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FUNDAMENTALS OF SHORT-CIRCUIT PROTECTION FOR TRANSFORMER

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BY

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FUNDAMENTALS OF SHORT- CIRCUIT PROTECTION FOR TRANSFORMER

By Raad Ibrahim Hussein HUSSEIN

January 2024

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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Raad Ibrahim Hussein HUSSEIN

ABSTRACT

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This thesis presents the design and implementation of computer components and hardware test systems (TSs) for assessing the operability of digital current protection in electric installations, along with their modeling in the MATLAB-Simulink dynamic simulation environment. The mathematical model for any component of the electric power system, viewed as a generalized electric power facility, is grounded in both rigid and flexible models. Rigid models, based on the mathematical descriptions of the electrical and magnetic circuits of power system elements, serve as benchmarks for comparing the results of simulating similar facilities. In contrast, flexible models of a generalized electric power facility are designed for integration into the MATLAB-Simulink dynamic simulation system's library, which includes the Sim-Power-Systems extension package. These models focus on the simulation of electrical devices. The thesis delves into the detailed calculation of parameters for the main library blocks of Sim-Power-Systems, which form the basis of the power system model. It also introduces models for a three-phase group of current transformers, featuring a secondary winding and load connection based on the "star with a neutral wire" (Y-connection) scheme, and a model of digital current protection—both crafted using standard Simulink blocks and not part of the core library. Furthermore, the thesis explores the use of differential protection relay and fuzzy logic for power transformers, demonstrating their effectiveness in defending against internal and external faults, and in distinguishing between fault and non-fault conditions. Utilizing the MATLAB/SIMULINK platform, this research offers valuable insights into the performance and capabilities of the differential protection relay system.

2024, 75 pages

Keywords: Power transformer protection, Differential relay, Fuzzy logic control, Fault detection, Mathematical model, Current transformer

ÖZET

TRAFO İÇİN KISA DEVRE KORUMASININ TEMELLERİ

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Bu tez, elektrik tesisatlarındaki dijital akım korumasının işlevselliğini değerlendirmek için bilgisayar bileşenlerinin ve donanım test sistemlerinin (TS) tasarımını ve uygulamasını MATLAB-Simulink dinamik simülasyon ortamında modellenmesi sunulmuştur. Elektrik güç sisteminin herhangi bir bileşeninin matematiksel modeli, genelleştirilmiş bir elektrik güç tesisatı olarak ele alındığında, hem rijit hem de esnek modeller üzerine kurulmuş durumdadır. Rijit modeller, güç sistemi elemanlarının elektriksel ve manyetik devrelerinin matematiksel açıklamalarına dayanarak, benzer tesisatların simülasyon sonuçlarını karşılaştırmak için referans noktaları olarak hizmet etmekte olmuştur. Buna karşın, genelleştirilmiş bir elektrik güç tesisatının esnek modelleri, MATLAB-Simulink dinamik simülasyon sistemi kütüphanesine entegrasyon için tasarlanmış olup, bu kütüphane Sim-Power-Systems eklenti paketini içermektedir. Bu modeller, elektrik cihazlarının simülasyonuna odaklanmış durumdadır. Çalışma, Sim-Power-Systems'ın ana kütüphane blokları için parametrelerin detaylı hesaplamasına dalmış ve güç sistemi modelinin temelini oluşturmuştur. Ayrıca, "yıldız bağlantılı ve nötr teli" (Y-bağlantı) şemasına dayalı ikincil sargı ve yük bağlantısı içeren üç fazlı akım trafoları için modeller ve dijital akım koruması için bir model sunmuş, her ikisi de standart Simulink blokları kullanılarak hazırlanmış ve temel kütüphanenin bir parçası olmamıştır. Dahası, çalışma, güç trafoları için diferansiyel koruma rölesi ve bulanık mantık kullanımını araştırmış, bu sistemlerin iç ve dış hatalara karşı savunmada ve hata ile hata olmayan durumları ayırt etmede etkinliğini göstermiştir. MATLAB/SIMULINK platformunu kullanarak, bu araştırma diferansiyel koruma röle sisteminin performansı ve yetenekleri hakkında değerli bilgiler sunmuştur.

2024, 75 sayfa

Anahtar Kelimeler: Güç trafosu koruması, Diferansiyel röle, Bulanık mantık kontrolü, Arıza tespiti, Matematiksel model, Akım trafosu

PREFACE AND ACKNOWLEDGEMENTS

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Raad Ibrahim Hussein HUSSEIN
Çankırı-2024

CONTENTS

LIST OF SYMBOLS

P_{OSL}	Additional loss happen by winding skin effect and adjacent effect
Φ	Alternating magnetic flux
P_F	Core additional loss and its' proportion is relatively small
S_m	Cross-section of the magnetic circuit
$I_{2(h)}$	Harmonic-current on the secondary side of the transformer
E_M	Induced-potential amplitude of transformers
H	Magnetic-field strengths in the magnetic-circuit
l_m	Middle line length related to the magnetic-circuit
P_{NL}	No-load core loss
P_{TL}	Overall theoretical loss of transformers
$Cos\Phi_2$	Power factor
K	Ratio of turns
B_m	Silicon-core working flux density
$X_{1(h)}$	Transformer primary-side leakage resistance for the h-th harmonic
$N_{p,s}$	Turns numbers on the primary-sides and secondary-sides

LIST OF FIGURES

1. INTRODUCTION

Introducing modern technologies within the power industry, the growth of capacities generations, the complication of the distribution as well as the transmissions in topology of electric-power are the reasons of the emergence of new operation modes in the power system. These circumstances demands manufacturers of digital-protections relays or switches to expirment these protections planned within conditions closer to real practical conditions. The most effective expirment is modeling, that obtaining the primary experiences of implemented solutions (Ugli 2021).

Analog and electrodynamic models of electric power systems are widely used for their accuracy and cost-effectiveness. However, the complexity involved in building these models limits their widespread adoption. Modern Testing Sets (TSs) employ mathematical methods to generate input signals for digital relays and switches. These signals closely resemble actual signals in both shape and magnitude. TSs serve two main purposes: they are instrumental in developing new guidelines for constructing digital protection systems and in evaluating performance during emergency operational scenarios. Additionally, TSs are utilized to gather signal information from digital protection relays and switches in both emergency and normal operating conditions of the protected devices. TSs comprise both software and hardware components. The software component leverages complex models and instrument transformers adaptable to personal computers, while the hardware is responsible for converting and amplifying codes, facilitating real-time testing of digital protection relays and switches. This methodology enhances the efficiency and accuracy of simulations in electric power systems.

1.1 Principle of Operation of the Transformer

The electromagnetic induction phenomenon explain the transformer operation principle.Considering this phenomenon, the alternating magnetic fields are existed. the magnetic-circuits are adopted to form the magnetic fields. Consequently, the basics of the transformer devices are the magnetic-circuits.

The ideal transformers' electromagnetic circuit is illusterated in Figure.1.1

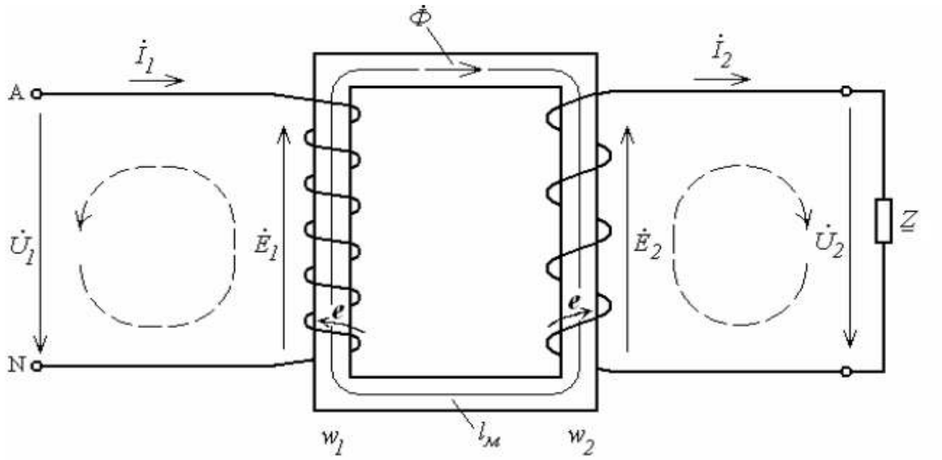


Figure 1.1 Ideal transformer electromagnetic circuit

In such a transformer, the magnetic-circuits can be a rectangular ferromagnetic core, on which two electric windings are placed. Each of the windings has a certain turns number (w_1 and w_2) covering the cores of the magnetic-circuit.

The winding with the turns number w1 is called the primary-winding and is linked to terminals A-N of the AC power supply $\dot{U}_1$. Winding with the turns number w2 is called secondary. An electric-power receiver with resistance Z is linked to the terminals of the secondary winding.

Under the action of an alternating voltage source $\dot{U}_1$ in the primary-winding, a primary-current $\dot{I}_1$ is created. This current, closing along the turns of the primary-winding, creates a variable magnetomotive force (EMF). Under the action of VMF, an alternating magnetic-field arises.

In this situation, the magnetic flux $\dot{\Phi}$, closing along the ferromagnetic core, penetrates all turns of both windings. According to the law of electromagnetic induction, an alternating magnetic flux $\dot{\Phi}$, penetrating the turns of the windings, induces an EMF of induction e in each of them. The positive direction of the EMF of one turn e corresponds to the magnetic flux direction. In this situation, its value is determined by change of the magnetic flux rate as in Equation (1.1).

$$\dot{e} = \frac{d\dot{\Phi}}{dt} \quad (1.1)$$

Then in the primary-winding with the turns number w_1, an induction EMF $\dot{E}_1$ is created proportional to the turns number w_1 as in Equation (1.2)

$$\dot{E}_1 = \dot{e}w_1 \quad (1.2)$$

In the secondary winding of the turns number w_2, an EMF is created $\dot{E}_2$ as proportional for the turns number w_2 as in Equation (1.3)

$$\dot{E}_1 = \dot{e}w_2 \quad (1.3)$$

Equation (1.4) shows the ratio in magnitude between the primary and secondary voltages is called the transformation ratio.

$$k_T = \frac{U_1}{U_2} \quad (1.4)$$

Equation (1.5) and Equation (1.6) are called the equations of the electric state of an ideal transformer.

$$\dot{U}_1 = \dot{E}_1 \quad (1.5)$$

$$\dot{U}_2 = \dot{E}_2 \quad (1.6)$$

Equation (1.7) and Equation (1.8) calculated the ratio of turns

$$k_T = \frac{U_1}{U_2} = \frac{E_1}{E_2} \tag{1.7}$$

$$k_T = \frac{ew_1}{ew_2} = \frac{w_1}{w_2} \tag{1.8}$$

Therefore, the transformer, through the magnetic coupling of two windings in a magnetic-circuit, converts the electric-power of the source with voltage U_1 into electric-power given to the receiver with voltage U_2. In this situation, the secondary voltage shows in Equation (1.9).

$$U_2 = \frac{U_1}{k_T} \tag{1.9}$$

1.2 Transformer State Equations

The magnetic state's equation is compiled in the magnetic-circuits analysis related to the transformers. It should emphasize that the electric circuits related to the secondary and primary-windings aren't interlinked. The windings are combined by common magnetic-circuits, to form magnetic-circuits. The connections between the secondary and primary circuits are expressed by the magnetic state's Equation (1.10) as follows:

$$\dot{H} l_m = \dot{I}_1 w_1 - \dot{I}_2 w_2 \tag{1.10}$$

Where: H refers to the magnetic field's strength and $l_m$refers to the middle line length of the magnetic-circuit. The center line length related to the magnetic-circuits is indicated by its design. The strength related to Magnetic-field is expressed as Equation (1.11):

$$H = \frac{\Phi}{S_m} \tag{1.11}$$

Where S_m refers to the magnetic-circuit cross-sections. The right side of Equation (1.10) relies on the mode of operation. In particular, when the receiver is turned off, an idle mode happens when the receiver current (secondary-current of the transformer) I_2 is null ($I_2 = 0$). The primary-current in this mode is called no-load current (I_0). In this situation, in the equation, according to the law of overall current, the second term is zero, and the first term is determined by the no-load current as follows in Equation (1.12).

$$\dot{H} l_m = \dot{I}_0 w_1 \tag{1.12}$$

Also, the Equation (1.10) could be written as in following Equation (1.13):

$$\dot{I}_0 w_1 = \dot{I}_1 w_1 - \dot{I}_2 w_2 \tag{1.13}$$

Transform the last Equation (1.14) yields:

$$\dot{I}_1 = \dot{I}_0 + \dot{I}_2 \frac{w_2}{w_1} \tag{1.14}$$

Also can be written as in Equation (1.15)

$$\dot{I}_1 = \dot{I}_0 + \frac{\dot{I}_2}{k_T} \tag{1.15}$$

1.3 Features of a Real Transformer

A real transformer's operation involves considering additional features that significantly affect its characteristics. The transformer windings, when combined, create a working magnetic flux F, which closes along the circuits and provides magnetic coupling between the secondary and primary circuits. In addition to the main magnetic flux, additional magnetic fluxes arise, such as the primary-winding leaking-flux, which closes inside the winding and outside along the air paths. This flux does not adhere to the secondary winding and does not provide their magnetic connection. The secondary winding also creates the secondary-winding leaking-flux, which induces self-induction EMF each in its own winding. To account for these phenomena, inductive elements are introduced into the electromagnetic circuits of the transformer with the corresponding inductive leakage resistances of the secondary and primary-windings.

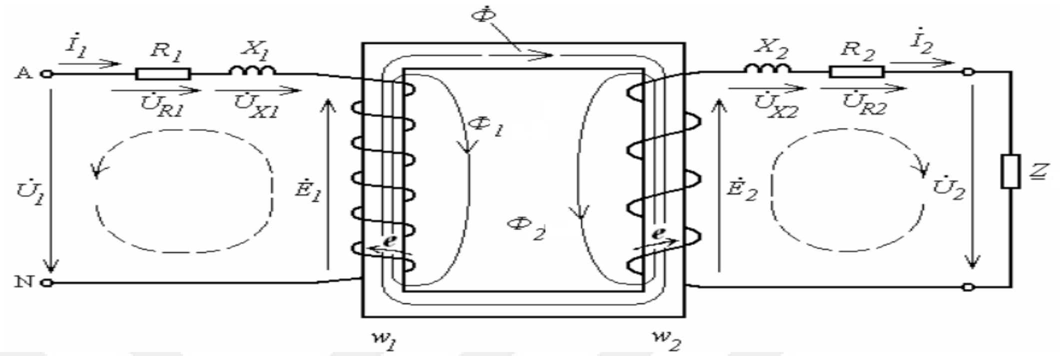


Figure 1.2 Electromagnetic-circuits of a real transformer

The Equation (1.16), Equation (1.17) and Equation (1.18) of the electric and magnetic state describing the processes in the electric and magnetic-circuits of a real transformer.

$$\dot{U}_1 = \dot{E}_1 + \dot{I}_1(R_1 + jX_1) \tag{1.16}$$

$$\dot{U}_2 = \dot{E}_2 - \dot{I}_2(R_2 + jX_2) \tag{1.17}$$

$$\dot{I}_1 = \dot{I}_0 + \dot{I}_2/k_T \tag{1.18}$$

The transformers' load is created by a receiver of electric-power linked to the terminals of its secondary winding. Those, the load value should be understood as the power of this receiver, which is determined by its voltage U_2 and current I_2 as following in Eqauiton (1.19).

$$P_2 = U_2 I_2 \cos\,\varphi_2 \tag{1.19}$$

Under certain conditions, it is permissible to disregard variations in the voltage U_2. In such cases, the power received can be considered directly proportional to the current I_2. This allows us to interpret the load value as the secondary current's magnitude. Consequently, alterations in the transformer's secondary voltage, when its operational mode changes, are effectively described by the relationship between the secondary voltage and the secondary current, denoted as $U_2 = f(I_2)$. This relationship is known as the transformer's external characteristic. From this, it can be inferred that an increase in the secondary current (corresponding to a heightened load) leads to a reduction in the secondary voltage (Wu *et al.* 2020). This variation in secondary voltage is attributable to the voltage drop across the transformer's inherent active and inductive resistances (Piskunov and Mokeev 2021).

2. LITERATURE REVIEW

The literature review for the protection relay and fuzzy logic relay thesis is an extensive analysis of twenty-eight specialized research papers and journals within the realm of electrical engineering. This comprehensive review facilitates a detailed comparison between the findings of this project and other works in the field. The subsequent pages provide summaries of various research papers, offering a cohesive overview of the existing knowledge and advancements pertinent to the thesis's scope.

