Effect of Transformer Magnetizing Current and Transformer Saturation Characteristics of Ferroresonance

by

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I have made efforts in this project. However, it would not have been possible without the kind support and help of many individuals and organizations. I would like to extend my sincere thanks to all of them. Thank you.

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LIST OF ABBREVIATIONS

PSCAD	Power Systems Computer Aided Design
MTM	Malaysia Transformer Manufacturing
AC	Alternating current
DC	Direct Current
ANSI	American National Standards Institute
RLC	Resistor (R), Inductor (L) and Capacitor (C)

LIST OF SYMBOLS

A	Ampere
V	Volt
kV	Kilovolt
KW	KiloWatt
PF	Power Factor

Kesan Arus Magnetisasi Pengubah dan Ciri-Ciri Ketepuan Pengubah dalam Ferosalunan

ABSTRAK

Dalam konteks sistem tenaga moden, pengubah memainkan peranan penting dalam pemindahan tenaga elektrik secara cekap dan selamat. Namun, keadaan operasi tertentu boleh menyebabkan impak negatif terhadap fungsi pengubah, dengan salah satu keprihatinan penting ialah pengaruh arus pemagnetan. Operasi pengubah berhampiran titik saturasi boleh memicu fenomena yang dikenali sebagai ferosalunan, yang mengakibatkan fluktuasi voltan yang ketara dan risiko kemudaratan kepada peralatan. Objektif utama projek ini merangkumi beberapa aspek utama. Pertama, objektif adalah untuk membina model komprehensif pengubah menggunakan perisian PSCAD/EMTDC. Melalui model ini, niatnya adalah untuk meredakan akibat arus pemagnetan pengubah terhadap prestasi keseluruhan. Selanjutnya, projek ini bertujuan untuk meneroka ciri saturasi pengubah semasa kejadian fenomena ferosalunan. Skop usaha ini melibatkan beberapa komponen. Pertama, ia melibatkan penciptaan model pengubah yang tepat untuk menangani kesan ferosalunan. Kemudian, projek ini merangkumi siri simulasi yang direka untuk mengkaji ciri saturasi semasa kejadian ferosalunan. Penyiasatan ini cuba untuk menetapkan korelasi antara arus pemagnetan dan ferosalunan. Model dan simulasi dijalankan dalam konteks sistem pemindahan 132/11 kV yang spesifik. Dengan menganalisis bentuk gelombang voltan dan arus yang dihasilkan dari model-model ini, pemahaman yang lebih jelas terhadap tingkah laku sistem diperoleh. Kajian simulasi juga mendedahkan implikasi penting terhadap aliran pemagnetan, dengan kesudahannya mempengaruhi saturasi pengubah. Oleh itu, hasil pencapaian penyelidikan ini selari dengan objektif yang telah ditetapkan. Khususnya, penyelidikan ini memberikan sumbangan dengan menawarkan cadangan untuk meningkatkan rekabentuk dan amalan operasi pengubah. Tambahan pula, ia memajukan pemahaman kolektif terhadap operasi pengubah dan rumitnya fenomena ferosalunan. Selanjutnya, projek ini memupuk kerjasama antara penyelidik dan pakar industri, memudahkan pertukaran pandangan dan kepakaran. Pada hakikatnya, usaha penyelidikan ini membawa wawasan berharga kepada optimasi dan operasi pengubah, memperkayakan asas pengetahuan berkaitan tingkah laku pengubah dan fenomena ferosalunan.

Effect of Transformer Magnetizing Current and Transformer Saturation Characteristics of Ferroresonance

ABSTRACT

In the context of modern power systems, transformers hold a pivotal role in the efficient and secure transmission of electrical energy. However, specific operational circumstances can lead to adverse impacts on transformer functionality, with one significant concern being the influence of magnetizing current. Operating a transformer near its saturation point can trigger a phenomenon known as ferroresonance, resulting in pronounced voltage fluctuations and the potential for equipment harm. The primary goals of this project encompass several key aspects. Firstly, the objective is to construct a comprehensive model of the transformer using PSCAD/EMTDC software. Through this model, the intention is to alleviate the repercussions of transformer magnetizing current on its overall performance. Furthermore, the project aims to delve into the saturation characteristics of the transformer during instances of ferroresonance phenomena. The scope of this endeavor involves multiple components. Initially, it entails the creation of a precise model of the transformer to counteract ferroresonance effects. Subsequently, the project encompasses a series of simulations designed to scrutinize saturation characteristics during ferroresonance occurrences. The investigation seeks to establish a correlation between magnetizing current and ferroresonance. The modeling and simulations are carried out within the context of a specific 132/11 kV transmission system. By analyzing the resultant voltage and current waveforms from the models, a clearer understanding of the system's behavior is obtained. The simulation studies reveal noteworthy implications on the magnetizing inrush, ultimately impacting the transformer's saturation. Consequently, the achieved outcomes of this research align with its set objectives. Notably, this research contributes by offering recommendations for enhancing transformer design and operation practices. Additionally, it advances the collective understanding of transformer operation and the intricacies of ferroresonance phenomena. Furthermore, this project fosters collaboration among researchers and industry experts, facilitating the exchange of insights and expertise. In essence, this research endeavor brings valuable insights to transformer optimization and operation, enriching the knowledge base surrounding transformer behavior and ferroresonance phenomena.

CHAPTER 1 : INTRODUCTION

1.1 Project Background

The electricity supply system for industry and household consumers is a comprehensive system designed by electrical and mechanical engineers. Malaysia's energy supply system begins with the power station, which generates a voltage ranging from 11 kV to 23 kV. The voltage is then increased from 132 kV to 500 kV via a long high voltage transmission line. It enters a high voltage switch station (SSU) with a voltage range of 132 kV to 500 kV before proceeding to the main entry substation (PMU) to lower the voltage.

