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Title:

Design and Implementation of Numerical Differential Relay

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Abstract

Differential protection is one of the principal power system protection elements. This widely used protection technique is concerned only with internal faults. It is a very sensitive technique that detects nonzero differential current and it consequently isolate the protected element. Moreover, differential relays are extremely fast. A failed element can be taken out of service in less than a cycle. However, some external abnormal conditions can be similar to internal faults and make the differential relay detects a nonzero differential current, resulting in an unnecessary tripping of the circuit breaker.

In this project, an improved algorithm of a power transformer numerical differential relay has been proposed, implemented and simulated. The hybrid technique used to distinguish between the internal fault and the other unnecessary operating conditions is based on a combination of three performant techniques: Dual slope percentage differential characteristic method, even (second and fourth) harmonic restraint and odd (fifth) harmonic blocking.

The behavior of the presented relay has been tested versus various situations such as transformer energization with inrush current, internal fault, external fault and transformer energization with an existing fault. The obtained results show that the implemented algorithm provides good result in term of security, dependability and speed.

Dedication

In the name of Allah the most beneficent and the most merciful
I have the pleasure to dedicate this work to my sweet and loving Mother and to my dear father for their support encouragement and prays of day and night to make me able to get such success and honor,
And also to my supporting little sister.
I would like also to dedicate this work to my teachers who helped me through my years of study.
At the end, I dedicate this work to all my friends, uncles and cousins for being there for me when I needed them.

Amir Benbrik

Dedication

In the name of Allah, the most beneficent and the most merciful
I have the pleasure to dedicate this work to my sweet and loving Mother, my dear father and my supporting little brother for their encouragement and prays to make me able to get such success and honor. I would like to make a special dedication to my supporting aunts which without I would not be able to be here today.
I would like also to dedicate this work to my teachers who helped me through my years of study.
At the end, I dedicate this work to all my friends, uncles and cousins for being there for me when I needed them.

Rachid Guernouti

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TABLE OF CONTENTS

List of tables

LIST OF FIGURES

List of Abbreviations and Acronyms

CB	Circuit breaker
CT	Current transformer
DC	Direct current
FFT	Fast Fourier transform
FPGA	Field Programmable Gate Arrays
I_{diff}	Differential current
I_{dmax}	Maximum allowed differential current
I_{ds}	Differential current lower set point
I_h	Differential current harmonic content
I_{op}	Operating current
I_{rst}	Restraining current
I_{tp}	Turning point current
SLP	slope

General introduction

The electrical energy is one of the fundamental resources of modern society and its use became a vital need in the daily life. Its high efficiency and reasonable cost made it the most popular and the most used form of energy among all the other energy types.

Electric power must be available to the user continuously at the correct voltage, frequency and exactly at the amount that is needed. To achieve these performances, correct operation of the power system elements is essential at the three main stages which are in order as follows: the production, the transmission and finally the distribution. Yet, the power system is subject to disturbances created by random load changes, or faults caused by natural causes and sometimes because of equipment or operator failure.

In order to ensure the needed performances for users, huge investments have been made in the power domain. A good part of those investments and researches were, and still are being made in the protection field. For it being the most critical one in the whole power system, since any failure in any subsystem of the latter, can be mitigated in terms of damage, if the protection system is working properly, whereas a failure in the protection system itself can lead to serious losses.

Protective relays have been first introduced as simple electromechanical devices, they have now evolved to the more complex, smart and practical numerical type, complex for using intricate algorithms, smart for their use of microcontrollers, and practical for offering various types of protections, being very configurable and adaptive. Among those new adaptive relays, the differential relay is the most used in the field of the power system protection.

The differential relay is a very selective, sensitive and fast clearing protection technique. For that reason, it is used to protect the important and expansive elements in power systems. One of these important elements that may be protected by the differential relay, is the power transformer. It function as link between the different voltage levels on the grid makes the continuity of its operation as a vital importance in maintaining the continuous supply of the electrical power.

The differential protection is an in-zone protection technique. It consists of comparing the current entering and the current leaving the protected zone and takes a decision according to the comparison made between the two currents. A non-zero differential current is significant of an internal fault and a disconnection action of the protected element must be taken immediately. However, in the case of the power transformers this non-zero differential current can be caused by other factors and operating conditions than internal faults. Among the various causes susceptible of causing a false tripping of the differential relays comes the challenging problems of the energization magnetization current, over excitation, the current transform saturation and measurement errors. Several methods and techniques to discriminate between the previously sited operating conditions and internal faults have been developed.

Through this project, the differential protection is introduced with its different types. The principal of working of the differential relay is explained in general and in particular for the protection of the transformers. In addition to that, the problems causing the transformer differential protection to operate unnecessarily are exposed and some of the most used discrimination techniques are presented and explained.

At the end, an improved numerical differential relay has been developed, simulated and tested. The logic used to overcome the problems found in the conventional protection of a transformer and to distinguish between the internal fault and the other unnecessary operating conditions is based on the harmonic content of the differential current.

The behavior of the presented relay has been implemented, simulated and tested versus various situations such as inrush current, internal fault, external fault and energization of the circuit win an existing fault. The obtained results show that the proposed algorithm model of the power transformer differential protection provides good discrimination and gives satisfactory results.

Differential Protection

1.1 Introduction

Power-system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults by disconnecting the faulted parts from the rest of the electrical network. The objective of a protection scheme is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Among the protection techniques used to perform this task comes the differential protection.

1.2 Principle of differential protection

Differential protection is a very sensitive and selective technique of protection. This type of protection is very sensitive to the fault that occurs within the zone of protection but least sensitive to the fault that occurs outside the protected zone. Electrical quantities (voltages or currents) at both extremities of the protected zone are measured and compared to each other. If the quantities are found to be not equal it means a fault exists within the protected zone.

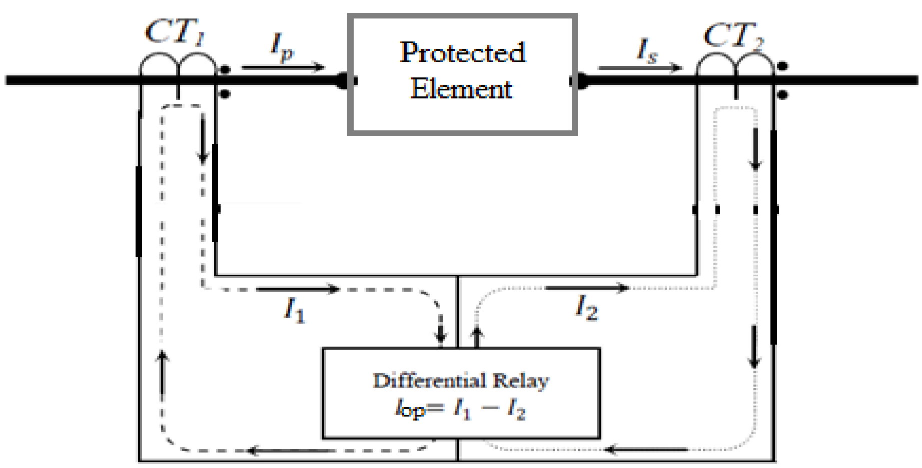

Figure 1-1: Basic Differential Relay Scheme [1].