2.1 Protection Relay and Fuzzy Logic Protection Relay

Salih *et al.* (2021) present a thesis on differential protection relay systems for a prototype power transformer. The researchers utilize Matlab/Simulink for simulation purposes. The thesis evaluates the performance of the proposed protection algorithm on a 2KVA power transformer considering various fault conditions. The differential protection scheme aims to quickly detect faults and trigger appropriate actions to safeguard the transformer. The research paper demonstrates the successful simulation and evaluation of a differential protection relay system for a prototype power transformer. The proposed relay system effectively differentiates between no-fault and fault conditions. It accurately detects both internal and external faults and initiates the appropriate actions, such as sending trip signals to circuit breakers.

Onah and Ezema (2020) propose differential protection as a better alternative, especially for protecting transformers and other equipment. The differential protection scheme operates based on the difference between entering and leaving currents in a section, and it is effective in scenarios where coordination is complex or quick fault clearance is necessary. The authors delve into the principles and factors affecting current-differential protection, such as current transformer errors, phase angle errors, and mismatching caused by tap-changing and power transformer exciting current surges. The implementation of the differential protection scheme is also explored, highlighting the importance of proper current transformer selection and correction factors for relay operation. Additionally, the authors discuss the challenges associated with current transformer errors, phase angle errors, and other factors affecting the accurate functioning of the protection scheme. Also, They propose solutions or approaches for overcoming these challenges, potentially involving correction factors, biasing arrangements, and advanced techniques for mitigating issues like transformer inrush currents..

Ihedioha (2016) utilizes the MATLAB/SIMULINK platform to analyze the functionality of a differential protection relay in the context of a sizable power transformer. The primary goal is to ensure that the relay effectively detects and responds to internal faults, thereby preventing operational disruptions. The results obtained from the thesis indicate that the proposed differential relay system successfully distinguishes between inrush currents, faults, and non-fault conditions, highlighting its appropriate action in maintaining transformer stability. The research successfully explores the implementation of differential protection using relay technology for power transformers. The proposed system demonstrates its effectiveness in safeguarding transformers against internal faults and differentiating between fault and non-fault conditions. By utilizing the MATLAB/SIMULINK platform, the thesis provides valuable insights into the performance and capabilities of the differential protection relay system.

Traditional phasor-based differential protection techniques, crucial for electrical power systems, often fail to detect internal faults in power transformers and are susceptible to relay misoperations. This research proposes a novel method that utilizes the energy of the boundary wavelet coefficient to reconstruct phase current and negative-sequence current differential components using the wavelet transform. It accounts for non-linear inductance to accurately represent magnetization effects, which could otherwise lead to incorrect differential currents. The thesis models and simulates the proposed PAD-based method for transformer differential protection using Simulink, integrated with MATLAB, as per (Iqteit and Yahya 2020).

Oyedoh and Obasohan (2019) present a comprehensive simulation exploring the differential protection scheme under various operating conditions, including the challenging scenario of magnetizing inrush currents. Their thesis simulates the activation of a primary breaker, inducing magnetizing inrush current at the transformer's primary side, while leaving the secondary side unaffected. The differential protection scheme's implementation is successful, showcasing enhanced switching responsiveness upon fault signal detection. The system's performance under multiple conditions was thoroughly evaluated, with the simulated results affirming its satisfactory operation.

Banerjee and Khosla (2019) present a novel method for distinguishing among magnetizing inrush currents and internal defects in power transformers that employs the wavelet transform. The wavelet transform method, processing transient signals in both time and frequency domains, provides a detailed signal representation for precise fault classification. Conducted in the MATLAB environment, their simulation demonstrates quicker operational speed and reduced fault clearing time, thus improving fault differentiation in power transformers.

Rafa (2017) introduces a novel digital differential relay designed to protect power transformers against internal faults and external disturbances. This relay employs a unique discrimination method, based on the slope comparison of primary and inrush current waves, moving away from traditional harmonic-based methods. This approach ensures reliable protection without unnecessarily blocking the relay during transformer energization or false tripping during external faults. The digital differential relay effectively tackles the challenge of distinguishing between internal faults and inrush currents, relying on the current wave's slope for accurate protection without additional interposing current transformers.

Das *et al.* (2017) address the detection of minor turn-to-turn faults in power transformers, a challenge during transformer energization where conventional algorithms lose sensitivity. They propose a new relay prototype combining negative-sequence current and voltage to enhance sensitivity in such scenarios. Comparing their approach with existing techniques, the authors provide experimental evidence of its effectiveness. Their novel fault detection algorithm demonstrates superior performance over traditional methods, maintaining effectiveness during transformer energization.

Patel *et al.* (2015) propose a unit-type protection scheme integrating percentage biased differential protection with a sequence component-based phase angle comparison technique. This method aims to address the maloperations caused by CT saturation and high-resistance internal faults in standard differential protection schemes. Utilizing Discrete Fourier Transform for phase angle calculations and a low-pass Butterworth filter for signal correction, the thesis demonstrates the proposed algorithm's effectiveness through extensive simulations in PSCAD/EMTDC software. The algorithm accurately distinguishes between internal and external faults, proving its reliability even in high-resistance internal fault scenarios where traditional methods might falter.

Kainth and Sharma (2014) introduce a novel technique based on Clark transformation to enhance the sensitivity of digital differential relays in power transformers. This method significantly improves the discrimination between inrush currents and fault currents. The technique is rigorously tested using MATLAB/SIMULINK across various scenarios, demonstrating its effectiveness in accurately distinguishing between the different types of currents, thus offering a promising enhancement to digital differential relay performance in power transformer protection.

Oliveira *et al.* (2014) propose a new approach to percentage differential protection for three-phase power transformers, utilizing transient signal analysis. They employ discrete wavelet transforms (DWT) to extract transient features from non-stationary signals, effectively presenting these signals in a time-frequency representation. Implemented and tested in MATLAB and evaluated through case studies in BPA’s ATP/EMTP software, their research indicates that this algorithm provides improved performance, precision, and practicality in differential protection systems.

Mishra and Prakash (2013) review the fundamentals and evolution of directional elements in protection systems. The paper focuses on the sensitivity limits of these elements, exploring their design progression and application in voltage loss conditions. Through practical field examples, it provides insights into the challenges and solutions in applying and setting modern directional relays, emphasizing the importance of careful thesis of sensitivity levels in newer designs.

Zimmerman and Costello (2010) delve into the foundational principles and evolution of directional elements in protection systems. Addressing challenges from new power system disturbances, the paper offers insights into the design and application of modern directional relays. They suggest the use of local positive sequence source impedance for setting parameters and introduce a positive-sequence impedance directional element as a solution for LOP conditions, enhancing redundancy in protection systems. The authors also caution the use of automatic settings for directional elements, highlighting the need for a thorough understanding of underlying assumptions.

Abniki *et al.* (2010) present a new technique for protecting three-phase transformers, effectively distinguishing magnetizing inrush currents from internal fault currents using symmetrical components. This innovative criterion is designed to differentiate between these currents during various faulty conditions, such as switching or short circuits. The algorithm is validated through simulations under diverse conditions, including over-flux and CT saturation scenarios. The research demonstrates that the proposed scheme effectively discriminates between inrush currents and internal faults in power transformers, showcasing its accuracy and reliability even in challenging scenarios..

Monsef and Lotfifard (2007) introduce an innovative method for the differential protection of power transformers, combining wavelet transform with ANFIS (Adaptive Neuro-Fuzzy Inference System). This method focuses on analyzing the amplitude differences of wavelet transform coefficients within a specific frequency range pertinent to faults and inrush currents. The effectiveness of this approach is validated through simulations in PSCAD/EMTDC software, along with testing on real data from a laboratory prototype transformer. This research showcases a novel differential protection method that skillfully employs wavelet transform and ANFIS, demonstrating its capacity to accurately distinguish internal faults from inrush currents and offering swift and precise protection.

Golshan *et al.* (2004) introduce a novel algorithm for the digital differential protection of power transformers. This algorithm centers on processing the second harmonic components of differential currents. It exhibits a remarkable ability to distinguish internal faults from inrush current conditions promptly and effectively, without the need for threshold selection. The algorithm's practical applicability and effectiveness are affirmed through simulations on a representative power system.

Azizan *et al.* (2020) highlight the crucial role of transformer protection within electric power systems, stressing the importance of rapid and accurate protection mechanisms, especially against internal faults. The authors conduct a successful simulation of a differential relay using MATLAB/Simulink, designed to protect power transformers from various internal fault scenarios, including double line-to-ground, single line-to-ground, and line-to-line faults. The thesis's findings underline the vital function of differential relays in safeguarding transformers against internal faults and preventing disruptions in the power network. The effective simulation and evaluation of the proposed differential relay illustrate its proficiency in swiftly detecting and responding to diverse fault scenarios, thereby reinforcing its importance in electric power systems.

Dapshima *et al.* (2023) underscore the importance of power transformers and the necessity of protecting them from faults. They introduce fuzzy logic as a novel methodology for fault detection and protection. Utilizing the fuzzy logic toolbox in MATLAB/SIMULINK, they develop a simulation system capable of diagnosing transformer faults and monitoring operational conditions. The thesis demonstrates that fuzzy logic can effectively detect and protect power transformers from various fault conditions, leading to enhanced relay control and substantial cost savings in maintenance and repairs. Their simulation results show that the fuzzy logic system effectively discerns normal operating conditions, as indicated by output responses close to zero under normal current levels.

Marei *et al.* (2021) propose an innovative power transformer protection system that incorporates fuzzy logic. The primary protection for the transformer is provided by a digital differential relay, complemented by an overcurrent relay serving as the secondary safeguard. A key feature of this system is the use of a fuzzy logic controller (FLC). This controller facilitates seamless integration of the primary and backup protections, ensuring effective coordination of the operation of the protection relays and the detection of any abnormal behaviors. Through MATLAB/SIMULINK simulations, the performance of this system is successfully evaluated, demonstrating the effectiveness of incorporating fuzzy logic in protective systems. This approach significantly enhances the system's ability to promptly and reliably detect abnormal activities and internal faults.

Hosseinimoghadam *et al.* (2021) discuss the issue of magnetizing inrush currents causing false trips in differential protection for power transformers. They propose a solution that integrates fuzzy systems and Clarke transforms to enhance the accuracy of differential protection. The algorithm, based on differential current analysis and fuzzy logic, determines the appropriateness of issuing a cutoff command to the protection relays. Tested on a substation transformer model using PSCAD/EMTDC software and MATLAB, the research presents a method combining Clarke transform and fuzzy logic to improve differential protection performance. The simulation results confirm the efficiency of this approach in enhancing differential relays.

Dashtdar *et al.* (2021) address transformer interruptions due to magnetizing inrush currents and their impact on differential relay operations. They propose a solution applying Clarke transform to the differential current and using fuzzy logic for decision-making regarding protection relay cutoff commands. Validated through simulation software, their algorithm demonstrates improved efficiency in enhancing differential relay performance. The paper presents an innovative approach to power transformer differential protection, utilizing Clarke transform and fuzzy systems to effectively manage the impact of magnetizing inrush currents. The algorithm shows improved accuracy and reliability in distinguishing fault scenarios compared to existing methods.

Mehmet (2020) emphasizes the critical role of power transformers in power systems and the need for robust protection mechanisms. The paper focuses on the use of differential protection relays and the integration of fuzzy logic to enhance their operation. The thesis develops a fuzzy-based relay algorithm incorporating features like flux-differential current derivation, harmonic restriction, and percentage differential curves. The results showcase the success of utilizing fuzzy logic in controlling protection relays for power transformers. The fuzzy-based relay algorithm effectively identifies faults and abnormalities, highlighting the potential of fuzzy logic in transformer protection.

Dinesh (2019) focuses on developing a differential protection scheme for power transformers, utilizing a fuzzy logic controller to enhance the performance of relays. This scheme is designed to be responsive during internal faults while remaining insensitive to external faults or magnetizing inrush currents. The goal is to ensure rapid tripping for internal faults and to avoid false operations for external faults. Simulation results demonstrate the effectiveness of the fuzzy logic-based differential relay in achieving fast tripping during internal faults and in accurately discriminating external faults. The research introduces a novel protection scheme that leverages fuzzy logic for improved differential relay performance, offering rapid and precise tripping during internal faults and preventing false operations during external faults and inrush currents.

Abasi *et al.* (2019) introduce a novel method to enhance the performance of differential relays, employing fuzzy logic. This method aims to protect short transmission lines against cross-country faults, a challenge where traditional differential relays may experience operational interruptions. The propose method incorporates fuzzy logic alongside adjustments in per-unit values and modifications to the slope of the differential relay. These enhancements notably improve the relay's stability. The thesis's findings indicate that this fuzzy logic-based technique significantly boosts differential relay performance, particularly in long-distance fault scenarios. The approach stands out for its simplicity, adaptability, and effectiveness in managing external faults, even under conditions of current transformer saturation.

Parihar *et al.* (2017) emphasize the importance of power transformers within power transmission systems and the need for reliable protection mechanisms. They introduce a new relaying algorithm based on fuzzy logic in MATLAB/Simulink to enhance fault detection sensitivity. This approach aims to effectively differentiate between fault and non-fault conditions, ensuring reliable operation of power transformer differential relays. The paper demonstrates that the fuzzy logic-based relay designed for power transformer protection effectively detects various fault and inrush current conditions, offering advantages such as improved reliability, reduced energy loss, and enhanced power supply stability.

Bejmert *et al.* (2014) address the limitations of the conventional second harmonic restraint method in differentiating between fault currents and inrush currents in power transformers. They introduce a novel multi-criteria stabilization algorithm based on fuzzy logic, designed to offer improved discrimination capabilities for inrush conditions. The research presents a new multi-criteria fuzzy logic transformer inrush stabilization algorithm that overcomes the drawbacks of traditional second harmonic restraint methods.

Dey *et al.* (2012) aim to develop a protection and monitoring system for power transformers using fuzzy logic and Clarke's transform. Fuzzy logic is used to analyze various operating conditions of the transformers, while Clarke's transformation preprocesses input signals for decision-making by the fuzzy system. The proposed methodology is validated through comprehensive simulations and real-time hardware implementation, showcasing the synergy between Clarke's transform and fuzzy logic in enhancing differential protection for power transformers.

Abbas (2009) focuses on enhancing the sensitivity and reliability of power transformer protection using a novel relaying algorithm based on fuzzy logic. The primary challenge addressed is differentiating between magnetizing inrush currents and internal faults, especially in scenarios with low second harmonic components for inrush and high for internal faults. The research presents a fuzzy logic-based approach to power transformer protection, addressing the challenges associated with distinguishing between inrush currents and internal faults.

In this thesis, we aim to model, simulate, and analyze differential relay and fuzzy differential relay behavior for power transformer protection using MATLAB/SIMULINK. Previous studies have examined different conditions for analyzing these relays, and both differential relay and fuzzy logic relays have been used for transformer protection. The current thesis uses a fuzzy logic differential relay with vector group (phase shifts) for transformer protection. The simulation model developed using MATLAB/SIMULINK showed high sensitivity to internal faults and stable performance during external faults and normal operation. Phase shift analysis revealed that extreme external faults near the transformer cause CT saturation, causing changes in RMs value and potential mal-operation of relays. Behavior analysis examined the relay's behavior in response to different fault scenarios and operating conditions, focusing on sensitivity to internal faults and stability during external faults and normal operation.

3. GENERAL BACKGROUND

A transformer is an electromagnetic device that was developed by Michael Faraday to enable the transmission of rotating current. Initially, DC-based systems couldn't be exchanged over long distances due to control issues within lines. Without a transformer, AC transmission would not be possible, as the issues would still exist. The transformer allows AC to be transmitted at high voltage but low current, addressing line issues due to the value of I2R. It is used to convert high voltage, low current power to high current power for final distribution within a community without changing the frequency or control transmitted from the producing station. Single-phase transformers are the most efficient way to use a voltage transformer (Figure 3.1).

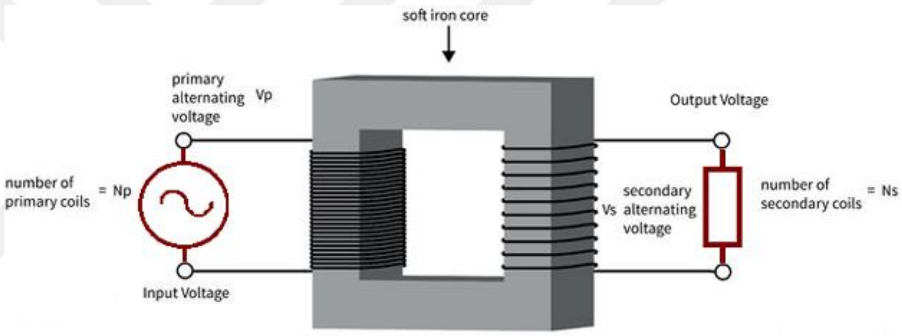


Figure 3.1 Single-phase transformer

A Single stage transformer consists of a primary and secondary coil, connected by an electric connection, forming a common attractive press at the transformer's center. This ensures control transmission through electromagnetic acceptance, making transformers useful for separation of connections. Two main effects define transformer operation: current flowing through a wire creates an attractive field around the wire, which is inversely proportional to the sum of current passing through the wire. The greater the attractive field, the larger the field is, and when applied to the primary coil, it activates a field around the transformer's center. The moment impact, combined with the primary, explains transformer operation. When a conductor is wound around a magnet and magnet, the field changes, causing a current within the conductor, which is usually determined by the turns number of the conductor coil. This current is then energized by the auxiliary coil. When a voltage is connected to the primary coil, it creates an attractive field around the center, and the quality depends on the linked current. The created field activates a current in the secondary coil, which is influenced by the attractive field and the turns number of the auxiliary coil. This operational rule explains why AC is needed, as the transformer will work when there is a variation in the linked voltage or current, preventing it from being used for DC.

