current flow. In general, transformers efficiently convert electrical energy to the proper voltage levels for transmission, distribution, and safe use. They function as the voltage chameleons of the power grid.

Power transformer can also be used in Regulation by Helping in regulating voltage levels within the power system to ensure consistent and stable power supply. [4]

II.1.5. Operating Principle

II.1.5.1.General principle

The basic principle behind working of a transformer is the phenomenon of mutual induction between two Windings linked by common magnetic flux. Basically, a transformer consists of two inductive coils: primary winding and secondary winding.

The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as useful flux or main flux, and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is Called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary). The electromagnetic induction and mutual induction principles of faraday's law underpin the transformer's operation.

On the transformer core, there are typically two coils: a primary coil and a secondary coil. The strips are used to link the core laminations.Mutual inductance between the two coils is high. The magnetic flux changes as an alternating current flow through the primary coil. This shift in magnetic flux causes an EMF (electromotive force) to be induced in the secondary coil, which is connected to the core's primary coil, in accordance with Faraday's law of electromagnetic induction.Mutual induction is what's happening here.
In general, a transformer performs the following tasks:

- Transfer of electrical energy from one circuit to another
- Transfer of electrical power through electromagnetic induction
- Electric power transfer without any change in frequency
- Two circuits are linked with mutual induction. [5]

The magnetic flux lines that form around a wire carrying current is depicted in the figureII-4. The normal of a wire's cross-section is parallel to the normal of the plane that contains the flux lines.

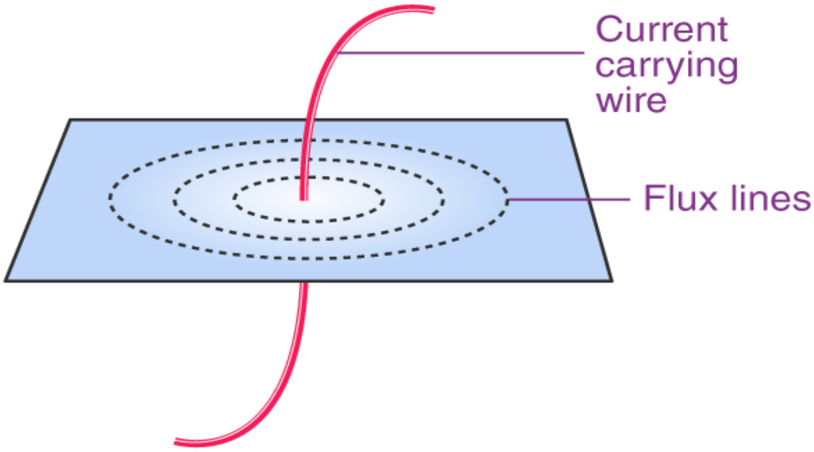

Figure II-4The magnetic flux lines that form around a wire carrying current

The creation of different magnetic flux lines around a wire wound is depicted in the figureII-5. It's noteworthy to note that the opposite is also true: a wire will produce a current when a magnetic flux line fluctuates around it. The basic operating principle of transformers and electric generators was discovered by Michael Faraday in 1831.

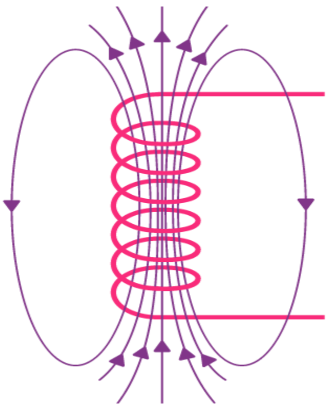

Figure II-5 different magnetic flux lines around a wire. [6]

II.1.5.2.Three Phase Transformer Connection:

When three single phase transformers are electrically connected internally to make single three phase transformer, this is referred to as a three-phase transformer connection.
There are three possible designs for connecting the primary and secondary windings: delta, star (wye), or combinations of both.

The transformation ratio, phase shift between the primary and secondary voltages, grounding provision, and other factors are determined by the kind of connection.

Certain connections are acceptable for specific purposes based on these considerations.

The following are the main types of three phase transformer connections:

- Delta - Delta (Δ - Δ) Connection
- Star - Star (Y - Y) Connection
- Delta - Star (Δ - Y) Connection
- Star - Delta (Y - Δ) Connection
- Open Delta or V-V Connection
- Zig-Zag (Z) Connection

[7]

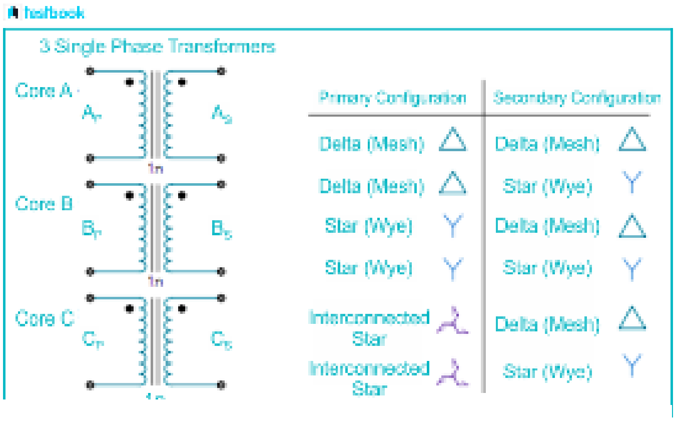

Figure II-6 transformer main connections.

Delta - Delta (Δ - Δ) Connection:

The delta-delta connection is a commonly used configuration for three-phase transformers. It consists of connecting the primary and secondary windings of the transformer in the shape of a triangle (delta).

In this type of connection, both the three-phase primary and secondary windings are connected in Delta. [8]

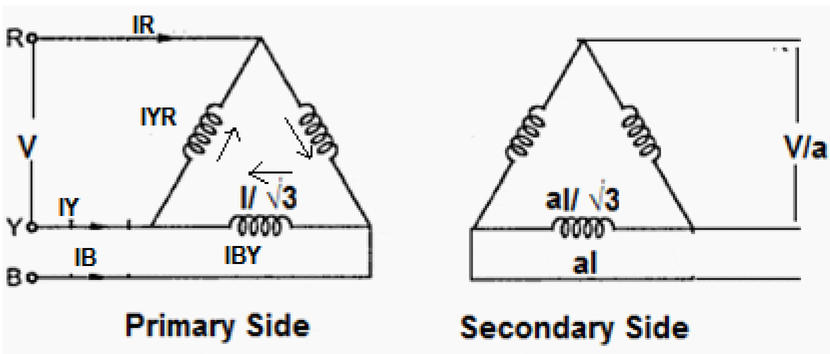

Figure II-7 Delta Delta connections Diagram circuit.

Star-Star (Y-Y) Connection:

The star-star connection is a commonly used configuration for three-phase transformers. It consists of connecting the primary and secondary windings of the transformer in a star shape.

The figure depicts the transformer's star-star connection. Here, each winding's opposite end is removed to serve as the line terminal, with the three terminals on the primary and secondary sides joined at a common point known as the neutral point. When there is a star-star connection, they are in phase and the phase current is equal to the line current. Three times the phase voltage is the line voltage. In addition, there is a 30° phase discrepancy between the phase and line voltages. [9]

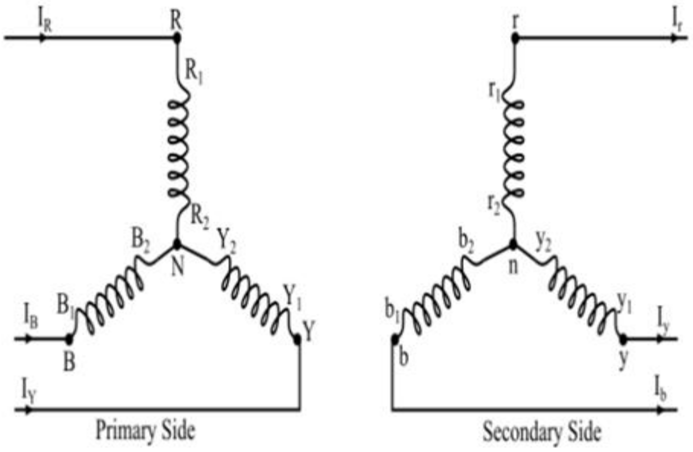

Figure II-8 Wye Wye connection diagram circuit.

Delta-Star (Δ-Y) Connection:

The Δ -Y connection, also known as the delta-wye connection, is a commonly used configuration for three-phase transformers. It combines the advantages of delta and star connections, providing increased flexibility and security.

The transformation is used to establish equivalence for networks with three terminals. Where three elements terminate at a common node and none are sources, the node is eliminated by transforming the impedances. For equivalence, the impedance between any pair of terminals must be the same for both networks.

The equations given here are valid for complex as well as real impedances. Complex impedance is a quantity measured in ohms which represents resistance as positive real numbers in the usual manner, and also represents reactance as positive and negative imaginary values. [10]

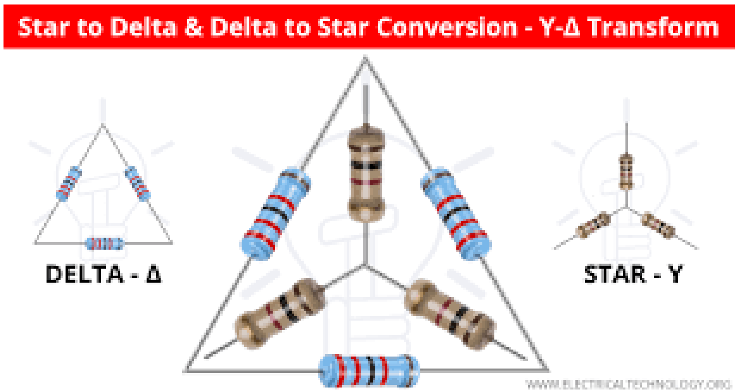

Figure II-9 Delta Wye connections.

Star-Delta (Y- Δ) connection:

Y-Delta (or Wye-Delta) connection in transformers is a method of connecting windings to achieve specific electrical characteristics it is basically a type of transformer winding configuration where the primary winding is connected in a Star (Y) configuration, and the secondary winding is connected in a Delta (Δ) configuration. This arrangement is commonly used in power distribution systems and motor starting circuits to balance load and reduce starting currents. The Star connection provides a neutral point, allowing for phase voltage to be lower, while the Delta connection ensures full line voltage and provides three-phase power to the load.

Zig-Zag (Z) Connection:

The Zig-Zag connection, sometimes called the Scott-T connection or phase-shifted connection, is a method of connecting three-phase transformers that provides a balanced three-phase electrical supply from a three-phase source. This method is often used in electrical power systems to reduce voltage imbalances between phases and harmonics.

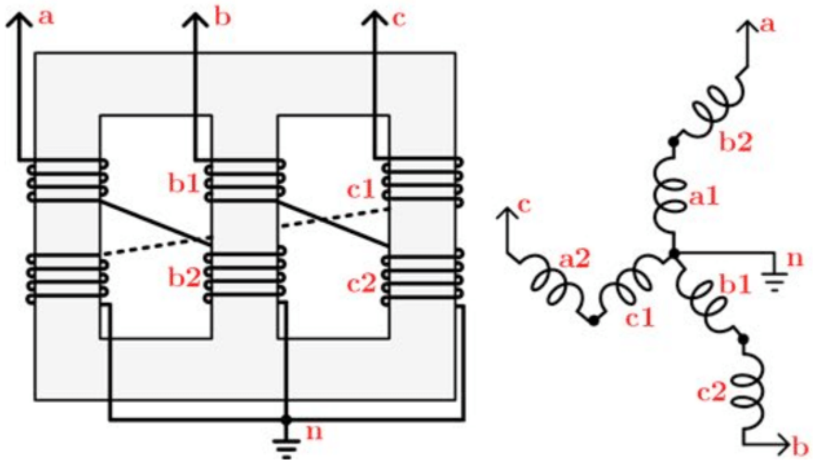

Figure II-10 Power transformer connected with zigzag connection.

In a Zig-Zag connection, each primary and secondary winding of each phase is divided into two equal parts. The windings are then connected in series in a specific way, forming a zigzag structure. Each secondary phase is formed by connecting the two halves of the primary and secondary windings of a primary phase with the halves of the windings of adjacent phases.

This specific configuration helps reduce voltage imbalances between phases by equally distributing the load between transformers. Additionally, it helps reduce harmonics in the electrical system by providing a path for harmonic currents so that they can combine and cancel each other in the transformer.

Zig-Zag connection is commonly used in applications where power quality is critical, such as power systems for equipment sensitive to voltage and current variations, as well as in industrial and commercial power distribution systems. [11]

II.1.5.3.Equivalent electrical circuit

In the context of transformers, an equivalent circuit is a simplified model used to represent the electrical behavior of a transformer. This simplified model is often used to analyze the transformer under various operating conditions without having to consider all the details of its physical construction.

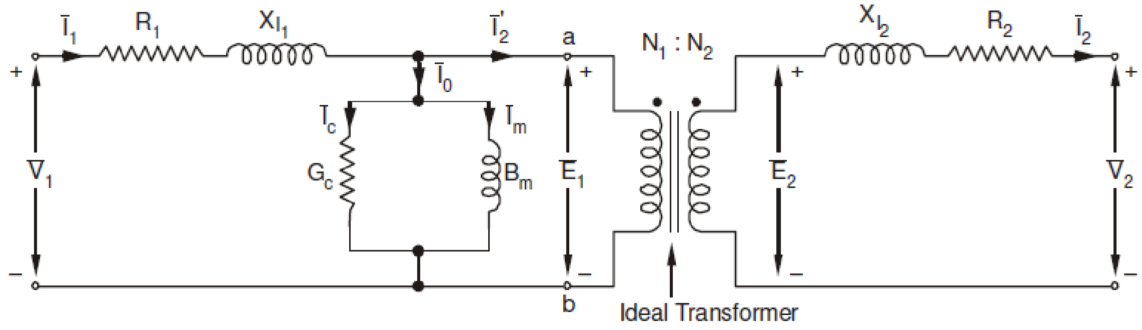

Figure II-11 Equivalent circuit. [12]

Utilizing Kapp approximation to simplify the math we neglect the B_m and G_C.

II.1.5.4.Short circuit tension:

Short-Circuit Voltage (Impedance Voltage):

The voltage that develops across a transformer's terminals when its secondary terminals are shorted while the main side is powered at rated voltage is known as short-circuit voltage. The reason it's named "short-circuit voltage" is that it's measured in a fault-simulation scenario in which the secondary winding is shorted.

The magnetizing reactance of the transformer core and the leakage reactance of the transformer windings are the main factors influencing short-circuit voltage.

In power transformers, it is usually less than 8%, while for distribution transformers, it is normally between 3% and 8% of the rated voltage.

Calculating fault currents, evaluating the effectiveness of protective devices, and measuring the stability of the power system under fault situations all depend on short-circuit voltage.

Short-Circuit Current

Short-circuit current is the current that flows through the windings of a transformer when its secondary terminals are shorted. The magnitude of the short-circuit current depends on the impedance of the transformer windings, the applied voltage, and the system impedance. It can be several times higher than the rated current of the transformer, especially for distribution transformers.

Short-circuit current is crucial for sizing protective devices such as fuses, circuit breakers, and relays to ensure they can interrupt fault currents safely and protect the transformer from damage.

It's also important for assessing the impact of short-circuit faults on the stability and reliability of the power system. [13]

II.1.5.5. Adjustments:

Tap Changer Adjustment:

Tap changers are tools that are used to modify the transformer's turn's ratio, which in turn controls the output voltage.

By allowing adjustments to the turn's ratio while the transformer is powered, on-load tap changers (OLTC) provide continuous voltage management without cutting off the power supply.

Off-load tap changers are appropriate for situations where voltage control might be momentarily disrupted because they need that the transformer be de-energized during tap changes.

For the purpose of adjusting voltage variations brought on by changes in the load, transmission line voltage drops, or power supply fluctuations, tap changer adjustment is essential.

Figure II-12 Power transformer adjustment taps.

Vector Group Adjustment: The vector group of a transformer determines the phase relationship and polarity between its primary and secondary windings.

Adjusting the vector group may be necessary to ensure compatibility with the system's phase angles, particularly in situations involving parallel operation or transformer banks.

Vector group adjustments may involve rewiring the transformer's connections to achieve the desired phase relationship.

Cooling System Adjustment: Transformers release heat produced while they are operating in order to avoid insulation damage and overheating. Enhancing heat dissipation and improving the transformer's thermal performance are the goals of cooling system adjustment.

The cooling system may need to have extra cooling fans installed, airflow pathways optimized, or forced air or oil circulation replaced with a more effective cooling technique.

Load Tap Adjustment: Load tap adjustments involve setting the switching points at which the tap changer changes the transformer's turns ratio based on the load conditions. Fine-tuning load tap settings helps maintain the desired voltage regulation and minimize voltage deviations under varying load levels.

Load tap adjustments are particularly important for transformers serving loads with fluctuating demand or operating in systems with voltage-sensitive equipment.

Protection Settings Adjustment: Transformers are equipped with protective devices to detect and isolate faults, preventing damage to the transformer and the power system.

Adjustment of protection settings involves configuring relay settings, coordination with other protective devices, and setting the tripping characteristics of circuit breakers.

Properly adjusted protection settings ensure rapid fault detection and selective isolation to minimize downtime and equipment damage during fault conditions.

Winding Configuration Adjustment: Winding configuration adjustments may be necessary to modify the transformer's voltage or current ratings or adapt it to different system configurations. Changes to winding configuration may involve rewinding the transformer or altering the existing winding arrangement to meet specific performance requirements.

Careful design and testing are essential when making winding configuration adjustments to ensure compatibility with the transformer's design parameters and operating conditions.

These adjustments play a crucial role in optimizing transformer performance, ensuring system reliability, and meeting the evolving needs of power distribution and transmission networks. Each adjustment requires thorough analysis, engineering expertise, and adherence to safety standards to achieve the desired outcomes without compromising transformer integrity or system reliability. [14]

II.1.6. General construction of the power transformer

Two principal types of transformer construction embody the requirements of economics, ease of manufacture, insulation, mechanical strength, and ventilation: core-type and shell-type. The key distinction between the two types lies in the core and winding placement. For core-type transformers, the windings encircle the core, while in shell-type transformers, the core encircles the windings. Here's a general overview of the construction of a power transformer:

II.1.6.1. Magnetic circuit:

A magnetic circuit is a circuit generally made of ferromagnetic material through which a magnetic field flow circulates. The magnetic field is generally created either by windings enclosing the magnetic circuit and crossed by currents, or by magnets contained in the magnetic circuit.

When several electric circuits are wound around the same magnetic circuit, they constitute magnetically coupled circuits.

Constitution, manufacturing:

It is made up of an assembly of parts made of ferromagnetic materials. It can include an air gap: small air space in the circuit. This air gap can be:

Structural: this is the case in rotating machines where the rotor is separated from the stator by a desired air gap as small as possible.

Intentional: avoids saturation of the magnetic circuit and gives greater linearity to the inductance thus created.[15]

Armored type and column type:

Figure II-13 Armored type transformer.

An armored-type transformer, also known as a shielded transformer, is designed with additional protective features to enhance safety and durability. This type of transformer typically includes a robust enclosure that provides mechanical protection and shields against environmental hazards such as moisture, dust, and physical damage. The armored design helps to prevent electrical faults, ensures the longevity of the transformer, and enhances operational safety, making it suitable for use in harsh or demanding environments where additional protection is necessary.

Column-type:

Also known as a core-type transformer, is a specific design of transformer where the windings are positioned around the vertical legs or columns of a laminated steel core. The core typically consists of three limbs or columns for three-phase transformers, with the primary and secondary windings concentrically wound around these limbs. This arrangement provides an efficient magnetic path and minimizes leakage reactance. Column-type transformers are commonly used in power distribution and transmission systems due to their robustness, ease of cooling, and cost-effectiveness.

II.1.6.2.Electric Circuit

An electrical circuit is a closed loop or path through which electric current can flow. It consists of various electrical components connected by conductive wires or traces, allowing the movement of charged particles, typically electrons, to transfer electrical energy in the transformer we have:

Windings:

Single Concentric Winding

A typical winding configuration seen in electrical transformers is single concentric winding. A single coil of wire twisted concentrically around a central axis or core makes up the winding in this arrangement. The salient points and attributes of a single concentric winding are broken down as follows:

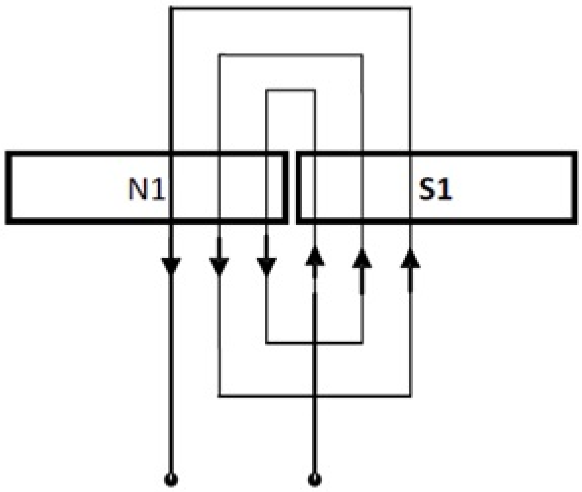

Figure II-14 Diagram of a single concentric winding.

single Coil: In a single concentric winding, there is just one coil as opposed to multiple winding configurations, which include separate coils for the main and secondary windings. This makes the transformer's manufacturing and installation simpler.