The operating current in the differential relay is equal to:

$$I_{op} = | I_1 - I_2 | \tag{1-1}$$

If:

Iop = 0 => No internal fault.

Iop ≠ 0 => An internal fault occurs.

The General Idea behind the Differential Protection is that the current transformers (CTs) on the primary and secondary side must transform the respective line currents to the same value. For the Bias Coils in the relay to function without any damage, this transformed current may lie between 1A and 5A. Hence, the function of the CT's is to transform the line currents to the same magnitude and phase under normal operation of the Transformer [1].

1.3 Differential relay

The differential relay is one of the different types of relays used in power system protection. It is a commonly used relay for protecting transformers, generators and transmission lines. It operates when the difference between two or more similar electrical quantities that enters and leaves the protected equipment or zone, exceeds a predetermined value.

In differential relay scheme circuit, two currents come from two parts of an electrical power circuit. These two currents are transformed to a suitable range that is between 1A and 5A, by using a current transformer, and then the two currents meet at a junction point where a relay coil is connected. According to Kirchhoff Current Law, the resultant current flowing through the relay coil is nothing but summation of two currents, coming from two different parts of the electrical power circuit. If the polarity and amplitude of both the currents are so adjusted that the phasor sum of these two currents, is zero at normal operating condition. Thereby there will be no current flowing through the relay coil at normal operating conditions. But due to any abnormality in the power circuit, if this balance is broken, that means the phasor sum of these two currents no longer remains zero and there will be non-zero current flowing through the relay coil thereby relay being operated.

1.3.1 Types of differential relay

There are two commonly used types of differential relay depending upon the principle of operation.

1.3.2 Current differential relay

A relay, which senses and operates to the phase difference between the current entering into the electrical system and the current leaving the electrical system, is called a current differential relay. An arrangement of overcurrent relay connected to operate as a differential relay is shown in the figure below.

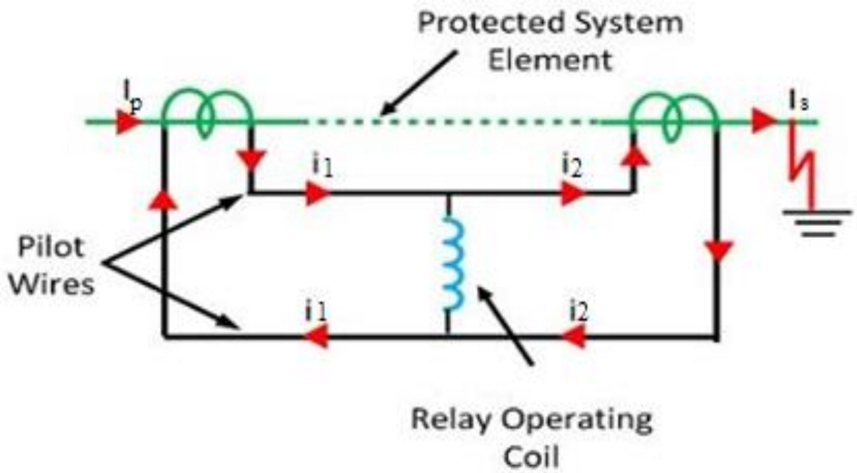

Figure 1-2: Current differential relay scheme [2].

The dotted line shows the section which is protected. The current transformer is placed at both the ends of the protected zone. The secondary of the transformers is connected in series with the help of the pilot wire. Thereby, the current induces in the CTs flows in the same direction. The operating coil of the relay is connected on the secondary of the CTs.

In the normal operating condition, the magnitude of current in the secondary of the CTs remains same. The zero current flows through the operating coil. On the occurrence of the fault, the magnitude of the current on the secondary of CTs becomes unequal because of which the relay starts operating [2].

1.3.2.1 Limitations of current differential relay

The limitation of the current differential relay are due to external conditions like a probability of mismatching in cable impedance from CT secondary to the remote relay panel and the pilot cable’s capacitance that may cause incorrect operation of the relay when large external fault occurs to the equipment.

As a solution to those problems that may happen to the current differential relay, the percentage differential relay is used. The conventional percentage differential relay is designed to response to the differential current in term of its fractional relation to the current flowing through the protected section. In this type of relay, there are restraining coils in addition to the operating coil of the relay. The restraining coils produce torque opposite to the operating torque. Under normal and through fault conditions, restraining torque is greater than operating torque. Thereby relay remains inactive.

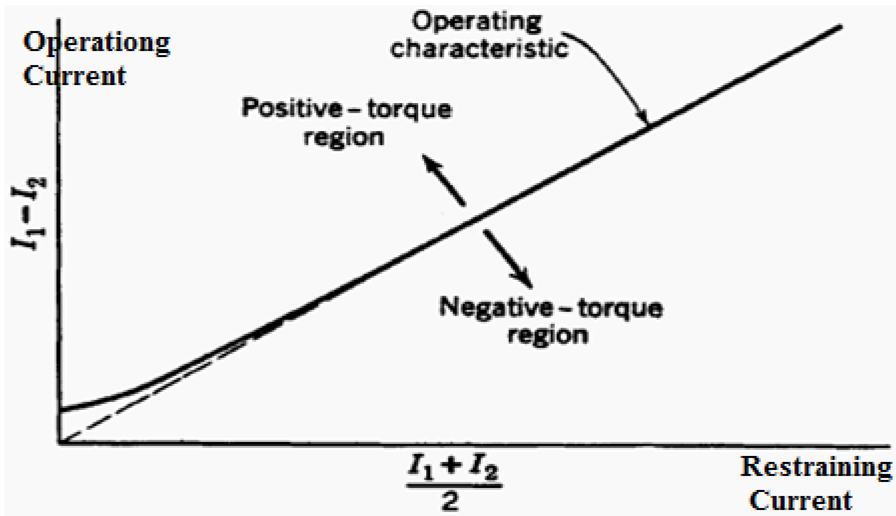

Figure 1-3: Operating characteristic of a percentage-differential relay [3].