3.1 Construction of the Transformer

Transformers are fundamental components in electrical engineering, designed to transfer electrical energy between two or more circuits through electromagnetic induction. A typical transformer consists of several key elements, each playing a crucial role in its functionality and efficiency:

1) Inductive Coils: A transformer typically comprises two coils of wire, known as the primary and secondary windings. These coils are electrically isolated from each other but magnetically linked through the core. The primary winding receives the input voltage, and the secondary winding delivers the transformed voltage. The ratio of the number of turns in these windings determines the voltage transformation ratio of the transformer.
2) Core: The core of a transformer serves to provide a path for the magnetic flux. It is usually made of high-permeability silicon steel or other ferromagnetic materials. The core's design and material significantly influence the transformer's efficiency and losses.
3) Laminations: The core is typically constructed from thin laminations of silicon steel or similar materials, stacked together. These laminations are insulated from each other to minimize eddy current losses, which are currents induced within the core that can cause significant energy loss and heating. Laminated cores are more effective in reducing these losses compared to solid cores.
4) Insulation: The coils are insulated from each other and from the core to prevent electrical contact, which could lead to short circuits and transformer failure. Insulation

materials must withstand the operational temperatures and electrical stresses experienced by the transformer.

5) Magnetic Circuits: The core and yoke (the part of the core that forms the magnetic circuit outside the windings) constitute the transformer's magnetic circuits. These components ensure a continuous path for the magnetic flux, which is essential for the transformer's operation. The design of these circuits influences the transformer's efficiency and performance.
6) Core Shapes: Transformers can have cores of various shapes, each designed to optimize certain aspects of performance. Common shapes include E-I and L cores. Each shape has its own advantages in terms of ease of winding, magnetic flux distribution, and manufacturing considerations.
7) Reduction of Eddy Currents: The laminated construction of the core helps in reducing eddy currents, which are circular currents induced in the core due to the alternating magnetic field. These currents can cause significant power losses and heating. By using thin laminations and insulating them from each other, eddy currents are minimized, thus enhancing the transformer's efficiency.

Transformers are essential in power transmission and distribution systems, enabling the efficient transfer of electrical energy over long distances and between different voltage levels. The design and construction of transformers have a direct impact on their performance, efficiency, and suitability for specific applications. Figure 3.2 shows the HV windings and LV windings.

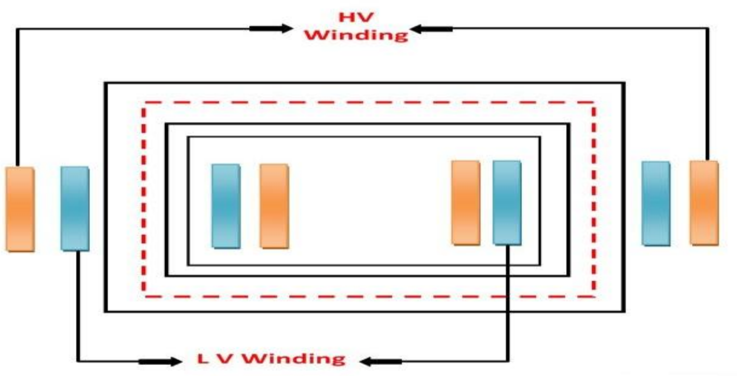


Figure 3.2 HV windings and LV windings

There are three major shapes of the covered steel sheets to select from, which are E-I as illusterated in Figure 3.3, and L as illusterated in Figure 3.4.

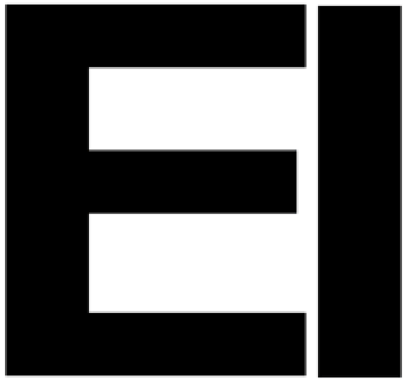


Figure 3.3 Transformer core E-I lamination

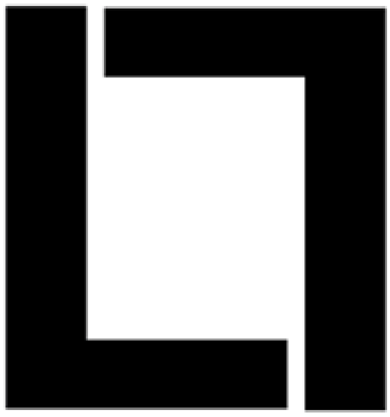


Figure 3.4 Core L lamination

When stacking covers for a center, rotate the sides of the joint to avoid hesitance at joints. For example, sheets are assembled as front-facing during the primary assembly and back-facing for the next assembly. It is crucial to indicate the type of transformer as step up or step down, as this determines the turns number in the essential or auxiliary coil (Figure 3.5).

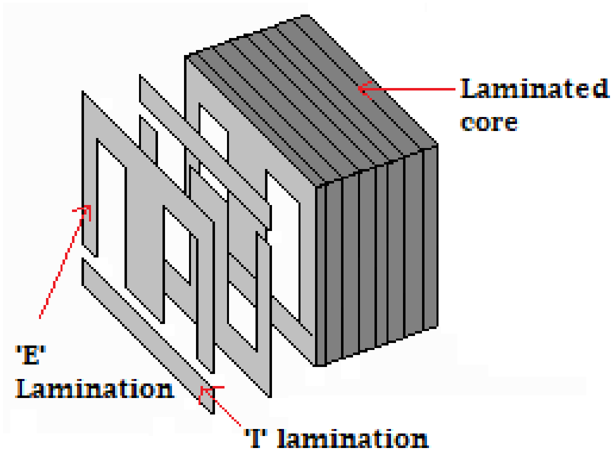


Figure 3.5 Stacking the lamination together to form the core

3.2 Transformer Types based on Voltage Level

Transformers are devices that conduct power through electromagnetic flux without any electric connection. They have different windings or coils on the essential and auxiliary sides, with some being center-tapped. They can change voltage levels from the essential side to the auxiliary side and are categorized into Step-Down Transformer, Separation Transformer, and Step-Up Transformer based on voltage levels. These transformers are designed to handle different situations and voltage levels.

3.2.1 Step down transformer

Step-down transformers may be a sort of transformers which changes over the tall voltage and moo current from the essential side to the moo voltage and tall current esteem on the auxiliary side as illusterated in Figure 3.6.

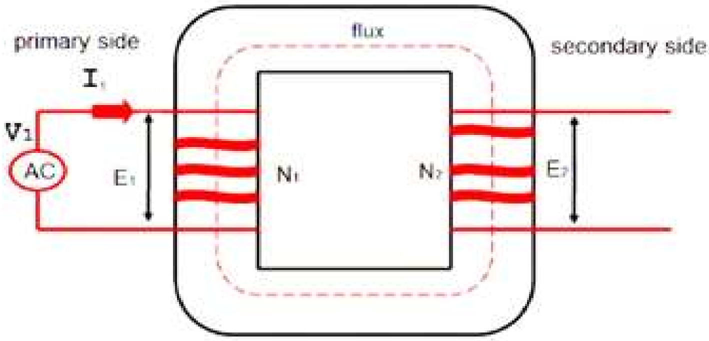


Figure 3.6 Step down transformer

The voltage curve of primary and secondary coils are illusterated in Figure 3.7.

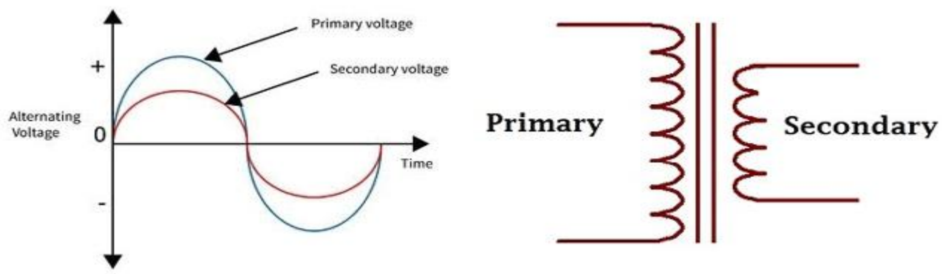


Figure 3.7 Step-down transformers voltages

Transformers may be a sort of inactive electric gear that changes electric to attractive vitality and once more to the electric vitality as illusterated in Figure.3.8. A step-down transformer features a wide assortment of applications in electric frameworks and transmissions lines (Totonchi *et al.* 2020).

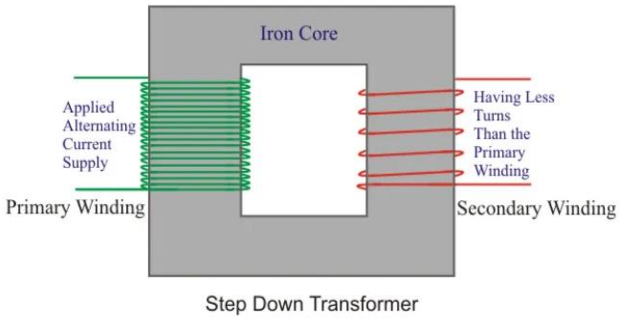


Figure 3.8 Step down transformer block

LV (voltages up to 1kV) and HV application (voltages over 1kV) can be generally isolated into bunches. Just as transformers can step down the voltage – going from a better essential side voltage to a reduce auxiliary side voltage – they can moreover step up the voltage. The transformer's turns proportion (n) of a step-down transformers is around corresponding to the voltage proportion as in following Equation (3.1).

$$n = \frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{3.1}$$

The last Equation (3.2) is arranged as output's ecpression named step-down transformer's formula.

$$V_s = \frac{N_s V_p}{N_p} \tag{3.2}$$

3.2.2 Step-up transformers

The step-up transformers could be a part of inactive electric gear that changes electric vitality to the attractive vitality (within the transformers' attractive-center) and once more to the electric vitality (on the auxiliary part). Step-up transformer that shows in Figure 3.9 contains various applications in electric frameworks and transmissions lines.

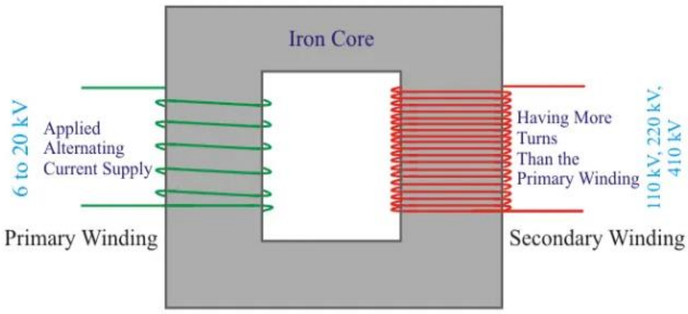


Figure 3.9 Step up transformer

The working recurrence and ostensible control are roughly break even with on the essential and auxiliary sides since the transformers may be an exceptionally productive piece of hardware – whereas the values of current and voltage are diverse. A transformer gives segregation within the electric systems. (Ugli 2021) Because of the two fundamental highlights, the transformers are the foremost critical portion of the electric framework and gives temperate and solid transmissionss and dissemination of electric-power (Akbari and Rezaei-Zare 2020).

Theoretically, any transformer is ready to work as a step- down or a step-up sort. It as it were relies on the vitality streaming directions. The HV winding contains a tremendous turns comparing to the LV winding. The last one wire contains a greater cross-sections than HV wire.

The ratio (n) of turns is roughly corresponding to the voltage proportion as in Equation (3.3).

$$n = \frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{3.3}$$

The primary-side usually has a lower turns than the secondary one. Which means the power streams from the LV-side to the HV-side. The voltage is ventured up from the essential voltage to the auxiliary voltage (yield voltage). This condition can be modified for the equation for the yield voltage. This can be some of the time alluded to as the step up transformer Equation (3.4).

$$V_s = \frac{N_s V_p}{N_p} \tag{3.4}$$

3.3 Losses in Transformer

As illusterated in Figure 3.10 various kinds of misfortunes like press, copper or hysteresis-misfortunes, as well as vortex current misfortunes, stray, and dielectric misfortunes.

These hysteresis-misfortunes occur since the magnetization's variation within thier centers.

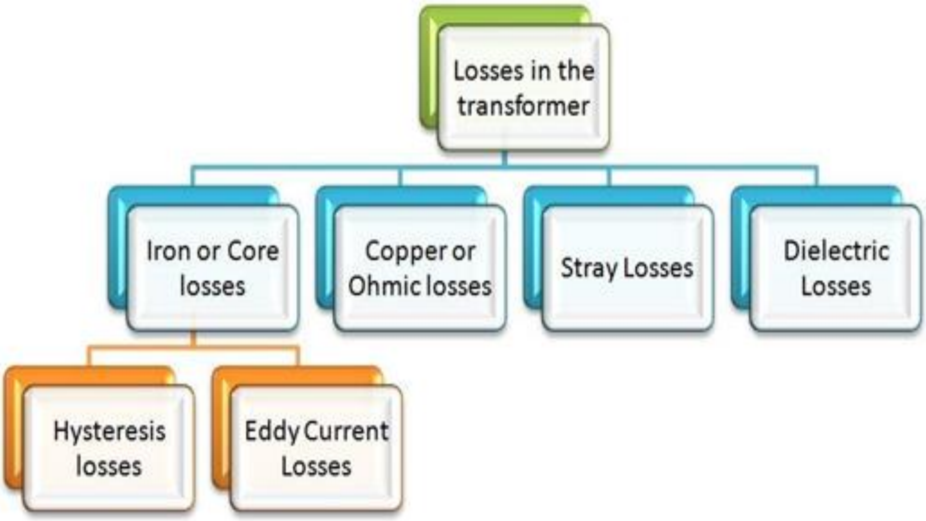


Figure 3.10 Transformer losses kinds

As the electric transformers could be inactive gadgets, mechanical losses in transformers does not come into picture regularly. Consequently, we are considering as it was electric misfortunes in transformers. Misfortunes in any device are defined broadly as the distinction between yield and input control. Hysteresis-misfortunes in transformers and Whirlpool-current misfortunes are misplaced as (I_2R) misfortunes, since these windings have inner resistance. The essential ones are called center misfortunes or press-misfortunes in transformers and the others are known as ohmic misfortunes or copper-misfortunes. Another misfortunes happens in transformers, known as Stray Misfortunes, because of Stray fluxes link with the winding conductor and mechanical structures.

The transformers' loss are devided into the categories: copp, iron, and dielectric loss. Considering the Steinmetz observations relation and the IEEE.Std.C57.110 standards, the transformer misfortunes are communicated as the entirety of the transformers stack winding and loss no-load core loss:

$$P_{TL} = (K_1 f B_m'' + K_2 f^2 B_m^2 t^2)G + p_F + P_{I^2R} + P_{EC} + P_{OSI} \quad (3.5)$$

In the given context, K_1 and K_2 are dependent on the characteristics of the silicon steel. B_m'' represents the amplitude of the working flux density of the silicon core. Additionally, G denotes the core mass, and 't' refers to the thickness of the silicon wafer. The term p_F is used to describe the core's additional loss, which generally constitutes a relatively small proportion. Finally, P_{EC} signifies the loss due to transformer winding resistance.

3.3.1 Transformer core harmonic loss

The transformer's unit-core losses portion can be defined as in Equation (3.6)

$$P_N = K_1 f B_m^n + K_2 f^2 B_m^2 t^2 + p_F' \tag{3.6}$$

Where K_1 and K_2 refers to the core-hysteloss coefficient (Kh) and the core vortex losses coefficient (Kc), respectively. n is the hysteresis coefficient, considered generally equal to 2 nd p_F'unit-additional core losses. Also, maximum value of flux density in wb/m2 *Bm* determined as in Equation (3.7)

$$B_m = \frac{E_m}{4.44fNA} \tag{3.7}$$

In this context, E_m represents the amplitude of the induced electromotive potential (EMF) in a transformer. N denotes the number of turns in the winding, and A refers to the effective cross-sectional area of the transformer's core.