Concentric Layout: The transformer's core, or center axis, is encircled by a concentrically coiled wire. This indicates that the wire is coiled around the core in a circle, with each turn sharing the same center.

Primary and Secondary: The transformer's single physical coil fulfills the roles of both primary and secondary. The main winding of a winding is the one that is linked to the input voltage, while the secondary winding is the one that is connected to the output load.

Insulation: To maintain enough isolation between the primary and secondary windings and to avoid short circuits, insulation is placed between consecutive turns of wire.

Voltage Regulation: In transformers where exact voltage regulation is not necessary, single concentric windings are frequently employed. Applications like low-voltage distribution transformers for home or small business use are typical places to find them.

Space Efficiency: The single concentric winding design has the potential to save space, which makes it appropriate for uses where small size required. [16]

Double concentric winding

Double concentric winding is a winding configuration commonly used in electrical transformers. Unlike a single concentric winding where there is only one coil of wire wound around a central axis, a double concentric winding consists of two separate coils wound concentrically around each other, sharing a common center.it consist of:

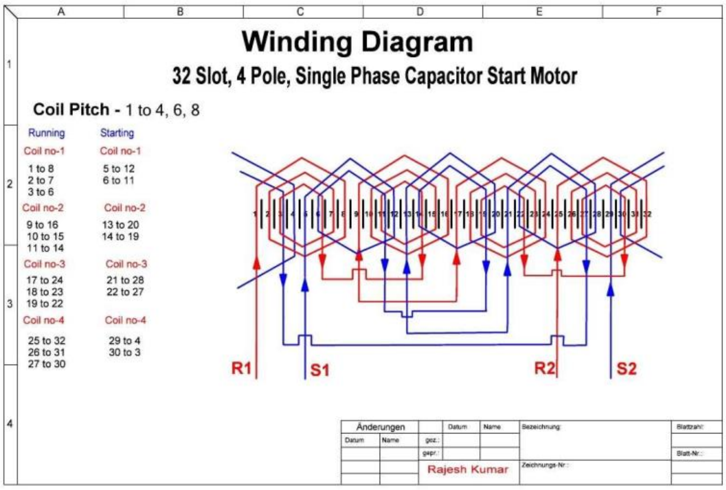

Figure II-15 Double concentric winding .

Two Separate Coils: In a double concentric winding, there are two distinct coils of wire wound around a common central axis. These coils are typically insulated from each other to prevent short circuits and ensure proper isolation.

Concentric Layout: Similar to a single concentric winding, each coil in a double concentric winding is wound concentrically around the central axis or core of the transformer. The coils share the same center but have different radii.

Primary and Secondary: The two coils in a double concentric winding serve the primary and secondary functions of the transformer. The coil connected to the input voltage is considered the primary winding, while the coil connected to the output load is considered the secondary winding.

Isolation: Although the coils share a common center, they are typically insulated from each other to ensure electrical isolation between the primary and secondary windings. This isolation is crucial for safety and to prevent unwanted interactions between the two circuits.

Voltage Regulation: Double concentric windings can offer improved voltage regulation compared to single concentric windings, as the separate coils allow for better control and adjustment of voltage levels.

Applications: Double concentric windings are commonly used in transformers where precise voltage regulation and isolation between primary and secondary circuits are important. They are often found in medium to high-power transformers used in industrial and utility applications. Overall, double concentric windings are an important winding configuration used in transformers to achieve specific voltage regulation and isolation requirements in various electrical applications. [17]

Bushings:

Bushings are critical components in electrical equipment, particularly in transformers, circuit breakers, and other high-voltage apparatus.

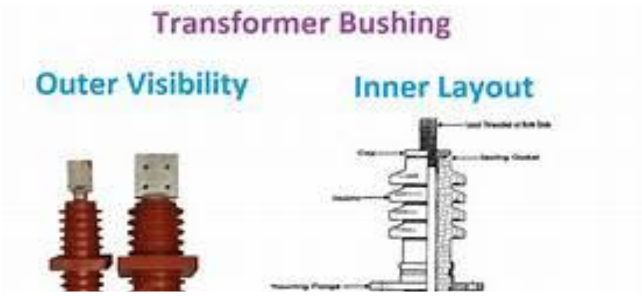

Figure II-17outer/inner view transformer bushing.

They serve several important functions:
Insulation: Bushings provide electrical insulation between the conductor (such as a transformer winding or a circuit breaker contact) and the grounded metal structure of the equipment. This insulation prevents electrical current from flowing through the equipment's casing and ensures safe operation.

Conductor Support: Bushing’s support and guide conductors, such as high voltage

cables or transformer windings, within the equipment. They help to maintain the proper alignment and positioning of the conductors, reducing mechanical stress and the risk of damage.

Sealing: In some transformer designs, bushings also serve as seals to prevent moisture, dust, or other contaminants from entering the transformer tank. This is especially crucial for transformers installed outdoors or in harsh environments.

Voltage Gradient Control: Bushings are often designed with specific shapes and materials to control the distribution of electrical stress and maintain a uniform voltage gradient along the length of the insulation. This helps to minimize the risk of electrical breakdown and ensures the effective insulation of the conductor.

Transformer bushings are usually composed of composite or porcelain, which are excellent insulators. They are made to endure harsh weather factors, temperature changes, and severe electrical stressors. The voltage rating, application, and installation requirements of a transformer, among other things, determine the kind and design of bushings that are used in it. [20]

Tap changer:

Transformers include a device called a tap changer that makes it possible to choose different turn ratios in discrete increments to do this, make connections to several access points also referred to as taps along the principal or secondary windings. There are two main types of tap changers: on-load tap changers (OLTC) that may alter their turn ratio while in operation, and no-load tap changers (NLTC) that must be de-energized before the turn ratio is changed. Any tap changer can have a manual tap changer, which is more typical for NLTC, or an automatic system, which is frequently the case for OLTC, for selecting the tap. It is possible to operate automatic tap changers on a lower or higher voltage winding, however for high-power production and automatic tap changers are frequently mounted on the higher voltage (lower current) transformer winding in

Figure II-18 Tap changer.

II.1.6.3.Insulation:

Cellulosic Insulation:

A form of insulating material called cellulosic insulation is created from recycled paper fibers that have been chemically treated to resist fire. It is frequently utilized as acoustic and thermal insulation in structures. Cellulosic insulation is not generally utilized in transformers; instead, oil-impregnated paper (OIP) is the major insulating material used in transformers. Transformer insulation serves as both a barrier against electrical breakdown and an electrical isolation for the various elements of the transformer. Both strong electrical qualities and resistance to high temperatures are requirements for the insulation. Despite being paper-based materials, cellulosic insulation and OIP differ in their characteristics and uses.
OIP insulation provides superior dielectric qualities, strong thermal conductivity, and great mechanical strength; it is particularly made for transformers. To increase its dielectric

strength and thermal conductivity it is treated with oil. It would not be standard procedure to use cellulose insulation in transformers because of variations in application appropriateness and performance. Transformers need insulating materials that are durable under strong electrical and thermal strains, and OIP has established itself as a dependable option in this regard. [18]

Liquid insulation transformers:

Liquid insulation transformers, also known as oil-filled transformers, are a common type of electrical transformer where the primary and/or secondary windings are immersed in an insulating liquid. The most used insulating liquid is mineral oil, although some transformers may use other types of liquids such as silicones or synthetic esters.:

Dielectric Properties: The insulating liquid provides excellent dielectric strength, which is crucial for preventing electrical breakdown and ensuring the safe operation of the transformer.

Heat Dissipation: The insulating liquid helps to dissipate heat generated during the operation of the transformer. This is particularly important in high-power transformers where efficient heat dissipation is essential to prevent overheating and maintain optimal performance.

Cooling: Liquid-filled transformers often have cooling systems such as radiators or oil pumps to maintain the temperature of the insulating liquid within acceptable limits. This helps to prolong the life of the transformer and ensure continuous operation under varying load conditions.

Mechanical Strength: The liquid insulation also provides mechanical support to the windings, helping to reduce mechanical stresses and vibrations during operation.

Environmental Considerations: While mineral oil is the most common insulating liquid used in transformers, there is growing interest in environmentally friendly alternatives such as biodegradable oils (natural esters) or silicone-based fluids. These alternatives offer improved fire safety and environmental sustainability compared to traditional mineral oil. [19]

transmission applications for convenience of access and to reduce the current burden while in operation.

The tank:

A transformer tank is an integral component of a power transformer, serving multiple crucial functions to ensure its efficient and safe operation. The tank is typically made of steel and is designed to contain the transformer's core, windings, and insulation oil.

Cooling System:

Includes radiators, fans, or pumps to dissipate heat generated during operation, maintaining optimal operating temperatures.

Conservator:

Maintains the oil level in the transformer tank, accommodating thermal expansion and contraction of the oil.

II.1.7. Types of power transformer

II.1.7.1.By construction:

Power transformers can be classified into several types based on their construction. Here are some common types:

Core-Type Transformer:

In core-type transformers, the windings are placed around the core limbs. The core is usually made of laminated steel sheets to reduce eddy current losses. This type provides a robust magnetic path and is commonly used in high-voltage applications.

Shell-Type Transformer:

In shell-type transformers, the core surrounds the windings, forming a shell-like structure. The magnetic path encircles the windings, which results in better protection and reduced leakage flux. This design is often more compact and provides better mechanical support for the windings.

Berry-Type Transformer:

Berry-type transformers have a cylindrical core with the windings placed around it, resembling the shape of a berry. This type is designed to minimize the leakage reactance and provide efficient cooling.

Toroidal Transformer:

In toroidal transformers, the core is toroidal, or doughnut shaped. The primary and secondary windings are wound around the core. Toroidal transformers are known for their compact size, low magnetic flux leakage, and low mechanical hum.

Autotransformer:

Autotransformers have a single winding that acts as both primary and secondary winding.

A portion of the winding serves as the primary, while another portion serves as the secondary. Autotransformers are used to step up or step-down voltages efficiently but provide less isolation between the primary and secondary circuits compared to traditional transformers.

Resonant Transformer:

Resonant transformers are designed to operate at or near resonance with the load.

They are commonly used in applications where high-frequency voltage conversion is required, such as in radio transmitters and switch-mode power supplies.

These are some of the main types of power transformers based on construction, each suited for specific applications depending on factors like voltage requirements, power capacity, efficiency, and size constraints.

II.1.7.2. By function:

Power transformers can also be classified based on their function or purpose. Here are some common types:

Step-Up Transformer: Step-up transformers increase the voltage level from the primary winding to the secondary winding. They are commonly used to raise the voltage for long-distance transmission to reduce energy losses.

Step-Down Transformer: Step-down transformers decrease the voltage level from the primary winding to the secondary winding. They are widely used in distribution networks to provide lower voltage levels for residential and commercial use.

Isolation Transformer: Isolation transformers electrically isolate the primary and secondary windings, providing galvanic isolation between the input and output circuits.

They are used to protect sensitive equipment from noise, voltage spikes, and ground loops.

Distribution Transformer: Distribution transformers are typically used in electrical distribution networks to step down the voltage for consumer use.

They are commonly installed on utility poles or in substations to supply power to residential, commercial, and industrial areas.

Instrument Transformer: Instrument transformers are used to measure voltage and current in high-voltage systems.

Current transformers (CTs) and potential transformers (PTs) are two common types used for metering, protection, and control purposes.

Rectifier Transformer: Rectifier transformers are designed to supply power to rectifiers, which convert alternating current (AC) to direct current (DC).

They are used in applications such as high-voltage direct current (HVDC) transmission, industrial rectifiers, and electrochemical processes.

Furnace Transformer: Furnace transformers are specialized transformers used to supply power to electric arc furnaces in steel mills and other industrial applications. They are designed to withstand high temperatures and heavy loads associated with electric arc furnace operations.

Variable Transformer (Variac): Variable transformers, also known as Variacs, allow for continuously adjustable output voltage. They are commonly used in laboratory experiments, testing equipment, and applications where precise control of voltage is required. [21]

II.1.8. Transformation ratio:

The mutual flux is common to each winding. Therefore, it must induce the same voltage per turn in each winding. If V_1' is the total induced voltage in the primary winding having N_1 turns, then the induced voltage per turn is V_1'/N_1. Similarly, the induced voltage per turn in the secondary winding is V_2'/N_2.

On no load, the applied voltage V_1 and the self-induced voltage V_1' are almost equal and $V_2 = V_2'$, so the above ratios are transposed and usually expressed as:

$$\frac{V1}{V2} = \frac{N1}{N2}$$

That is, on no load, the ratio of the voltages is equal to the ratio of the turns

Current Ratio

When the transformer is connected to a load, the secondary current I_2 produces a demagnetizing flux proportional to the secondary ampere-turns I_2N_2. The primary current increases, providing an increase in the primary ampere-turns I_1N_1 to balance the effect of the secondary ampere-turns. Because the excitation current I_0 is so small compared with the total primary current on full load, it is usually neglected when comparing the current ratio of a transformer. Therefore, the primary ampere-turns equal the secondary ampere-turns:

$$I1N1 = I2N2$$

Impedance Ratio

Although a main concern of audio and radio technicians, the impedance ratio is important to understand for electrical workers. The reason is that when the voltage goes down as a result of the turn's ratio, the current will go up for the very same reason. The impedance, or resistance if it makes it easier to understand, is a result of both changes, therefore the impedance ratio is the square of the turn's ratio.

$$\frac{Z2}{Z1} = \left(\frac{N2}{N1}\right)^2$$

Impedance to turn ratio equation

[22]

II.1.9. Transformer efficiency:

Transformers form the most important link between supply systems and load. Transformer's efficiency directly affects its performance and aging. The transformer's efficiency, in general, is in the range of 95 – 99 %. For large power transformers with very low losses, the efficiency can be as high as 99.7%. The input and output measurements of a transformer are not done under loaded conditions as the wattmeter readings inevitably suffer errors of 1 – 2%. So, for the purpose of efficiency calculations, OC and SC tests are used to calculate rated core and winding losses in the transformer. The core losses depend on the transformer rated voltage, and the copper losses depend on the currents through the transformer primary and secondary windings. Hence transformer efficiency is of prime importance to operate it under constant voltage and frequency conditions. The rise in the temperature of the transformer due to heat generated affects the life of transformer oil properties and decides the type of cooling method adopted. The temperature rise limits the rating of the equipment. The efficiency of transformer is simply given as:

$$\eta = \frac{output\ power}{output\ power + losses} \times 100\%$$

Transformer efficiency percentage equation

The output power is the product of the fraction of the rated loading (volt-ampere), and power factor of the load.

The losses are the sum of copper losses in the windings + the iron loss + dielectric loss + stray load loss.

The iron losses include the hysteresis and eddy current losses in the transformer. These losses depend on the flux density inside the core.

Maximum efficiency is:

$$\eta_{max} = \frac{xScos\theta}{xScos\theta + 2P_i}$$

Power transformer maximum efficiency equation

The variation of efficiency with loading can be represented by figure below:

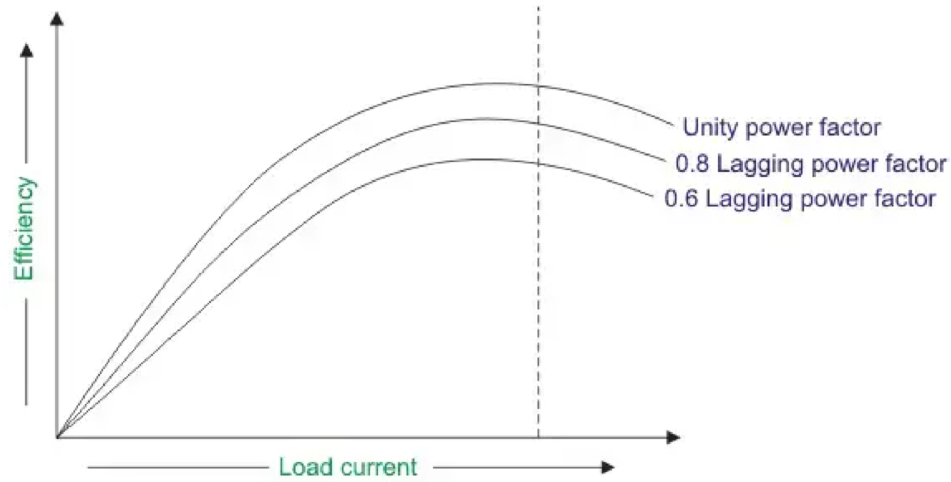

Figure II-19The variation of efficiency with loading.

We can see from the figure that the maximum efficiency occurs at unity power factor. And the maximum efficiency occurs at same loading irrespective of power factor of the load.

The transformation ratio determines the voltage ratio between the primary and secondary windings, which in turn affects the power transformation (voltage and current) in the transformer according to the principle of conservation of energy (assuming ideal transformer conditions). [23]

II.1.10. Hourly index

The Transformer Hourly Index is a metric used to assess the electricity grid's capability to accommodate power fluctuations caused by renewable energy sources like wind and solar. It measures the stress on transformers in the grid due to frequent changes in power flow, helping grid operators manage and maintain the stability of the electrical infrastructure. [35]

II.1.11. Power transformer classification:

Table II-1 Power Transformer classification

Application	○ Distribution Transformers: Used to step down high-voltage electricity from transmission lines to lower voltage levels for distribution to homes, businesses, and industrial facilities. ○ Power Transformers: used in high-voltage transmission networks to step up voltage levels for long-distance transmission and step-down voltages at substations for distribution.
Construction	○ Core-Type Transformers: In these transformers, the windings surround the core, resembling a shell. Examples include shell-type and core-form transformers. ○ Shell-Type Transformers: The core surrounds the windings, resembling a shell. ○ Toroidal Transformers: These transformers have a toroidal or doughnut-shaped core with windings wound around it.
Voltage Rating	○ Low Voltage Transformers: Typically used in residential and commercial applications with voltage ratings up to 1 kV. ○ Medium Voltage Transformers: Used for distribution and industrial applications with voltage ratings between 1 kV and 69 kV. ○ High Voltage Transformers: Used in transmission and substation applications with voltage ratings above 69 kV.

Cooling Methods	○ Oil-Immersed Transformers: These transformers are cooled by immersing the core and windings in insulating oil, which dissipates heat. ○ Dry-Type Transformers: These transformers use air or solid insulation instead of oil for cooling, making them suitable for indoor installations where oil-filled transformers are not desirable.
Function	○ Step-Up Transformers: Increase voltage from the primary winding to the secondary winding. ○ Step-Down Transformers: Decrease voltage from the primary winding to the secondary winding. ○ Isolation Transformers: Provide electrical isolation between the primary and secondary windings. ○ Autotransformers: Have a single winding that serves as both primary and secondary windings, providing variable voltage output.

Every kind of power transformer has a different design that considers many aspects including cost, size, efficiency, and environmental effect. It also performs a particular purpose. [24]

II.1.12. Cooling system:

The cooling system of a transformer refers to the mechanism used to dissipate heat generated during its operation. Transformers operate with electrical losses due to factors like resistance in the windings and hysteresis losses in the core, which manifest as heat. Proper cooling is essential to maintain the transformers.
temperature within safe limits and ensure efficient operation and longevity.

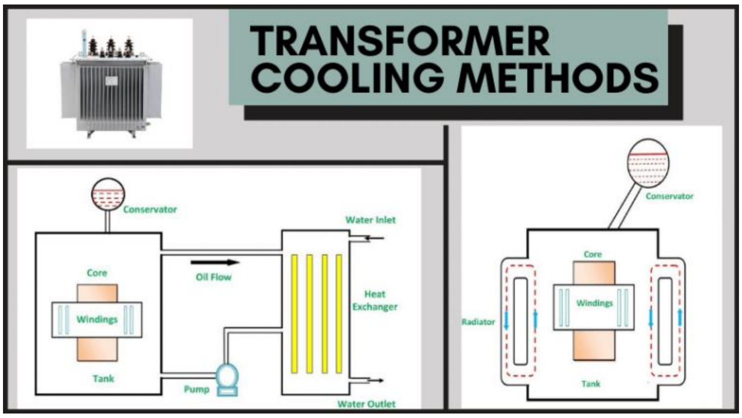

Figure II-20transformer main cooling method.