From the above figure, greater the current flowing through the restraining coils, higher the value of the current required for operating coil to be operated. The relay is called percentage relay because the operating current required to trip can be expressed as a percentage of through current [3].

1.3.3 Voltage differential relay

The current differential relays are not suitable for the protection of the feeders. For the protection of the feeders, the voltage balance differential relays are used instead. In this arrangement the current transformers are connected at either side of the equipment in such a manner that EMF induced in the secondary of both current transformers will oppose each other. That means the secondary of the current transformers from both sides of the equipment are connected in series with opposite polarity.

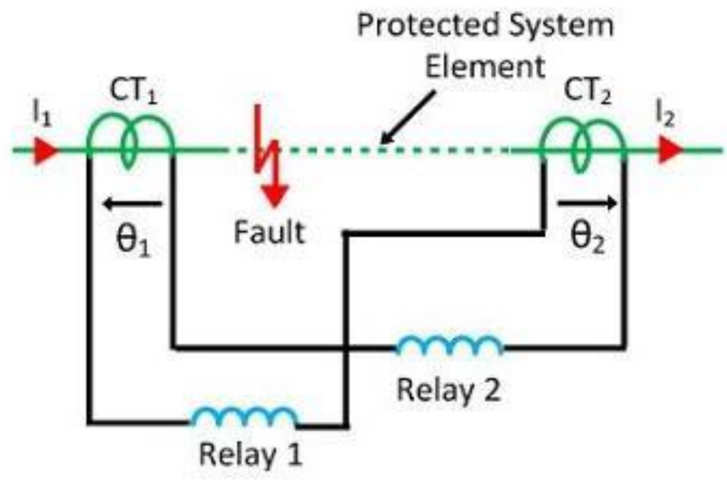

Figure 1-4: Voltage differential relay [2].

The relays are connected in series with the secondary of the current transformer. The relays are connected in such a way that no current flows through it in the normal operating condition. The voltage balance differential relay uses the air core CTs in which the voltages induces regarding current.

When the fault occurs in the protected zone, the current in the CTs become unbalance because of the voltage in the secondary of the CTs disturbs. The current starts flowing through the operating coil. Thus, the relay starts operating and gives the command to the circuit breaker to operate [2].

1.3.3.1 Limitations of voltage differential relay

There are some disadvantages in the voltage balance differential relay caused by the unbalance between current transformer pairs. For that, a multi tap transformer is required to accurate balance of currents.

The voltage differential relay is suitable for protection of cables of relatively short length. Otherwise, capacitance of pilot wires disturbs the performance. On long cables, the charging current will be sufficient to operate the relay even if a perfect balance of current transformer is achieved.

1.4 Application of differential relay and problems

The differential relay is very commonly used relay for protecting transformers, generators and transmission lines.

1.4.1 Differential protection of a generator

Differential protection for a generator is mainly employed for the protection of stator windings of generator against earth faults and phase-to-phase faults. The stator winding faults are very dangerous, and it causes considerable damage to the generator. For the protection of stator winding of the generator, the differential protection system is used for clearing the fault in the shortest possible time for minimizing the extent of a damage.

In order to perform an effective protection against earth faults and faults between phases, the Merz-Prize Circulating Current System is used. In this scheme of protection, currents at the ends of the protected sections is compared. When the system is in normal operating condition, the magnitude of currents is equal on the secondary windings of the current transformers. On the occurrence of the faults, the short-circuit current flows through the system and the magnitude of current become unequal. This difference of current under fault conditions is made to flow through the relay operating coil. The relay then closes its contacts, makes the circuit breaker to trip, and thus isolate the fault from the system [2].

The connection of that differential protection system requires two identical current transformers, which are mounted on both sides of the protected zone. The secondary terminals of the current transformers are connected in stars, and their end terminals are connected through the pilot wire. The relay coils are connected in delta. The neutral of the current transformer and the relay are connected to the common terminal. The relay is connected across equipotential points of the three pilot wires so that the burden on each current transformer is same. The equipotential point of the pilot wire is its center, so the relay is located at the midpoint of pilot wires.

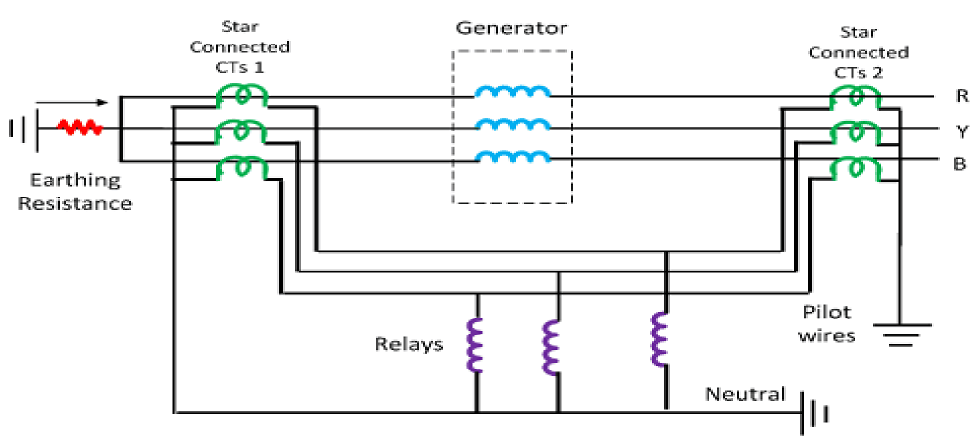

Figure 1-5: Merz-Prize Circulating Current System [2].

In figure 1-5, consider the fault occurs on the R phase of the network because of the insulation breakdown. Because of the fault, the current in the secondary of the transformer becomes unequal. The differential currents flow through the relay coil. Thus, the relay becomes operative and gives the command to the circuit breaker for operation.

If the fault occurs between any two phases, say Y and B then short-circuit current flows through these phases. The fault unbalanced the current flows through CTs. The differential current flows through the relay operating coil and thus relay trips their contacts [2].

1.4.1.1 Problem Associated with generator protection

A neutral resistance wire is used in the differential protection system for avoiding the adverse effect of earth fault currents. When an earth fault occurs near the neutral, it will cause a small, short circuit current to flow through the neutral point because of small EMF. The resistance of the neutral grounding further reduces this current. Thus, the small current will flow through the relay**.** This small current will not operate the relay coil, and hence the generator gets damage.