Through the transmission line, it then enters the main distribution substation (PPU) to lower the voltage value to 11 kV. This substation will be connected to the electrical substation (PE) via high voltage overhead cable or high voltage underground cable, and subsequently downgraded to 415 V low voltage. This supply will be extended to small industry users and domestic users. For mega-sized industries, the voltage supplied by the energy supply is like 132 kV and 275 kV. Medium-sized sectors are supplied with voltages of 11 kV and 33 kV as shown in Figure 1.1.

It then reaches the primary distribution substation (PPU) via the transmission line to drop the voltage to 11 kV. This substation will be linked to the electrical substation (PE) through high voltage overhead cable or high voltage underground cable before being lowered to 415 V low voltage. This supply will be extended to small industrial and home customers. The voltage supplied by the energy supply is typically between 132 and 275 kV for mega-sized businesses. Figure 1.1 shows that medium-sized sectors are supplied with voltages of 11 kV and 33 kV.

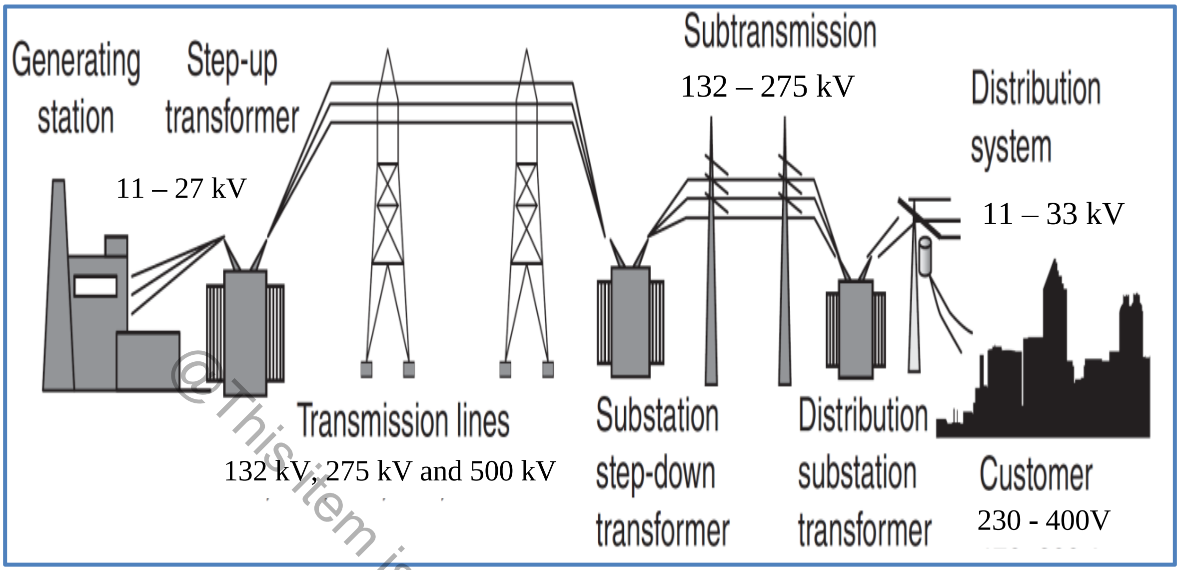

Figure 1.1: The electricity supply system

A distribution transformer is a critical electrical appliance that allows for the effective transmission of electrical energy across various voltage levels. Its principal role is to convert electrical voltage from high to low or low to high, depending on the electrical distribution system's specific requirements.

A common transformer used in distribution systems is one that converts high voltage to low voltage, allowing it to be delivered to end consumers. These transformers oversee lowering the voltage to a safe and manageable level, which is normally around 400 Volts in a three-phase system. The Dy11 vector group, often known as the DELTA - STAR connection, is a typical distribution transformer design.

Several reputable brands of distribution transformers are commonly utilized by Tenaga Nasional Berhad, a renowned utility company. These brands include MTM, EPE Wilson, Bonar Long, Crompton Parkinson, Gresham, Savigliano, Denis Ferranti, and SGB. Each brand offers its own set of features and specifications to cater to the diverse needs of the electrical distribution network.

Distribution transformers are classified into two types: hermetically sealed transformers and conservatory transformers. These Hermetically Sealed transformers have a completely sealed casing that protects the inside components from external environmental contaminants such as dust, moisture, and pollution. Hermetic sealing keeps air out and maintains a regulated atmosphere inside the transformer. This sort of transformer is typically filled with an insulating fluid, such as mineral oil, to improve its cooling and insulation qualities.

Conservatory transformers, on the other hand, are equipped with conservators or expansion tanks, as opposed to hermetically sealed transformers. These tanks allow for temperature fluctuations to cause the insulating fluid, commonly mineral oil, to expand and compress. By tolerating the expansion and contraction of the insulating fluid, the conservatory type allows for improved heat dissipation and ensures the transformer's longevity.

Both types of transformers serve the aim of transmitting electrical power safely and effectively across the network, although their specific uses may differ based on factors such as location, environmental conditions, and load needs.

Finally, distribution transformers are critical components of electrical distribution networks because they allow for the efficient movement of electrical energy across different voltage levels. They come in a variety of brands and configurations, including the Dy11 vector group, and are classified as hermetically sealed or conservatory transformers according on their design and insulation methods.