Table II-2 Cooling methods

	Represents "Oil Natural, Air Natural."

ONAN Cooling of Transformer	Using this cooling technique, the insulating oil and ambient air naturally convict to cool the transformer. Heat produced during operation is released into the surrounding air through the transformer tank and, if applicable, radiators.
ONAF Cooling of Transformer	Denotes "Oil Natural, Air Forced." Forced air circulation is added to improve cooling, much like in ONAN cooling. In order to improve heat dissipation and enable the transformer to run at greater power ratings, fans or blowers are utilized to drive air over the cooling surfaces.
OFAF Cooling of Transformer	Represents "Oil Forced, Air Forced." Using fans or blowers, this cooling technique actively circulates and cools the surrounding air as well as the insulating oil. This technique is appropriate for transformers with larger power ratings and offers more effective cooling than ONAF cooling.
OFWF Cooling of Transformer	Represents "Oil Forced, Water Forced." Pumps are used to actively cool both water and insulating oil during OFWF cooling. Heat from the oil is frequently dispersed using water-cooled heat exchangers, which effectively cool transformers running at extremely high power levels.
ODAF Cooling of Transformer	Represents "Oil Directed, Air Forced." This cooling technique uses forced air circulation to provide further cooling in addition to baffles or ducts to guide the flow of insulating oil to certain cooling surfaces.

ODWF Cooling of Transformer	Represents "Oil Directed, Water Forced." In order to improve heat dissipation, water cooling is added to ODAF cooling.

These cooling methods are designed to meet specific cooling requirements based on the transformer's power rating, operating conditions, and efficiency considerations. The choice of cooling method depends on factors such as the transformer's size, location, environmental conditions, and cooling requirements. [25]

II.2. Protection and maintenance of electrical power transformer

II.2.1. Power transformers common faults

II.2.1.1. Different types of faults:

Transformers can experience various types of faults, which can lead to disruptions in power supply, damage to equipment, and safety hazards. Here are some common types of transformers faults:

Short-Circuit Faults:

Short-circuit faults occur when a low-resistance path is formed between the windings or between a winding and the transformer core. These faults can result from insulation breakdown, internal winding faults, or external faults on the system.

Short-circuit faults can cause excessive currents, mechanical stresses, and thermal damage to the transformer windings.

Open-Circuit Faults:

Open-circuit faults occur when a connection within the transformer becomes disconnected or broken. These faults can result from broken conductors, loose connections, or faults in tap changers.

Open-circuit faults can lead to loss of continuity in the circuit, reduced voltage output, and damage to the transformer insulation.

Winding Faults:

Winding faults involve insulation breakdown or damage within the transformer windings.

Common winding faults include turn-to-turn faults, phase-to-phase faults, and phase-to-ground faults.

Winding faults can result from thermal stresses, mechanical vibrations, electrical overstress, or insulation degradation.

Transformer Overloading:

Overloading occurs when the transformer is subjected to currents or voltages higher than its rated capacity. Overloading can lead to overheating, insulation breakdown, and mechanical damage to the transformer.

Overloading may occur due to increased load demand, improper system configuration, or faults elsewhere in the system.

Insulation Breakdown:

Insulation breakdown occurs when the dielectric strength of the insulation material is exceeded, leading to arcing or short-circuiting. Insulation breakdown can result from thermal aging, moisture ingress, contamination, or mechanical damage to insulation materials.

Insulation breakdown can lead to short-circuit faults, winding faults, and damage to transformer components.

Moisture and Contamination:

Moisture and contamination can degrade the performance of transformer insulation and lead to insulation breakdown.

Moisture ingress can occur through leaking seals, damaged insulation, or improper storage and handling.

Contamination from dust, dirt, or chemicals can accumulate on transformer surfaces and degrade insulation properties.

Mechanical Faults:

Mechanical faults involve damage to transformer components such as bushings, cooling systems, and structural elements.

Mechanical faults can result from physical impacts, vibrations, or aging of mechanical components.

Mechanical faults can impair the operation of the transformer and lead to reduced reliability and efficiency. [38]

II.2.1.2.Statistics of failure causes:

While specific statistics on transformer failure causes can vary depending on factors such as the region, type of transformers, and operational conditions, some common factors contributing to transformer failures have been identified through industry research and analysis We find:

Electrical Stress: Overvoltage, voltage surges, and transient events can cause insulation breakdown, leading to short-circuit faults and winding failures.

Statistics show that electrical stress is a significant contributor to transformer failures, particularly in areas prone to lightning strikes or voltage fluctuations.

Overloading: Transformer overloading, where the transformer is subjected to currents or voltages higher than its rated capacity, can lead to overheating, insulation degradation, and winding failures. Overloading is a common cause of transformer failures, especially during periods of high demand or when transformers are improperly sized or configured.

Insulation Degradation: Insulation degradation due to aging, thermal stresses, moisture ingress, and contamination can lead to insulation breakdown and winding faults.

Statistics indicate that insulation degradation is a prevalent cause of transformer failures, particularly in older transformers or those exposed to harsh environmental conditions.

Mechanical Damage: Mechanical damage to transformer components, such as bushings, cooling systems, and structural elements, can impair the operation of the transformer and lead to failures.

Statistics show that mechanical damage from physical impacts, vibrations, or improper handling contributes to a significant number of transformer failures.

Moisture Ingress and Contamination: Moisture ingress and contamination from dust, dirt, or chemicals can degrade insulation properties, leading to insulation breakdown and short-circuit faults.

Statistics suggest that moisture ingress and contamination are common contributors to transformer failures, particularly in transformers located in humid or polluted environments.

Manufacturing Defects: Manufacturing defects such as poor craftsmanship, material defects, and design flaws can compromise the reliability and performance of transformers.

While less common, statistics indicate that manufacturing defects can lead to unexpected failures in transformers, especially in newly manufactured units.

External Factors:

External factors such as lightning strikes, seismic events, floods, and vandalism can cause sudden failures or damage to transformers.

Statistics show that external factors contribute to a significant number of transformer failures, particularly in regions prone to natural disasters or security threats.

II.2.1.3. Fault treatment policy

The fault treatment policy for transformers typically follows established norms, standards, and guidelines set forth by regulatory bodies, industry organizations, and manufacturers. Here are some key aspects of fault treatment policies for transformers:

Regulatory Requirements: Regulatory agencies and standards organizations often establish requirements and guidelines for the operation, maintenance, and repair of transformers. For example, organizations such as the International Electro technical Commission (IEC), the American National Standards Institute (ANSI), and national regulatory bodies set standards for transformer design, testing, and maintenance.

Manufacturer Guidelines: Transformer manufacturers provide guidelines, recommendations, and instructions for fault diagnosis, treatment, and repair. These guidelines typically include procedures for identifying different types of faults, assessing their severity, and determining appropriate corrective actions.

Diagnostic Testing: Diagnostic testing techniques such as insulation resistance testing, power factor testing, dissolved gas analysis (DGA), and partial discharge testing are used to assess the condition of transformers and identify potential faults. Fault diagnosis based on diagnostic test results helps determine the appropriate treatment strategy.

Prioritization of Faults: Not all transformer faults require immediate attention or extensive repair. A fault treatment policy typically involves prioritizing faults based on their severity, impact on transformer operation, and safety considerations. Critical faults that pose safety risks or threaten transformer reliability are addressed promptly, while less critical faults may be monitored or addressed during scheduled maintenance.

Corrective Actions: Depending on the nature and severity of the fault, corrective actions may include repairs, replacements, adjustments, or modifications to transformer components.

Corrective actions aim to restore the transformer to a safe and reliable operating condition while minimizing downtime and costs.

Preventive Maintenance: Preventive maintenance measures, such as regular inspections, cleaning, testing, and oil analysis, are essential for identifying and addressing potential faults before they lead to significant failures. A proactive approach to maintenance helps prevent transformer faults and extends the lifespan of transformers.

Documentation and Reporting: Fault treatment policies typically include procedures for documenting fault diagnoses, treatment actions, and outcomes. Detailed records of transformer faults, treatments, and maintenance activities facilitate tracking, analysis, and decision-making for future maintenance and operational strategies. [26]

II.2.2. Power transformer protection system

II.2.2.1. Definition and role of protection

A power transformer protection system comprises a comprehensive array of devices, equipment, and protocols meticulously crafted to detect and address potential faults and abnormal operating conditions in power transformers. At its core are relay protection devices, including overcurrent, differential, distance, and voltage relays, which monitor critical electrical parameters. These relays are calibrated to activate protective measures upon detecting deviations from predefined norms. Circuit breakers and disconnectors offer essential isolation mechanisms, swiftly isolating faulty sections of the electrical network to safeguard transformers from damage. Temperature monitoring devices, such as sensors and gauges, diligently oversee winding and oil temperatures, thwarting overheating, and insulation breakdown. The Buchholz relay, a specialized component, adeptly identifies internal faults, while pressure relief devices prevent catastrophic failures by releasing excessive pressure safely. Ground fault protection mechanisms ensure personnel and equipment safety, while communication and monitoring systems provide real-time updates, empowering operators to swiftly address anomalies and implement preventative measures. Altogether, this intricate system stands as a stalwart guardian, ensuring the uninterrupted and secure functioning of power transformers within electrical grids.

The protection of transformers encompasses a multifaceted approach aimed at addressing various aspects of equipment safety, system reliability, personnel safety, asset protection, grid stability, and risk management within electrical power systems.

At its core, transformer protection systems rely on a sophisticated array of devices, including relays, sensors, circuit breakers, and disconnectors, meticulously calibrated to detect deviations from normal operating conditions. These systems swiftly identify faults such as short circuits, overloads, and insulation breakdown, triggering protective measures to isolate faulty sections of the electrical network and prevent damage to transformer equipment.

Beyond safeguarding equipment, transformer protection plays a critical role in maintaining the reliability and availability of electrical power systems. By minimizing downtime and preventing cascading failures, protection systems ensure uninterrupted power supply to consumers, supporting essential services, industries, and infrastructure.

Moreover, transformer protection mechanisms contribute significantly to personnel safety by mitigating safety hazards associated with electrical faults. Ground fault protection devices, pressure relief mechanisms, and isolation measures reduce the risk of electrical accidents and injuries, fostering a safer working environment for personnel involved in maintenance and operation activities.

In addition to equipment and personnel safety, transformer protection strategies focus on asset protection and grid stability. These systems help extend the lifespan of transformers, optimize their performance, and mitigate risks associated with equipment failures. By maintaining grid stability and resilience, protection systems contribute to the reliable operation of electrical power systems under various operating conditions and contingencies.

Furthermore, transformer protection encompasses comprehensive risk management practices, including risk assessment, mitigation measures, and compliance with regulatory requirements. Utilities and operators employ proactive maintenance, testing, and monitoring regimes to identify potential failure modes, assess their consequences, and implement appropriate protective measures to mitigate risks effectively.

We conclude that, the protection of transformers is a multifaceted endeavor essential for ensuring the reliability, safety, and efficiency of electrical power systems. A holistic approach to transformer protection encompasses equipment safety, system reliability, personnel safety, asset protection, grid stability, and risk management, supporting the vitality and resilience of modern infrastructure.

II.2.2.2.Main qualities of a protection system

Reliability: The protection system must reliably detect and respond to abnormal operating conditions or faults to prevent damage to the transformer and ensure continuous power supply.

Sensitivity: It should be able to detect faults accurately and swiftly, even under challenging operating conditions, to minimize downtime and damage.

Selectivity: The protection system must be selective, meaning it should be able to accurately isolate the faulted section of the system while keeping the rest of the network operational.

Speed: Quick response time is crucial to prevent damage to the transformer and maintain grid stability. Fast fault detection and isolation can help minimize downtime and losses.

Security: The protection system should be robust and immune to false trips or maloperations caused by external disturbances or transient conditions.

Adaptability: It should be adaptable to various transformer configurations, operating conditions, and fault types to provide effective protection in different scenarios.

Communication and Coordination: Modern protection systems often include communication capabilities to coordinate with other protection devices and control systems, enhancing overall grid reliability and efficiency.

Monitoring and Diagnostics: The ability to monitor transformer health and performance continuously can help identify potential issues early and optimize maintenance schedules, improving overall system reliability and longevity.

II.2.2.3.Power transformer protection types:

Table II-3 power transformer types

II.2.3. **Protection Type**	**Description**
Overcurrent Protection	Detects excessive current flow through the transformer windings, indicating faults such as short circuits or overloads. Relays are used to trip circuit breakers or disconnectors to isolate the faulty section.
Differential Protection	Compares the currents entering and leaving the transformer windings. Any imbalance indicates an internal fault within the transformer. Differential relays are used to trip circuit breakers or disconnectors to isolate the transformer.
Overvoltage Protection	Monitors the voltage levels at the transformer terminals. Protection devices, such as surge arresters or voltage relays, are employed to divert excess

	voltage surges, protecting the transformer from insulation breakdown and damage.
Under frequency Protection	Detects a decrease in system frequency, which may indicate an imbalance between generation and load. Under frequency relays trip circuit breakers to disconnect the transformer from the grid, preventing damage due to excessive loading or instability.
Overheating Protection	Monitors the temperature of transformer windings and oil. Temperature sensors or gauges trigger alarms or protective actions, such as tripping circuit breakers, to prevent overheating and insulation breakdown, preserving the transformer's integrity and longevity.
Buchholz Relay Protection	Detects internal faults, such as short circuits or arcing, by analyzing gases generated within the transformer oil during abnormal conditions. The Buchholz relay triggers alarms or initiates protective actions to isolate the transformer and prevent further damage.
Earth Fault Protection	Detects faults between transformer windings and ground. Ground fault relays are employed to trip circuit breakers or disconnectors, isolating the transformer and preventing insulation damage or safety hazards.
Voltage Regulation	Ensures that the transformer maintains voltage levels within specified limits.
Loss of Excitation Protection	Monitors the excitation system of the transformer, ensuring that sufficient voltage is supplied to the transformer's windings. Loss of excitation relays trip circuit breakers to disconnect the transformer from the grid, preventing damage due to inadequate excitation.

These safety strategies protect workers, equipment, and the integrity of the power supply while guaranteeing the safe and dependable functioning of transformers in electrical power systems. [27]

An essential component of transformer safety and protection is tank earth protection, also referred to as tank grounding or tank earthling. In order to minimize the possibility of electric shock risks and to provide a low-resistance channel for fault currents, it entails making sure the transformer tank is adequately grounded to the earth. Here's a quick rundown:

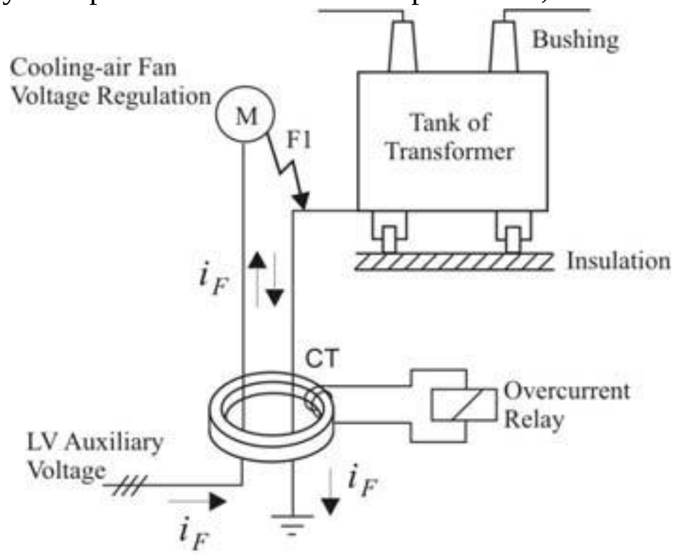

Figure II-21 tank earth protection scheme.

Tank earth protection:

Purpose: The primary purpose of tank earth protection is to ensure the safety of personnel and equipment by providing a low-resistance path to dissipate fault currents to the earth. This helps prevent dangerous voltage levels from developing on the transformer tank during faults.

Components: Tank earthling typically involves connecting the transformer tank to an earth electrode or grounding system using copper conductors or grounding straps. The earth electrode is buried in the ground near the transformer and provides a connection to the earth.

Design Considerations: The design of the tank earth protection system takes into account factors such as soil resistivity, fault current levels, and local regulations or standards governing grounding practices. The resistance of the earth electrode and connecting conductors should be low enough to ensure effective dissipation of fault currents and to limit the potential rise in earth potential during fault conditions.

Installation: Proper installation of the tank earth protection system is essential to ensure its effectiveness. Connections should be securely made, and corrosion-resistant materials should be used to minimize maintenance requirements and ensure long-term reliability.

Testing and Maintenance: Regular testing and maintenance of the tank earth protection system are necessary to verify its integrity and effectiveness. Testing methods such as ground resistance measurements and soil resistivity tests are performed to assess the performance of the earth electrode and grounding system.

Safety Compliance: Tank earth protection systems must comply with relevant safety standards and regulations to ensure the safety of personnel and compliance with legal requirements.

Standards such as IEEE 80 (Guide for Safety in AC Substation Grounding) and IEC 60364 (Electrical Installations for Buildings) provide guidelines for the design and installation of grounding systems.

Thermal protection:

Thermal protection for transformers is a vital aspect of ensuring their safe and reliable operation by monitoring and controlling the temperature of transformer components, particularly the winding insulation and transformer oil. Here's an overview of thermal protection for transformers:

Temperature Monitoring: Thermal protection systems continuously monitor the temperature of critical components such as transformer windings and oil. Temperature sensors, often placed within the windings and immersed in the transformer oil, provide real-time temperature readings.

Alarm Systems: Thermal protection systems include alarm systems that trigger visual or audible alarms when temperatures exceed predefined thresholds. Alarms alert operators to potential overheating issues, allowing them to take corrective action before damage occurs.

Temperature Controls: In some cases, thermal protection systems include temperature control devices that automatically adjust cooling mechanisms to regulate transformer temperature. Cooling systems, such as fans or oil pumps, may be activated or adjusted based on temperature readings to maintain safe operating conditions.

Differential Temperature Protection: Differential temperature protection compares the temperature of different transformer components, such as windings and oil, to detect abnormal temperature differentials that may indicate faults or insulation degradation. Differential temperature relays can initiate protective actions when significant temperature imbalances are detected.

Oil Temperature Protection: Monitoring the temperature of transformer oil is crucial, as excessive oil temperatures can accelerate insulation degradation and reduce transformer lifespan. Oil temperature sensors and temperature controls help maintain oil temperatures within safe operating limits.

Winding Temperature Protection: Monitoring the temperature of transformer windings is essential for preventing overheating and insulation breakdown. Winding temperature sensors provide accurate temperature readings, allowing operators to detect hot spots and potential issues with insulation integrity.

Thermal Imaging: Thermal imaging technology is sometimes used for comprehensive temperature monitoring, allowing operators to visualize temperature distributions across transformer components. Thermal imaging can help identify hot spots, insulation defects, and other abnormalities that may not be apparent through conventional temperature sensors.

Preventive Maintenance: Regular inspection, testing, and maintenance of thermal protection systems are essential for ensuring their effectiveness and reliability. Periodic calibration of temperature sensors, testing of alarm systems, and inspection of cooling mechanisms help identify and address potential issues before they lead to transformer failures. [28]

Oil temperature indicator protection: Transformer thermal protection systems require oil temperature indicators because they provide vital information regarding the oil's temperature. An outline of the protective mechanisms connected to transformer oil temperature indicators most importantly, they include alarm systems that provide an audible or visual signal to operators as soon as oil temperatures rise over preset levels. This allows for quick remedial action to avoid any overheating damage to transformers. In addition to certain indications, trip systems are designed to automatically initiate preventive actions such as activating circuit breakers to disconnect the transformer from the electrical system in case of overheating. Custom temperature thresholds may be set by operators to match transformer specs and operational needs, and sophisticated capabilities like historical data logging, trend analysis, and remote monitoring make proactive maintenance and troubleshooting easier. The accuracy and dependability of these indicators are guaranteed by routine calibration and maintenance, highlighting their critical role in protecting transformers and guaranteeing the integrity of electrical power systems.