Under single harmonics the unit-core losses can be calculated according to the upcoming expression in Equation (3.8) (Baoming *et al.* 2005).

$$P_{NL} = \frac{E^2 \quad mh}{4.44^2 N^2 A^2} \left(\frac{K_h}{f} + K_C t^2 \right) + p_F' \tag{3.8}$$

Then, under multiple harmonics the unit core-losses of the transformer is illstrate in Equation (3.9).

$$P_{NLh} = \frac{1}{4.44^2 N^2 A^2} \sum_{h=2}^{h_{\max}} E_{mh}^2 \left(\frac{K_h}{f} + K_C t^2\right) + p'_F \qquad (3.9)$$

3.3.2 Winding-harmonic losses

The type T proportionate show is frequently utilized to recreate the transformers operating guideline when analysis the transformers winding consonant misfortune, and the transformers consonant winding resistance is more often than not identical to $\sqrt{hR_{dc}}$ (h is the consonant arrange, Rdc is the DC resistance) in arrange to compute the transformers winding resistance misfortune P_{I^2R} and vortex misfortune PECh. The outside control supply could be respected as the superposition of free sources of diverse consonant components by utilizing T-type proportionate demonstrate, as appeared in Figure 3.11.

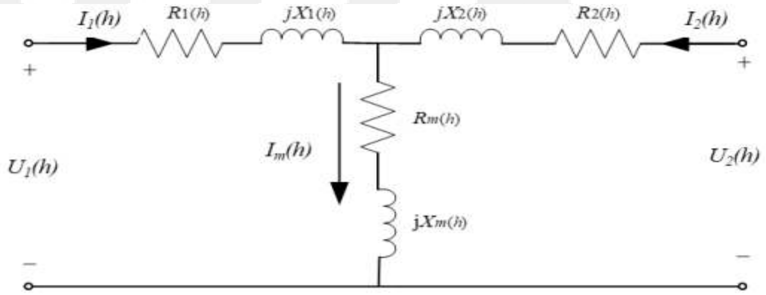


Figure 3.11 The model of type T equivalent-circuit

The primary-side transformer's active power losses harmonic winding is computed as in Equation (3.10):

$$P_{LLh1} = \sum_{h=2}^{h_{max}} \left|\frac{\dot{U}_{1(h)} - \dot{I}_{M(h)}\left(R_{m(h)} + jX_{m(h)}\right)}{R_{1(h)} + jX_{1(h)}}\right|^2 R_{1(h)} = \sum_{h=2}^{\infty} I_{1(h)}^2 R_{1(h)} \qquad (3.10)$$

The secondary side transformer's active power loss harmonic winding is computed as in Equation (3.11):

$$P_{LLh2} = \sum_{h=2}^{h} \left| \frac{\frac{1}{k} \dot{I}_{M(h)} (R_{m(h)} + jX_{m(h)}) - \dot{U}_{2(h)}}{R_{2(h)} + jX_{2(h)}} \right|^2 R_{2(h)} = \sum_{h=2}^{\infty} I_{2(h)}^2 R_{2(h)} \tag{3.11}$$

The calculations of harmonic winding losses of Three-phase transformers are in Equation (3.12) :

$$P_{Th} = 3(P_{LLh1} + P_{LLh2}) \tag{3.12}$$

3.3.3 Core loss in transformers

Hysteresis and eddy-current losses, depend upon materials attractive properties utilized for building the center of transformer and its plan. So these misfortunes are settled and don't rely on the stack current. So center misfortunes which is then again known as press misfortune in transformer can be considered as steady for all run of stack. Hysteresises loss in transformers are explain in Equation (3.13).

$$W_h = K_h f B_m^{1.6} \text{ watts} \tag{3.13}$$

3.3.4 Eddy current losses

In transformer, the alternating current which is in the primary generates alternating magnetic flux within the center and as the flux joins with auxiliary winding, actuated voltage will be in auxiliary, coming about current to stream through the stack associated with it. A few of the substituting fluxes of transformers; may too interface with other conducting components like steel center or press body of transformer etc. As substituting flux joins with those components of transformer, a local actuated emf would be exicited. Because of these emfs, there would be streams that is able circulate locally at that components of the transformers. These alternating current (Figure 3.12) won't contribute in yield of the transformers and scattered as warm. This sort of vitality misfortune is called vortex current misfortune of transformer. It was a wide and straightforward clarification of whirlpool current losses (Taha *et al.* 2021).

Given that these currents cannot perform any practical tasks, they lead to the unfortunate occurrence of Eddy Current Losses, an intriguing phenomenon characterized by I^2R losses. This effect, along with hysteresis losses, contributes to an increase in the temperature of the magnetic material, albeit to varying degrees (Zeynelgil and Demiroren 2002). An alternative term for the combined issues of eddy currents and hysteresis losses, particularly in materials like magnetic cores, is magnetic losses, core losses, or iron losses (Madahi *et al.* 2020).

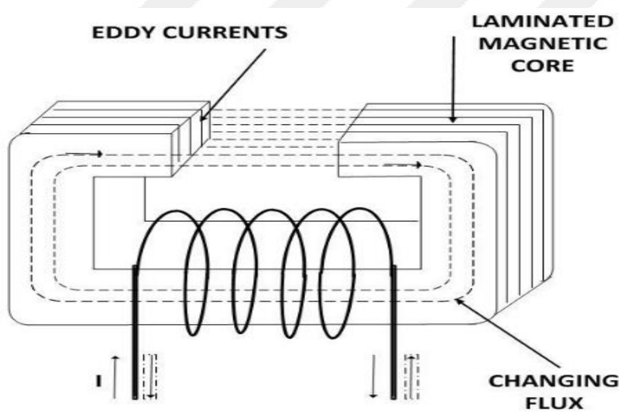


Figure 3.12 Eddy currents in transformer

Figure 3.12 presents a cross-sectional view of the magnetic core. Within this core, an electromotive force (EMF) is generated due to the interaction of fluctuating magnetic flux with the core material itself. This interaction unfortunately leads to the phenomenon known as Eddy Current Loss, often referred to as I^2R loss. In this context, 'I' represents the amplitude of the induced current, and R denotes the resistance of the path taken by the eddy currents. If the core has a significantly large cross-sectional area and is densely compacted, the magnitude of 'I' will be correspondingly large. Consequently, this leads to substantial energy losses, often referred to colloquially as 'a lot of money lost' due to increased power dissipation.

To diminish the vortex current loss basically there are two methods:

1) Reducing the magnitude of the eddy current

The current size can be decreased by component the strong center into lean sheets called laminations, within the parallel plane to the attractive field.

2) Laminating the core

The range of each area is diminished and Therefore the actuated emf too diminishes. As the zone through which the current is passed is littler, the resistance of whirlpool current way increments.

For physical considerations, thin plate of thickness (τ), adopted for reducing eddy losses. Thus, we are trying to write an approximate formula for eddy-losses for thin plates and identify the related parameters (Figure 3.13).

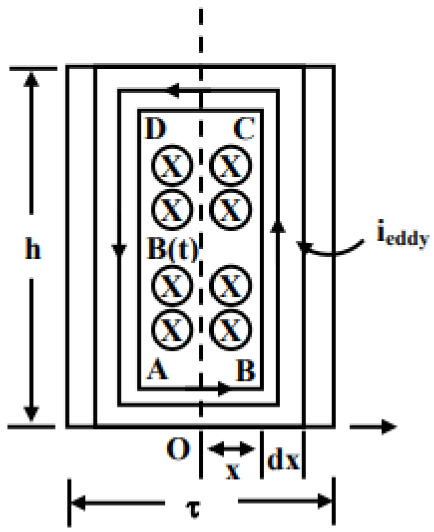


Figure 3.13 Element eddy-current curve

Eddy-current losses are I_2R basically misfortunes happening nner the center. The current is occured on by the initiated-voltage because of the changs in time field as appeared within the Figure.Considering a lean attractive plate of length L, the thickness τ and tallness h are little comparinw with h and L exceptionally.

$b = B_{max} \sin\ \omega t$ (3.14)

The field is opposite to the rectangular area formed by h and τ in Figure 3.14

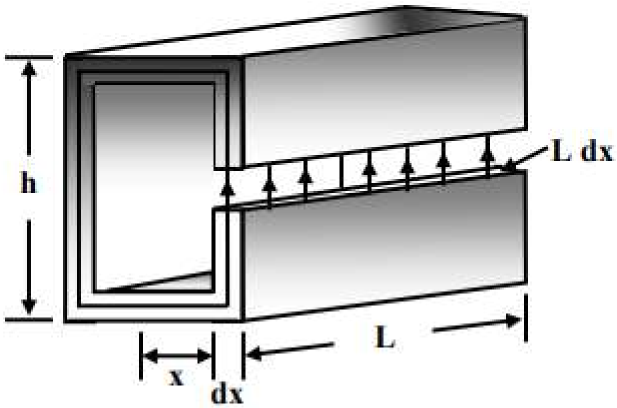


Figure 3.14 Section in the element eddy-current path

By the tests, the vortex-current control misfortunes is given by the conditions appeared in Equation (3.15)

$P_e = K_e B_m^2 t^2 f^2 V$ (3.15)

4. MATERIALS AND METHODS

4.1 Differential Protection Scheme

In typical conditions, the input energy of a system equals its output energy, a balance maintained by energy transformers. Normally, the differential coil in the system experiences no current flow. However, any malfunction in the designated area disrupts this current balance, leading to the closing of relay contacts and the generation of a trip signal. This signal activates the designated Circuit Breaker (CB), resulting in the disconnection of the faulty component. Differential relays are tasked with comparing the secondary and primary currents of the power transformer. The scaling down of these currents is efficiently achieved using current transformers (CTs). The operation of these differential relays is simplified and depicted in Figure 4.1. To prevent the flow of electricity through the relays, the polarity of the CTs is systematically reversed.

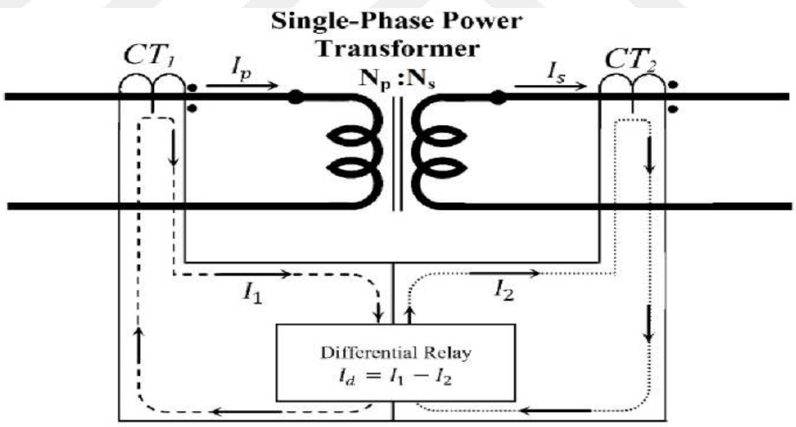


Figure 4.1 Differential protections for Single-phase two winding transformers

Selecting current transformer (CT) ratings to ensure a constant current on the secondary side requires careful consideration, particularly in matching them with the corresponding power ratings. A primary challenge lies in the availability of CT ratios, which are typically only accessible in standard formats. Unfortunately, these standard ratios often do not precisely align with specific requirements, thereby limiting the primary CT ratings. The turn ratio for the primary current is represented as one divided by N1, while for the secondary current, it is one divided by N2. By connecting the current transformer (CT) to the primary side of the power transformer, its secondary current can be calculated using Equation (4.1), as detailed in (Akbari and Rezaei-Zare 2020).

$$I_1 = \frac{I_p}{N_1} \tag{4.1}$$

Where: I_p the primary-current . I_1: the secondary current N_1: the turns number in the secondary side. In the exact method, the CT secondary-current calculated as in Equation (4.2)

$$I_2 = \frac{I_s}{N_2} \tag{4.2}$$

Where $I_s$the secondary-current, I_2 represented tothe secondary-current of CT_2 and N_2: the secondary side turns in the CT2. Since the differential-current is: $I_d = I_1 - I_2$, thus, Equations (4.1) and (4.2) indicate the differential-current I_d as in Equation (4.3):

$$I_d = \frac{I_p}{N_1} - \frac{I_s}{N_2} \tag{4.3}$$

In case of no internal error in the protected-zone, the current I_2 equals I_1 in magnitude but in opposite direction. The differential-current I_d= 0, as illusterated in Figure 4.2. The Equation (4.4) be:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \tag{4.4}$$

Where N_s, N_p is the secondary and primary turns, respectively and $\frac{N_s}{N_p}$ is the transformation ratio.

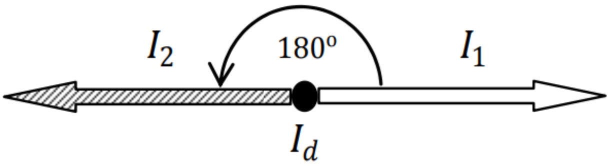


Figure 4.2 CT's output currents are opposite in directions but same in magnitude

In case of no internal error in the protected-zone, the current I_2 equals I_1 in magnitude but in opposite direction.Then the differential-current is $I_d = I_d\angle\theta$ has increased as illisterated in Figure 4.3.

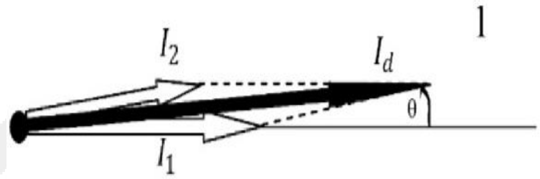


Figure 4.3 Output currents of the CTs (Current Transformers) are not equal

Equation (4.5) indicates the secondary-current as in (Jiao and Li 2018).

$$I_s = \frac{N_p}{N_s} I_p \tag{4.5}$$

Consequently, by manipulating Equations (4.3) and (4.5)

$$\begin{aligned} I_d &= \frac{I_p}{N_1} - I_p \frac{N_p}{N_s N_2} \\ I_d &= \frac{I_p}{N_1}\left(1 - \frac{N_p N_1}{N_s N_2}\right) \\ \lambda &= \left(1 - \frac{N_p N_1}{N_s N_2}\right) \end{aligned} \tag{4.6}$$

From Equation (4.7) shows that the term λ equals null for making $I_d = 0$

$$\begin{aligned} 1 - \frac{N_p N_1}{N_s N_2} &= 0 \\ \frac{N_2}{N_1} &= \frac{N_p}{N_s} \end{aligned} \tag{4.7}$$

When connecting three-phase power transformers, a 30-degree phase shift between the secondary and primary currents often needs to be considered, as illustrated in Figure 4.4. This phase displacement occurs in Δ-Y or Y-Δ transformers and is a result of the present conversions from Δ to Y or Y to Δ configurations.

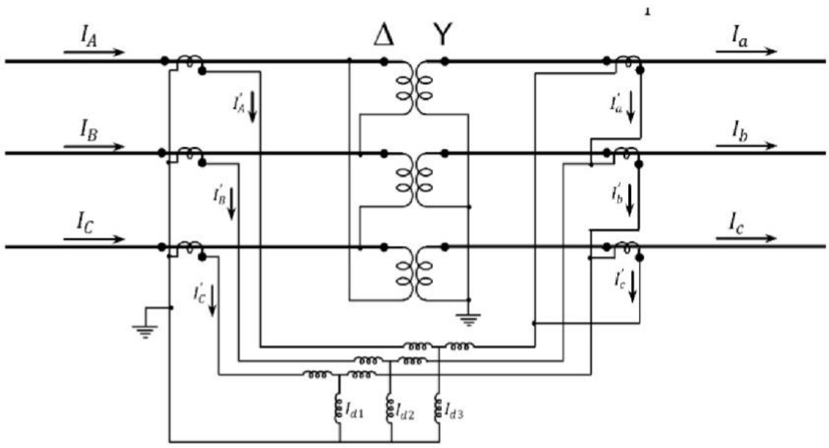


Figure 4.4 Connections of differential-protection of 3-phase Δ-Y transformers

Correcting this phase shift is straightforward: it involves connecting the secondary circuits of the Current Transformers (CTs) in the opposite direction to the phases of the power transformers. For a Y-Δ configuration, the transformer windings should be interconnected accordingly. Conversely, in a Δ-Y configuration, it's the CTs' secondary windings that need to be linked. To elucidate the phase displacement observed in Δ-Y transformer topologies, Figure 4.5 demonstrates the relationship between the phase voltage (Vph) and the line-to-line voltage (VLL), as explained by (Fan *et al.* 2017).