To overcome the problem, a modified scheme has been developed as illustrated in figure 1-6. In this scheme two elements are arranged, one for the protection of the phase fault and other for the earth fault protection. The phase elements are connected in stars along with the resistor. The earth fault relay is kept between the star and neutral. The two-phase elements together with a balancing resistor are connected in star, and the earth fault relay is connected between the star and neutral pilot wire.

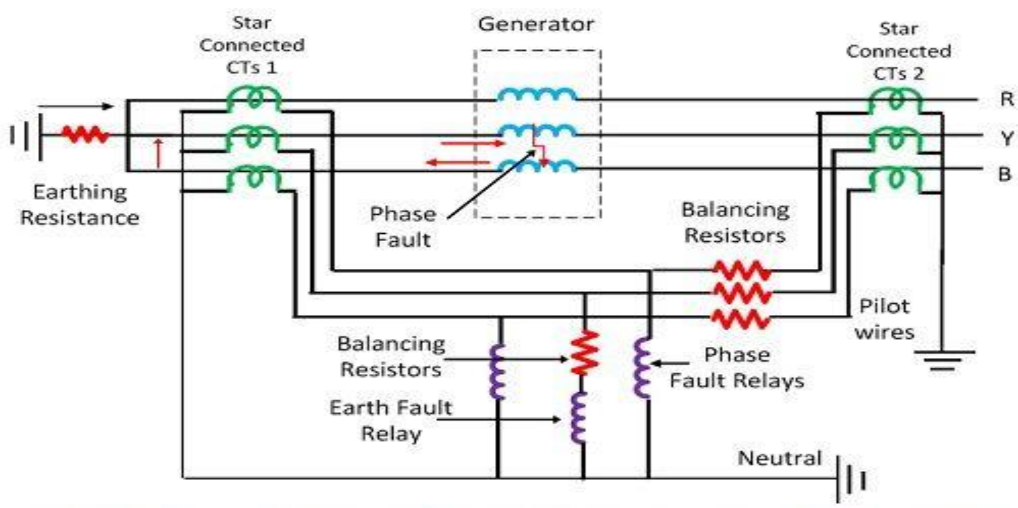

Figure 1-6: Modified scheme of differential protection for generator [2].

The star-connected circuit is symmetrical, and any balanced overflow current from the current circulating point will not flow through the earth fault relay. Therefore, in this system, the sensitive earth fault relay will operate at a high degree of stability [2].

1.4.2 The Differential Protection of a Transformer

The transformer is one of the major equipment in power system. It is a static device, totally enclosed and usually oil immersed, and therefore the fault occurs on them are usually rare. But the effect of even a rare fault may be very serious for a power transformer. Hence the protection of power transformer against possible faults is very important.

The fault that occurs on the transformer is mainly divided into two type external fault and internal fault. External fault is cleared by the relay system outside the transformer within the shortest possible time in order to avoid any damage to the transformer due. The protection for internal fault in such type of transformer is to be provided by using differential protection system.

Differential protection schemes are mainly used for protection against phase-to-phase fault and phase to earth faults. The differential protection used for power transformers is based on Merz-Prize circulating current principle. Such types of protection are generally used for transformers of rating exceeding two MVA.

The connection for differential protection of transformer is done with respect to the connection of the transformer. If the power transformer is star connected on one side and delta connected on the other side. The CTs on the star connected side are delta-connected and those on delta-connected side are star-connected. The neutral of the current transformer and power transformer are grounded. The restraining coil is connected between the secondary windings of the current transformers. Restraining coils controls the sensitive activity that occurs on the system. The operating coil is placed between the tapping point of the restraining coil and the star point of the current transformer secondary windings.

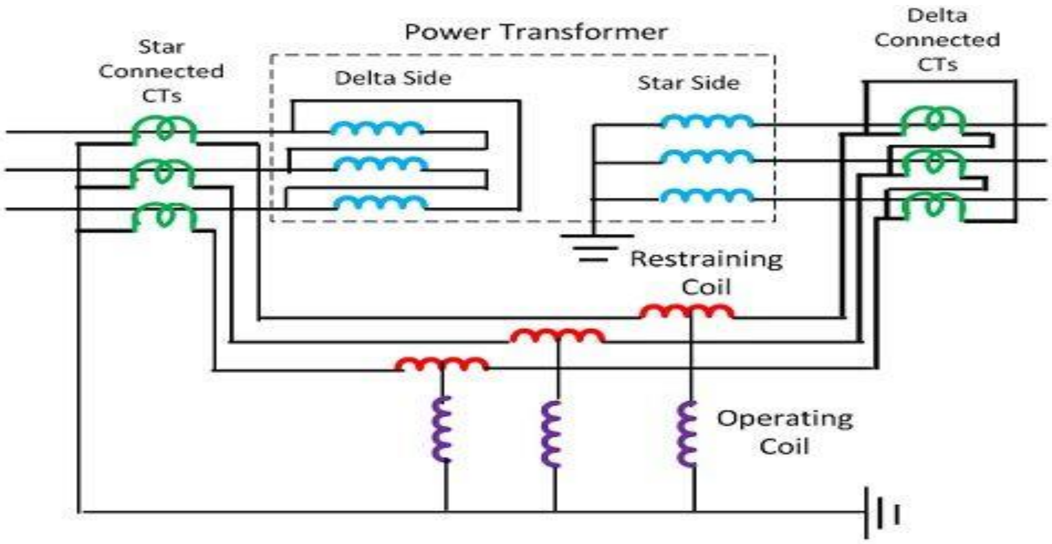

Figure 1-7: Differential protection for power transformers [2].

Normally, the operating coil carries no current as the current are balanced on both sides of the power transformers. When the internal fault occurs in the power transformer windings, the balanced current is disturbed and the operating coils of the differential relay carry current corresponding to the difference of the current between the two sides of the transformers. Thus, the relay trip the main circuit breakers on both sides of the power transformers [2].

1.4.3 The Differential Protection for transmission line

Several differential schemes are applied for protection of line but Mess Price Voltage balance system and Translay Scheme are most popularly used. The working principle of Merz Price Balance system is quite simple. In this scheme of line protection, identical CT is connected to each of the both ends of the line. The polarity of the CTs is same. The secondary of these current transformer and operating coil of two instantaneous relays are formed as a closed loop as shown in the figure 1-8. Also from the figure 1-8 it is quite clear that when the system is under normal condition, there would not be any current flowing through the loop as the secondary current of one CT will cancel out secondary current of other CT. If any fault occurs in the portion of the line between these two CTs, the secondary current of one CT will no longer equal and opposite of secondary current of other CT.