Protection by Buchholz relay:

The Buchholz relay stands as a critical safeguard within transformer protection systems, offering a specialized defense against internal faults such as short circuits and arcing. Positioned within the transformer's oil-filled tank, this relay diligently monitors the composition of gases generated within the oil during abnormal conditions. Upon detecting significant gas accumulation, indicative of internal faults, the Buchholz relay swiftly initiates protective measures, including alarm activation or circuit breaker tripping. Its sensitivity to gas accumulation enables rapid intervention, preventing further escalation of faults and minimizing the risk of extensive transformer damage. The Buchholz relay's role in early fault detection and swift response underscores its importance in maintaining transformer reliability and safety, making it an indispensable component of modern transformer protection systems. [29]

DGPT: Differential Gas Pressure Transformer." This type of transformer incorporates a differential gas pressure relay (DGPR), often referred to as a Buchholz relay, within its protection system. The Buchholz relay detects internal faults by monitoring gas pressure changes within the transformer tank. When a fault occurs, such as a short circuit or arcing, gas is generated due to the decomposition of insulating oil. The increase in gas pressure triggers the Buchholz relay, which initiates protective actions such as alarm activation or circuit breaker tripping. This helps prevent further damage to the transformer and ensures the safety and reliability of the electrical power system. DGPTs are commonly used in medium to large power transformers, providing an additional layer of protection against internal faults. [30]

Protection against external faults

Power surge protection:

Power surge protection refers to the implementation of measures and devices designed to safeguard electrical and electronic equipment from sudden and transient increases in voltage, known as power surges or voltage spikes. These surges can occur due to various factors such as lightning strikes, switching operations, or electrical faults within the grid. Power surges can potentially damage or degrade sensitive equipment by exceeding their voltage ratings or causing insulation breakdown. To mitigate the risks associated with power surges, surge protection devices (SPDs) are installed in electrical systems. SPDs divert excess voltage away from the protected equipment, thereby limiting the voltage level and preventing damage. Additionally, surge protection strategies may include proper grounding practices, isolation of sensitive equipment, and the use of surge-protective components in electrical circuits. Overall, power surge protection aims to ensure the reliability and longevity of electrical and electronic equipment by minimizing the impact of transient voltage disturbances.

There are 2 types of a Power surge protection:

Table II-4 power surge protection

Surge Arrester	Spark Gap
A more advanced surge protection tool called a surge arrester, often referred to as a lightning arrester or surge suppressor, is made to direct excess power away from delicate equipment. Usually, it comprises of gas discharge tubes (GDTs) or metal oxide visitors (MOVs) coupled to ground	A spark gap is an easy-to-use and reasonably priced surge protector that lets extra power safely drain. It is made up of two metal electrodes with a little space between them. A spark leaps over the gap to provide a low-resistance channel for the surge current to go to

and the protected circuit. A safe amount of voltage is clamped, and the surge current is shunted to ground by the MOVs or GDTs when the voltage across the arrester beyond a certain threshold. Surge arresters are extensively employed in electronic equipment, telecommunication networks, and electrical distribution systems to guard against power surges brought on by switching activities, lightning strikes, and other brief disruptions.	ground when the voltage across the electrodes reaches a specific threshold, usually determined by the gap distance. For additional safety, spark gaps are frequently used in combination with other surge protection devices.

Power surge protection is a crucial function of both spark gaps and surge arresters, which offer practical ways to reduce the dangers of brief voltage disruptions and protect electrical and electronic devices from harm.

Phase overcurrent protection:

In order to protect electrical circuits, machinery, and people from the harmful consequences of high current in particular phases of a power system, phase overcurrent prevention is an essential part of electrical protection systems. It functions by identifying current levels in one or more phases that are higher than predefined criteria, at which point it triggers preventive measures to isolate the malfunctioning area of the circuit. Relays, circuit breakers, and fuses are examples of overcurrent protection devices that are frequently used for this purpose. To avoid overheating, equipment damage, and possible safety risks, these devices monitor the current flow through the phases and trip or open the circuit when current levels surpass the predetermined criteria. Phase overcurrent prevention is necessary to keep electrical systems safe and dependable, to provide a steady supply of power, and to avoid damage to equipment and personnel. There are two protection types:

Table II-5 phase overcurrent protection types

Protection Type	Description
Primary Protection	Installed at the closest proximity to the source of the issue; makes use of components like high-speed circuit breakers or fuses. - Cuts fault currents quickly.
Secondary Protection	Put in place after the main security equipment. Makes use of components like backup circuit breakers or overcurrent relays. - Offers backup defense

This table succinctly outlines the key characteristics of both primary and secondary protection for phase overcurrent faults. [31]

Restricted Earth Fault (REF) Protection: REF protection is intended to identify earth faults in a designated power system zone, usually in proximity to the transformer.

- The phase and neutral conductor current imbalance is measured in order for it to function.

- The REF relay is activated when an earth fault happens inside the protected zone. This unbalanced current trips the circuit breaker, isolating the fault and initiating preventive measures.

- In order to safeguard transformer windings and related equipment from harm, REF protection is frequently utilized to offer transformers sensitive and selective protection. It also ensures that earth faults are quickly detected and isolated.

Differential Protection:

By comparing the currents entering and exiting the equipment, differential protection is a basic technique used to find internal problems in transformers, generators, and other electrical machinery. The differential relay functions to trip the corresponding circuit breakers and separate the equipment from the system if the difference between these currents beyond a certain threshold, signifying an internal malfunction. Differential protection ensures quick reaction to internal problems and guards against harm to the apparatus that is protected by providing sensitive and selective fault detection. In high-voltage transmission and distribution networks, it is extensively employed to protect vital components and uphold system dependability.

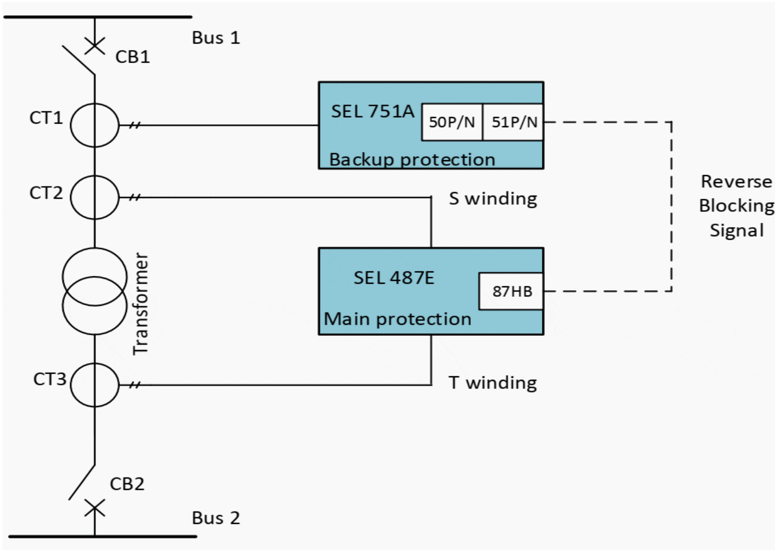

Figure II-22 Block Diagram of a differential protection.

Harmonic Protection:

Harmonic protection schemes are crucial components of power system protection strategies, particularly in environments where non-linear loads, such as variable frequency drives and power electronics, generate harmonics that can disrupt the operation of electrical equipment. These schemes aim to mitigate the adverse effects of harmonics on power quality and system performance by employing various techniques. One common approach involves the installation of harmonic filters, which are tuned to selectively attenuate specific harmonic frequencies, thereby reducing harmonic distortion in the system. Additionally, active harmonic mitigation devices, such as active filters or static VAR compensators, dynamically inject compensating currents to cancel out harmonics and maintain sinusoidal voltage and current waveforms. Furthermore, protective relays and monitoring systems are deployed to detect and respond to harmonic-related issues, such as overheating of equipment or resonance conditions, by initiating corrective actions such as load shedding or reconfiguration of the power network. Overall, harmonic protection schemes play a critical role in ensuring the reliability, efficiency, and longevity of electrical systems by mitigating the deleterious effects of harmonics and maintaining power quality within acceptable limits.

II.2.4. Power transformer maintenance

II.2.4.1. Introduction:

Transformers, like any mechanical or electrical equipment, are susceptible to deterioration, wear, and eventual breakdowns over time because of Several variables, including changes in temperature, the entry of moisture, and electrical strains.We explore all facets of transformer maintenance in this thorough reference on power transformer maintenance, from regular testing and inspection schedules to sophisticated diagnostic methods and new developments in predictive maintenance. Our goal is to give experts who manage and maintain electrical power systems useful insights and helpful advice.

II.2.4.2. Maintenance objective

The primary objective of maintenance for power transformers is to ensure the continued reliability, safety, and optimal performance of these critical assets within electrical power systems. This overarching goal encompasses several key objectives:

Preservation of Equipment Health: Maintenance activities aim to identify and address potential issues that could compromise the integrity of transformer components. By conducting regular inspections, testing, and servicing, maintenance personnel can prevent deterioration, extend equipment lifespan, and mitigate the risk of unexpected failures.

Prevention of Unplanned Downtime: Proactive maintenance practices, such as predictive and preventive maintenance, are implemented to identify and rectify issues before they escalate into critical failures. By addressing potential problems early, utilities can minimize unplanned outages, reduce downtime, and ensure the uninterrupted flow of electricity to consumers.

Optimization of Asset Performance: Maintenance efforts are directed towards optimizing the performance and efficiency of power transformers. This includes tuning protective relay settings, optimizing cooling systems, and implementing efficiency-enhancing measures to maximize transformer performance and minimize energy losses.

Enhancement of Safety and Reliability: Maintenance activities are geared towards enhancing the safety and reliability of power transformers, as well as the overall power system. By ensuring that transformers operate within safe temperature and voltage limits, maintenance helps prevent equipment failures, minimize the risk of electrical fires, and protect personnel and assets from harm.

Compliance with Regulatory Standards: Maintenance programs are designed to ensure compliance with regulatory standards and industry best practices. Utilities must adhere to regulatory requirements regarding transformer maintenance, testing, and reporting to ensure the safety and reliability of electrical power systems and meet regulatory obligations. [46]

II.2.4.3. The importance of maintenance

Maintenance plays a pivotal role in ensuring the reliability, safety, and optimal performance of power transformers and other critical assets within electrical power systems. Its importance is multifaceted and encompasses several key aspects:

Reliability and Continuity of Service: Maintenance activities are essential for preventing unexpected failures and minimizing downtime. By identifying and addressing potential issues proactively, utilities can ensure the uninterrupted operation of power transformers, minimizing disruptions to electricity supply and maintaining continuity of service for consumers.

Safety and Risk Mitigation: Maintenance helps mitigate safety risks associated with transformer failures, such as electrical fires, equipment damage, and personnel injury. By conducting regular inspections, testing, and servicing, utilities can identify and rectify potential hazards before they escalate, ensuring a safe working environment for personnel and protecting surrounding assets and infrastructure.

Optimal Performance and Efficiency: Maintenance efforts are directed towards optimizing the performance and efficiency of power transformers. By tuning protective relay settings, calibrating instrumentation, and optimizing cooling systems, utilities can maximize transformer performance, minimize energy losses, and enhance overall system efficiency.

Asset Management and Lifecycle Optimization: Maintenance is essential for managing the lifecycle of transformer assets and maximizing their value over time. Through routine inspections, condition monitoring, and predictive maintenance techniques, utilities can extend the lifespan of transformers, defer capital expenditures, and achieve a higher return on investment in their asset portfolio.

Compliance and Regulatory Requirements: Maintenance programs ensure compliance with regulatory standards, industry guidelines, and manufacturer recommendations. Utilities must adhere to regulatory requirements regarding transformer maintenance, testing, and reporting to ensure the safety, reliability, and regulatory compliance of electrical power systems. [33]

II.2.4.4.Different forms of maintenance:

There are different forms of maintenance that utilities can employ to achieve these objectives:

Preventive Maintenance:

This proactive approach involves scheduled inspections, lubrication, cleaning, and component replacements to prevent equipment failures before they occur. Preventive maintenance helps identify and rectify potential issues early, minimizing the risk of unplanned downtime and extending the lifespan of transformer assets.

Predictive Maintenance:

Predictive maintenance utilizes advanced diagnostic techniques, such as oil analysis, thermography, and vibration analysis, to monitor the condition of transformer components and predict potential failures. By analyzing trends and anomalies in data collected from monitoring systems, utilities can identify impending issues and take corrective action before failures occur.

Corrective Maintenance:

Corrective maintenance involves repairing or replacing components after a failure has occurred. While corrective maintenance is reactive in nature and can result in downtime, it is necessary for addressing unexpected failures and restoring equipment to operational condition promptly.

Condition-Based Maintenance:

Condition-based maintenance combines elements of preventive and predictive maintenance, focusing on monitoring key parameters and performance indicators to determine the optimal timing for maintenance activities. By basing maintenance decisions on the actual condition of transformer components, utilities can optimize maintenance schedules, minimize downtime, and maximize asset reliability.

II.2.4.5.Maintenance techniques for power transformer:

Power transformer maintenance methods use a comprehensive approach to guaranteeing these essential parts of electrical power networks continue to function reliably. Visual inspections are performed on a regular basis to evaluate the exterior condition of transformers, looking for physical damage, leaks, or corrosion. To assess the integrity of transformer insulation and detect pollutants, degradation products, and moisture levels that may jeopardize it, oil sample and analysis are essential. Testing for insulation resistance gauges the materials' resistance, revealing information about their dielectric strength and identifying any degradation or moisture intrusion. Gases dissolved in transformer oil are monitored by dissolved gas analysis (DGA), which uses variations in gas levels and ratios as markers of possible internal problems like overheating or arcing by using thermal imaging techniques, temperature anomalies inside transformer components may be found, and hot patches that may indicate insulation breakdown or weak connections can be identified. Vibration analysis uses vibration patterns and frequencies to detect mechanical anomalies, such as loose windings or core laminations. In order to warn of probable insulation deterioration and approaching failures, partial discharge monitoring finds and monitors partial discharges inside transformer insulation. Utilities may obtain meaningful insights into transformer health by incorporating these approaches into complete condition monitoring systems. This allows for prompt maintenance interventions to minimize risks and maximize asset performance.

These are essential measurements conducted during maintenance checks to assess the health and performance of power transformers: [34]

- **Electrical measurement :**

Table II-6 electrical measurements

Measurement	Information/method
Measurement of Transformation Ratio	The transformer is operating as intended that is, transferring voltage from the primary to secondary windings at the designated ratio. Method: The main and secondary voltages are measured under specific conditions, usually with no load attached and the applied rated frequency, in order to calculate the transformation ratio. Equipment: To measure primary and secondary voltages precisely, a potential transformer or precision voltmeter are employed. Acceptance Criteria: Within certain tolerance bounds, usually outlined by standards or manufacturer's instructions, the measured transformation ratio must

	coincide with the transformer's rated transformation ratio.
No-Load Current Measurement	Goal: This measurement evaluates the transformer's magnetizing current drain when it is activated and not attached to a load. Method: To measure the no-load current, wire an ammeter in series with the primary winding and power the transformer at its rated voltage and frequency while leaving the secondary side unloaded. Interpretation: An unusually high no-load current might be a sign of internal defects, core saturation, or an excessive magnetizing current. Equipment: For this measurement, an ammeter with accurate low current measurement capabilities is utilized.
Winding Resistance Measurement	The goal of this measurement is to make sure the transformer windings' resistance is within allowable bounds. Procedure: A precision ohmmeter is used to detect the voltage drop across a winding after a known DC current is sent through it to determine the winding resistance. Interpretation: Problems like weak connections, deteriorating insulation, or high resistance joints may be indicated by a large departure from the intended resistance value. For this measurement, a precision ohmmeter

Leakage Reactance Measurement	**Purpose:** This measurement evaluates the inductive reactance associated with the leakage flux in the transformer. **Procedure:** The leakage reactance is determined by measuring the voltage drop across the transformer when a rated current is passed through it, typically using an AC voltage source and a precision voltmeter. **Interpretation:** Deviations from expected values may indicate issues affecting the transformer's impedance characteristics and its ability to regulate voltage under load conditions. **Equipment:** A precision voltmeter and AC voltage source are used for this measurement.
Frequency Response Analysis	Goal: This analysis looks at how the transformer reacts to different frequencies during the course of its operation. The methodology involves the utilization of specialized equipment that can generate a variety of frequencies and measure the transformer's reaction in order to study the transformer's response to variations in frequency. Interpretation: Frequency response abnormalities, such as resonance situations or mechanical flaws, may point to possible problems that might impair transformer operation. Tools: This investigation makes use of signal generators and frequency response analyzers.

[35]

- **Dielectric measurements:**

Dielectric measurements are used to evaluate the quality, integrity, and performance of insulating materials by measuring their electrical characteristics, such as capacitance, dielectric constant, and insulation resistance. Since insulating materials are crucial for preventing electrical breakdown and preserving insulation integrity, these tests are necessary to guarantee the dependability and safety of electrical equipment and systems. Capacitance meters, dielectric analyzers, insulation resistance testers, and partial discharge monitors are just a few of the tools and methods used to assess dielectric properties. Engineers and technicians can evaluate the condition of insulation, identify any flaws or degradation, and take preventative action to stop electrical failures and guarantee the continuous functioning of electrical systems by examining the dielectric characteristics of insulating materials. [36]

Dissipation factor and capacitance measurement*:*

The ESR is a derived quantity with physical origins in both the dielectric's conduction electrons and dipole relaxation phenomena. In dielectric only one of either the conduction electrons or the dipole relaxation typically dominates loss. For the case of the conduction electrons being the dominant loss, then.

$$ESR = \frac{\delta}{\varepsilon\omega^2 c}$$

Equivalent series resistance equation

Where:

- δ is the dielectric's bulk conductivity,
- ε is the lossless permittivity of the dielectric, and
- ω is the angular frequency of the AC current I,
- C is the lossless capacitance.

When representing the electrical circuit parameters as vectors in a complex plane, known as phasors, a capacitor's dissipation factor is equal to the tangent of the angle between the capacitor's impedance vector and the negative reactive axis, as shown in the adjacent diagram. This gives rise to the parameter known as the loss tangent tan δ where.

$$\frac{1}{Q} = \tan(\delta) = \frac{ESR}{|XC|} = DF$$

Dissipation factor equation

DF will vary depending on the dielectric material and the frequency of the electrical signals. In low dielectric constant (low-κ), temperature compensating ceramics, DF of 0.1–0.2% is typical. In high dielectric constant ceramics, DF can be 1–2%. However, lower DF is usually an indication of quality capacitors when comparing similar dielectric material.

Measurement of DC insulation resistance:

The measurement of DC insulation resistance is a crucial diagnostic test used to assess the integrity and quality of insulation in electrical equipment, including power transformers, cables, motors, and generators. Insulation resistance (IR) testing is performed to determine the resistance of insulation materials to direct current (DC) voltage, indicating their ability to prevent leakage current and withstand electrical stress. [37]

Oil analysis:

Oil analysis is a critical diagnostic technique employed in the maintenance of power transformers and other oil-filled electrical equipment. This process begins with the careful sampling of insulating oil from the transformer, ensuring a representative sample is collected. The collected sample is then sent to a specialized laboratory equipped with analytical instruments for comprehensive testing. Physical tests evaluate visual appearance, color, clarity, and viscosity, while chemical tests assess acidity, moisture content, and dissolved gas analysis (DGA). The interpretation of analysis results by experienced analysts considers various factors, including equipment type, operating conditions, and historical data. Deviations from expected values or abnormal trends in the analysis may indicate potential issues such as insulation degradation, overheating, or contamination. Based on the analysis findings, recommendations for maintenance actions or further diagnostic tests are provided, such as oil filtration, replacement, or equipment inspection. By integrating oil analysis into routine maintenance programs, utilities and operators can proactively identify potential issues, prevent failures, and optimize the reliability and longevity of their electrical equipment. [38]

II.2.4.6. The implementation of transformer maintenance

The implementation of transformer maintenance involves the systematic execution of various proactive strategies and practices aimed at ensuring the reliability, safety, and optimal performance of transformers within electrical power systems.

Maintenance of external transformer components:

The maintenance of external transformer components is an essential aspect of ensuring the reliability, safety, and optimal performance of transformers within electrical power systems. Here's a breakdown of the key components and maintenance practices:

Bushings: Inspect bushings regularly for signs of damage, cracking, or contamination. Clean bushings as needed to remove dirt, dust, or other debris that could compromise their performance. Check for signs of leakage around bushing connections and replace any damaged or deteriorated bushings promptly.

Cooling Systems: Maintain cooling systems, such as radiators or fans, to ensure effective heat dissipation from the transformer. Clean cooling fins and surfaces regularly to remove dirt, debris, or vegetation that could obstruct airflow. Monitor coolant levels and quality and replenish or replace coolant as needed to maintain proper cooling performance.

Tap Changers: Inspect tap changers for signs of wear, corrosion, or damage. Lubricate tap changer mechanisms regularly to ensure smooth operation and prevent sticking or binding. Test tap changer functionality periodically to verify proper operation and adjust tap settings as needed to maintain voltage regulation.

Conservator: Monitor the level of oil in the conservator and ensure it remains within the specified operating range. Inspect the conservator for signs of oil leakage, corrosion, or damage. Clean and repaint the conservator exterior as needed to prevent corrosion and maintain a protective barrier against environmental elements.