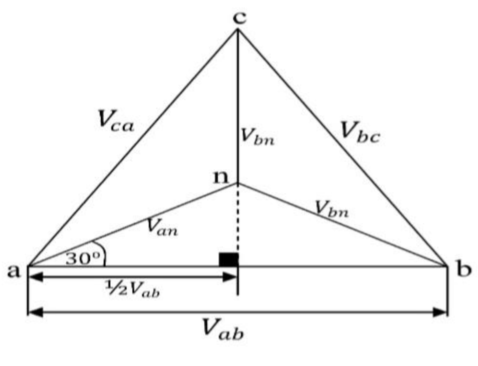


Figure 4.5 The relation between VLL and Vph in Δ-Y or Y-Δ linked transformers

Equation (4.8) indicates the relation between VLL and Vph (Piskunov and Mokeev 2021).

$$V_{ab} = \sqrt{3}V_{an} \quad (4.8)$$

4.2 Phase Differential Protection

Figure 4.6 (A) illustrates that, as the fault is located outside the protected zone, the fault current flows through it before escaping. In this scenario, only the coils affected by the fault have the capability to transmit secondary current, while the functional coils do not.

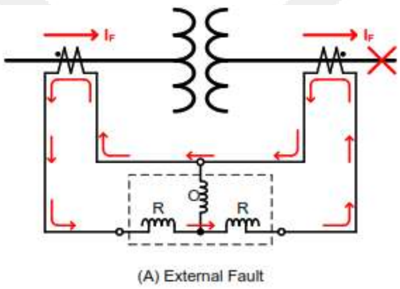


Figure 4.6 Current differential protections for power transformers

Figure 6.6 (B) demonstrates that when a fault occurs within the protected zone, the secondary current flows through both the operating coil and the restraining coil. However, choosing a readily available CT ratio is not an effective strategy for power transformer differential protection. To minimize discrepancies, compensatory circuits or specialized relay designs are employed. Differential protection can be enhanced with the use of restraining coils, which apply an initial 'torque' to the trip contacts. For the trip mechanism to activate, the current in the operating coils must surpass a specific proportion of the current in either of the restraining coils. This proportion, often referred to as the 'gradient,' is a critical aspect of the system's operational characteristics.

4.3 Transformers Differential Protection

This component does an association between the current recompense rule for transformers differential assurance and AT adjust conditions of the ensured transformers. It moreover clarifies the reason of a differential relation that takes after the short circuit current remuneration rule guarantees the location of inside transformers brief circuits. Considering begin with standards and adjusting the ATs permit for the advancement of current recompense rule for non-standard transformers associations.

Figure 4.7 clarifies the sample Y-delta transformer.

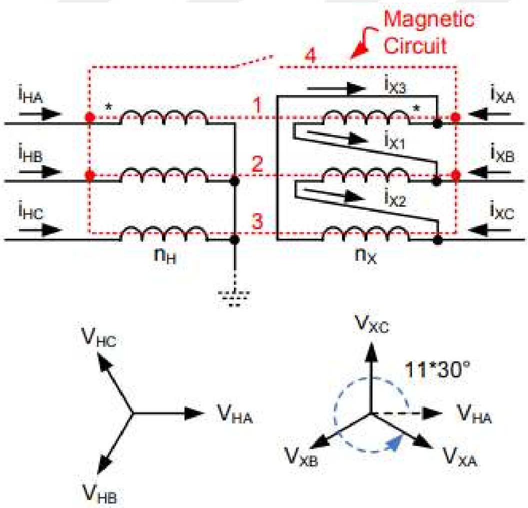


Figure 4.7 The Y-delta power transformer

The three legs Equation (4.9) after dismissing the magnetizing branch of the core

$$AT_1 = n_H i_{HA} + n_X i_{X_1}$$
$$AT_2 = n_H i_{HB} + n_X i_{X_2} \quad (4.9)$$
$$AT_1 = n_H i_{HC} + n_X i_{X_3}$$

Equation (4.10) of nodes current balance of the delta windings according to Kirchhoff's current:

$$
\begin{aligned}
i_{XA} - i_{X_1} + i_{X_3} &= 0 \\
i_{XB} - i_{X_2} + i_{X_1} &= 0 \\
i_{XC} - i_{X_3} + i_{X_2} &= 0
\end{aligned} \tag{4.10}
$$

Instep, we dispose of the delta-winding streams within the conditions from (4.10) utilizing the AT conditions in (7) which means in Equation (4.11):

$$
\begin{aligned}
n_X i_{XA} + n_H(i_{HA} - i_{HC}) - (AT_1 - AT_3) &= 0 \\
n_X i_{XB} + n_H(i_{HB} - i_{HA}) - (AT_2 - AT_1) &= 0 \\
n_X i_{XC} + n_H(i_{HC} - i_{HB}) - (AT_3 - AT_2) &= 0
\end{aligned} \tag{4.11}
$$

As clarified, ATs on any leg combine are rise to in any situation. By blending core-legs, we are able compose AT adjust conditions around the coming about attractive circuit circles as in Equation (4.12)

$$
\begin{aligned}
(AT_{P1} + AT_{S1}) - (AT_{P3} + AT_{S3}) &= 0 = AT_1 - AT_3 \\
(AT_{P2} + AT_{S2}) - (AT_{P1} + AT_{S1}) &= 0 = AT_2 - AT_1 \\
(AT_{P3} + AT_{S3}) - (AT_{P2} + AT_{S2}) &= 0 = AT_3 - AT_2
\end{aligned} \tag{4.12}
$$

The adjust conditions for the transformer in Figure 4.8 gotten to be Equation (4.13):

$$
\begin{aligned}
n_X i_{XA} + n_H(i_{HA} - i_{HC}) &= 0 \\
n_X i_{XB} + n_H(i_{HB} - i_{HA}) &= 0 \\
n_X i_{XC} + n_H(i_{HC} - i_{HB}) &= 0
\end{aligned} \tag{4.13}
$$

These rules yield selecting the following Equation (4.14) matrices:

$$
T_H = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}, T_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.14}
$$

Figure 4.8 clarifies the vector diagram, by considering it, the transformer rules current compensation

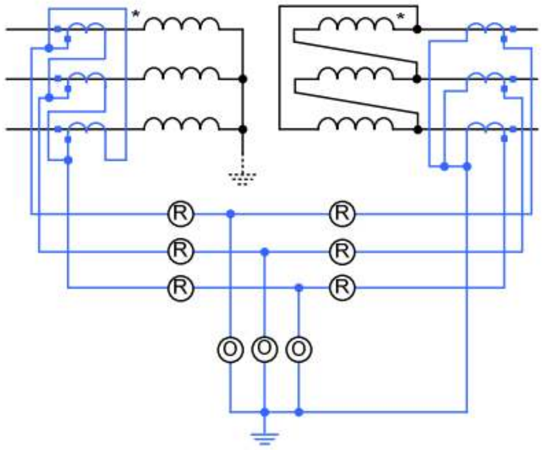


Figure 4.8 Application with external CT compensation

4.4 Three-phase Systems

Majority of devices which we bargain with are three-phase ones. Comparative to electric frameworks that are built as four wires Y or three wires delta ones, the attractive circuits of Three-phase transformers are built as a three-legged center or with a low reluctance return way as a magnetic short circuits that strength the AT to entirety spillage flux: AT1=AT2=AT3=0.

Where: AT is the ampere turns sum on the exact core-leg. Index (1, 2, and 3) refers to the core-leg with coils.

A three-legged center demands assist examination. We utilize symmetric components hypothesis for analyzing lopsided Three-phase electric frameworks. This procedure is valuable in understand the contrasts between a four and three legged center. Symmetric elements allow to break group of Three-phase streams down into the taking after elements:

- Positively-sequences
- Negatively-sequences
- Zero-sequences

The negative and positive sequence component are adjusted and whole to zero. AT and coming about flux from these elements streaming within the transformer's coils moreover sum to null, so there's no demand for a return way for flux. In this way, there's no contrast between a four legged and three-legged center for the negative and positive sequence component of the stage streams. In addition, zero sequence streams are in stage with each other and break even with in size. Since the zero-sequence streams don't entirety to null, they demand a return path to stream. It is existing for the streams within the electric circuits and the attractive circuits' fluxes, or the zero-sequence current cannot stream.

On the off chance that the zero-sequence currents gives balanced Ats, the fluxes whole to null on each core-leg, and there is no requirement for the fourth center leg. For situation, in various situations, a delta-winding is included. A delta winding clarifies up as an electric brief circuit to the zero-sequence voltages on the related Y-linked winding. Therefore, for any zero-sequence current passing within the Y-linked windings.

4.5 Zero and Negative Sequence

In three-phase systems, the AC vectors representing voltages and currents can be either balanced or unbalanced. A system is considered balanced when all three vectors have equal magnitude and are symmetrically positioned at 120-degree intervals, resulting in their combined sum being zero. Conversely, an unbalanced system is indicated when the vectors have unequal magnitudes and their resultant vector does not sum to zero. An imbalanced system is characterized by three distinct sets of components: positive, negative, and zero sequence, each representing different system characteristics.

- The positive sequence component, indicating current flow from source to load, consists of Three-phases of equal magnitude that are phase-displaced by 120 degrees from each other, with their phase sequence matching the original system.
- The negative sequence component, also indicating current transmission from source to load, is composed of three identical phases, each phase-shifted by 120 degrees. However, their phase sequence is the reverse of the original phases.

- Lastly, the zero sequence component comprises Three-phases of equal magnitude that are parallel to each other, with no phase displacement. This configuration indicates current flow from the source to the ground.

4.6 Symmetrical Components in Power Transformers

Extensive research in transformer differential protection has led to various strategies, such as relay desensitization or delay, to effectively manage transients. Inductance-based methods develop to distinguish between inrush currents and internal faults. A prevalent approach for detecting magnetizing inrush currents is the harmonic constraint differential protection, which uses one of the main phase voltages to generate a control signal. Additionally, artificial intelligence (AI) systems have increasingly been applied in power system protection.

Several factors can influence differential current in transformers, including CT saturation, over excitation, and magnetizing inrush currents. Optimal CT ratio selection is crucial to mitigate issues arising from saturation. The differential current is also affected by primary and secondary voltages, the degree of phase displacement in the transformer, the control taps of the voltage transformer, and the phase shift in the regulating transformer. Typical percentage differential relays in transformers operate within a range of fifteen to sixty percent, catering to less sensitive elements while ensuring reliable and precise operation. Numeric relays often utilize harmonic constraints, where the second harmonic is predominant in magnetic inrush currents. Presence of extremely high amplitudes of odd harmonics is indicative of over excitation. Combining fixed % differential relays with variable percentage relays is a common practice.

In wiring differential relays, it's crucial to measure currents in each phase, ensure adequate restraint windings to match the transformer windings, and account for every potential failure source. If feeder-side CTs are connected in parallel, the currents should be in phase, with minimal, ideally non-existent, current difference under load and fault conditions. The approach involves a methodical and analytical methodology, starting with phasing to align primary and secondary currents, followed by ratio adjustment, which involves precise determination of the correct CT ratio and relay tap setting to minimize the relay's operating current.

4.7 Fuzzy Logic Protective Relay

Fuzzy systems demonstrate superior performance compared to traditional differential protection strategies, particularly in defect detection and handling imprecise inputs without compromising data integrity. Fuzzy logic, a subset of logical systems, plays a significant role due to its ability to emulate human-like reasoning within complex environments. As highlighted by Arulmozhiyaly and Baskaran (2010), fuzzy logic is a robust method for identification and precise calibration. Unlike Boolean and classical logic systems, which assume binary true or false values, fuzzy logic can interpret and provide approximate solutions to problems based on a repository of approximate data that is extensive but not infallible. As noted by Kasztenny et al. (1998), fuzzy logic is highly effective for representing complex mathematical relationships. The rules governing the relationship between input and output variables in a fuzzy logic system depend on specific functions involved. Fuzzy logic methodologies are utilized for analyzing and managing power system contingencies. Figure 4.9 depicts the primary components of fuzzy inference systems.

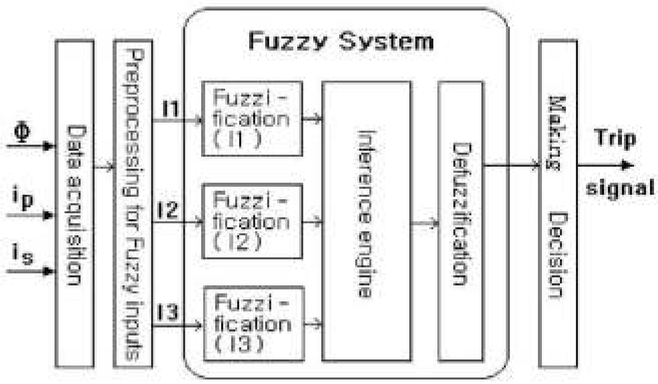


Figure 4.9 Block of fuzzy logic relay technique

Resolution was concurrently achieved using fuzzy deduction, a process in which data integrity is preserved throughout, as per (Shah *et al.* 2020). This intrinsic advantage leads to more accurate fault detection compared to conventional differential relay systems. In the specific fuzzy-based differential relay system under discussion, the inputs are defined as follows: I1 represents the ratio of dt/dϕ (the derivative of the phase angle) to dt/di (the derivative of the current). I2 stands for the second harmonic component, obtained by removing the current values. I3 is calculated as the ratio of the current magnitude (ir/id) to the difference between the current values, representing the restraint current. Figure 4.9 illustrates the preferred method for the differential relay. These principles underpin the digital protected relaying method: The flux-differential current slope can be examined with a positive and assured approach. By using technical terms and an academic tone, the complexities of this phenomenon can be effectively explored. The remainder flux does not influence the flux-differential current slope method, which relies on the slope of the (dΦ/di-id) curve for analysis. This technique successfully addresses the limitations of the earlier flux-current approach. Equation (4.15) can be used for calculating the flux differential current slope method).

$$\left(\frac{d\Phi}{di_d}\right)_k = \frac{\left\{\frac{\Delta t}{2}\left(v_{p,k}-v_{p,k-1}\right)-L_p\left(i_{p,k}-i_{p,k-1}\right)\right\}}{\left(i_{p,k}-i_{s,k}\right)-\left(i_{p,k-1}-i_{s,k-1}\right)} \tag{4.15}$$

When considering the second harmonic differential current, it's important to note the condition of magnetization inrush current. This phenomenon causes a substantial increase in the primary current flowing through the power transformer upon activation. Typically, this increase ranges from 6 to 10 times the rated current of the primary winding. As a result, a significant differential current is produced, characterized by a considerably higher second harmonic component compared to the fundamental component. This observation was detailed by Mason in 1956. Additionally, advancements in the enhancement of the core steel of power transformers have led to a notable reduction in magnetizing resistance.

The proposed controller is designed with both input and output variables. The input variable is the detection signal from the differential relay. This signal's range is carefully selected to differentiate between the current levels during normal and abnormal operating conditions. On the output side, the controller sends an isolation signal to the unit protection system. The values of this output signal are crucial, as they determine whether to trip (activate the protection mechanism) or block (prevent a false trip) based on the input values and predefined operational rules as shows in Figure 4.10.

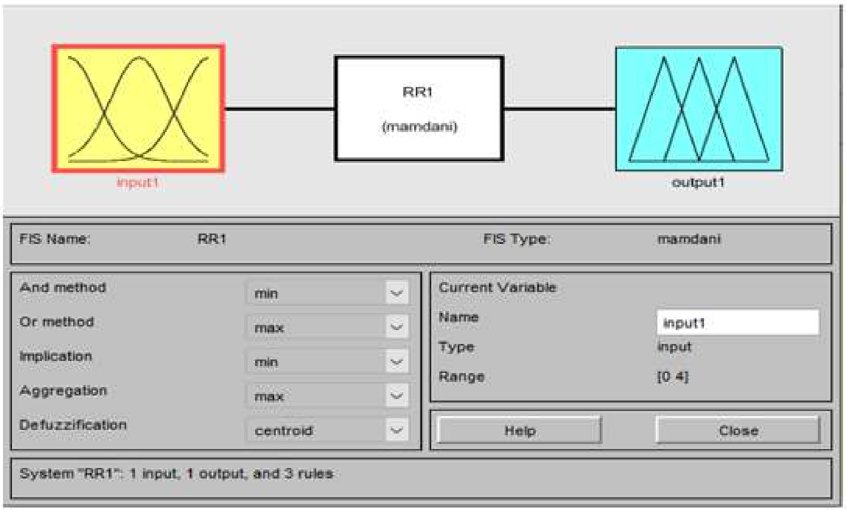


Figure 4.10 Fuzzy logic protective

The membership function in a differential relay method assigns a value between zero and one to quantify certain characteristics. This function is divided into three sets, each representing a different level of constraint on the differential current. These levels are categorized as 'small,' 'medium,' and 'large,' and are illustrated in Figure 4.11. This categorization effectively facilitates the anticipated relay response.

Regarding the output of the membership function, it is bifurcated into two categories: trip and non-trip. The categorization criterion is based on a threshold value: if the output value is 2 or more, it is classified as 'trip,' and if it is 2 or lower, it falls under 'non-trip.' This approach helps in accurately determining the relay's action based on the differential current values.