A transformer is built around an iron core that is wrapped in a coil. If the transformer is a high voltage step up to high voltage, it has three primary windings and three secondary windings, therefore the voltage is boosted from 23 kV to 500 kV. Similarly, transformers that reduce high voltage to high voltage, such as 132 kV step-down 33 kV, have the same number of coils as transformers that reduce high voltage to low voltage, such as 11 kV down to 415 V, but they have three primary winding cores and four secondary winding cores.

The transformer idea is based on an essential truth of electricity. When an electric current flows through a wire, it creates a magnetic field (invisible magnetic pattern) or "magnetic flux" surrounding it. As illustrated in Figure 1.2, magnetic strength (also known as relatively technical magnetic flux density) is directly related to electric current measurement. As a result, the greater the present, the greater the magnetic flux. Another fascinating truth about electricity. When a magnetic flux swings around a piece of wire, it generates an electrical current within the wire. If place the second wire coil on the first side and apply a variable electric current to the first coil, we will create an electric current on the first side.

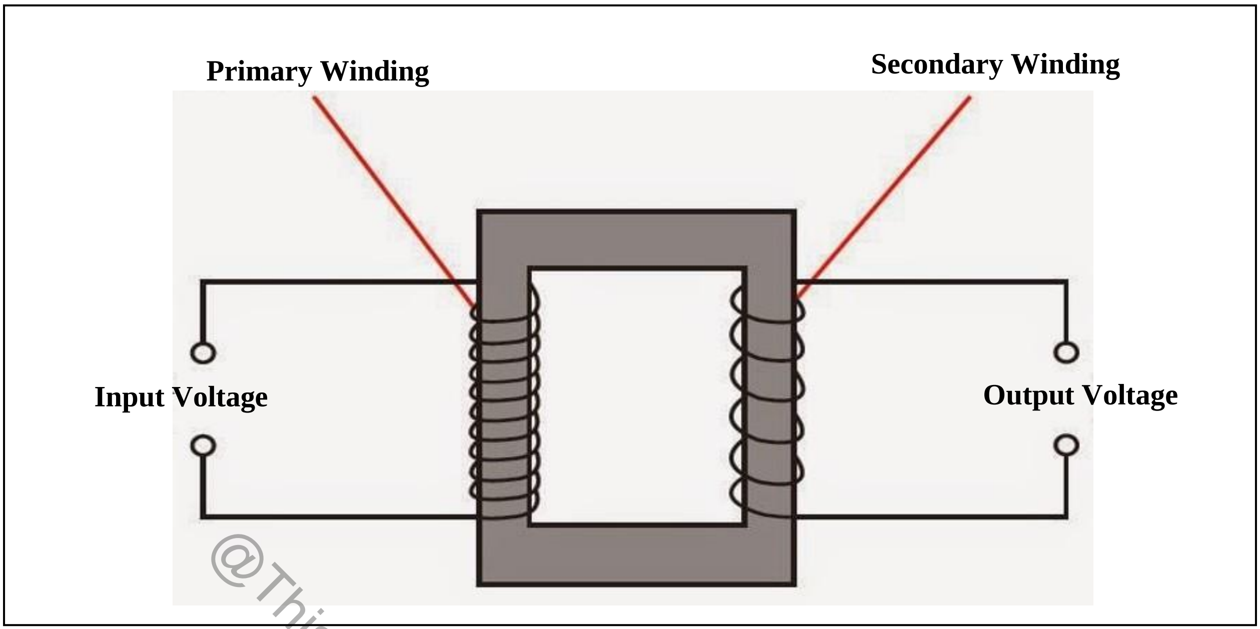

Figure 1.2 : Basic Transformer contsruction [2]

To make a winding of wire, simply roll the wire into a loop or ("turn" because physicists like to call it). If the secondary winding has an equivalent number of turns because of the first winding, the electrical current on the second winding is nearly identical to that on the primary winding. But (and this is the smart part) if have turned on the second winding, it makes the secondary current and voltage greater or less than the primary current and voltage as shown in Figure 1.3.

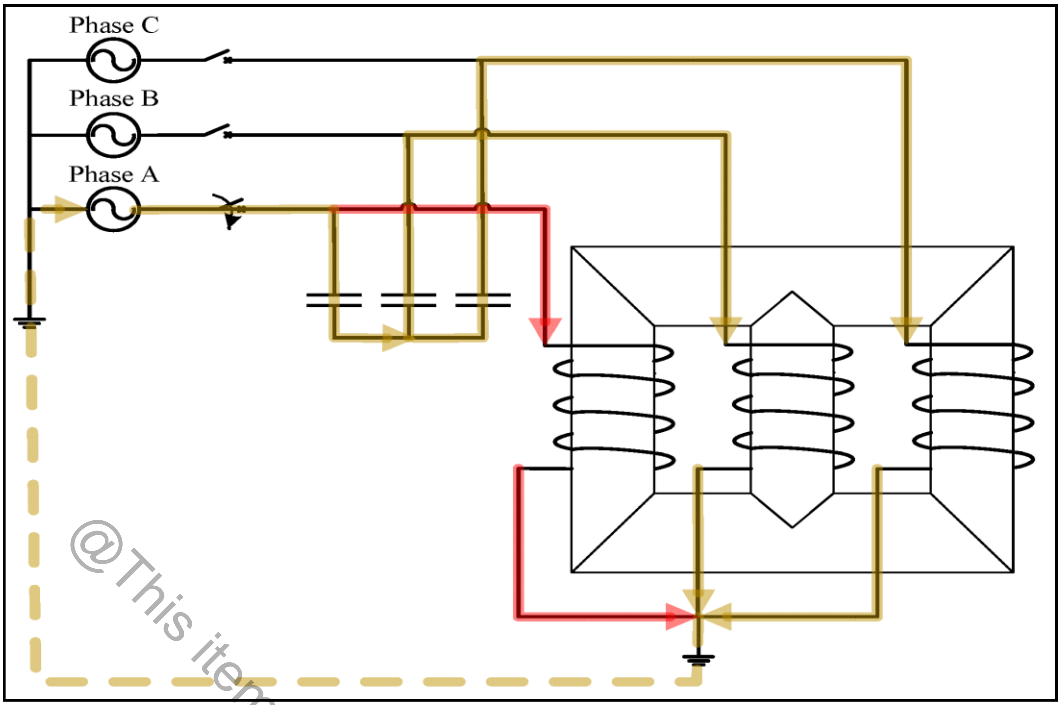

Figure 1.3 : Schematic diagram of the transformer connected to a circuit breaker and capacitors