Breather: Check the condition of the breather regularly and replace desiccant or silica gel as needed to maintain proper moisture control within the transformer. Clean the breather housing and replace filter elements periodically to ensure optimal performance and prevent moisture ingress into the transformer.

Pressure Relief Devices: Test pressure relief devices periodically to verify proper operation and ensure they can effectively relieve excess pressure buildup within the transformer. Inspect relief device connections and seals for signs of damage or deterioration and replace any faulty components promptly.

Grounding System: Inspect grounding connections and electrodes regularly to ensure they are intact and securely bonded to the transformer and grounding grid. Test grounding resistance periodically to verify compliance with safety standards and maintain effective fault current path to ground.

Nameplate and Identification Labels: Ensure that nameplates and identification labels are legible, securely attached, and contain accurate information about the transformer, including ratings, serial numbers, and manufacturer details. Replace damaged or illegible nameplates and labels promptly to facilitate proper identification and documentation.

By implementing a proactive maintenance program for external transformer components, utilities and operators can ensure the reliability, safety, and longevity of transformers within electrical power systems. Regular inspection, cleaning, lubrication, and testing of external components help identify potential issues early, prevent failures, and optimize transformer performance.

Maintenance of internal transformer components:

For transformers to operate as safely, reliably, and optimally inside electrical power networks, internal transformer component maintenance is essential. This all-inclusive method entails routine testing, inspection, and maintenance of important internal parts such cooling systems, tap changers, Buchholz relays, gaskets and seals, windings, core, and insulating oil. A combination of visual inspections, diagnostic testing, and monitoring procedures are used to evaluate internal component status and identify any problems before they become serious. To keep an eye on the state of insulating oil and spot possible issues like contamination or deterioration, regular oil sample and analysis are done. Cleaning, lubricating, adjusting, repairing, and replacing components as necessary to guarantee optimal performance and avert malfunctions are examples of maintenance tasks. Utilities and operators may minimize the risk of unplanned failures, maximize equipment performance, and guarantee the dependability and durability of transformers within electrical power systems by putting in place a proactive maintenance program for internal transformer components.

So, Utilities and operators may minimize the risk of unplanned failures, maximize equipment performance, and guarantee the dependability and durability of transformers within electrical power networks by putting in place a proactive and methodical strategy to transformer maintenance. [39]

II.3.CONCLUSION:

Protecting and maintaining electrical power transformers is essential to guaranteeing their dependability, security, and peak performance. Transformers are protected by the protection system against a variety of electrical failures, guaranteeing a steady supply of power and averting infrastructure and equipment damage.

CHAPTER.III. Methodology

III.1. Introduction

In this chapter, we will examine the existing protection system employed by Enel, identify the challenges it faces, and simulate some key issues to analyze the transformer's response to these problems using MATLAB to approach the real results and optimize the behavior of transformers and avoid the immense losses by understanding the importance of electrical tests of the transformer:

III.2. Description of the existing system

We are going to discuss the main protection system of power transformer used to distribute the electrical power to the principal workshops in Enel starting by:

III.2.1. Power distribution transformer HT/LT

three-phase HT/LT transformer is the workhorse of industrial and high-power distribution systems. It efficiently steps down high voltage (HV) electricity transmitted over long distances to the low voltage (LV).

in this follow up table we are representing the main characteristics of the used sub-transformer in Enel to distribute the power after receiving it from the main power transformer which is connected to SONALGAZ electrical network [40].

The main specifications are:

Apparent Power S: 800 kVA

Primary VoltageV1: 10 kV (Delta Connection)

Secondary VoltageV2: 0.4 kV (Wye Connection)

calculating other specifications basing on these givens:

Current calculating:

Primary Current (Delta Configuration)

$$I1 = S / \sqrt{3} * V1$$
$$I1 = 800000/\sqrt{3} * 10000$$
$$I1 \approx 46.19\ A$$

Secondary Current (Wye Configuration)

$I2 = S / \sqrt{3} . V2$
$I2 = 800000 / \sqrt{3} * 400$
$I2 \approx 1154.70$ A

Turns Ratio (N1/N2):

The turns ratio in a transformer is given by the ratio of the primary voltage to the secondary.

$N2/N1 = V2/V1$ So: $N2/N1 = 0.4$ KV/10 kV
$N2/N1 = 25$

Short-circuit Voltage (Vsc) in ideal conditions:

$Vsc = 0.06 \times Vprimary = 0.035 \times 10{,}000$ V= 350V

Resistance in both windings:

$R = V^2/S$

Inductance in both windings:

$L = V/(2\pi f * I)$

In summary these are the main specifications of the given power transformer:

Apparent Power S: 800 kVA

Primary VoltageV1: 10 kV (Delta Connection)

Secondary VoltageV2: 0.4 kV (Wye Connection)

Primary Current (Delta Configuration): 46.19 A

Secondary Current (Wye Configuration): 1154.70 A

Turns Ratio (N1/N2): 25

Primary Winding Resistance (R1): $R1 \approx 125\Omega$

Secondary Winding Resistance (R2): $R2 \approx 0.2\Omega$

Primary Winding Inductance (L1): $L1 \approx 3.427$ mH

Secondary Winding Inductance (L2): $L2 \approx 0.0011$ m

ELECTRO-INDUSTIES AZAZGA EPE_SPA	POWER DISTRIBUTION TRANSFORMER 800 KvA/ l0 KV /0.4 KV DIN 425I1

Characteristics

Type	**Indoor with cable box, Breathing, with oil conservator**
Primary Voltage (kV)	**10**
Secondary Voltage (kV)	**0.4**
Off-load Taps (%)	**5**
Service	**50**
Frequency (Hz)	**Continuous**
Connection	**Dyn 5**
No-load Current (%)	**1.5**
No-load Losses (W)	**1450**
On-load Losses at 75°C	**11000**
Short-circuit Voltage at 75°C (%)	**6.0**
Cooling Method	**ONAN**
Cooling and Insulating Fluid	**Mineral oil**
Maximum Ambient Temperature (°C)	**40**
Altitude (m)	**< 1000**

DIMENSIONS AND WEIGHT

Length (mm)	**1820**
Width (mm)	**1080**
Height (mm)	**2090**
Center distance between rollers (mm)	**670**
Oil weight (kg)	**623**
Total weight (kg)	**2430**

Table III-1 Specification of the currently used power transformer in Enel.

Surveillance Equipment:

Buchholz Relay with Two Floats and Two Contacts.

Dial Thermometer with Two Contacts.

Air dryer.

Figure III-1Visual inspection of the surveillance equipment.

III.2.1.1. The Dny5 connection:

A Delta-Wye (Δ-Y) transformer connection is a common method used in electrical power systems to convert three-phase electrical power from one voltage level to another. This type of connection is widely used because it offers several advantages, including the ability to step up or step down voltages and provide a neutral point for grounding. [41]

Primary Side: The primary winding of the transformer is connected in a Delta configuration.

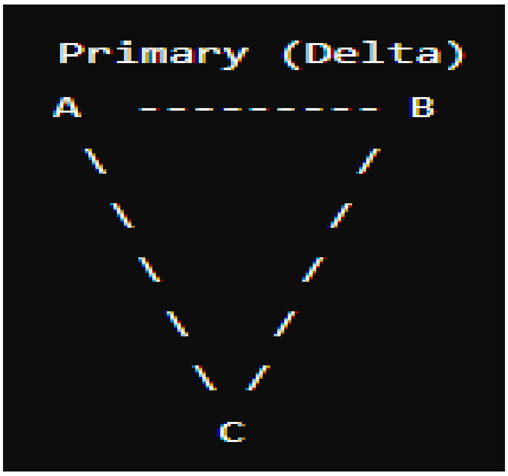

Figure III-2 Delta configuration.

Secondary Side: The secondary winding of the transformer is connected in a Wye configuration.

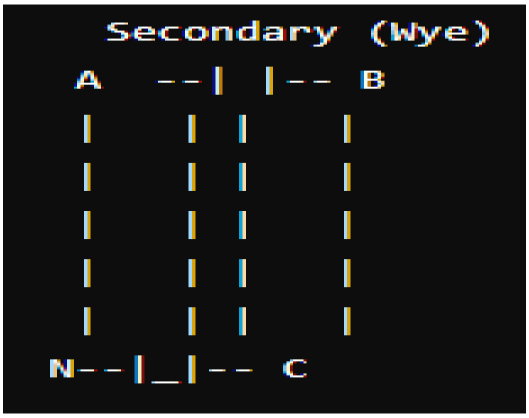

Figure III-3 Wye configuration.

Now since we have Dny 5 that's means that the hourly index is 5π/6.

The phase shift existing between the primary voltage and the secondary voltage is:

5π/6= 30×5=150 leading to figure (2.4):

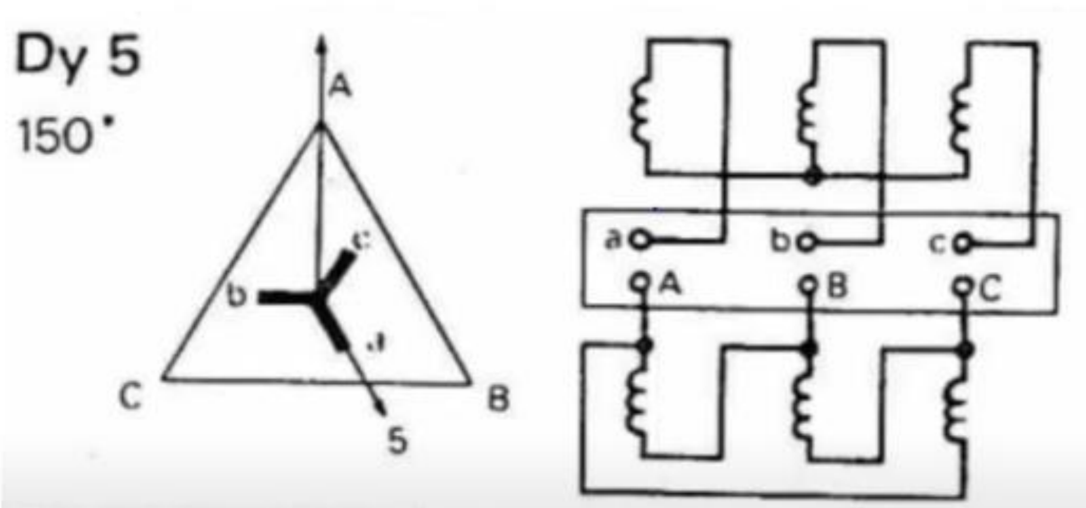

Figure III-4 Delta-Wye 5 connections scheme

III.2.2. Power transformer protection system in Enel

After we Have presented the existing system and its primary components, we will now delve into the protection systems applied to it:

III.2.2.1. Differential protection:

Differential protection is an electrical protection method that involves comparing the incoming current and the outgoing current of a device. If the two currents are different, the protection system concludes that there is a fault within the device and triggers its disconnection from the electrical network, known as "tripping." Differential protection is widely used and is particularly employed to protect busbars, generators, and transformers. This protection is used to detect fault currents lower than the nominal current For instantaneous tripping since selectivity is based on detection and not on timing. [42]

Now presenting a simple of the differential protection following by the one used in ENEL then going through the scheme and naming its components define them and explaining briefly their function shown in the figures (2- 5) and (2- 6):

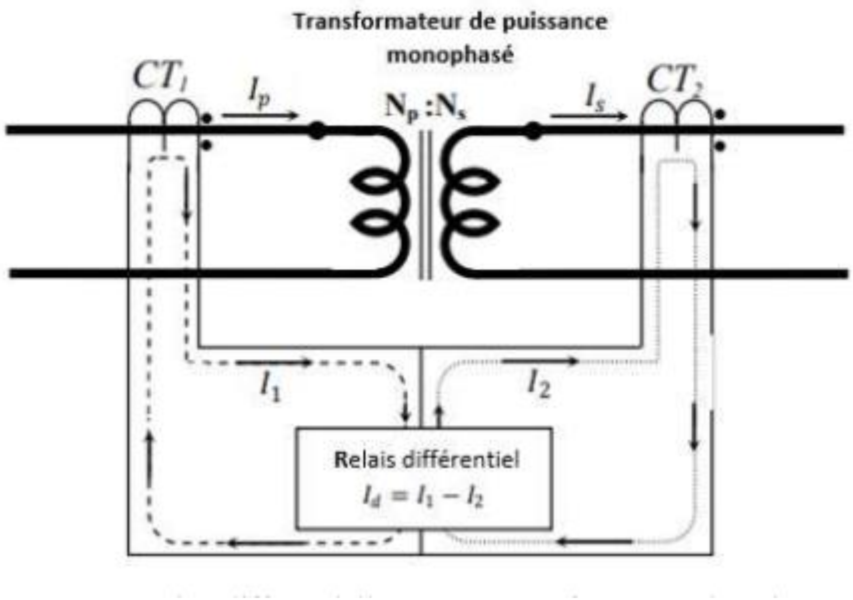

Figure III-5A simple of differential protection of a power transformer.

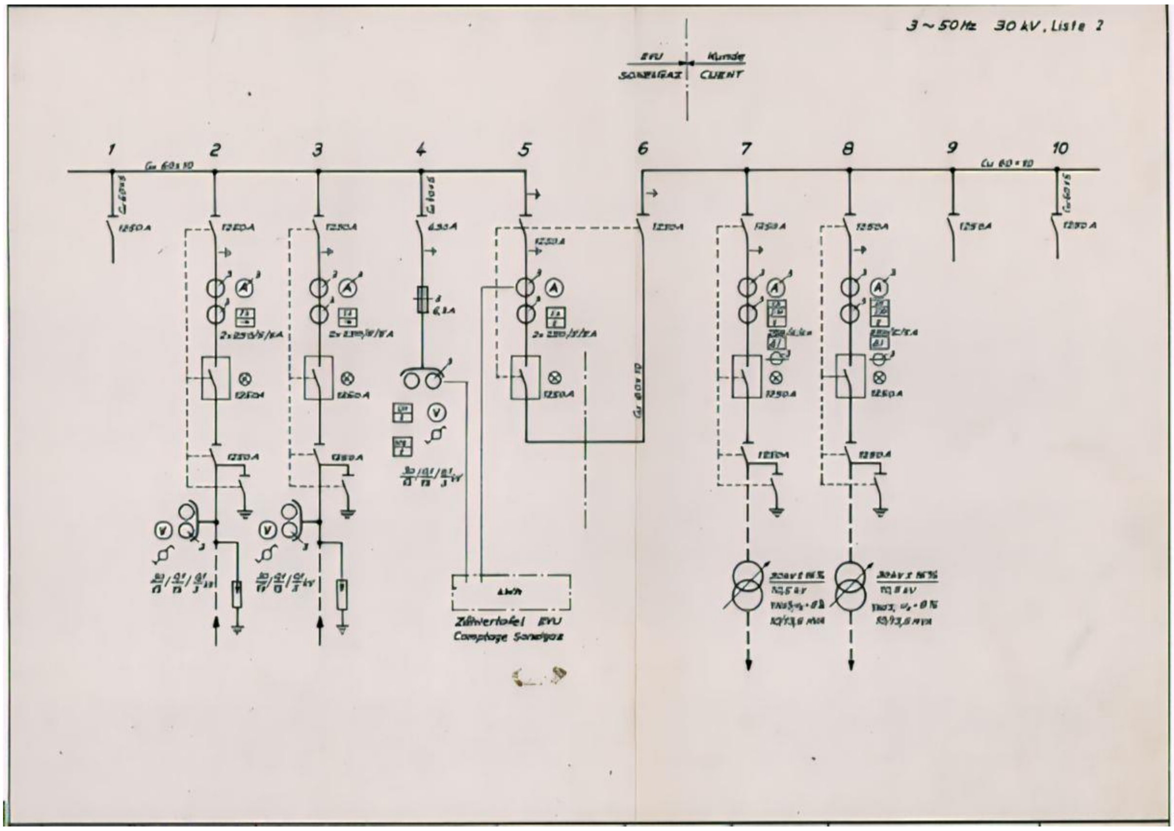

Figure III-6Differential protection scheme used in Enel.

Components of the previous scheme:

Current Transformers (CTs): here are two CTs shown in the circuit, labeled "Ge 601 10" and "Cu 60-80 10" They are denoted by circles with a winding symbol inside.

Main equation **(Is): Is = (Np / Ns) * Ip**

Main Connection: Each CT is connected in series with one winding of the power transformer. The CT on the left (Ge 601 10) is connected in series with the primary winding, and the CT on the right (Cu 60-80 10) is connected in series with the secondary winding. The CTs step down the high currents in the transformer windings to a lower level suitable for the protection relay.

Differential Relay: represented by the block labeled "GSPA" in the center. This block compares the currents from the two CTs.

Main Connection: The secondary windings of the CTs are connected to the differential relay (GSPA block). The relay compares the magnitudes and phases of these currents.

Circuit Breaker: an electrical safety device designed to automatically interrupt the flow of current in a circuit when it exceeds a safe level. It essentially acts as a resettable fuse, protecting electrical equipment from damage caused by overload or short circuits.

Main Connection: The differential relay (GSPA block) would have a trip output that connects to the control circuit of the circuit breaker. If the differential current exceeds a preset threshold, the relay trip signal would trigger the circuit breaker to open and isolate the faulty transformer.

Resistors: Resistors might be used for calibration, biasing the differential relay or limiting fault currents within the protection circuit.

Fuses: Fuses might be used for protection against short circuits within the differential circuit itself.

Grounding: Grounding connections are present to ensure safety and proper reference potential within the circuit.

Burden Resistors: These resistors are connected across the secondary windings of the Current Transformers (CTs).

Zener Diodes: These diodes might be used for:

Surge protection: Zener diodes can be used to clamp voltage spikes or transients that could potentially damage the differential relay or other sensitive components in the circuit.

Disconnecting Switches: These could be manually operated switches that allow isolating parts of the differential protection circuit for maintenance or testing purposes.

Connections:

The CTs are connected in series with their respective transformer windings (primary and secondary).

The secondary windings of the CTs are connected to the differential relay (GSPA block).

The differential relay (GSPA block) have an output connection to the control circuit of the circuit breaker.

The auxiliary components would have connections within the differential circuit for their specific functions.

III.2.2.2. The Buchholz relay:

an essential protective device used in oil-filled power transformers to detect and provide early warning of faults. It's a gas-actuated relay that detects the presence of gases produced by the decomposition of insulating oil due to electrical faults within the transformer. [43]

As in the previous protection here it is a simple of the Buchholz relay scheme:

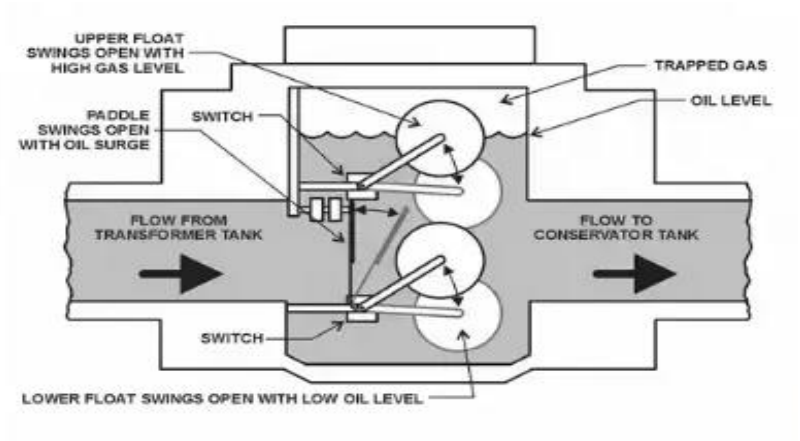

Figure III-7 circuit diagram of a Buchholz relay.

Wiring Diagram of the BUCHHOLZ Relay in ENEL:

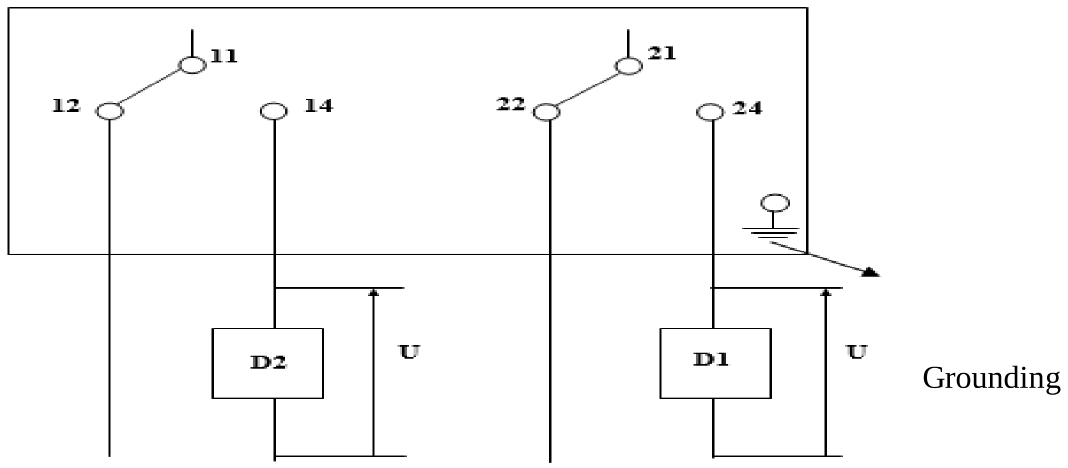

Figure III-8 Wiring Diagram of the BUCHHOLZ Relay Terminal Box

D1 and D2 Monitoring Devices

D1: Alarm: Terminals 21-24

D2: Trip: Terminals 11-14

The permissible load for the contacts under inert gas-filled magnetic control during the opening and closing of control circuits is as follows:

Direct voltage: 24 to 220 V, 2A / 440 W

Alternating voltage: 24 to 220 V, 2A / 440 VA

To test the conductivity of the contacts under the bulb, a minimum alternating voltage of 20 V must be applied.