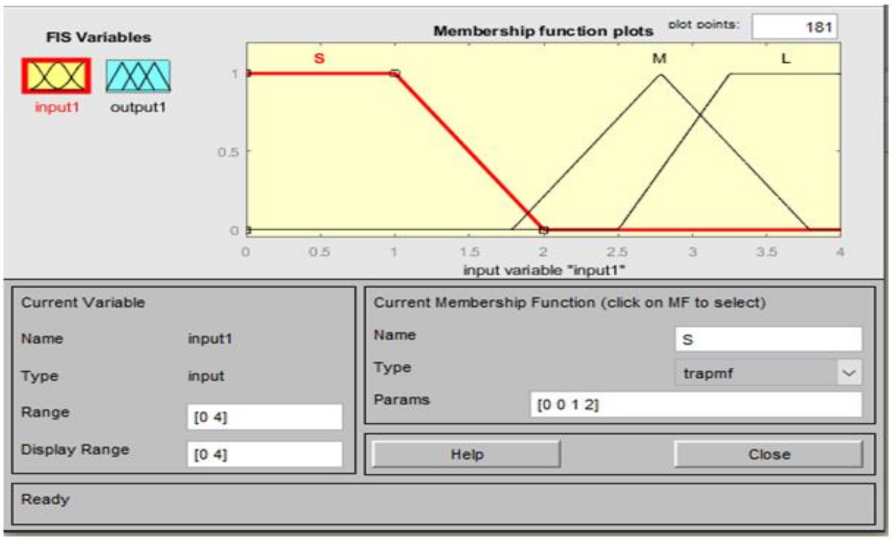


Figure 4.11 Membership function current input

Figure 4.12 depicts the bifurcation of the membership function for the output variable in the differential relay system. In this illustration, the 'trip' output is characterized by values that are greater than or equal to 2. Conversely, the 'non-trip' output is defined by values that are less than 2. This clear demarcation in the membership function facilitates the accurate determination of the relay's response based on the analyzed values.

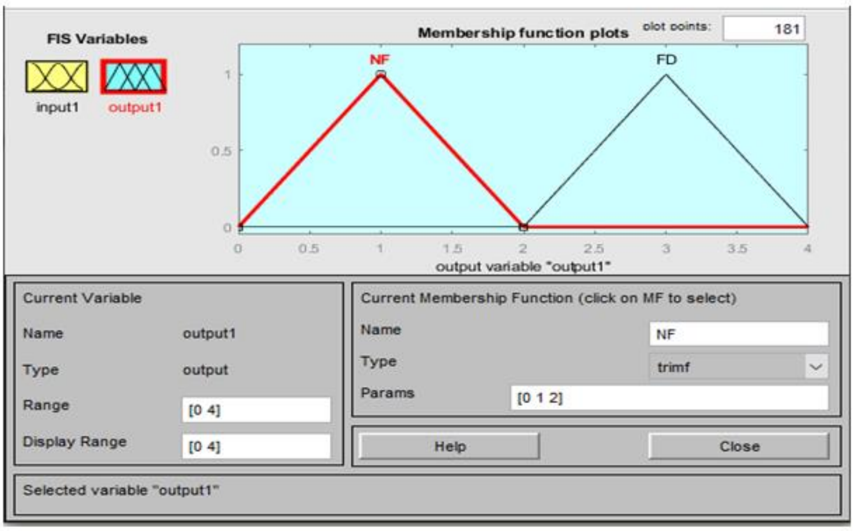


Figure 4.12 Membership function output

4.8 Differential Protection and Fuzzy Logic Relay

Differential protection functions as a precise selector in power system protection. It is essential to analyze both the magnitudes and angles of currents on either side of the designated protection zone, as underscored by (Ali *et al.* 2018). The operational scope of a differential relay is confined exclusively to this protection zone. Figure 4.13, which presents a schematic diagram, illustrates the configuration of this type of protection system.

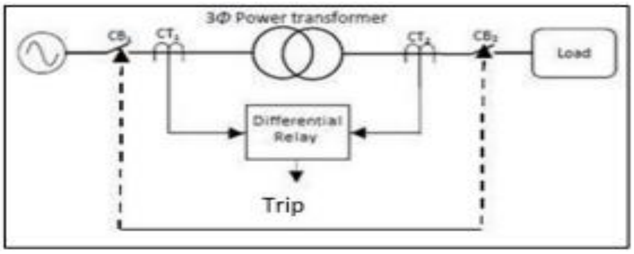


Figure 4.13 Basic configuration of differential relay

Under normal operating conditions, a differential protection system does not typically produce a significant differential current. However, the presence of internal faults within the system leads to a marked increase in differential current. This escalation can be viewed as a reliable indicator of fundamental breakdowns within the system. It's important to note, however, that while an increase in differential current can be due to internal faults, such an increase does not always conclusively indicate an internal fault.

$$\Delta I = |I1 - I2| \qquad (4.16)$$

Where, ΔI represents the differential current, which is calculated based on the secondary currents measured by two current transformers. Specifically, I1 is the secondary current measured by CT1, and I2 is the secondary current measured by CT2.

4.9 Protection Relay without Vector Group

Figure 4.14 illustrates a Simulink model for protecting a relay transformer from short circuit. The protection block consists of illustrated stages, including inputs (RMS of input and output current), preprocessing (compute inputs difference, absolute values), and determining the comparator threshold.

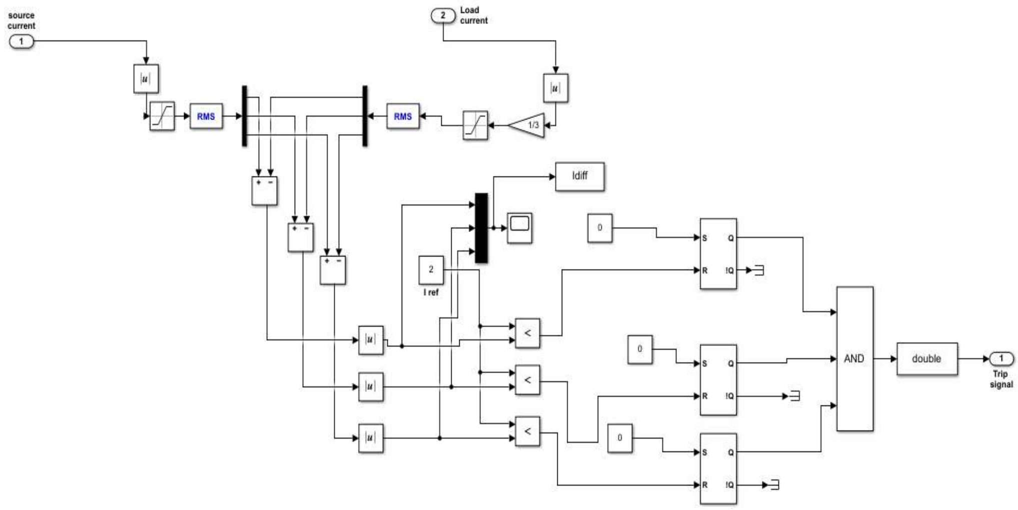


Figure 4.14 Protection relay block subsystem in Simulink Matlab

The Simulink diagram in Figure 4.14 illustrates the configuration of a differential relay, consisting of input ports In1 and In2, with output currents Id1 and Id2 respectively. To analyze the system, the two input signals are separated into separate paths. In this system, the first signal is immediately routed to an amplitude comparator block, whereas the second signal is directed to a harmonic comparator module. Following their respective processing, both signals converge at an amplitude comparator component. The generation of the second signal is a direct outcome of the harmonic test. After evaluating the magnitudes of the input currents In1 and In2, the amplitude comparator sends a signal that highlights the disparity between them to the comparator module. Simultaneously, the harmonic comparator module receives dual signals from two subsystem blocks, analyzes the input signal for the presence of harmonics, and transmits the result to the comparator. An SR flip-flop is attached to the comparator's output for additional processing.

The control signal based on the comparator signal using SR-flip flop.SR- flip flop as illustrated in Figure 4.15 includes a reset (R) and set (S). In this configuration, when “S” is active, the output “Q” is high, and “Q‘” is low.

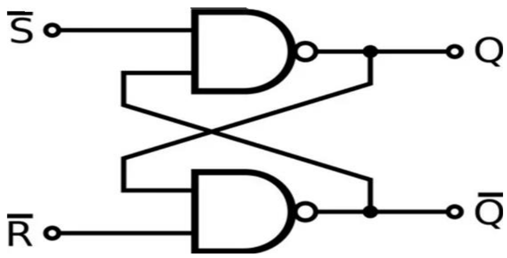


Figure 4.15 SR-Flip flop

When the outputs are being implemented, the circuit wiring is maintained until R or S is high, or the power is shutted down. The two outputs, as illusterated above, are the inverse of each other.

The flow chart of protection relay process is illustrated in Figure 4.16

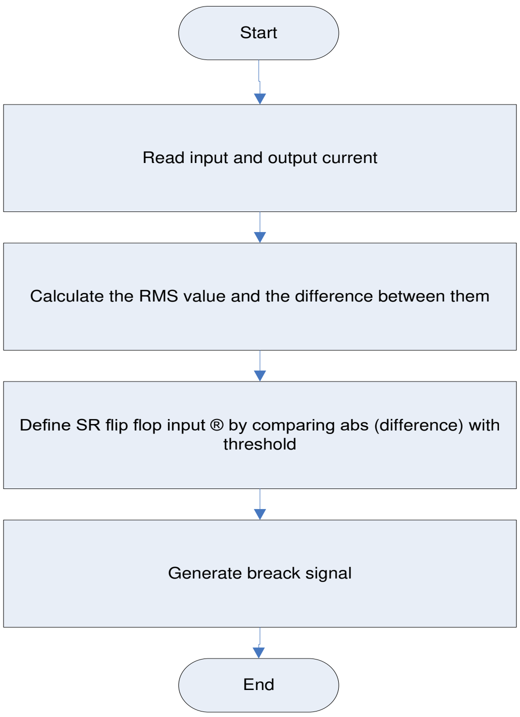


Figure 4.16 Flow chart of protection relay process

4.10 Protection relay with Vector Group

To improve transformer protection, the vector group or phase shift technique is integrated with differential protection, incorporating phase angle comparison of sequence current components. This phase shifting is capable of differentiating between external and internal faults. In terms of both sensitivity and speed, the phase-shifting method has shown superior performance compared to the traditional current differential approach. When it comes to detecting defects, the phase shift approach has consistently proven to be highly effective. The Simulink diagram in Figure 4.17 illustrates the configuration of a differential relay, consisting of input ports In1 with vector group block and In2 with zero block, with output currents Id1 and Id2 respectively

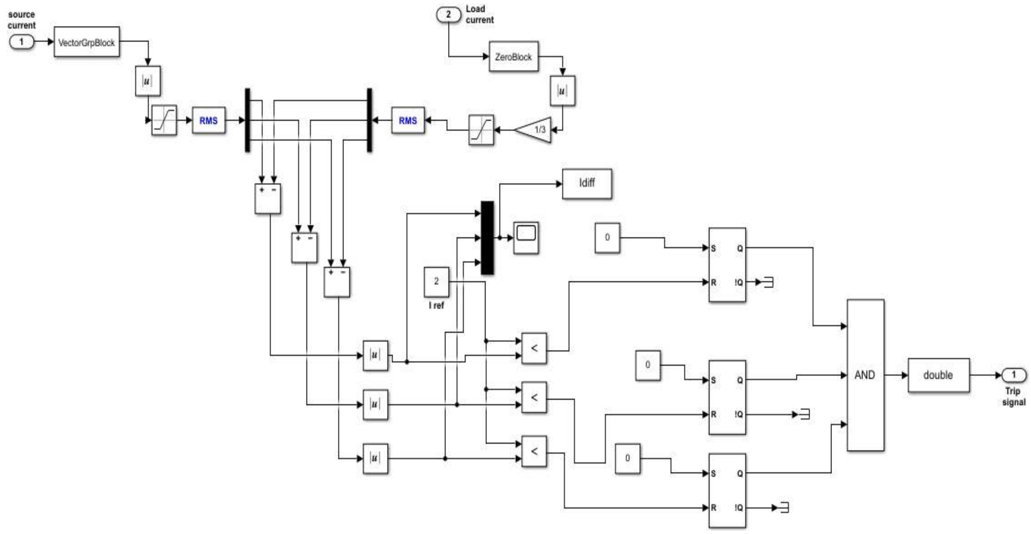


Figure 4.17 protection subsystem with zero block and vector group block

4.11 Three-phase Transformer with Protection Relay

Figure 4.18 and Figure 4.19 presents a model of a three-phase transformer equipped with protective measures, comprising several key components:

The model features a three-phase voltage source connected in series with an RL branch. The phase-to-phase voltage (Vrms) is set at $11*10^3$ volts, and the system operates at a frequency of 50 Hz. For current and voltage measurements in the ideal three-phase system, the units used are amperes per unit (for current) and volts per unit (for voltage). The voltage measurement is specifically phase-to-ground. The model constructs a three-phase transformer using three single-phase transformers. This design allows for adjustments in winding connections to a 'Yn' configuration, providing access to the neutral point of the Y connection.

A three-phase series R-L-C load is also implemented in the model. The nominal voltage (Vn), measured phase-to-phase, is 3310^3 Vrms. The nominal frequency (Fn) is set at 50 Hz. Additionally, the model includes an inductive-reactive power (QL) of 5010^3 positive var. This detailed configuration ensures a comprehensive representation of a three-phase transformer with protective components, facilitating the simulation and analysis of its behavior under various operating conditions.

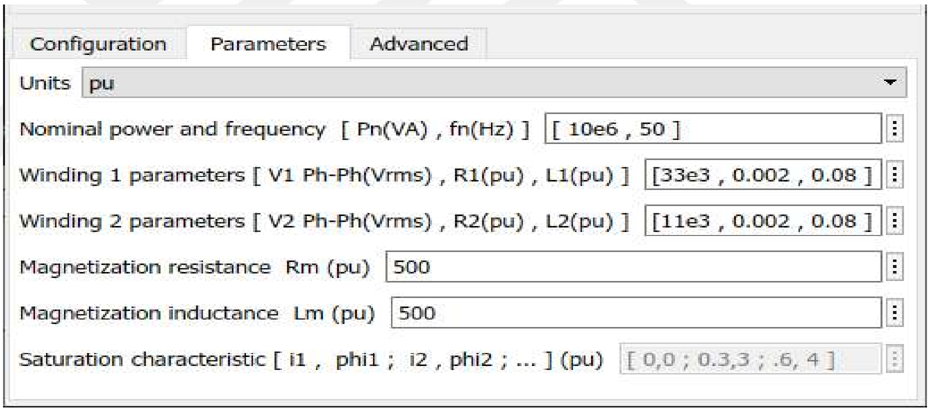


Figure 4.18 Transformer parameters

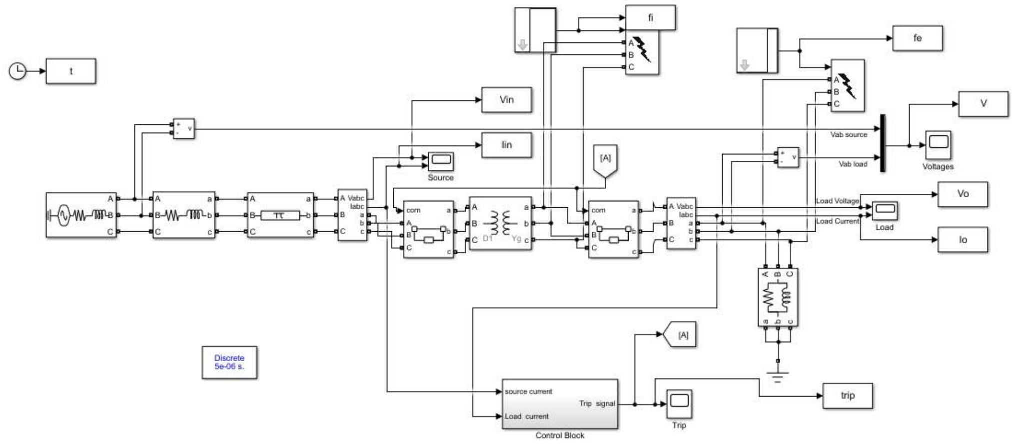


Figure 4.19 Three-phase transformer with protection relay

The MATLAB/Simulink model of a power system incorporates a differential relay, which forms a crucial connection between a transmission line and a three-phase source through a three-phase breaker. The model utilizes a three-phase Voltage-Current (V-I) measuring technique to calculate the load current. To accurately represent the system's overall demand, a three-phase series RLC load is integrated at the end of the transmission line. This comprehensive model facilitates the simulation and analysis of the differential relay's performance, focusing specifically on its capabilities in fault detection and protection.

4.12 Simulation of Fuzzy Logic Protection

Implementing effective transformer protection measures is crucial to ensure the reliability and optimal performance of electrical power systems. Differential protection relays, known for their rapid response time, heightened sensitivity, and discerning nature, are commonly employed to detect faults in power transformer windings. This makes the differential relay a popular choice for safeguarding high-capacity transformers. To address the challenges in transformer protection, various approaches have been developed, with fuzzy logic emerging as a particularly notable option. However, these methods often encounter limitations in terms of speed, reliability, and complexity.