It should be noted that this method only works if the electric current changes in some way. In other terms, an alternating current (AC) with a transformer must be employed. Transformers do not operate on direct current (DC), which is a mild current that always flows in the same direction [2].

1.2 Problem Statement

The consequences of power outages, inefficient energy consumption, and electrical waste go beyond monetary repercussions. These issues are also harmful to the environment, as excessive energy usage contributes to increased greenhouse gas emissions and exacerbates climate change [2]. Furthermore, reliance on poor energy consumption impedes sustainable development initiatives and weakens the shift to cleaner and more sustainable energy sources [1].

The issues with transformer equipment in power supply sources have far-reaching repercussions. Energy is dissipated and efficiency is reduced because of iron core losses induced by magnetic hysteresis and eddy currents. Copper losses due to resistive heating in transformer windings contribute to further energy waste. Overheating not only affects transformer lifespan but also poses safety issues. Overuse capacity, or operating transformers at or beyond their specified limits, strains the equipment and results in inferior performance. Poor insulation can cause electrical leaks and short circuits, compounding energy losses and increasing the danger of electrical mishaps.

Addressing these issues through research into Transformer Magnetizing Current and Transformer Saturation Characteristics of Ferroresonance can produce numerous advantages. Designers can develop ways to reduce losses and enhance efficiency by getting a thorough grasp of the effects of magnetizing current and saturation on transformer performance. This knowledge can be used to design and install transformers that run at maximum capacity, decreasing energy waste and associated costs.

Transformer manufacturers will be able to optimize their processes and raise profitability as a direct result of improved transformer efficiency and performance. Businesses can strengthen their competitive position and compete more effectively with items made in other places that use less energy by reducing their electricity use and related costs. In addition, implementing more advanced and cost-effective technology will improve the nation's overall financial performance, supporting economic development.

Improved transformer performance and efficient energy use will not only help specific enterprises, but also have broader effects on sustainability. Industries can reduce their environmental impact and help reduce greenhouse gas emissions by maximizing their use of power. This is in line with efforts being made around the world to battle climate change and transition to a greener, more sustainable future.

The frequency of maintenance work and transformer repairs can be decreased by detecting and addressing transformer-related problems, such as iron core losses, copper losses, and inadequate insulation. As a result, the supply authority experiences huge cost savings, which frees up funds for infrastructure development and other crucial projects [1].

The problem at hand revolves around the issues related to transformers, particularly focusing on two aspects: Transformer Magnetizing Current and Transformer Saturation Characteristics of Ferroresonance. These issues have significant implications for the efficiency and reliability of electrical systems.

The magnetizing current of a transformer is the current required to establish and maintain the magnetic field in the transformer's core. This current can lead to inefficiencies in the transformer's operation, as it represents energy that doesn't contribute directly to the output but still consumes power. If the magnetizing current is not properly managed, it can result in increased energy consumption, reduced efficiency, and higher operational costs. Therefore, understanding and controlling this magnetizing current is crucial for optimizing transformer performance.

Transformers are designed to operate within certain limits of voltage and current to ensure their proper functioning. When transformers are exposed to abnormal conditions, such as overvoltages or sudden changes in load, they can experience a phenomenon called ferroresonance. This can lead to saturation, where the transformer's core becomes saturated with magnetic flux beyond its normal operating range. Saturation can lead to distorted waveforms, increased heating, and potential damage to the transformer. Addressing and mitigating ferroresonance and saturation characteristics are vital to maintaining the reliability and longevity of transformers.

1.3 Project Objective

The main objectives of this project are:

a) To model and simulate the transformer using PSCAD/EMTDC software for mitigating ferroresonance phenomena.

b) To mitigate the effect of transformer magnetizing current on the ferroresonance phenomena.

c) To analyze the transformer saturation characteristics of ferroresonance phenomena.

1.4 Scope and Limitation

a) Run the experiment to gauge the strength and duration of the magnetizing current's effects on a transformer. Use mathematical formulas to determine the magnitudes and lengths of the voltage sag and the inrush current to facilitate the collecting of data for analysis.

b) Create a circuit model and run simulations using the PSCAD program to examine the ferroresonance transformer saturation characteristics. A circuit diagram must be designed, and several simulations must be run, to study the impacts of transformer magnetizing current and transformer saturation characteristics of ferroresonance under various circumstances.

c) Investigate the relationship between magnetizing transformer current and its impact on voltage sags. Determine the variables and factors that influence voltage sag magnitudes and durations through simulation modeling using PSCAD software.

d) Analyze the behavior of transformers under different levels of magnetizing current and saturation. Study the response of the transformers and the occurrence of ferroresonance phenomena using the simulated circuit model.

e) Identify and evaluate the effects of varying conditions on the transformer saturation characteristics during ferroresonance. Examine the changes in transformer behavior, such as voltage sags and potential overloads, under different magnetizing current levels.

f) Utilize the simulation results to determine optimal operational parameters and conditions that minimize the negative effects of transformer magnetizing current and saturation. Identify strategies to mitigate voltage sags and ensure efficient transformer performance.

g) Assess the accuracy and reliability of the simulation model in predicting the behavior of transformers during ferroresonance. Validate the model's results by comparing them with experimental data and existing theoretical frameworks.

h) Provide recommendations for industry stakeholders on optimizing transformer design and operation to mitigate the effects of magnetizing current and improve overall system performance.

i) Contribute to the advancement of knowledge in the field of transformer operation and ferroresonance phenomena through empirical data and simulation-based analysis.

j) Facilitate knowledge sharing and collaboration among researchers, industry professionals, and utility companies to enhance transformer technology and operational practices based on the findings of the study.