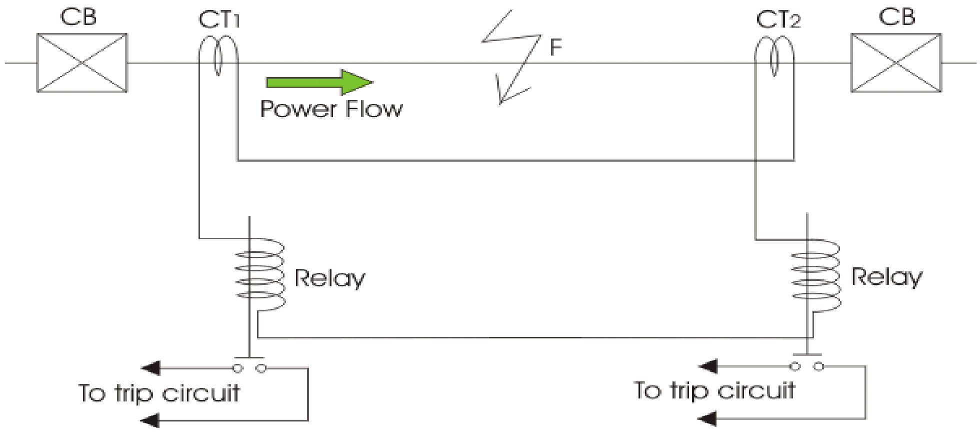

Figure 1-8: Differential protection scheme of transmission line [42].

Hence there would be a resultant circulating current in the loop. Due to this circulating current, the coil of both relays will close the trip circuit of associate circuit breaker. Hence, the faulty line will be isolated from both ends.

1.4.4 Differential protection for motors

Differential protection may be considered the first line of protection for internal phase to phase or phase to ground faults in the motor. Its function can only be used if both sides of each stator phase are brought out of the motor for external connection such that the phase current going into and out of each phase can be measured. The differential element subtracts the current coming out of each phase from the current going into each phase and compares the result or difference with the differential pickup level. If this difference is equal to or greater than the pickup level a trip will occur.

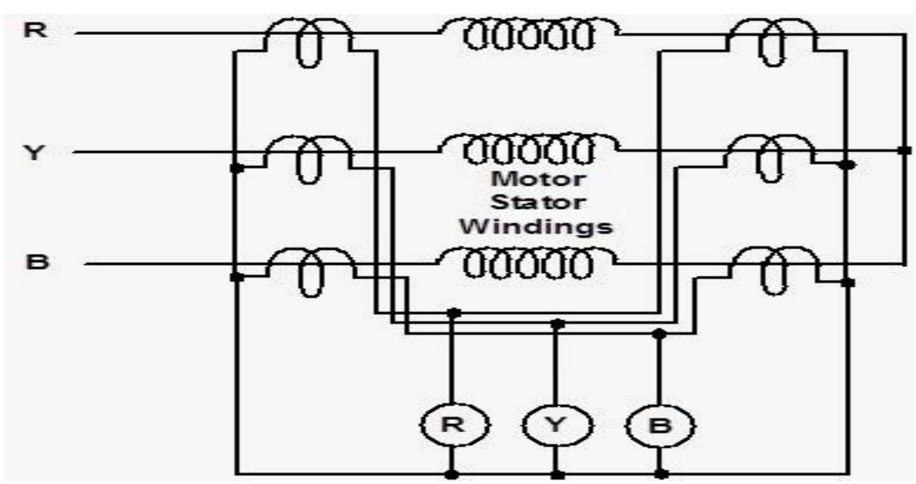

Figure 1-9: Differential protection scheme of motor [43].

Protection of Power Transformer

2.1 Introduction

The transformer is present in every part of the power system which make it one of the most vital devices of the electric power system and its protection is critical. For this reason, the protection of power transformers has taken an important consideration by the researchers. One of the most effective transformer protection elements is the differential protection.

2.2 Differential protection for transformers

Transformers are exposed to a wide variety of conditions that can cause different levels of faults and damages to the power system. The faults that occur on the transformer are mainly divided into two type external fault and internal fault. External fault is cleared by the relay system outside the transformer within the shortest possible time in order to avoid any damage to the transformer due to these faults. The protection for internal fault in such type of transformer is to be provided by using differential protection system.

Differential protection is a very sensitive and selective technique in protection. In this type of protection for power transformer, the differential relay is used. It compares the electrical quantities entering and leaving the protected zone or area. If the net difference equal zero, it means no fault exist.

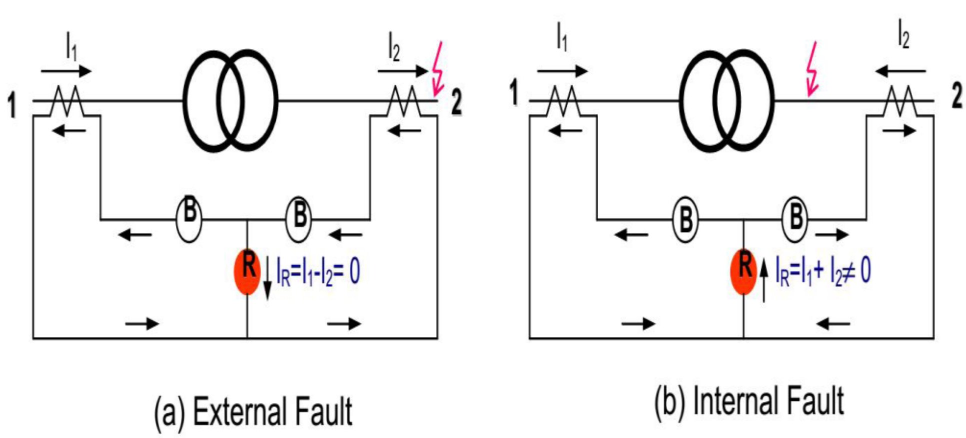

Figure 2-1: Principle of Differential Relay Protection [4].

2.2.1 The Differential protection scheme for power transformer

This scheme is based on the principle that the input power to the power transformer under normal conditions is equal to the output power. Under normal conditions, no current will flow into the differential relay current coil. Whenever a fault occurs, within the protected zone, the current balance will no longer exist, and relay contacts will close and release a trip signal to cause the circuit breakers (CBs) to operate in order to disconnect the faulty equipment/part.