III.2.2.3. Thermal relay:

Thermal relays also known as thermal overload relays are electromechanical devices used for overload protection in transformers. They function by monitoring the current flowing through the transformer and tripping (opening) the circuit when the current exceeds a safe level for a specific time duration**.** Its main function is:

Current Monitoring: The thermal relay has a heating element, typically a bimetallic strip composed of two dissimilar metals bonded together. This bimetallic strip heats up due to the current flowing through it (following the principle of I^2R losses).

Unequal Expansion: As the current increases, the bimetallic strip heats up. However, the two metals expand at different rates when heated. This unequal thermal expansion causes the bimetallic strip to bend.

Trip Mechanism: When the bending reaches a critical point and after a certain time (depending on the overload current), the bimetallic strip triggers a mechanical mechanism that opens the circuit contacts. This interrupts the current flow and protects the transformer from overheating**.** [44]

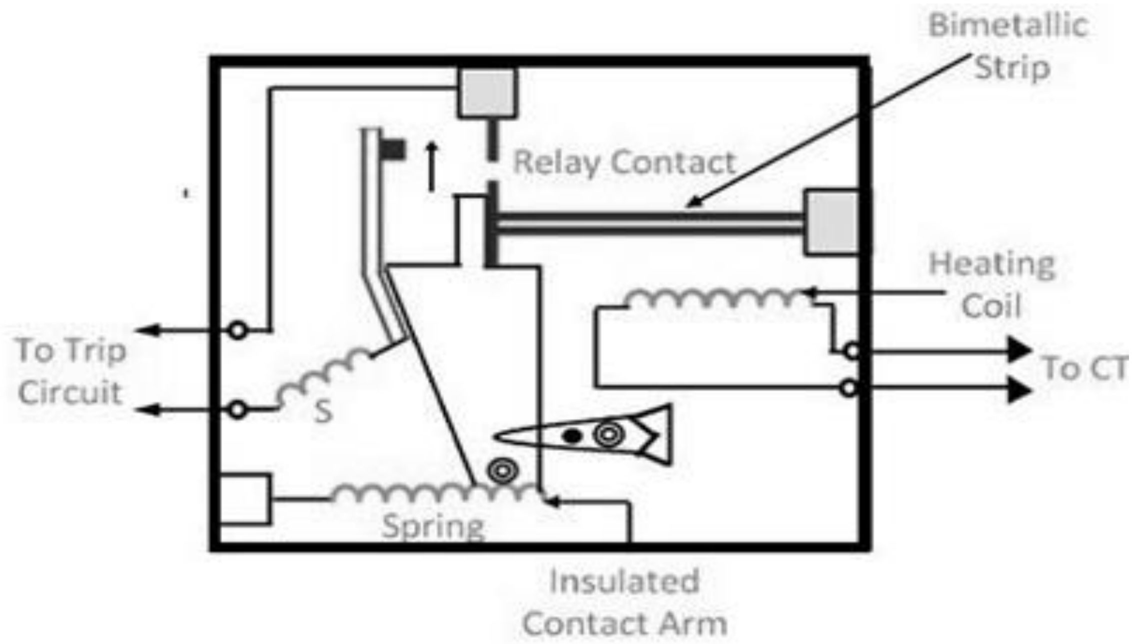

Figure III-9 Thermal relay inside sight. [45]

This previous figure helps to understand the mechanism of function of thermal relays during an overload of current which causes heating.

Connection diagram of a dual-contact thermometer to terminal boxes in ENEL:

Disconnection of the blue wire red wire alarm

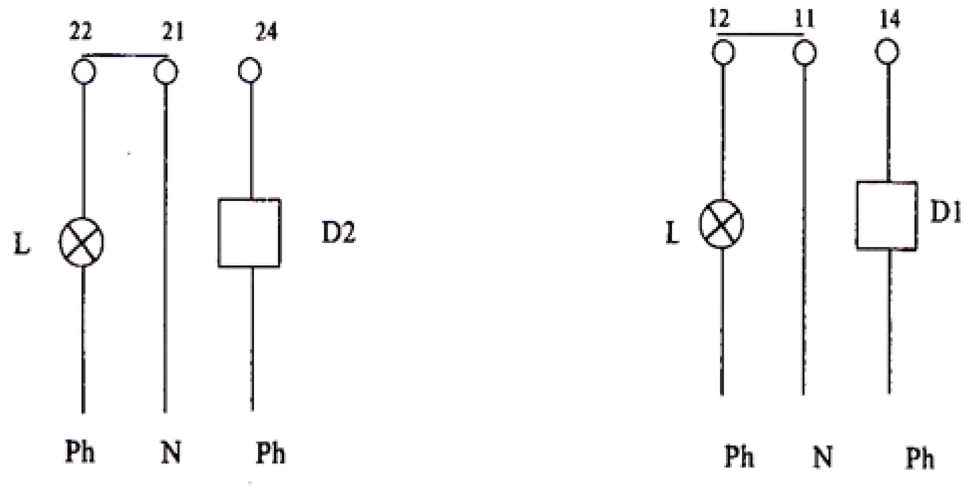

Figure III-10 Wiring diagram of the thermal relay in ENEL [46]

L: Indicator lamp for normal operation

D1: Monitoring device for alarm

D2: monitoring device for tripping

III.2.2.4. Cooling system:

ONAN (Oil Natural Air Natural) cooling is a widely used method for cooling power transformers, particularly in distribution transformers. [47]

Principle of ONAN Cooling:

Natural Convection: ONAN cooling relies on natural convection for both the insulating oil and the surrounding air to dissipate heat from the transformer.

The transformer's core and windings generate heat during operation due to losses, primarily in the form of resistive losses in the windings and hysteresis and eddy current losses in the core.

The insulating oil, which circulates through the windings and core, absorbs heat from these losses. [48]

Radiators or Cooling Fins: The transformer tank is equipped with radiators or cooling fins, which are extended surfaces that increase the surface area available for heat transfer to the surrounding air. The heated oil circulates through the tank and contacts the cooling surfaces, transferring heat to the radiators. [49]

Heat Dissipation: As the heated oil flows through the radiators, it transfers heat to the surrounding air by natural convection. Cooler oil then returns to the transformer, completing the cooling cycle. [49]

Main components:

Transformer Tank: The transformer tank houses the core, windings, and insulating oil.

It is typically constructed of steel and designed to withstand internal pressure and external environmental conditions. [50]

Radiators or Cooling Fins: Radiators or cooling fins are attached to the transformer tank to increase the surface area for heat dissipation.

They are usually made of aluminum or steel and are arranged in a vertical or horizontal configuration, depending on the transformer design. [51]

Insulating Oil: The insulating oil serves as both an electrical insulator and a coolant.

It circulates through the transformer tank, absorbing heat from the core and windings. [52]

Expansion Tank (Conservator): An expansion tank, also known as a conservator, is connected to the main tank to compensate for the expansion and contraction of the insulating oil due to temperature variations. [53]

III.3. The failure mechanisms of distribution transformer

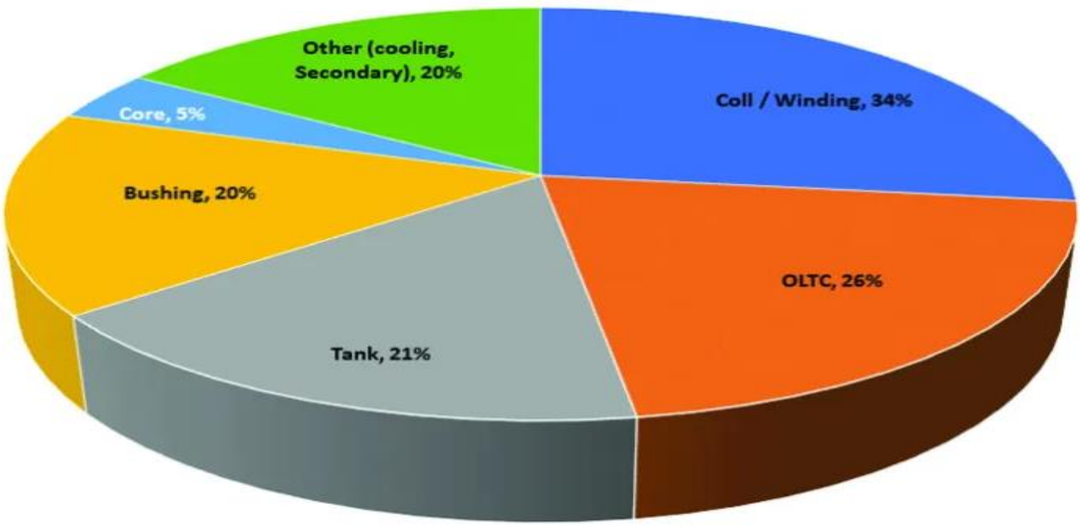

Figure III-11 The various types of faults that occurs in the transformer an their respective percentage. [54]

Understanding the fault that the power transformer faces under his function period can help us to develop a future sight about the optimization of the protection system also the importance of routine maintenance.

Noticing that the biggest percentage was for winding faults because of the nature of their function and the various changes in external factors.

The failure mechanisms of distribution transformers can be diverse, often influenced by factors such as design, manufacturing quality, operating conditions, maintenance practices, and environmental factors. Here are some common failure mechanisms:

Insulation Failure: Insulation breakdown is a primary cause of transformer failure. It can result from aging, thermal stress, mechanical damage, contamination, or manufacturing defects.

Insulation failures lead to short circuits between windings or between windings and ground, causing overheating, arcing, and eventual failure of the transformer. [55]

Overheating: Excessive heat generated within the transformer due to overload, high ambient temperatures, or poor cooling can lead to insulation degradation, thermal decomposition of oil, and structural damage. Overheating accelerates aging and reduces the lifespan of insulation materials, increasing the likelihood of failure. [57]

Short Circuits: Short circuits can occur within the transformer windings due to insulation breakdown, mechanical damage, or external faults.

Short circuits result in high fault currents, which can cause thermal and mechanical stresses, insulation damage, and winding deformation. [56]

Overloading: Continuous operation at or above the rated capacity can lead to overheating, insulation degradation, and mechanical stress on the transformer components.

Overloading reduces the transformer's lifespan and increases the risk of insulation failure and winding damage. [58]

Moisture Ingress: Moisture ingress into the transformer tank or insulation system can lead to insulation breakdown, corrosion of internal components, and degradation of insulating oil.

Moisture accelerates aging and reduces the dielectric strength of insulation materials, increasing the risk of failure. [59]

Mechanical Stress: Mechanical stress from transportation, installation, or external forces can cause deformation or misalignment of transformer components, leading to insulation damage, short circuits, and mechanical failure. [56]

Contamination: Contaminants such as dust, dirt, moisture, and conductive particles can accumulate on transformer surfaces or within the insulation system, leading to reduced dielectric strength, increased partial discharge activity, and insulation breakdown. [60]

Environmental Factors: Environmental factors such as temperature extremes, humidity, pollution, and seismic activity can contribute to transformer failure by accelerating aging, corrosion, or mechanical stress on transformer components.[61]

Poor Maintenance: Inadequate or irregular maintenance practices, such as neglecting oil testing, cooling system inspection, or insulation resistance measurement, can lead to undetected faults, deterioration of transformer condition, and eventual failure.[62]

Manufacturing Defects: Defects in materials, construction, or assembly processes during manufacturing can compromise the quality and reliability of transformers, leading to premature failure under normal operating conditions.

Understanding and mitigating these failure mechanisms through proper design, manufacturing, installation, operation, and maintenance practices are essential for ensuring the reliable performance and longevity of distribution transformers. Regular inspections, diagnostic testing, and condition monitoring are crucial for identifying potential failure risks and implementing preventive measures by doing electric tests to minimize downtime and enhance transformer reliability.[63]

III.4. The power transformer electrical tests:

As we already mention the transformer is vital dynamic component in the electrical power system and plays a crucial role that requires high reliability and maintainability to ensure the good functioning of the system concluded that the electrical test is a must to minimize the damages and avoid big losses that is why there are several tests which has many types such as routine tests to ensure good performance during the function time, type tests to validate the design and the performance against relevant standards, special tests to investigate specific aspect, field tests ensuring the safety after the transport and diagnostic tests monitor the condition of the transformer throughout its operational life.

III.4.1. Importance of electrical tests:

Electrical tests on power transformers are crucial for ensuring their safe and reliable operation throughout their lifespan. These tests assess various parameters of the transformer, helping to identify potential issues, validate design and construction integrity, verify insulation strength, and ensure compliance with performance standards:

Quality Assurance: Electrical tests are conducted during manufacturing to verify that the transformer meets design specifications and quality standards. These tests validate the integrity of materials, construction techniques, and manufacturing processes, ensuring the reliability and longevity of the transformer.

Insulation Strength: Insulation resistance tests, dielectric withstand tests, and partial discharge tests assess the insulation integrity of the transformer. Insulation degradation can lead to insulation breakdown, short circuits, and transformer failure. Electrical tests help identify weak spots in the insulation system and prevent catastrophic failures.

Diagnostic Tool: Electrical tests serve as diagnostic tools for assessing the condition of transformers during commissioning, maintenance, and periodic inspections. By monitoring parameters such as winding resistance, transformer turns ratio, impedance, and insulation resistance, potential faults or abnormalities can be detected early, allowing for timely corrective action to prevent costly failures and downtime.

Performance Verification: Routine electrical tests, such as transformer turns ratio tests, impedance tests, and load loss tests, verify the performance of the transformer under normal operating conditions. These tests ensure that the transformer operates within specified parameters, delivering the expected voltage transformation, impedance, and efficiency.

Safety Assurance: Dielectrics withstand tests and insulation resistance tests verify the electrical safety of the transformer under normal and fault conditions. Ensuring proper insulation strength and grounding reduces the risk of electrical hazards, such as electric shock, fire, or equipment damage, safeguarding personnel, and property.

Compliance Verification: Electrical tests help ensure compliance with industry standards, regulations, and specifications, such as ANSI/IEEE, IEC, and local electrical codes. Compliance verification ensures that the transformer meets safety, performance, and reliability requirements, providing confidence in its suitability for the intended application.

Condition Monitoring: Periodic electrical tests form part of a comprehensive condition monitoring program for transformers. Trending data from tests such as dissolved gas analysis (DGA), power factor measurement, and insulation resistance monitoring can indicate potential deterioration or impending failures, allowing for proactive maintenance and replacement planning.

Asset Management: Electrical tests provide valuable data for asset management and lifecycle planning of transformers. By assessing the condition, performance, and remaining life of transformers, informed decisions can be made regarding maintenance intervals, refurbishment, replacement, and investment prioritization.

In summary, electrical tests are essential for ensuring the safe, reliable, and efficient operation of power transformers. They provide critical insights into the condition, performance, and integrity of transformers, enabling proactive maintenance, risk mitigation, and optimization of asset management strategies. Regular testing and monitoring are key components of a comprehensive transformer maintenance program, contributing to enhanced reliability, safety, and longevity of power systems. [64]

III.4.2. Types of electrical tests:

Differential Protection Test: This test verifies the performance of the differential protection relay, which is responsible for detecting internal faults within the transformer windings. It checks the relay's sensitivity, stability, and responsiveness to fault conditions. [65]

Buchholz Relay Test: The Buchholz relay test verifies the proper operation of the relay, which detects incipient faults such as internal arcing, overheating, or oil leaks in the transformer. It checks for correct alarm and trip functions based on gas and oil flow within the transformer. [43]

Overcurrent Relay Coordination Test: This test ensures proper coordination between overcurrent relays installed in the transformer protection scheme and downstream protective devices. It verifies that the relays operate within their designated time-current characteristic curves and coordinate effectively to isolate faults. [66]

Transformer Turns Ratio Test: The turns ratio test measures the ratio of primary to secondary turns in the transformer windings. It ensures that the transformer provides the correct voltage transformation and verifies the integrity of the windings. [67]

Insulation Resistance Test: This test assesses the insulation condition of the transformer by measuring the resistance between windings and between windings and ground. It helps identify insulation deterioration, contamination, or moisture ingress, which can lead to insulation breakdown. [68]

Power Factor (Tan Delta) Test: The power factor test evaluates the dielectric properties of the insulation system by measuring the power factor or tan delta. It detects insulation aging, moisture content, or contamination, which can affect the transformer's insulation strength. [69]

Winding Fault Test: Winding fault tests, such as impulse or surge tests, are conducted to simulate transient overvoltage and assess the insulation withstand capability of the transformer windings. These tests help detect weaknesses or defects in the insulation system. [70]

Core Fault Test: Core fault tests evaluate the structural integrity of the transformer core and its connections. They may include magnetic balance tests, which verify the symmetry of magnetic flux distribution within the core, ensuring efficient and stable operation. [71]

III.5. Simulation of Fault scenarios

Electrical testing is a critical aspect of ensuring the reliability and performance of power.

In This part we will apply some specific diagnostic electrical tests by simulating fault scenarios using MATLAB in order to optimize the protection system and the reliability of the power system in general.

Objectives:

- Develop a comprehensive understanding of power transformer electrical tests, simulation techniques, and internal faults.
- Evaluate the impact of simulated internal faults on transformer performance.
- By developing a comprehensive understanding of power transformer electrical faults and their affectation on it, we can gain deep insights into the behavior of transformers under fault conditions. This approach helps in optimizing protection strategies, enhancing preventive maintenance, and ensuring the reliable operation of power transformers within the electrical grid and ensure the longevity and the best performance of power transformer.

Also guarantee important benefits such as :

Early Detection: By simulating faults, you can identify potential issues early, allowing for preventive maintenance and reducing the risk of catastrophic failures.

Pattern Recognition: Understanding the characteristic waveform changes during faults helps in recognizing similar patterns in real-world scenarios, improving diagnostic capabilities.

Validation of Design: Simulation helps verify that the transformer design can handle faults without excessive damage, ensuring reliability and safety.

Optimization: By analyzing the simulation results, engineers can optimize the design parameters (like resistance and inductance) to improve performance under fault conditions.

Risk Analysis: Assess the potential risks and impacts of winding faults on the transformer and connected systems, helping in developing mitigation strategies.

Protective Measures: Design appropriate protective measures (like circuit breakers and fault protection systems) based on the simulation data.

Learning Aid: Provides a hands-on learning experience for students and engineers to understand the dynamic behavior of transformers under fault conditions.

Visualization: Helps in visualizing the effects of faults, making it easier to grasp complex electromagnetic phenomena

Reduced Testing Costs: Simulating faults in a virtual environment reduces the need for extensive physical testing, which can be costly and time-consuming.

Damage Prevention: Prevents potential damage to actual transformers during experimental fault testing.

Transient Analysis: Allows detailed analysis of transient responses in the transformer, which is crucial for understanding the impact of sudden changes in voltage and current.

Data Collection: Collects valuable data that can be used to improve transformer models and simulations, leading to better predictive maintenance also open the possibility of using a learning machine system in the future to strength the system.

III.5.1. Simulation techniques

We discuss the MATLAB software starting by an overview to their utilizations:

III.5.1.1. MATLAB:

short for Matrix Laboratory, is a sophisticated high-performance programming language and environment developed by MathWorks. Designed primarily for numerical computing, MATLAB has become an essential tool in engineering, scientific research, and applied mathematics. It stands out due to its powerful capabilities, extensive library of functions, and ease of use. [72]

Core Components of MATLAB:

MATLAB core components are:

High-Level Programming Language: MATLAB’s high-level language allows for easy and intuitive programming. The syntax is designed to be straightforward, enabling users to write scripts and functions without the need for extensive programming knowledge.

Interactive Environment: The interactive environment of MATLAB facilitates iterative problem-solving, design, and testing. Users can execute commands one at a time and immediately see the results, which is particularly useful for debugging and data exploration.