1.5 Research Questions

a) What are the findings of this study?

b) Why is this project being studied when many of these projects have been done before?

c) Why this project uses PSCAD in making an investigation of magnetism transformers?

d) How much can study expectations about this project be implemented?

e) What is the difference between this project and the previous project?

f) What is the percentage of accuracy of the results of this study?

g) Why does this study not require a more in-depth mathematical solution?

h) Will the project under study be successful in solving ferroresonance problems?

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

The well-known phenomenon of ferroresonance has been the subject of extensive research by academics and engineers. When saturable inductors are turned on in series with the inductor by capacitance, a phenomenon known as ferroresonance results. It is characterized by overvoltages and erratic wave patterns, according to the Institute of Electrical and Electronics Engineers (IEEE). A series resonance is how it is categorized [1].

A series resonance circuit is made up of a series combination of capacitors and line or transformer inductances, in accordance with IEEE Standard 519-1992. In the series circuit between the inductor and the capacitor, this layout offers a low impedance pathway for harmonic currents and can lead to significant voltage distortion of levels.

Ferroresonance is a complex and unpredictable electrical phenomenon that has led to extensive research. It is believed to be caused by the interaction of non-linear inductance and capacitive properties. The ANSI/IEEE Std 100-1984 Standard defines ferroresonance as an overvoltage and waveform mismatch resulting from the relationship between saturated inductors and capacitors in series. Guidelines, such as using MOV Surge Arrester and improved magnetic response in transformers, along with transient events like switching, lightning strikes, or short circuits, have been developed to enhance ferroresonance performance. One of the dangers of ferroresonance is its rapid and abrupt transitions between different modes, as even slight changes in system parameters can result in significantly different ferroresonance conditions [2],[4],[12].

Ferroresonance is a well-known power quality disturbance in AC power systems with a long history. It is characterized by severe symptoms, including high currents, overvoltages exceeding 4 p.u.[2], and significant waveform distortion. Numerous incidents have resulted in blackouts and equipment damage attributed to ferroresonance. The phenomenon occurs due to the interaction between system capacitances and the non-linear inductances of power transformers and instrument voltage transformers. The constantly changing inductances during the magnetizing and demagnetizing cycles of the transformer lead to multiple stable and unstable operating points, known as ferroresonance modes [3].

Ferroresonance, first mentioned in 1920, is a phenomenon characterized by non-linear oscillation involving multiple inductance values and a capacitance value. This variation in inductance can be observed in a saturable transformer, where the inductance is significantly lower in the saturation region of the transformer core compared to the normal region. Various electrical faults such as lightning strikes, short circuits, switching transients, and unsymmetrical flux distribution can cause the transformer to enter the saturation condition. Additionally, the capacitance contributing to ferroresonance can result from system capacitance accumulation due to line charging, capacitor banks, capacitive voltage dividers, and grading capacitance caused by circuit breaker openings [3],[4],[28].

Ferroresonance is a phenomenon that arises when a capacitor and a nonlinear saturable magnetization inductor resonate with each other. The first analytical work on ferroresonance was presented in the 1950s, and this phenomenon occurs when there is insufficient damping in the system. In power systems, inductive units are typically power transformers, and capacitors are used for series compensation in transmission lines. Ferroresonance is mainly characterized by series or parallel RLC circuits. Mathematical analysis of ferroresonance equivalent circuits involves using Kirchhoff's voltage and current laws, resulting in a system of equations based on the supply frequency (ω), upstream-grid voltage, circuit breaker grading capacitance, phase-to-earth capacitance (Cline), and the nonlinear magnetization characteristics of the saturable magnetization inductor (WG iron core) [26].

Ferroresonance is a non-linear energy oscillation that occurs between capacitive and inductive units. Different types of ferroresonance have been historically observed, including fundamental mode, subharmonic mode, quasi-periodic mode, and chaotic mode. Analyzing ferroresonance can be challenging due to its complexity and non-linearity. However, it can be explained more comprehensively using a graphical representation based on fundamental phasor analysis. In this representation, the harmonics induced by non-linearity are disregarded for simplicity [25].

For other research, ferroresonance is a phenomenon that can have several negative effects on a power network. One of the main impacts is the potential for overvoltages or overcurrents to occur on non-linear elements within the network. This particularly affects voltage instrument transformers (VIT), which can experience these excessive electrical conditions. Another consequence of ferroresonance is an increase in

Total Harmonic Distortion (THD), which can lead to malfunctions in protection relays. Therefore, ferroresonance can cause detrimental effects such as overvoltages, overcurrents, and THD increase, potentially resulting in malfunctioning VITs and protection relays [5].

The form of ferroresonance that is connected to transient switching events has been shown to be the most prevalent in literature. One example is when a long feeder is opened from a distance and a trapped charge is left to build up on the cable capacitance. Ferroresonance may occur because of this cable capacitance's parallel relationship to the iron core inductance of the potential transformer (PT) [6],[30].