The differential relay compares the primary and secondary side currents of the power transformer. Current transformers (CTs) are used to reduce the amount of currents in such a way their secondary side currents are equal. The polarity of CTs is such as to make the current circulate normally without going through the relay, during normal load conditions and external faults. Current transformers ratings are selected carefully to be matched with the power transformer current ratings to which they are connected so as the CTs secondary side currents are equal. However, the problem is that the CTs ratios available in the market have standard ratings. They are not available exactly as the desired ratings. Therefore, the primary ratings of the CTs are usually limited to those of the available standard ratio CTs. Commonly the primary side of the current transformer has only one turn (1) and the secondary side has many turns depending on the transformation ratio (N) of the CT, which is selected to match the ratings of the power transformer. Since the transformation ratio of transformers is the ratio between the numbers of turns in the primary side to the number of the turns in the secondary side. Therefore, the turn ratio of the primary current transformer is $\frac{1}{N1}$ and the turn ratio of the secondary side current transformer is $\frac{1}{N2}$ [5]. The secondary current of the CT located in the primary side of the power transformer is

$$I1 = \frac{Ip}{N1} \tag{2-1}$$

Where:

Ip : The primary side current of the power transformer,

$I1$: The secondary side current of CT1

N1: Number of turns in the secondary side of CT1

With the same manner for the CT located at the secondary side of the power transformer, the CT secondary current is:

$$I2 = \frac{Is}{N2} \tag{2-2}$$

Where:

Is: The secondary side current of the power transformer

I2: The secondary side current of the CT2

N2: Number of turns in the secondary side of CT2.

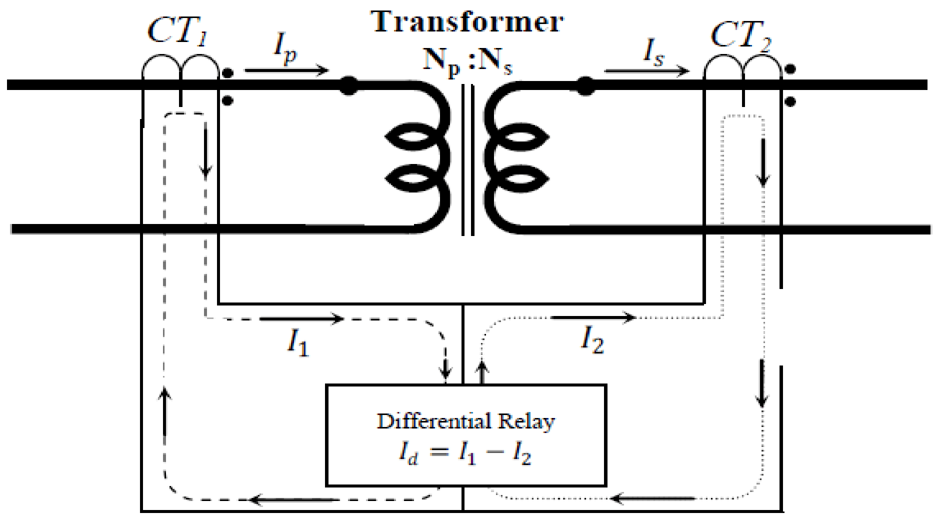

Figure 2-2 : Differential relay scheme [5].

From figure 2-2, Since the differential current is: *Id = I1 – I2*, then, from the two previous equations the differential current flowing in the relay operating coil current *Id* can be calculated as:

$$Id = \frac{Ip}{N1} - \frac{Is}{N2} \tag{2-3}$$

If there is no internal fault occurring within the power transformer protected zone, the currents *I1* and *I2* are assumed equal in magnitude and opposite in direction. That means the differential current *Id =0.*

In power transformers, the input power is equal to the output power. However, the voltage and the current in both the primary and secondary sides are different depending on whether the transformer is step up or step down. For instance, if the transformer is step up that means; the input voltage of the power transformer is low and the current is high, meantime the voltage in the secondary side is high and the current is low. This action makes both the input and output power equal. Due to this nature the CTs in the primary and the secondary sides of the power transformer do not have same turn ratio. However, they are carefully selected, in terms of turn ratio and magnetizing characteristics, so that they have the same output current at normal conditions of operations. If identical CTs are not available, the closer ones are chosen and then the mismatch between them is compensated by using the interposing CTs. The interposing CTs can fix the mismatch in the CTs; however, they add their own burden to the output of the main CTs [6] [7].

The same argument is applied for three phase (3ϕ) transformers, except some extra issues may appear in polyphase transformers.

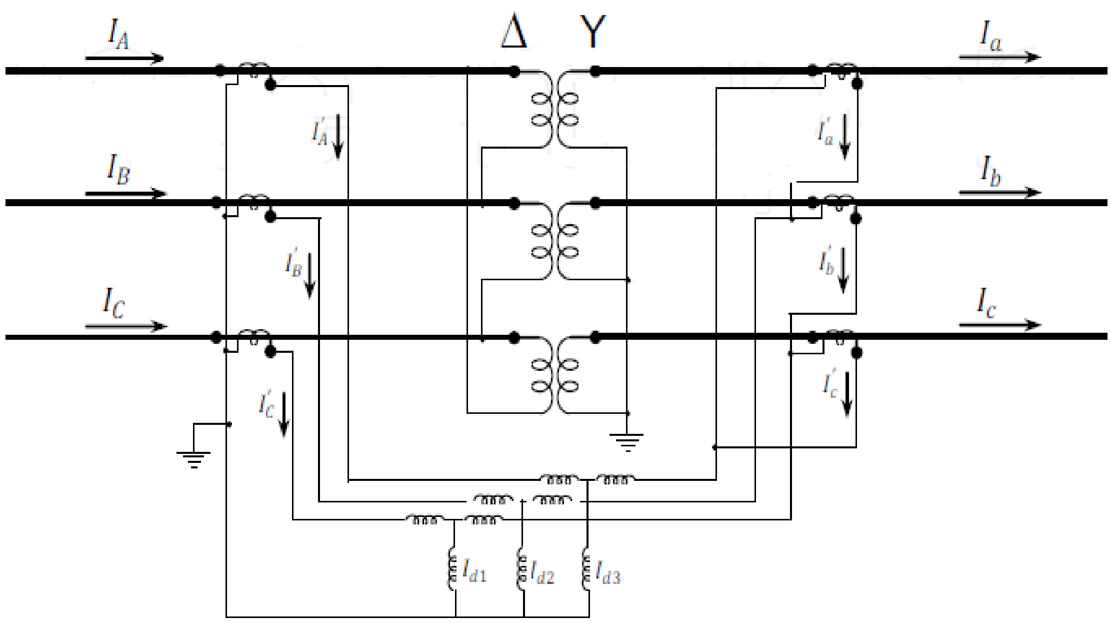

Figure 2-3: The schematic diagram of the three-phase differential protection [8].