Extensive Mathematical Functions: MATLAB comes with an extensive library of built-in functions for various mathematical computations, including:

Linear Algebra: Functions for matrix operations, eigenvalues, and singular value decomposition.

Statistics: Functions for data analysis, probability distributions, and statistical testing.

Fourier Analysis: Functions for fast Fourier transforms (FFT) and spectral analysis.

Optimization: Solvers for linear programming, quadratic programming, and nonlinear optimization.

Differential Equations: Solvers for ordinary differential equations (ODEs) and partial differential equations (PDEs).

Graphics and Visualization: MATLAB excels in data visualization with powerful tools for plotting data in 2D and 3D. Users can create line plots, scatter plots, histograms, surface plots, and more. The visualization capabilities are enhanced by features like interactive plots, customizable graphics, and advanced plotting functions.

Toolboxes and Specialized Functions: MATLAB offers a range of specialized toolboxes that extend its capabilities in specific domains. Each toolbox includes functions, apps, and examples tailored to particular fields such as:

Signal Processing: Tools for filtering, signal analysis, and spectral estimation.

Control Systems: Functions for designing and analyzing control systems, including PID controllers and state-space models.

Neural Networks: Tools for creating, training, and simulating neural network models.

Image Processing: Functions for image enhancement, filtering, and analysis.

Financial Modeling: Tools for risk management, portfolio optimization, and financial time series analysis. [72]

Integration and Connectivity: MATLAB integrates seamlessly with other programming languages and environments. It supports calling functions written in C, C++, Java, .NET, and Python. MATLAB can also interact with hardware platforms like Arduino, Raspberry Pi, and various data acquisition systems, facilitating real-time data processing and control applications. MATLAB is a versatile and powerful platform for numerical computing and data analysis. Its high-level programming language, extensive mathematical functions, and robust visualization tools make it an invaluable resource for engineers, scientists, and researchers. Whether for simulating complex systems, analyzing data, or developing algorithms, MATLAB provides the capabilities needed to solve intricate technical problems and advance innovation across various fields.

III.6. Simulation application:

In this subtitle we will simulate the used power transformer in Enel using MATLAB software to analyze the behavior of the currents passing through the primary and the secondary windings in three main cases: during normal operation during a winding fault test then last a core fault test.

III.6.1. MATLAB simulation:

III.6.1.1. Normal operation:

In the first scenario, the simulation illustrates the normal operation of the power transformer under fault-free conditions. The input voltage is represented as a sine wave, and the corresponding currents in the primary and secondary windings are graphically plotted over time, showcasing the transformer's typical performance.

Parameters of the transformer:

Primary VoltageV1: 10 kV (Delta Connection)

Secondary VoltageV2: 0.4 kV (Wye Connection)

Primary Current (Delta Configuration): 46.19 A

Secondary Current (Wye Configuration): 1154.70 A

Frequency: 50 Hz

No load current:1.5 A

Overview of the code:

This MATLAB code simulates and plots the primary and secondary current waveforms for a three-phase delta- wye connection transformer. The parameters include primary and secondary voltages, frequency, no-load current, primary current, and secondary current. The code

calculates the secondary current based on the turns ratio and generates time vectors to plot the current waveforms for each phase.

Code steps:

Initialization: Define primary and secondary voltages, frequency, no-load current, primary current, and secondary current.

Turns Ratio Calculation: Calculate the turns ratio (Ns/ Np)

Use the turns ratio to calculate the secondary current from the primary current.

Time Vector Generation: Generate a time vector for one cycle of the waveform based on the frequency.

Current Waveforms Calculation: Calculate the current waveforms for the primary and secondary phases, considering the phase shifts in a delta connection.

Plotting: Plot the primary and secondary current waveforms for the three phases.

Mathematical equations:

- **Primary phase current waveform for phase 1**:

$Ip(phase\ 1)=Ip*\sin(2\pi ft)$

Primary phase current waveform for phase 2 (shifted by 120 degrees): $Ip(phase\ 2)=Ip*\sin(2\pi ft-\pi/3)$

Primary phase current waveform for phase 3 (shifted by 120 degrees): $Ip(phase\ 3)=Ip*\sin(2\pi ft+\pi/3)$

- **Secondary Current Waveforms**:

For phase 1 (reference phase): $Is1(t)=Is*\sin(2\pi ft)$

For phase 2 (shifted by 120 degrees): $Is2(t)=Is*\sin(2\pi ft-2\pi/3)$

For phase 3 (shifted by 240 degrees): $Is3(t)=Is*\sin(2\pi ft+2\pi/3)$

f is the frequency of the alternating current (AC) waveform.

t is the time

the plots demonstrate the sinusoidal nature of the currents in both the primary and secondary windings of the transformer, with appropriate amplitudes and phase relationships based on the specified parameters and transformer characteristics.

III.6.1.2. Winding fault test scenario:

In this scenario we simulate a short circuit in the primary winding causing a winding fault:

Parameters of the transformer:

Primary VoltageV1: 10 kV (Delta Connection)

Secondary VoltageV2: 0.4 kV (Wye Connection)

Primary Current (Delta Configuration): 46.19 A

Secondary Current (Wye Configuration): 1154.70 A

Frequency: 50 Hz

Short-circuit voltage: 350 V.

Overview of the code:

Initialization: Define transformer parameters: primary and secondary voltages, frequency, currents, resistances, inductances, and mutual inductance.

Define the simulation time vector and input voltage waveform.

Fault Simulation: Loop through the time vector to simulate the currents in both primary and secondary windings.

Introduce a fault (short circuit) in the primary winding between 0.01 and 0.03 seconds by setting the input voltage Vin to 0

Differential Equations: Calculate the derivatives of the currents using the transformer equations.

Update the current values based on the time step.

Plotting: Plot the current waveforms for both primary and secondary windings.

Fault Simulation: The fault is introduced by setting Vin(i) = 0 between 0.01 and 0.03 seconds, which simulates a short circuit in the primary winding.

Mathematical equations:

Differential equations of the current in each winding:

Primary Coil: **Vin=R1*I1+L1*dI1/dt+M*dI2/dt**

Secondary Coil**: 0=R2*I2+L2*dI2/dt+M*dI1/dt** leading to:

$dI1=(Vin-R1*I1-M*dI2)/ L1$

$dI2= (M*(Vin-R1*I1) -R2*I2)/ L1*L2-M^2$

value OF No-load Current ($I_{no\_load\ V}$): **$I_{no\text{-}load\ V}=I_{n\text{-}load}*I1= 1.5/100\times46.19\approx0.69285$**

Primary Winding Resistance (R1): **$R1=V1/I1 \approx216.49$Ohms**

Secondary Winding Resistance (R2): **$R2=R1\times (1/25)^2\approx 0.346384$**

Primary and Secondary Winding Inductance (L1 and L2): **$L1\approx0.0199H$**

$L2=L1/25^2=0.0199/625\approx3.18\times10^{-5}H$

Inductive reactance: **$X1=L1/2\pi f =6.25$ Ohms**

$X2=L2/2\pi f=0.01$

Mutual Inductance (M): **$M=k\sqrt{(L1\times L2)}$, assuming perfect coupling k=1**

$M\approx0.00796$ H

Short Circuit Current (Isc): calculating the expected short circuit current during the fault.

$Isc1=(800000/400\times0.035) \approx91.4284$ A

$Isc2=800000/(10000\times0.035)\approx2285.71$ A

The short circuit voltage rate taken in ideal conditions is 0.035%

the provided equations are for simulating the dynamics of currents in the primary and secondary windings of a power transformer. They accurately capture the interplay between voltage sources, resistances, and inductances that govern the transformer's behavior in both normal and fault conditions.

III.6.1.3. Core Fault test scenario :

In this third scenario, we are causing a fault is introduced in the core by simulating a breakdown. The simulation shows the response of the power transformer to this core fault. we simulate a core fault in the transformer. This fault is represented by setting the mutual inductance (M) to zero between 0.02 and 0.05 seconds. At 0.02 seconds, the primary inductance L1 is halved to simulate a core fault. As a result, The inductive reactance Xl is reduced, leading to a decrease in the overall impedance of the primary winding.

Parameters of the transformer:

Primary VoltageV1: 10 kV (Delta Connection)

Secondary VoltageV2: 0.4 kV (Wye Connection)

Primary Current (Delta Configuration): 46.19 A

Secondary Current (Wye Configuration): 1154.70 A

Frequency: 50 Hz

Short-circuit voltage: 350 V.

The MATLAB script code:

- **Overview of the code:**

Initialization: Parameters such as primary voltage (Vp), secondary voltage (Vs), frequency (f), primary current (Ip), secondary current (Is), time step (timestep), and assumed values for missing parameters (R1, R2, L1, L2, M) are set.

Time Vector Generation: A time vector (t) is generated to simulate the behavior over a specified duration (0 to 0.1 seconds).

Input Voltage Waveform: The input voltage waveform (Vin) is generated using the primary voltage (Vp) and the frequency (f).

Simulation Loop: The simulation loop iterates over each time step and calculates the currents (I1 and I2) flowing through the primary and secondary windings.

Core Fault Introduction: A core fault is introduced between the time intervals of 0.02 and 0.05 seconds by setting the primary inductance L1 is halved to simulate a core fault. As a result, the inductive reactance Xl is reduced, leading to a decrease in the overall impedance of the primary winding. This simulates a breakdown or malfunction in the transformer core.

Integration: The differential equations are numerically integrated using a time-stepping method (in this case, Euler's method) to update the currents (I1 and I2) at each time step.

Plotting: Finally, the currents (I1 and I2) are plotted over time to visualize the behavior of the system under the core fault condition.

- **Mathematical equations:**

Differential Equations of the current I1 AND I2

dI1=(Vin*−R1*I1−M*dI2)/L1

dI2= (M*(Vin(−R1*I1) −R2*I2)/(L1*L2−M^2)

Added to the previous calculations we already did in the previous simulation.

the provided equations are for simulating the dynamic behavior of currents in the primary and secondary windings of a power transformer. They effectively capture the interactions between voltage, resistance, inductance, and mutual inductance, essential for understanding transformer performance under various operating conditions.

CHAPTER.IV. Results and discussion

IV.1. Introduction:

In this chapter, we will systematically analyze the results of each scenario, beginning with normal operations and progressing through various fault conditions. By examining the graphs corresponding to each case, we aim to elucidate the behavior of the currents in both the primary and secondary windings. This analysis will provide valuable insights into the functional integrity and operational capacity of the power transformer following these steps:

Analysis of Normal Operation: We start with an assessment of the transformer under normal operating conditions. During this phase, the primary and secondary currents exhibit stable, sinusoidal waveforms that correspond to the expected load and supply conditions. The primary current reflects the input voltage and frequency, while the secondary current is proportionally scaled according to the transformer's turns ratio. This baseline behavior serves as a reference for detecting anomalies and understanding the transformer's performance under ideal conditions.

Analysis of Winding Fault Scenario: In the second scenario, we introduce a winding fault, specifically a short circuit in the primary winding. The graphs illustrate a dramatic increase in the primary current immediately following the fault's inception. This surge is attributable to the reduction in impedance caused by the short circuit, which allows a significantly higher fault current to flow. The secondary current also exhibits disturbances, reflecting the influence of the primary winding's abnormal behavior.

During the fault, the excessive primary current can lead to overheating and potential damage to the transformer windings and insulation. The secondary current fluctuations might result in voltage instability and affect downstream equipment. Post-fault analysis shows the importance of rapid fault detection and isolation to prevent sustained damage and maintain system stability.

Analysis of Core Fault Scenario: The third scenario simulates a core fault, characterized by a breakdown in the core material and a subsequent short circuit between the primary winding and the core. The graphs reveal a substantial increase in the primary current, similar to the winding fault scenario, due to the direct path formed by the short circuit. The secondary current, while affected, shows less dramatic fluctuations compared to the primary current.

The core fault disrupts the magnetic coupling between the primary and secondary windings, diminishing the transformer's efficiency and potentially causing core saturation. This condition necessitates immediate intervention to prevent extensive damage to the transformer and maintain operational reliability.

Comparative Analysis and Impact Assessment: By comparing the graphs across the three scenarios, we gain a comprehensive understanding of the transformer's response to different operating conditions. Normal operation serves as a control, highlighting the deviations observed during fault conditions. Both winding and core faults result in significant current anomalies, underscoring the critical need for robust protection mechanisms.

Implications for Transformer Function and Maintenance: The analysis demonstrates that faults significantly impact the power transformer's function, leading to potential overheating, insulation failure, and operational inefficiencies. Effective protection and maintenance strategies, including regular testing and condition monitoring, are imperative to detect and mitigate faults promptly. This proactive approach enhances the transformer's longevity and ensures the reliability of the electrical power system.

In summary, the systematic examination of current behaviors under normal and fault conditions provides a deeper understanding of power transformer dynamics. This knowledge is essential for developing effective protection and maintenance protocols, ultimately contributing to the stability and efficiency of power distribution networks.

Before we go any further, we may have to remind you with the main specification and the equations of the presented transformer. Check the characteristics table.

IV.2. The reached results:

IV.2.1. Power transformer normal operation:

We are simulating the primary and secondary currents of a Delta-Wye (Dyn5) transformer with his already given parameters.

The time vector is created for one cycle of the waveform with 0.002s

The follow up figure represent the currents in the primary winding by Delta connection and the second winding by Wye connection:

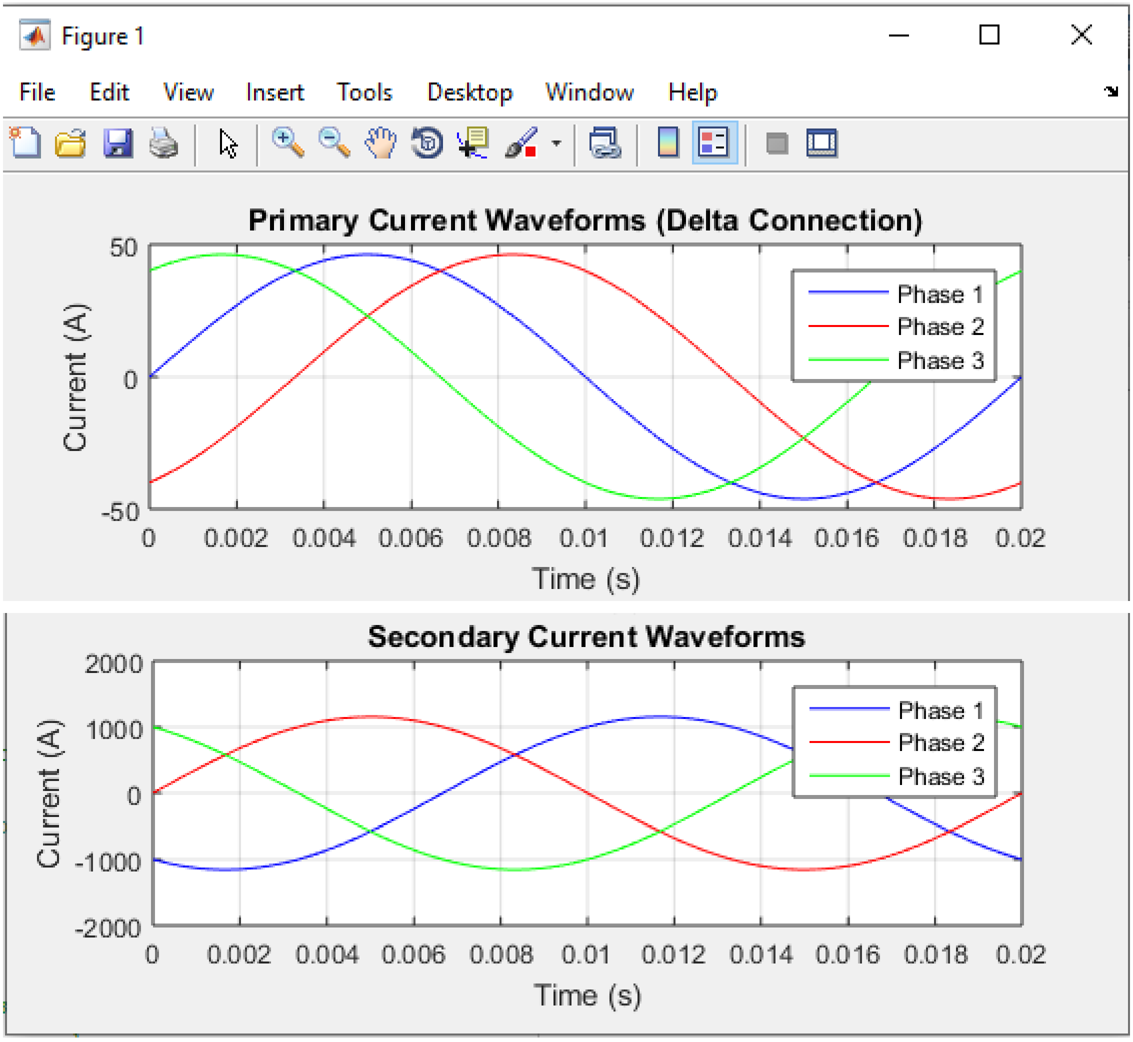

Figure IV-1 The current behavior in both transformer windings.

IV.2.1.1. Simulation process:

Normal Operation: The primary and secondary currents (I1 and I2) are computed using coupled differential equations that accurately represent the behavior of the transformer under normal operating conditions. These equations account for the interdependencies between the windings, the applied sinusoidal input voltage, and the inherent inductive and resistive properties of the transformer. The resulting current waveforms confirm stable and predictable operation, with no anomalies or deviations, thereby validating the transformer's performance and efficiency in its standard operating state.

IV.2.1.2. General observation:

This MATLAB simulation accurately demonstrates the phase currents in a Delta-Wye (Dyn5) transformer connection. The primary winding currents (delta connection) and secondary winding currents (wye connection) show the expected sinusoidal waveforms with correct phase shifts and amplitudes. This simulation provides a clear visualization of the transformer's operation under ideal conditions, highlighting the fundamental behavior of three-phase transformers. Considering that we had simulate an ideal power transformer neglecting all the losses.

IV.2.1.3. Analyzing the results:

Primary Current Waveforms (Delta Connection):

Primary Phase Currents: The primary currents Ip1, Ip2 and Ip3 are sinusoidal waveforms with a magnitude of 46.19 A.

Each phase current is phase-shifted by 120 degrees (or 2π3 radians) relative to each other.

This phase shift results in a balanced three-phase system where the sum of instantaneous currents in all three phases is zero at any point in time.

The waveforms show a perfect sinusoidal shape, indicating no distortions or harmonics, representing an ideal operating condition.

Secondary Current Waveforms (Wye Connection):

Secondary Phase Currents: The secondary currents Is1, Is2, and Is3 are sinusoidal waveforms with a magnitude of 1154.70 A.

Similar to the primary currents, each secondary phase current is phase-shifted by 120 degrees (or 2π/3adians) relative to each other.

The waveforms indicate a balanced three-phase system on the secondary side, just like the primary side.

The secondary currents have a much higher amplitude compared to the primary currents due to the step-down nature of the transformer (10 kV to 0.4 kV).

Magnitude of Currents: The primary current (46.19 A) is much smaller than the secondary current (1154.70 A), consistent with the transformer's turns ratio.

The turns ratio ensures that the power transferred from the primary to the secondary remains constant (neglecting losses), so the lower voltage on the secondary side requires a higher current to maintain power balance.

Waveform Shape: The sinusoidal shape of the currents indicates that the transformer is operating under ideal conditions without distortions or harmonics.

The consistent amplitude and phase shift between the currents demonstrate balanced loading and proper functioning of the transformer.

IV.2.1.4. Summary:

the currents in both the primary and secondary windings exhibit sinusoidal waveforms that closely follow the input voltage, indicating that the transformer is operating under normal conditions. This behavior is consistent with the theoretical expectations for transformer performance, where the primary current mirrors the input voltage waveform, and the secondary current, scaled by the turn's ratio, maintains a proportional relationship. No abnormalities or deviations from expected operational parameters are observed, confirming the transformer's integrity and efficiency in converting electrical energy across windings. This normal operational state serves as a critical benchmark for comparative analysis, highlighting the significance of maintaining such conditions for optimal transformer functionality and reliability.

IV.2.2. Winding Fault in Primary Winding:

In the second scenario, a winding fault occurs in the primary winding of the transformer. Specifically, a short circuit is simulated in the primary winding between 0.01 and 0.05 seconds. And we observed the current behavior.