4.12.1 Three-phase transformer with fuzzy protection relay

Ali *et al.* (2018) emphasize the importance of utilizing a power transformer model to generate the necessary faults for calibrating a fault detection system. This calibration is a crucial step in developing a relay protection scheme. The project was effectively carried out in the Matlab/Simulink environment. Figure 4.20 graphically presents the fuzzy protection relay integrated within the MATLAB/Simulink power system model. This relay is a key component, enabling the connection of a transmission line to a three-phase source via a three-phase breaker. A three-phase Voltage-Current (V-I) measuring technique is meticulously employed to determine the load current magnitude flowing through these components. At the end of the transmission line, a three-phase series RLC load is incorporated to accurately represent the system's total demand. This comprehensive model allows for the analysis and simulation of the fuzzy protection relay's performance, particularly focusing on its capabilities in fault detection and protection, as detailed by (Bahmanifirouzi *et al.* 2011).

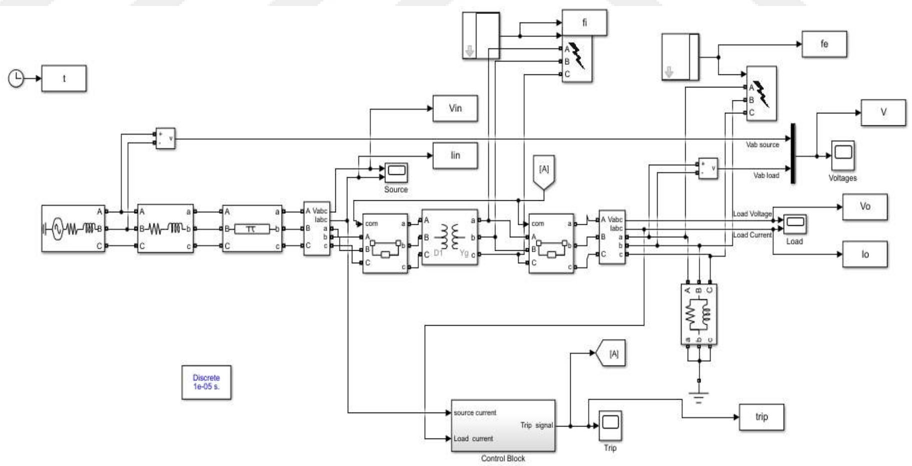


Figure 4.20 Three-phase transformer with fuzzy protection relay

4.12.2 Fuzzy Protection relay block subsystem in Simulink Matlab

Figure 4.21 illustrates a model in Simulink for protecting transformers from short circuits using fuzzy protection relay. The protection block consists of stages such as inputs, outputs, vector group, and zero blocks. The preprocessing stage calculates inputs difference, absolute values, and comparator threshold using fuzzy logic.

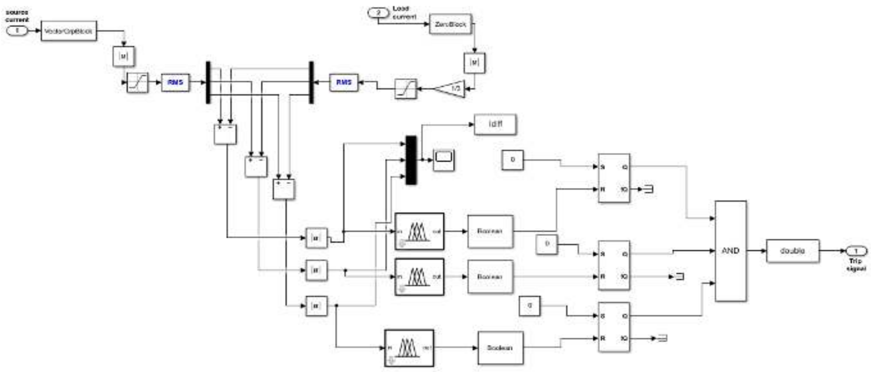


Figure 4.21 Protection subsystem fuzzy with zero block and vector group block

The Simulink diagram in Figure 4.18 illustrates the configuration of a fuzzy protection relay, consisting of input ports In1 with vector group block and In2 with zero block, with output currents Id1 and Id2 respectively. To analyze the system, the two input signals are separated into separate paths. In this system, the first signal is immediately routed to an amplitude comparator block. Concurrently, the second signal is directed to a harmonic comparator module. Following this, both signals are then channeled into a unified amplitude comparator component. The genesis of the second signal is the harmonic test. The amplitude comparator plays a crucial role by assessing the difference in input currents, referred to as In1 and In2. Once this difference is calculated, it sends a signal to the comparator block to highlight the disparity between these two input currents. Simultaneously, the harmonic comparator module receives dual signals from two subsystem blocks, analyzes the input signal for the presence of harmonics, and transmits the result to the comparator. An SR flip-flop is attached to the comparator's output for additional processing.

The flow chart of fuzzy protection relay process is illustrated in Figure 4.22.

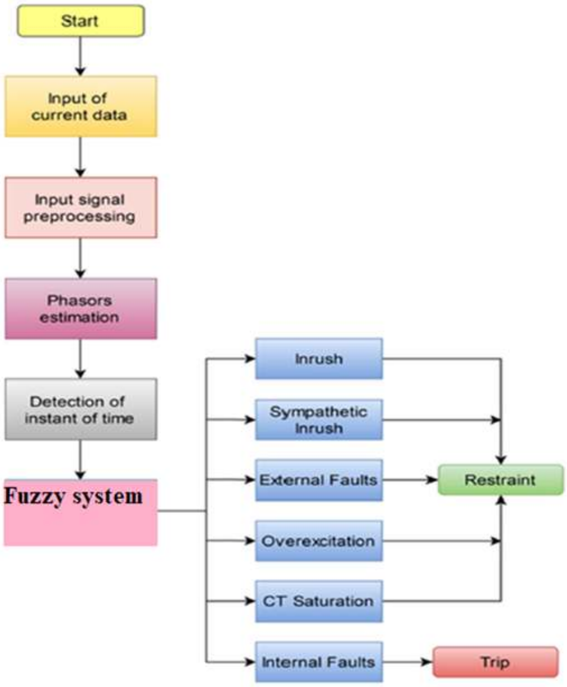


Figure 4.22 Flow chart of fuzzy protection relay process

5. RESULTS AND DISCUSSIONS

Systematically introducing failures is key to evaluating the system's efficiency. This process entails subjecting the system to deliberate faults or anomalies to assess its detection and response capabilities. Analyzing the system's performance under these controlled failure conditions provides essential insights into its reliability and effectiveness. The relay, specifically designed to detect changes or anomalies in the current flow through the transformer, is tested under various fault conditions. The data collected from the system's tripping responses enhances our understanding of the relay's behavior, particularly its effectiveness in detecting and responding to faults.

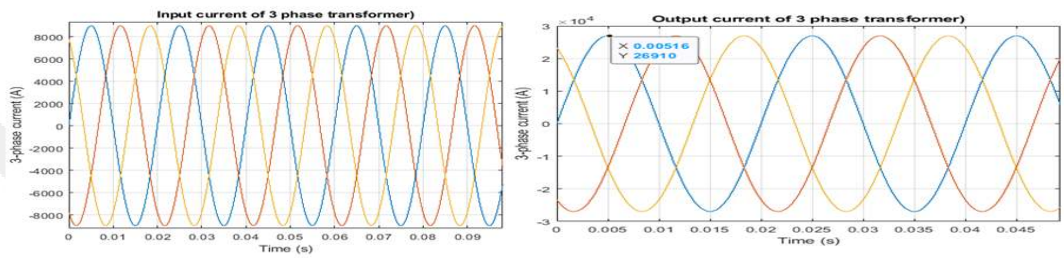
5.1 Simulation of Differential Protection

In the context of differential protection for transformers, this implies that the total currents entering and leaving the transformer should be equal. A discrepancy in these currents, particularly if their sum exceeds zero, could indicate a potential short circuit. The core objective of any protection system is to swiftly deactivate any segment of the power system experiencing issues, such as short circuits or abnormal conditions that could jeopardize the overall functionality of the system.

To achieve this, circuit breakers are strategically integrated into the transmission equipment. These breakers are engineered to disconnect the faulty segment upon relay activation. They must possess the capacity to handle the transient flow of the maximum short-circuit current and to safely interrupt it. Furthermore, these circuit breakers should be robust enough to endure the process of engaging and then breaking such a short electrical connection, all while strictly conforming to designated operational standards. The efficient functioning of these protective elements is crucial for maintaining the stability and integrity of electrical systems.

5.1.1 Operation without vector group

Simulation results confirm the accuracy of the relay during normal operation. Primary and secondary currents exhibit expected behavior, with the relay not issuing any tripping commands. In Figure 5.1 it can be seen that when the simulation model is in normal operation the Three-phase current waveform are sinusoidal and the phase difference between each two phase is 120 degree and the value of differential current is small.

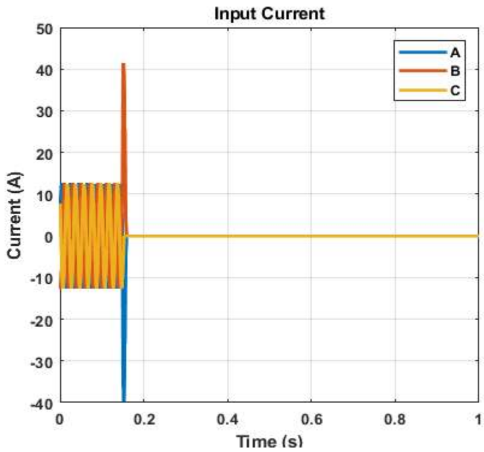


a b

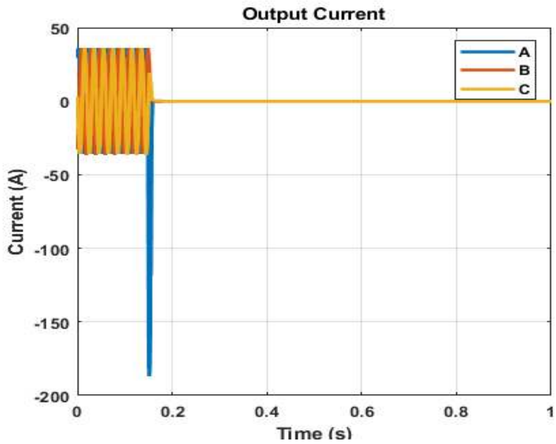
Figure 5.1 Current waveform during normal operation a) input b) output

To assess the algorithm's effectiveness in responding to external anomalies, a failure scenario is simulated wherein all Three-phases (A, B, and C) are connected to the ground. This external fault is initiated approximately 0.15 seconds after the load side enters the protected zone. To simulate this, a connection is established between the Three-phases and the ground of the cable. By grounding all Three-phases for a duration of 0.3 seconds, we are able to mimic an internal fault scenario occurring between CT1 and CT2.

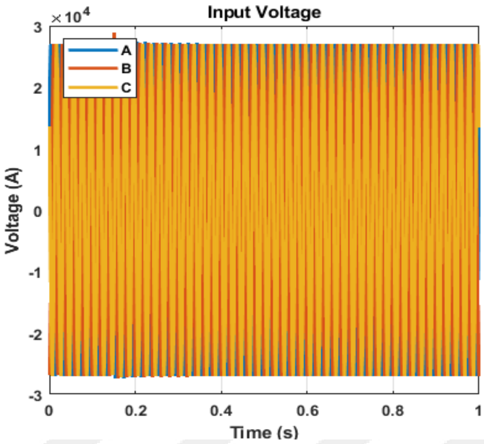
Under normal conditions, the secondary and primary current display identical magnitudes and phases before any fault occurs. However, as shows in Figure 5.2, the fault leads to a notable increase in both primary and secondary currents. This situation measurable change in current, clearly demonstrating the fault's impact.



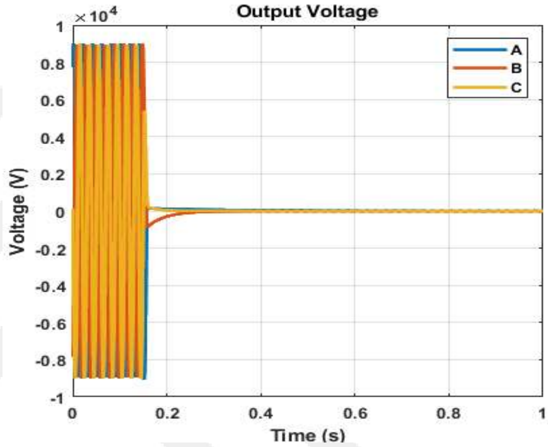
(a) Input current of 3-phase



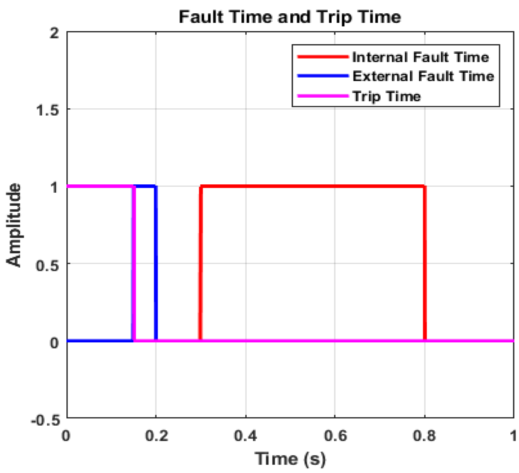
(b) Output current of 3-phase



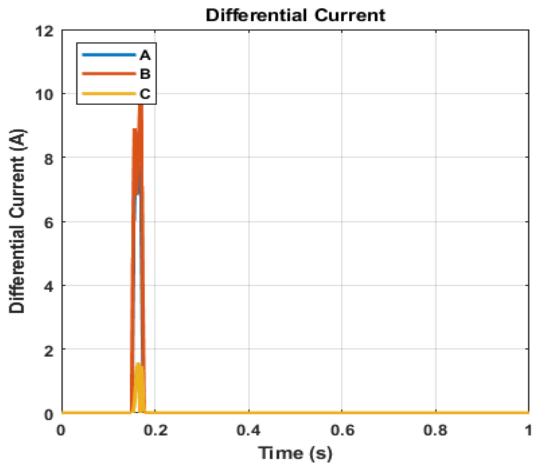
(c) Intput voltage of 3-phase



(d) Output voltage of 3-phase transformer



(e) Trip time at 0.15 sec external fault



(f) differential current at 0.15 external fault

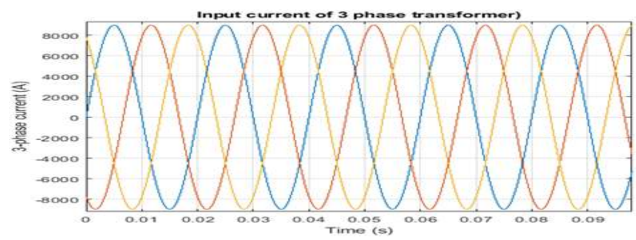
Figure 5.2 External and internal fault conditions in simulink protection relay

The relay appears to be incapable of distinguishing between internal and external faults. Instead of identifying an internal fault, the protection relay detects an external fault.

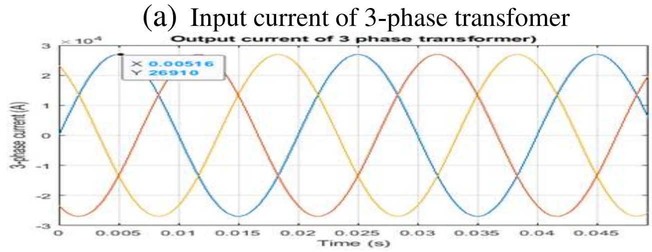
Simulation tests were conducted to evaluate the system's performance and fault detection effectiveness. The relay responded appropriately to external faults, detecting harmonic components and amplitudes, leading to the transformer's disconnection from the grid. However, the results also highlighted challenges in fault detection, particularly when differential currents alone are insufficient for distinguishing between external and internal faults. This underscores the need for more advanced relaying techniques to handle various conditions.

5.1.2 Opration with vector group (phase shift)

Simulation results confirm the accuracy of the relay during normal operation, where primary and secondary currents exhibit expected behavior without the relay issuing any tripping commands. Figure 5.3 illustrates that when the simulation model operates normally, the three-phase current waveforms are sinusoidal. Additionally, the phase difference between each pair of phases is 120 degrees, and the differential current value is very small.