In some cases, of 3ϕ power transformer connections, a 30° phase shift between primary and secondary currents is taking place. This phase shift occurs in the Y-Δ or Δ-Y connected transformers due to the transformation of the current from Y-Δ or Δ-Y.

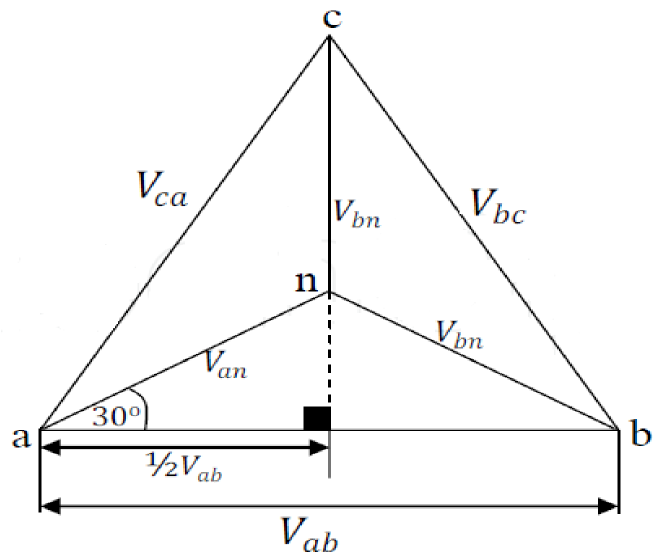

Figure 2-4: The relationship between line to line voltage and the phase to neutral voltage and the phase shift between them which reflects the phase shift in Y-Δ or Δ-Y connected transformers [8].

$$\frac{Vab}{2} = Van * \cos(30°) \quad (2\text{-}4)$$

$$\frac{Vab}{2} = Van\frac{\sqrt{3}}{2} \quad (2\text{-}5)$$

$$Vab = \sqrt{3}\ Van \quad (2\text{-}6)$$

This phase shift can be corrected easily by connecting the CTs secondary circuits in opposite way to the way that the power transformer phases are connected. For a DELTA-WYE connected power transformer, in order for the phase to be the same at both the primary and secondary CT, the CT's must be connected as WYE-DELTA. By doing this, the resultant phase that is seen by the relay is effectively zero. (Similarly, for a WYE-DELTA connected power transformer, the CT's must be connected as DELTA-WYE). For many solid-state electronic and microprocessor-based relays, the phase shift is made internally in the relay and the CT's may be connected the same on the primary and secondary sides of the transformer regardless of the transformer winding connections.

2.3 Problems associated with transformer differential protection

To provide an effective protection for faults within a transformer and security for transient abnormal operation and external faults, the design and application of transformer protection must consider factors such as:

- Magnetizing inrush current.
- Winding arrangements and connections.
- CTs Mismatch and Transformation ratio.
- Over excitation.

Those conditions induce the differential relay to release a false trip signal without the existing of any fault. These complications must be overcome in order to make the differential relay working properly. This means that the relay should trip as fast as possible for any transformer internal fault and, at the same time should not operate for any external fault condition. Misoperation should also be avoided for any other non-fault condition while still providing protection for conditions that are harmful if the duration of transformer exposer is significant.

To satisfy all of these requirements, today's advanced state-of-the-art transformer protection relays combine multiple protection functions and algorithms with multiple restrained inputs. [9]

2.3.1 Issues due to C.T characteristics.

The performance of the differential relays depends on the accuracy of the CTs in reproducing their primary currents in their secondary side.

In many cases, the primary values of the CTs, located in the high voltage and low voltage sides of the power transformer, does not exactly match the power transformer currents. Due to this difference, a CTs mismatch takes place, which in turn creates a small false differential current, depending on the amount of this mismatch. Sometimes, this amount of the differential current is enough to operate the differential relay. Therefore, CTs ratio correction has to be done to overcome this CTs mismatch [10].

2.3.2 Problems related to tap changer

Tap changers are installed on the power transformer to control automatically the transformer output voltage, whenever there are heavy fluctuations in the power system voltage. The transformation ratio of the CTs can be matched with only one point of the tap-changing range. Therefore, if the tap changer is changed, unbalance current flows in the differential relay operating coil. This action causes CTs mismatches. This current will be considered as a fault current which makes the relay to release a trip signal.

2.3.3 Trouble due to zero sequence

In all wye connected windings, the ground provides a way for current to enter the differential zone without being measured by a phase differential CT. This can unbalance the differential current during external phase to neutral faults. If the differential protection is to resist improperly tripping for external faults, this current has to be removed from differential calculations.

The first removal method is to simply connect the CT secondary circuit in opposite connection with respect to transformer windings. This straightforward method is used in electromechanical. In digital applications with wye connected CT secondary circuits, the ground current has to be removed numerically. This is done by either converting the currents to delta quantities [11].

2.3.4 Problems related to power transformer magnetization:

Transformer abnormal operating conditions can be divided to two categories permanent abnormal conditions as example of windings faults where the transformer is not expected to return to normal working condition and transient abnormal operating conditions where the transformer return to perform properly after some time duration. Although, those transient conditions as inrush current are not harmful since they not last, they can cause differential protection mal operation. Understanding inrush current phenomena require a basic understanding of the magnetic circuit.

2.3.4.1 Magnetic circuit characteristic:

Transformer is an electromagnetic induction device. The electrical energy is first converted to magnetic energy in the primary side of the transformer then reconverted to electrical energy in the secondary side. Energy is transferred from one side to another through a ferromagnetic core. The transformer work principal is governed by two major equations Ampere's law and faradays law [12].

The ampere's law stats that the integral of the magnetic field intensity in a closed loop equals the current passing within that loop.

$$\oint H \cdot dl = I_{\text{net}} \tag{2-7}$$

H is magnetic field intensity produced by the current I_{net}.

dl a differential element of length along the path of integration.

If a ferromagnetic core with mean path l is wrapped with a winding of N turns then the magnitude of the magnetic field intensity H is

$$H = \frac{Ni}{l} \tag{2-8}$$

The total flux produced depends also on the permeability of the ferromagnetic material used. The relationship between the magnetic field intensity and the magnetic field density β is given by:

$$\beta = \mu H \tag{2-9}$$

Where μ is the permeability of the ferromagnetic core material. Thus, the total flux produced in the core is:

$$\varphi = \int \beta \cdot dA \tag{2-10}$$

φ: is the total flux in the core and dA is the differential unit of area.

The steel core used in transformers contains many small regions called domains, those domains have their magnetic moments randomly oriented. An external magnetic field applied to the core will make the domains to point in the direction of the applied field and thus increasing the magnetic flux inside the core (fig.2-5) [12].