The results:

Upon writing and executing the previous winding fault script in MATLAB, the results will be as follows:

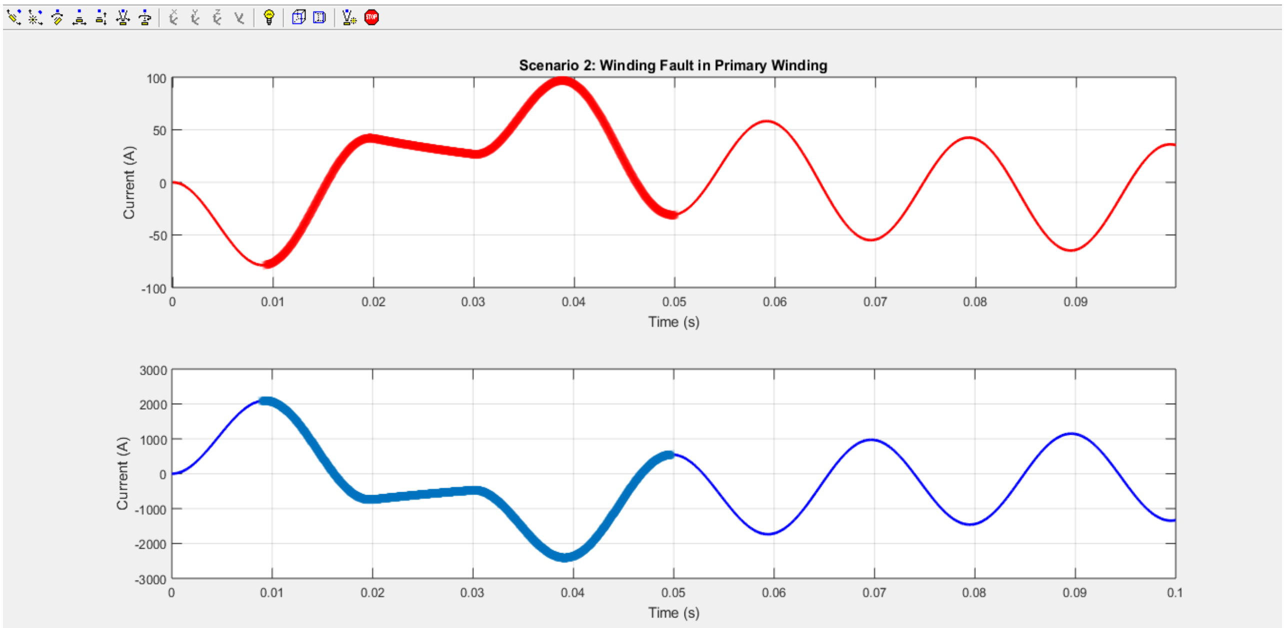

Figure IV-2Currents in the primary and secondary windings during a winding fault

IV.2.2.1. Simulation process:

Normal Operation: The primary and secondary currents (I1and I2) are computed using the coupled differential equations reflecting normal operation.

Fault Condition: From 0.01 to 0.05 seconds, the input voltage (Vin) is set to zero, simulating a short circuit in the primary winding.

Post-Fault Condition: After 0.05 seconds, the input voltage is restored, and the system resumes normal operation.

IV.2.2.2. General observation:

Analyze the results:

- **Primary Current (I1):**

Pre-Fault (0 to 0.01 seconds): The current in his normal values oscillates sinusoidally, driven by the input voltage.

During Fault (0.01 to 0.05 seconds): The current increase significantly because the short circuit current simulated by the sudden absence of driving voltage the short-circuit current is approximately 95 A.

Post-Fault (after 0.05 seconds): The current returns to its pre-fault sinusoidal behavior, but with potential transient responses due to the sudden reapplication of the input voltage.

- **Secondary Current (I2):**

Pre-Fault (0 to 0.01 seconds): The current oscillates sinusoidally in his ordinary values, induced by the primary current through the mutual inductance.

During Fault (0.01 to 0.05 seconds): The current increase significantly due to the lack of induced EMF from the primary winding reaches approximately 2000 A.

Post-Fault (after 0.05 seconds): The current resumes its sinusoidal oscillation with transients corresponding to the restoration of the primary voltage.

Observations discussion:

- **Current Response:**

When the short circuit occurs in the primary winding, the primary current (I1) spikes to a high value almost instantaneously changing the I_{MAX} to approximately 95 A. This behavior is expected because a short circuit in the primary winding leads to a sudden increase in current due to the low impedance path.

Since the secondary winding is unaffected by the fault in the primary winding, the secondary current (I2) also responds accordingly due to mutual inductance .

- **Steady-State Behavior**:

Once the transient response settles, the currents in both windings stabilize, but at different levels compared to the normal operation scenario.

The currents may remain elevated due to the fault condition, and this sustained high current can lead to overheating and damage if not addressed promptly.

IV.2.2.3. Impact on the Transformer:

The high current resulting from the winding fault can lead to excessive heating of the windings and insulation, potentially causing insulation breakdown or other damage to the transformer.

The fault condition can also lead to voltage imbalance, affecting the performance of the connected electrical system.

This fault is modeled as a short circuit, which means that a low impedance path is created within the primary winding itself. This type of fault scenario can occur due to various reasons such as insulation breakdown, physical damage to the winding, manufacturing defects, or environmental factors like moisture or contaminants.

When a short circuit occurs in the primary winding, it essentially bypasses a portion of the winding's resistance, allowing a significant amount of current to flow through the short-circuited section. This sudden increase in current flow can have several consequences:

- **Elevated Currents**: The primary current, which is usually regulated by the load impedance, spikes to a very high value almost instantaneously due to the low impedance path created by the short circuit. This elevated current flow can lead to overheating and potential damage to the winding and transformer components.
- **Transient Response**: The sudden change in current due to the short circuit results in a transient response in the transformer's behavior. The system attempts to adjust to the new operating conditions, which can cause fluctuations in currents and voltages until a new equilibrium is reached.
- **Secondary Effects**: While the fault occurs in the primary winding, it also affects the secondary winding indirectly. The secondary current responds to changes in the primary current, although with some delay due to the transformer's inherent inductance. This can lead to disturbances in the secondary voltage and current levels, affecting the performance of connected loads.
- **Impact on System Stability**: The sudden increase in current and associated voltage drops across the winding resistance can affect the stability of the electrical system. Voltage levels may drop, and protective devices may operate to isolate the transformer from the system to prevent further damage.

IV.2.2.4. Summary:

By simulating this fault scenario, the code facilitates a comprehensive analysis of the transformer's response to such events. This simulation offers valuable insights into the system's behavior under fault conditions, enabling a deeper understanding of the dynamics involved. The detailed analysis provided by the simulation results helps engineers and researchers identify critical changes in current behavior and potential vulnerabilities within the transformer system.

Understanding these fault-induced changes is essential for designing and implementing effective protection and mitigation strategies. These strategies are crucial for ensuring the safety, reliability, and longevity of the transformer and the overall electrical network. By preemptively addressing potential fault scenarios, engineers can develop robust systems that minimize the risk of catastrophic failures, enhance operational stability, and maintain continuous power supply.

In conclusion, the ability to simulate and analyze fault conditions in transformers plays a pivotal role in advancing the field of electrical engineering. It not only contributes to the theoretical knowledge base but also directly impacts practical applications, leading to the development of more resilient and efficient power systems.

IV.2.3. Core fault:

A transformer's operation hinges on the magnetic coupling between its primary and secondary windings. This coupling is facilitated by the core, typically made of laminated steel, which ensures efficient magnetic flux linkage. The mutual inductance (M) is a measure of this coupling. Under normal conditions, the magnetic flux generated in the primary winding induces a corresponding flux in the secondary winding, enabling voltage transformation.

The results:

Upon writing and executing this script in MATLAB, the results will be as follows:

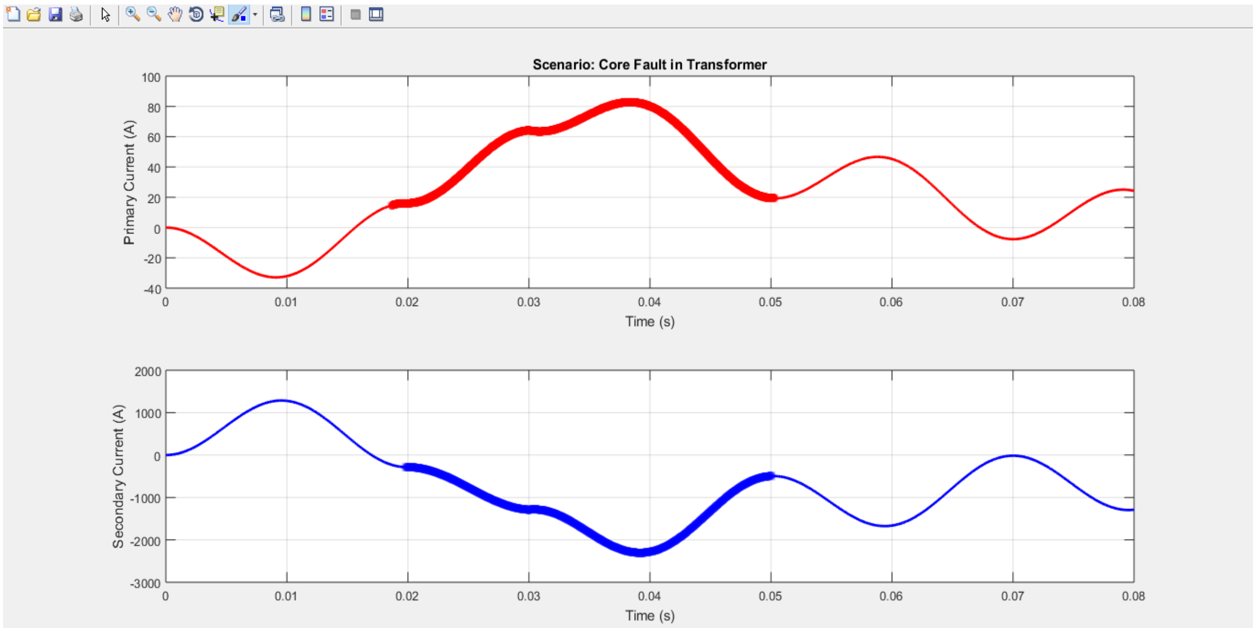

Figure IV-3Currents in the primary and secondary windings during a core fault

IV.2.3.1. Simulation process:

Normal Operation: The primary and secondary currents (I1 and I2) are computed using the coupled differential equations reflecting normal magnetic coupling.

Fault Condition: From 0.02 to 0.05 seconds, he primary inductance L1 is halved to simulate a core fault.

Post-Fault Condition: After 0.05 seconds, the mutual inductance is restored, Transient oscillations followed by a return to steady-state sinusoidal waveform.

IV.2.3.2. General observation:

Analyzing the results:

- **Primary Current (I1):**

Pre-Fault (0 to 0.02 seconds): The current oscillates sinusoidally, driven by the input voltage.

During Fault (0.02 to 0.05 seconds): The current magnitude increases due to the sudden drop in inductive reactance. The waveform showed oscillations or ringing immediately following the introduction of the fault as the system attempts to stabilize.

Post-Fault (after 0.05 seconds): The current returns to its pre-fault sinusoidal behavior, though transients may be observed due to the sudden reinstatement of mutual coupling.

- **Secondary Current (I2):**

Pre-Fault (0 to 0.02 seconds): The current oscillates sinusoidally, induced by the mutual inductance M and follows a sinusoidal waveform similar to I1.

During Fault (0.02 to 0.05): The fault in the primary winding affects the magnetic coupling between the primary and secondary windings. As the fault current flows through the core, it induces additional currents in the secondary winding. reflecting the increased primary current and reduced impedance.

Post-Fault (after 0.05 seconds): Transient oscillations followed by a return to steady-state sinusoidal waveform.

Observations discussion:

The core fault results in immediate cessation of power transfer to the secondary side, leading to load loss.

- **Current Response**

Primary Current (I1): When the core fault occurs, the primary current (I1) exhibits a sudden change in behavior. Initially, it may spike to a high value due to the sudden drop in inductive reactance.

However, since the fault is characterized by a breakdown in the core rather than a short circuit in the winding, the increase in primary current may not be as drastic as in a winding fault scenario.

Secondary Current (I2): The secondary current (I2) also responds to the core fault, The loss of mutual inductance results in a temporary interruption in the induced EMF in the secondary winding, causing an increase in amplitude corresponding to the primary current deformations shows by transient spikes and oscillations due to the reduced inductance.

- **Steady-State Behavior:**

After the transient response settles, both primary and secondary currents stabilize, but at different levels compared to normal operation.

Since the fault condition persists throughout the simulation, the currents may remain unlike the normal operation current. This sustained high current can lead to overheating and potential damage if not addressed promptly.

Detecting core faults early through monitoring primary current anomalies and implementing protective relays can prevent damage.

Regular maintenance and thermal management of the core can mitigate the risk of core faults.

IV.2.3.3. Impact on the Transformer:

Overheating and Damage: The sustained high currents resulting from the core fault can lead to excessive heating of the windings and insulation. This overheating poses a significant risk of insulation breakdown and damage to transformer components.

Imbalance: The core fault can also lead to voltage imbalance, affecting the performance of the connected electrical system. Unbalanced voltages can cause operational issues in downstream equipment and disrupt the stability of the electrical network.

Elevated Currents: While the primary current may not spike as dramatically as in a winding fault scenario, it remains instable due to the fault condition.

Transient Response: The sudden change in operating conditions due to the core fault results in a transient response in the transformer's behavior. This transient behavior can cause fluctuations in currents and voltages until a new equilibrium is reached.

IV.2.3.4. Summary:

simulating a core fault provides invaluable insights into the behavior and resilience of transformers under adverse conditions. Through this simulated test, engineers and researchers gain a comprehensive understanding of how transformers respond to core faults, enabling them to assess the transformer's performance, identify vulnerabilities, and develop effective mitigation strategies. The simulation of a core fault offers several key benefits:

Understanding Transformer Behavior: By observing the transformer's response to a core fault, engineers gain insights into how core faults impact key operational parameters such as current levels, voltage stability, and thermal characteristics. This understanding is essential for optimizing transformer design and operation.

Assessment of Protection Systems: Core fault simulations allow for the evaluation of protective measures and relay settings designed to detect and isolate faults promptly. This assessment helps ensure that protection systems are robust and effective in safeguarding transformers and electrical networks.

Development of Maintenance Strategies: Insights gained from core fault simulations inform the development of proactive maintenance strategies aimed at preventing and mitigating the effects of core faults. By identifying potential failure modes and vulnerabilities, operators can implement targeted maintenance activities to enhance transformer reliability and longevity.

Enhancement of Grid Resilience: By addressing vulnerabilities exposed through core fault simulations, operators can enhance the resilience of electrical grids against transformer failures. This proactive approach minimizes downtime, reduces the risk of cascading outages, and ensures the continuity of electrical supply.

In summary, simulating core faults is a valuable tool for transformer testing and analysis, offering a proactive means of assessing transformer performance, optimizing protection systems, and enhancing grid resilience. By leveraging the insights gained from core fault simulations, operators and engineers can effectively manage transformer assets, mitigate risks, and maintain the reliability of electrical power systems.

IV.3. Conclusion:

In conclusion, simulation of normal operation in conjunction with fault scenarios offers a well-rounded educational experience that enables students to grasp the intricacies of transformer behavior across a range of conditions. By examining the interplay between normal and abnormal operating states, students gain valuable insights into transformer performance, diagnostic techniques, and the importance of proactive maintenance practices in electrical power systems then the simulation of winding and core faults in transformers provides a valuable educational tool for studying the behavior of these systems under fault conditions. Through analysis of simulation results, students gain insights into fault dynamics, system performance, fault identification, and the importance of proactive maintenance strategies in ensuring the reliability and safety of electrical power systems.

The simulation of winding and core faults in a transformer system provides valuable insights into the behavior of such systems under various fault conditions. In an academic context, this simulation serves several important purposes and yields significant conclusions:

Understanding Fault Dynamics: The simulation allows students and researchers to comprehend the dynamic behavior of transformers when subjected to winding and core faults. By observing the response of currents in the primary and secondary windings, they can gain a deeper understanding of how faults impact the overall operation of the transformer.

Identification of Fault Types: Through the simulation, students can learn to distinguish between different types of faults, such as winding faults and core faults. By analyzing the characteristic responses of the currents in each scenario, they develop the ability to identify the nature and severity of faults that may occur in real-world transformer systems.

Impact on System Performance: The simulation demonstrates the significant impact that faults can have on the performance of transformer systems. Winding faults, such as short circuits or open circuits, result in abnormal current flow patterns, potentially leading to overheating, voltage instability, and damage to the transformer. Similarly, core faults disrupt the magnetic coupling between the windings, affecting the efficiency and reliability of the transformer.

Importance of Early Detection and Mitigation: By observing the simulation results, students gain an appreciation for the importance of early fault detection and mitigation strategies in transformer maintenance and operation. They learn that timely identification and remediation of faults can prevent costly downtime, equipment damage, and safety hazards in electrical power systems.

Application of Theoretical Concepts: The simulation reinforces theoretical concepts related to transformer operation, including principles of electromagnetism, circuit theory, and dynamic systems analysis. Students can relate theoretical knowledge to practical scenarios, enhancing their ability to apply concepts learned in the classroom to real-world engineering problems.

In addition to simulating winding and core faults, incorporating a simulation of normal operation in a transformer system provides a comprehensive understanding of its behavior across different operating conditions and specific connections also:

Baseline Performance Assessment: The simulation of normal operation establishes a baseline for the transformer's performance under ideal conditions. By observing the expected behavior of currents in the primary and secondary windings during normal operation, students can understand the typical operating parameters and efficiency of the transformer.

Comparison with Fault Conditions: Contrasting the results of normal operation with those of fault scenarios enables students to identify deviations from expected behavior when faults occur. This comparison highlights the significance of abnormalities in current flow and voltage regulation, signaling the presence of faults and the need for diagnostic measures.

Validation of Theoretical Models: The simulation of normal operation validates theoretical models of transformer behavior by confirming that the system operates within expected parameters under ideal conditions. Students can verify the accuracy of mathematical equations and circuit models used to describe transformer operation, enhancing their confidence in applying theoretical concepts to practical engineering problems.

Enhanced Diagnostic Skills: By understanding the characteristic responses of currents and voltages during normal operation, students develop diagnostic skills that facilitate the identification and localization of faults when they occur. Recognizing deviations from normal behavior enables early detection and effective troubleshooting, minimizing downtime and optimizing maintenance efforts.

Holistic Understanding of Transformer Systems: Integrating simulations of normal operation and fault scenarios provides students with a holistic understanding of transformer systems, encompassing both idealized and real-world operating conditions. This comprehensive perspective enhances their ability to analyze complex systems, anticipate potential challenges, and implement robust solutions to ensure system reliability and performance.

General Conclusion

General conclusion

In conclusion, the exploration of transformer protection and maintenance has unveiled critical insights into the operation, safeguarding, and longevity of these indispensable components within electrical power systems.

Beginning with a presentation of the company ENEL discussing its main functions and the manufactured products then we have moved to a detailed examination of transformer fundamentals, including construction and function, a solid foundation was laid for understanding the intricate interplay between electrical, magnetic, and mechanical components within transformers. This foundational knowledge underscores the importance of effective protection and maintenance strategies in preserving the integrity and reliability of transformer assets.

Delving deeper into fault mechanisms, a comprehensive understanding of the diverse range of potential issues affecting transformers was elucidated. From electrical faults such as short circuits and overloads to mechanical faults like insulation degradation and winding displacement, the multifaceted nature of transformer faults necessitates a holistic approach to protection and maintenance.

The discussion on transformer protection types revealed a spectrum of techniques and technologies employed to detect and mitigate faults swiftly and effectively. Traditional protection methods, such as differential and distance protection, were juxtaposed with emerging technologies like online monitoring systems and intelligent relays, highlighting the evolution of protection strategies to meet the demands of modern power systems.

Equally significant is the emphasis on transformer maintenance, which encompasses a continuum of proactive and reactive measures aimed at prolonging equipment lifespan and optimizing performance. From routine inspections and oil analysis to advanced diagnostic techniques like thermography and dissolved gas analysis, the arsenal of maintenance practices empowers operators to preemptively address potential issues and mitigate risks.

Furthermore, the integration of transformer tests into maintenance regimes provides a vital tool for assessing transformer health and operational integrity. By conducting comprehensive tests, including insulation resistance, turns ratio, and power factor tests, operators gain valuable insights into transformer condition, enabling informed decision-making and targeted maintenance interventions.

The culmination of this exploration involved the simulation of transformer scenarios under normal operation, winding faults, and core faults. Through detailed analysis of simulation results, valuable insights were gleaned into the dynamic behavior of transformers under fault conditions, reaffirming the critical role of robust protection and maintenance strategies in ensuring system resilience and reliability.

In summary, the synthesis of transformer protection and maintenance principles underscores their paramount importance in sustaining the integrity and performance of electrical power systems. By leveraging comprehensive protection schemes, proactive maintenance practices, and rigorous testing protocols, operators can mitigate risks, optimize asset performance, and uphold the reliability of transformer assets in the face of evolving operational challenges.

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