The study aimed to identify the most hazardous ferroresonance occurrences based on the current magnitude in transformer windings. To achieve this, calculations were performed for different lengths of the feeder line and total line lengths in the network, considering asymmetric operating modes such as phase breaks and phase-to-earth short circuits [6],[30].

By understanding the causes and characteristics of ferroresonance, engineers and researchers can develop strategies to mitigate its effects and prevent potential equipment damage or system disruptions. Continued research and investigation in this field contribute to the overall improvement and reliability of power systems [1].

During normal operation, a circuit's capacitive of reactance (XC) is normally lower from its inductive of reactance (XL). However, voltage variations can occur during switching transients, resulting in core saturation in a potential transformer (PT).

The inductive reactance (XL) decreases as a result of saturation. As a result, the condition XL = XC can be satisfied, resulting in the development of a series resonant circuit [1].

A more thorough explanation of this particular kind of ferroresonance is given in Figure 2.1 [1]. The stray capacitance of transformer windings or bushings, cables, overhead power lines, or other sources can all contribute to the phenomenon's capacitance [1]. During particular operating circumstances, these capacitances help form the series resonant circuit along with the inductance of the PT core. For designing and operating electrical systems to prevent its development and mitigate its potential negative impacts, it is essential to understand the traits and reasons causing this form of ferroresonance.

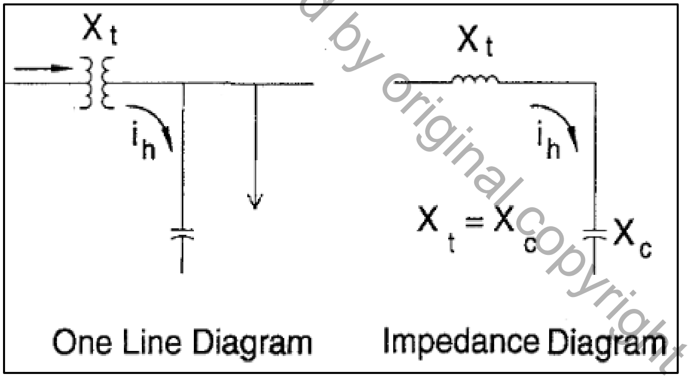

Figure. 2.1: A series resonance circuit [1].

Ferroresonance can manifest in various modes and frequencies, including fundamental, subharmonic, quasiperiodic, and chaotic patterns. As documented, instances of ferroresonance have been observed at subfrequencies such as 20 Hz and 30 Hz. This phenomenon can result in the saturation of the core in a potential transformer, leading to a reduction in its inductive reactance (XL). When the capacitive reactance

(XC) matches the reduced XL, A series resonant circuit is formed [4]. This type of ferroresonance, caused by transient switching events, has been extensively studied [1].

The grade of capacitors for circuit breakers are coupled to different type of ferroresonance, as shown in Figure 2.2. Grading capacitors is parallel to each circuit breaker, placed in high-voltage applications to create a stable voltage distribution. Grading capacitances for SF6 breakers and minimum oil breakers typically range from 1500 to 1600 pF and 800 to 1350 pF, respectively. The ferroresonance behavior using grading capacitors is less studied in comparison to the behavior caused by transient switching occurrences. Consequently, to understand this type of ferroresonance, a detailed analysis is required. [1].

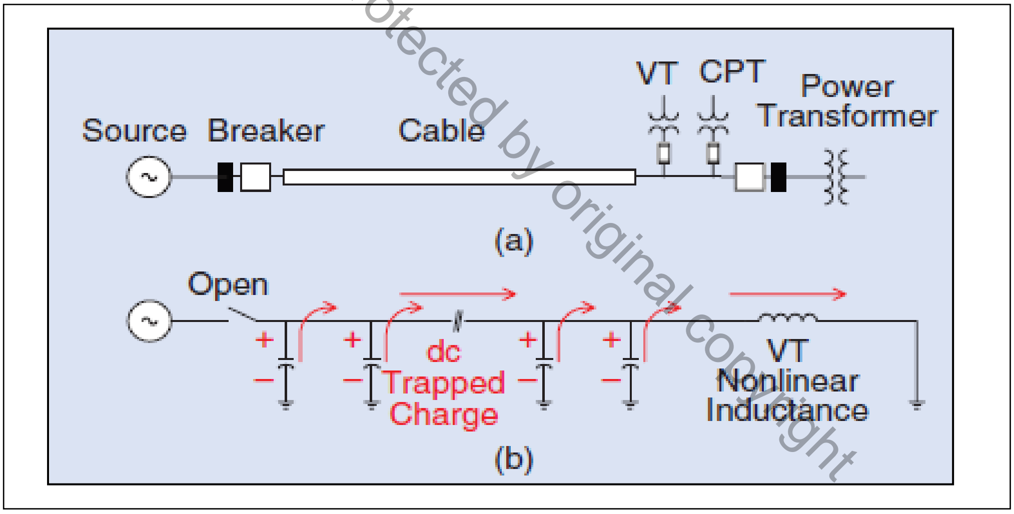

Figure. 2.2: During transient switching, there is a ferroresonance condition [1].

A realistic ferroresonance event at a reoperated 138 kV bus in the Canadian properties power resulted in an abnormally high voltage in [1]. A PSCAD simulation model is utilized to thoroughly evaluate the incident, and field measurement data is used to prove its correctness. The simulation results corroborate the idea that the observed ferroresonance and overvoltage issue is caused by the interaction of circuit breaker grading capacitors and the PT. The paper aims to provide readers with a better knowledge of this particular ferroresonance incidence by presenting PSCAD simulation results. In addition, a feasible solution to reduce ferroresonance is proposed.