(a) Input current of 3-phase transfomer



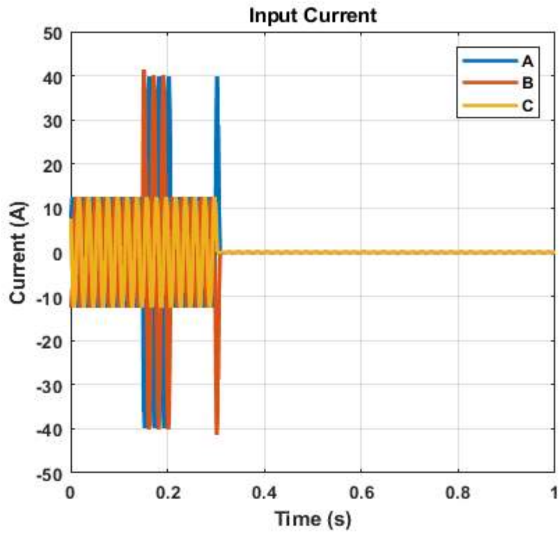
(b) Output current of 3-phase transformer

Figure 5.3 Current waveform during normal operation

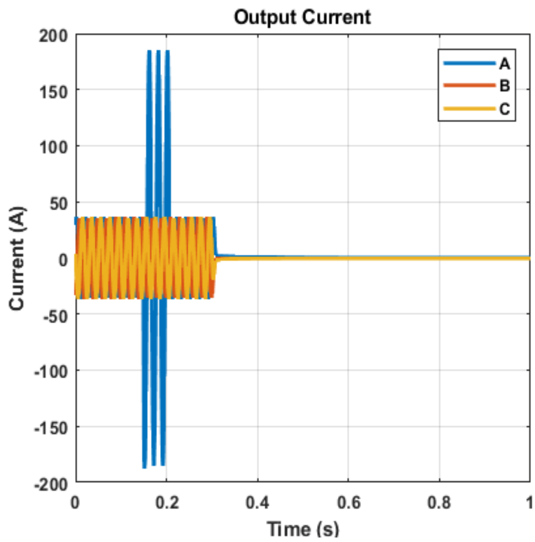
To evaluate the algorithm's capability of detecting both internal and external defects, a three separate phases to ground failure is induced. At 0.15 second intervals, an external defect is simulated upon the load side, resulting in the grounding of all Three-phases.

After 0.3 seconds, an internal defect is induced, at which point all Three-phases become grounded. By utilizing this, the efficacy of the system can be more accurately evaluated.

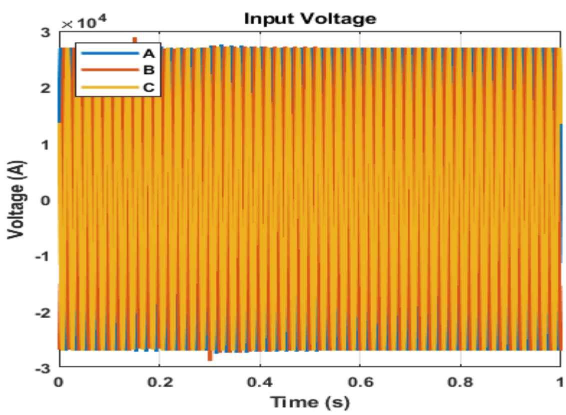
The primary and additional currents are in phase and of equal magnitudes under normal operating conditions until the issue appears. Nevertheless, these currents are greatly amplified as a consequence of the fissure. Under typical circumstances, the currents are balanced. However, as soon as the defect is detected, the simulation results clearly show an imbalance in the different current. This demonstrates the relay's capability to differentiate between external and internal errors. The device effectively identifies internal faults, distinguishing them from external faults that occur outside the transformer's protected area. As a result, as depicted in Figure 5.4, the relay promptly generates a trip signal every 0.3 seconds, indicating its responsiveness to internal faults.



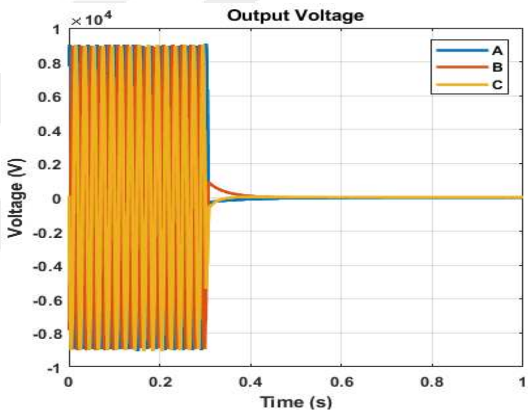
(a) Input current of 3-phase-to ground



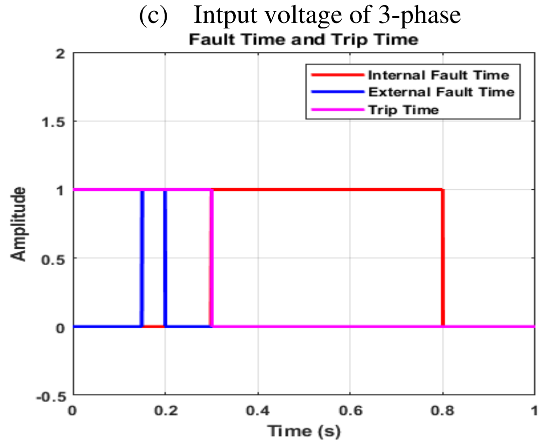
(b) Output current Three-phase-to-ground



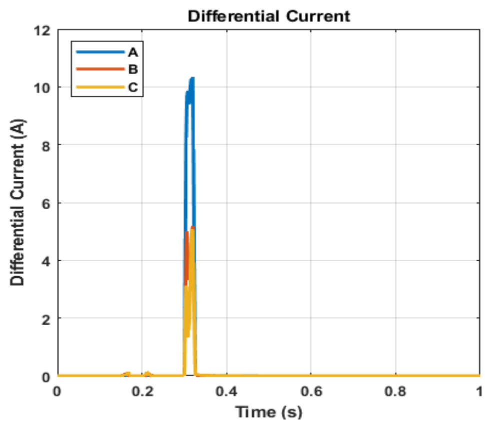
(c) Intput voltage of 3-phase



(d) Output voltage of 3-phase transformer



(e) Trip time at 0.3 sec internal fault



(f) Differential current at 0.3 internal fault

Figure 5.4 Internal and external fault conditions in protection relay with vector group

As seen in Figure 5.4, the differential protection relay demonstrates exceptional proficiency in promptly initiating tripping procedures in the presence of internal anomalies inside the safeguarded area of the power transformer. This effectively showcases the relay's fault-segmentation abilities. It is essential for the differential relay to promptly initiate the circuit breaker trip in the event of internal faults, which are characterized by current fluctuations lasting among zero and three-quarters of a second. This particular feature is of utmost importance in order to prevent any erroneous activations resulting from external defects, as shown by the occurrence lasting a mere 0.15 seconds.

The power transformer relay demonstrates an impressive reaction time of 0.3 seconds, effectively addressing internal faults with efficiency and promptness. The relay system excels in accurately differentiating between external and internal faults, thus preventing unwanted tripping and ensuring optimal transformer operation. Simulation studies were conducted to assess the relay's effectiveness in detecting and responding to various fault scenarios. Consistently, the relay showed reliable responses in both internal and external fault simulations. It proved its ability to identify and appropriately distinguish between these faults by detecting increases in current amplitude associated with fault conditions. Conversely, for external faults occurring outside the protected zone, the relay effectively avoided false tripping by accurately differentiating between the fault currents.

Furthermore, the vector group's phase shift capability plays a crucial role in distinguishing between internal and external errors, thus supporting the implementation of robust protection strategies.

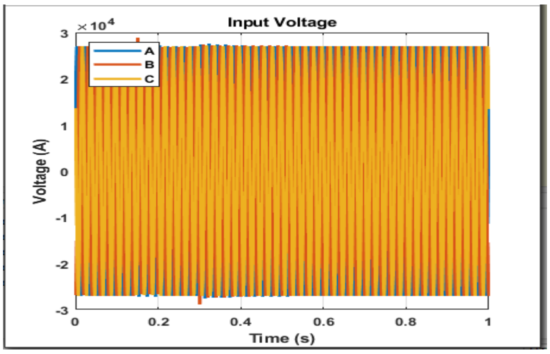
5.2 Fuzzy Logic Protection

Differential protection relays are commonly used to detect faults in power transformer windings, primarily due to their high sensitivity, selectivity, and rapid response capabilities. These attributes make them an invaluable component in safeguarding transformers against various types of faults. These relays are particularly prevalent in transformers with high capacity, where the stakes for protection are elevated. To address the challenges associated with transformer protection, various techniques, including fuzzy logic, have been developed. However, these methods often come with their own set of limitations, particularly in terms of response speed, dependability, and complexity.

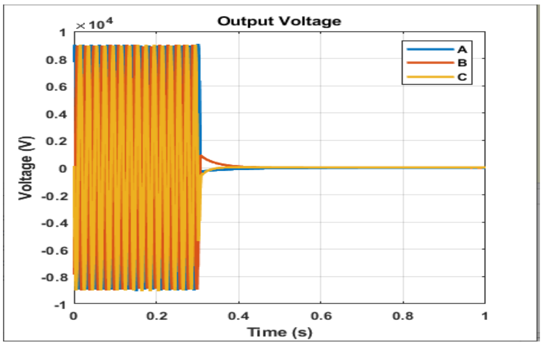
5.2.1 Fuzzy Protection relay with vector group (phase shifte)

A phenomenon called CT saturation becomes apparent when significant through-faults occur in the protected zone, leading to the failure of transformer protection. To assess the algorithm's ability to withstand external faults, a simulation is conducted that incorporates a Three-phase to ground fault. At 0.15 seconds on the load side, close to the protective zone, this external fault is created when phases A, B, and C are connected to ground via the secondary side of the power transformer's load wire. Yet, a simulated inner fault occurs precisely 0.3 seconds between CT1 and CT2, and all Three-phases ground simultaneously. The simulation results demonstrate the protection relay's ability to detect both internal and external issues. Impressively, the relay can detect internal defects and send out a trip signal in as little as 0.3 seconds.

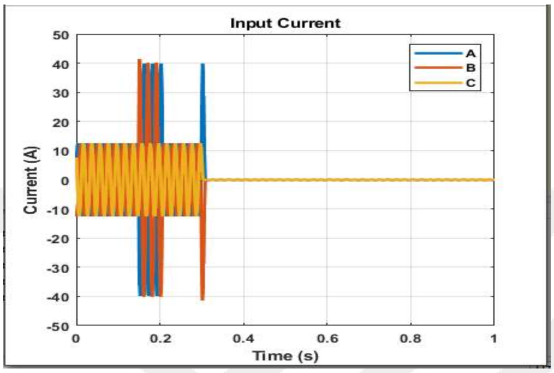
When an internal failure occurs inside the safeguarded area of the transformer, the differential relay, which operates on the principles of fuzzy logic, demonstrates exceptional performance. This is shown in Figure 5.5, where it efficiently activates the tripping mechanisms without delay. The relay has the capability to discern between internal and external issues. During the time interval of 0 to 0.3 seconds, it is of utmost importance that the differential relay expeditiously transmits a trip signal to the circuit's breaker in instances when internal faults are present. This ensures the rapid and efficient response to varying transformer currents. This ensures that the occurrence of the 0.15 second event serves as conclusive evidence that the fuzzy control mechanism effectively prevents any erroneous tripping resulting from flaws that lie beyond the protected zone.



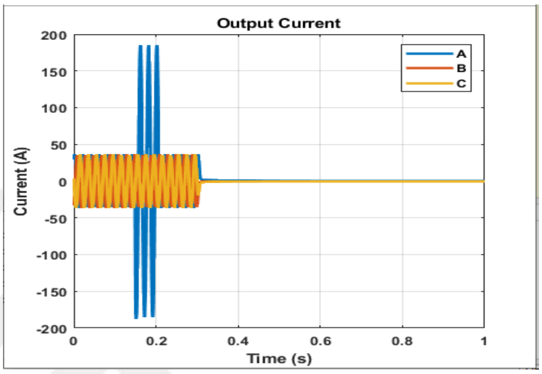
(a) Intput voltage of 3-phase



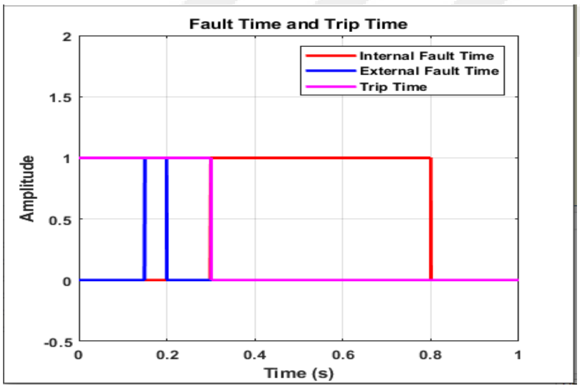
(b) Output voltage of 3-phase transformer



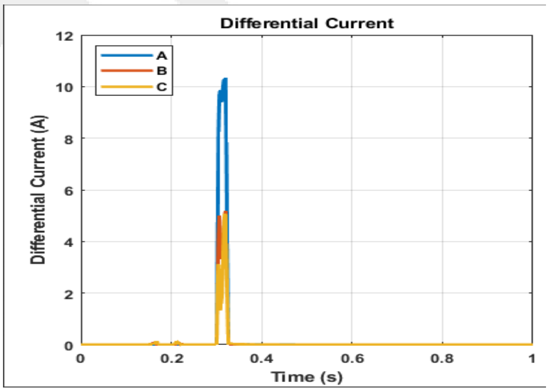
(c) Input current of 3-phase –to ground



(d) Output current Three-phase-to-ground fault



(e) Trip time at (0.3)sec ınternal fault



(f) Differential current at (0.3) internal fault

Figure 5.5 Fuzzy logic protection relay with vector (phase shifte)

The power transformer relay's trip time is 0.3 seconds, demonstrating a rapid response to internal faults. The fuzzy differential relay system is proficient in accurately distinguishing between external and internal faults, thereby preventing unnecessary tripping and ensuring efficient operation of the transformer. Simulation tests were conducted to assess the relay's effectiveness in detecting and responding to faults. Throughout the course of these testing, the relay demonstrated commendable performance by promptly and accurately responding to internal faults. It successfully detected and distinguished changes in amplitude that are indicative of such situations, effectively separating them from exterior faults. This showcases the relay's ability to properly discern between both internal and external problem scenarios.

The relay accurately detects internal faults within the protected zone, isolating the transformer within 0.3 seconds of the fault's occurrence. It also successfully differentiates between internal and external fault currents, thus preventing false tripping. The relay's sensitivity, particularly its reliance on phase shift, enables it to discriminate efficiently between internal and external faults, facilitating effective protection schemes. Overall, the fuzzy differential relay system has proven its effectiveness in fault detection and response.

6. CONCLUSION AND RECOMMANDATION

This thesis presents models for both a differential protective relay and a fuzzy differential protective relay, specifically designed for the protection of 3-phase power transformers. It provides a detailed overview of electric transformers, including their elements, properties, and applications. The thesis focuses on the methods of protecting transformers from internal and external faults, with simulations conducted in a Simulink environment. The differential-protection system disclosed comprises three primary units: an input calculation unit, a comparison and threshold definition unit, and a control signal production unit. Both the fuzzy logic-based and differential relay models show their efficacy in promptly initiating tripping operations in the face of internal faults occurring inside the protected zone of the transformer. The relays exhibit exceptional aptitude for discerning between internal and external defects. Upon encountering a short circuit, the relay model demonstrates its efficiency by effectively disconnecting the circuit, thereby ensuring the protection of the transformer system. Additionally, the fuzzy controller method provides enhanced options for circuit protection, particularly in response to changes in voltages and currents. The simulation results show exceptional sensitivity to internal errors and robust stability against external errors.

This research involves evaluating, simulating, and analyzing the performance of both differential and fuzzy logic differential relays in power transformer protection, utilizing MATLAB/SIMULINK. Building on previous studies that explored various scenarios for relay evaluation, this work innovatively incorporates a fuzzy logic differential relay with vector group modifications, including phase shifts, to enhance transformer protection. The constructed simulation model exhibits remarkable sensitivity to internal faults, while demonstrating stable operation during external faults and under normal conditions.

A significant part of the thesis focuses on the effects of severe external faults near the transformer, particularly how they can lead to CT saturation. This saturation might alter RMS values, potentially causing relay malfunctions. An extensive behavioral analysis is conducted, meticulously examining the relay's response across a range of fault scenarios and operational conditions. The primary focus is on evaluating the relay's vulnerability to internal faults and its robustness in handling external faults and normal operating states.

For future works and recommandations, we suggest delving deeper into the integration of advanced machine learning techniques with traditional differential protective relays. This approach could significantly enhance the accuracy and speed of fault detection and isolation in power transformers. Future research should focus on exploring the potential of neural networks and deep learning algorithms in improving the discrimination between internal and external faults, especially in complex and variable power grid conditions. Additionally, considering the rapid evolution of renewable energy sources and their integration into power grids, it is imperative to examine how these new energy sources affect the performance of protective relays. Research could also benefit from the development of more sophisticated simulation models that closely mimic real-world scenarios, including the impacts of grid modernization and smart grid technologies.

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