A phase with phase to ground fault was caused on June 8, 2018, at 20:00:51 by a fault in the bus-tie current transformer of the 138 kV south bus in substation [1]. Four circuit breakers were opened to resolve the issue. Following the identification of the broken current transformer, the 138 kV south bus was determined to be energized but separated from any other electrified equipment. An incomplete electrical drawing single line schematic of this system is shown in Figure 2.3.

In the presence of intermittent power sources like wind power and photovoltaics, the grid complexity and uncertainty factors increase. Therefore, it is crucial to find a method that can effectively eliminate voltage transformer (VT) resonance from its root cause. Conventional active ferroresonance elimination devices are insufficient to meet the growing demands of power grids. In response to this challenge, we propose an active VT ferroresonance elimination method based on PID control. This method aims to address the shortcomings of existing solutions and provide a more effective approach to mitigate VT ferroresonance in the dynamic and evolving power grid environment [21].

A phase A-to-ground fault was caused on June 8, 2018, at 20:00:51 by an issue with the bus-tie current transformer of the 138 kV south bus at the substation show in Figure 2.4 [1]. Four circuit breakers were opened to fix the problem. The 138 kV south bus was discovered to be energized but unconnected from any other electrical equipment after the broken current transformer was identified. The voltage on the South Bus that was measured at 138 kV during switch opening as show in Figure 2.5. The south bus PTs were thermally scanned as Figure 2.6. [1].

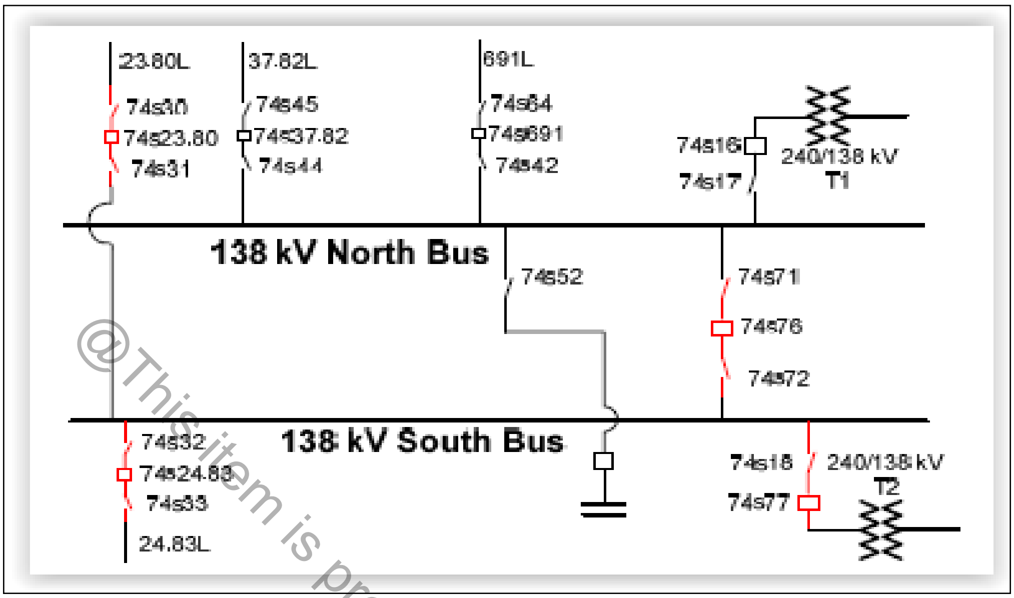

Figure 2.3: A piece of the 138 kV system's single line electrical schematic.

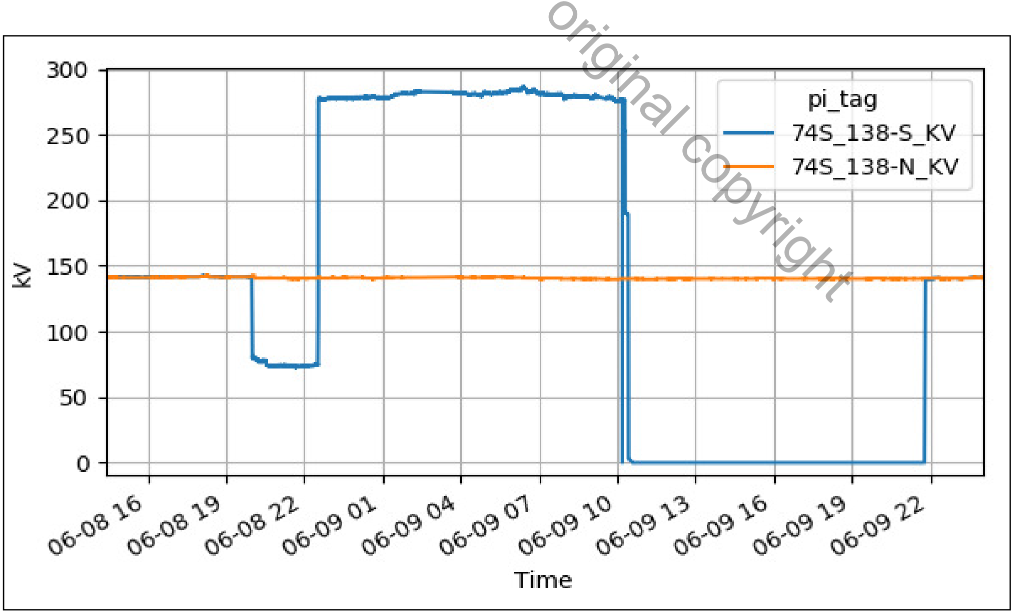

Figure 2.4: The voltages on 138 kV South Bus case from June 8 to June 9, 2018, are recorded.

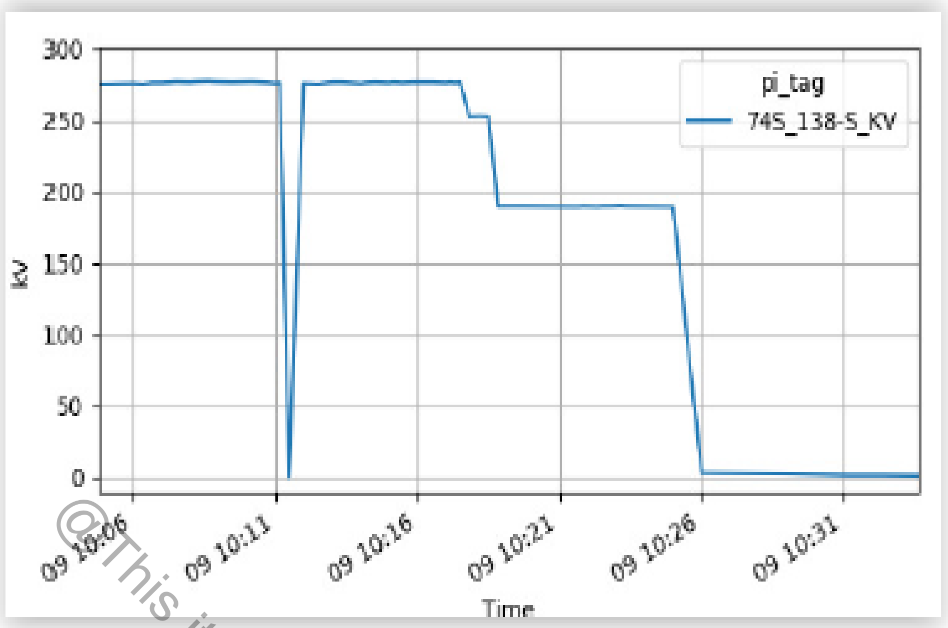

Figure 2.5: The voltage on the South Bus that was measured at 138 kV during switch opening.

Figure 2.6: The south bus PTs were thermally scanned.

2.2 Root Cause Analysis

There are three primary categories into which the causes of overvoltage in power systems can be divided:

1. Fast front transient overvoltage: This kind of overvoltage is usually brought on by lightning strikes and lasts for a brief period generally less than 300 microseconds times.

2. Slow transient overvoltage: Power system switch processes can cause slow front transients, which typically last 20 milliseconds or less. When circuit breakers or other switching devices are opened or closed, these transients take place.

3. Low frequency overvoltage: This category includes both temporary and continuous overvoltage events. Temporary low frequency overvoltage lasts for a duration of less than 1 hour, while continuous low frequency overvoltage persists for longer periods, typically exceeding 1 hour.

Low frequency continuous overvoltage is the category in which the phenomenon examined in this study belongs. If no disconnect switches had been opened, the incident's overvoltage would have persisted for more than 12 hours. Low frequency continuous overvoltage may have several potential causes, including excessive reactive power, resonance, or ferroresonance. The investigation of ferroresonance and its role in the reported overvoltage problem is the main objective of this study.

To solve the continuous overvoltage problem at the 138 kV in south bus, the circuit breakers attached to this bus were turned on, isolating it from the other electrified parts of the substation. The capacitor banks at this position were wired to the north bus, which is an important detail to note. The incident was documented in field recordings from the Dynamic Disturbance Recorder (DDR), and all circuit breakers were open. At 19:36:49 [1], all circuit breakers connected to the south bus were opened in order to directly address the issue in phase A to ground (A-G) of the current transformer. At 22:08:15, the disconnect switches 74s71 and 74s72 were likewise turned on [1].

According to a review of the DDR recordings, the voltage on the south bus increased gradually as the circuit breakers were opened. The voltage suddenly increased when the disconnect switches 74s71 and 74s72 were opened, reaching a constant state overvoltage level on all three phases. It is worth noting that the two minimum oil breakers were installed in the circuit breaker connected to the south bus, each with two grading capacitors with a combined capacitance of 500 pF in series.

Ferroresonance is strongly likely to be of root cause of the overvoltage reported at 138 kV south bus based on the field data at hand and prior study [1]. Ferroresonance has been identified as a potential root cause due to its characteristic behavior and known association with overvoltage incidents. Further investigation and analysis will be conducted to validate this suspicion and gain a deeper understanding of the ferroresonance phenomenon in this specific case.

During the disconnector's opening operation, when the breaking voltage exceeded the voltage needed to break the fracture, a single breakdown occurred in the fracture. The breakdown voltage of the fracture increased as the gap of the contact movement widened until the fracture's breakdown condition was met. This entire process represents the insulation recovery stage [24].

2.2.1 Analytical Analysis of Ferroresonance

An equivalent circuit can represent the event in this research in Figure 2.7 [2]. The following differential equations can be used to represent the equivalent circuit:

$$1\frac{1}{\omega}\frac{dv}{dt}+\frac{1}{R\omega(Cb+Cg)}V+\frac{1}{R\omega(Cb+Cg)}(i)=\frac{Cb}{Cb+Cg}\sqrt{2E\cos\theta} \qquad (2.1)$$

$$\frac{d\lambda}{dt}=V \qquad (2.2)$$

$$\frac{d\theta}{dt}=\omega \qquad (2.3)$$

$$i=f(\lambda) \qquad (2.4)$$

When current through the PT, the flux linkage, the supply voltage's phase angle, its RMS value, and the voltage across the PT Cb is the circuit breaker's grading capacitor, and Cg is its general busbar capacitance to going ground.