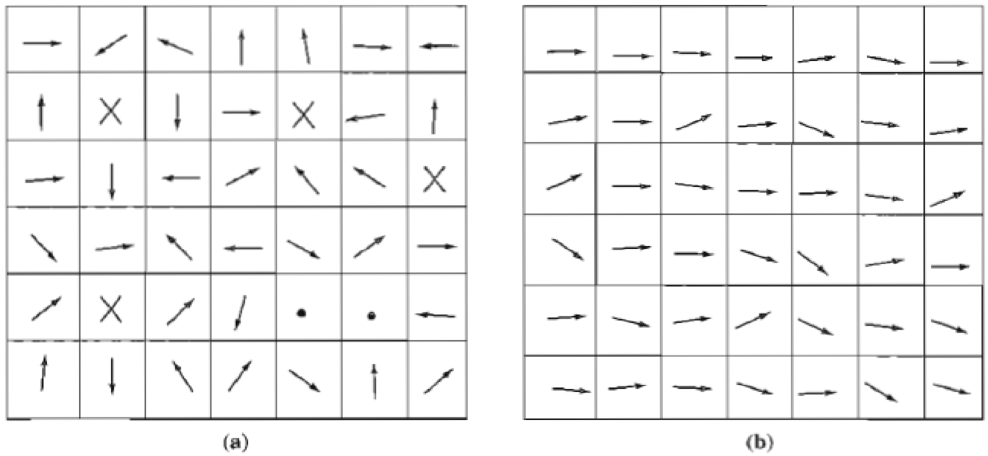

Figure 2-5: magnetic domains in a ferromagnetic material.(a) Magnetic domains oriented randomly.(b) Magnetic domains lined up in the presence of an external magnetic field [12].

At a certain strength of the applied magnetomotive force (the excitation voltage in the case of the transformer), the majority of the domains will be reoriented, further increase in the field strength will cause minor change in the flux inside the core. At this point the iron is said to be saturated. If the external force is removed the domains will not be completely randomize and some residual flux will still in the core. Opposite external force is needed to provide energy that will break the domains alignment. This energy loss called hysteresis in addition to the saturation property of the iron core give the shape of the magnetization curve shown in figure 2-6.

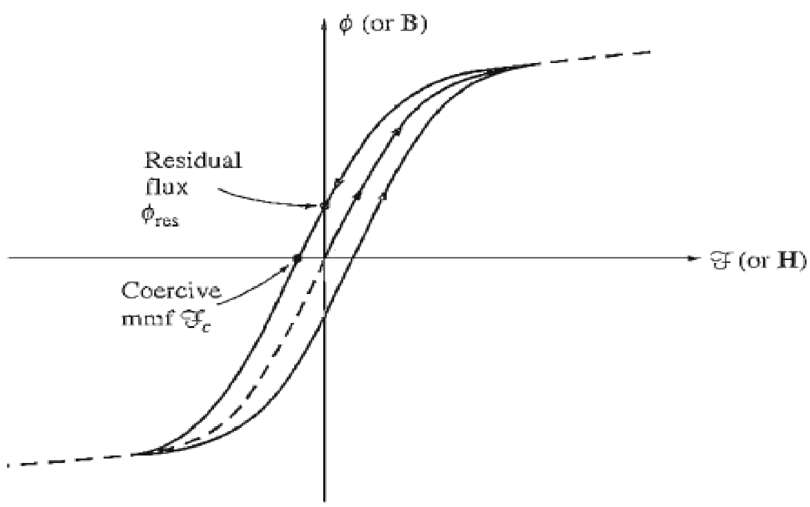

Figure 2-6: hysteresis curve of the transformer [16].

Faraday's law states that if a flux φ passes through a coil of wire, it will induce a voltage proportional to the rate of change of the flux with respect of time [12] [13].

If N is the number of turns in the coil and if the same flux is assumed to pass through all of the turns, then the voltage induced across the whole coil e_{ind} is given by

$$e_{ind} = -N\frac{d\varphi}{dt}$$

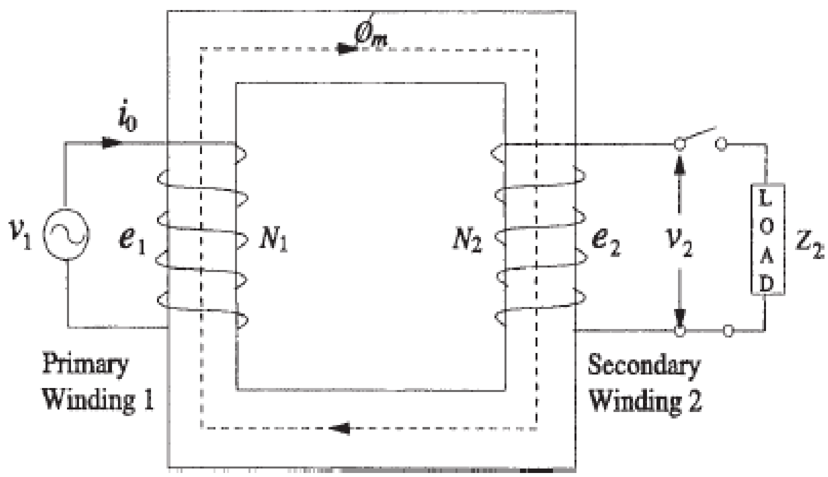

Figure 2-7: Transformer in no-load condition [12]

By rearranging the Faraday's law, the average flux in the core is given by:

$$\varphi_{avg} = \frac{1}{N}\int V_p(t)dt \quad (2\text{-}11)$$

Where φ_{avg} is the average flux in the core, N the number of turns of the primary side and $V_p(t)$ the voltage applied on the primary side.

If the primary voltage is of the form $V_p(t) = V_M \cos wt$, then the resulting flux is

$$\varphi_{avg} = \frac{V_M}{wN}\sin wt \quad (2\text{-}12)$$

When the transformer is connected to an AC source, current flows in its primary circuit even if the secondary is open. This magnetizing current is the required current to produce the flux in the ferromagnetic core.

As it can be seen in the previous equation (2-12), the flux will be lagging the voltage by 90º and also will be the magnetizing current as it is in phase with the flux.

The steady state magnetizing current can be obtained from the steady state flux by using the magnetic curve (B-H or φ-i curve).

Due to magnetic saturation of the transformer, the magnetizing current i_m is not a purely sinusoidal. Some high frequency components (harmonics) are present in the magnetizing current [14].

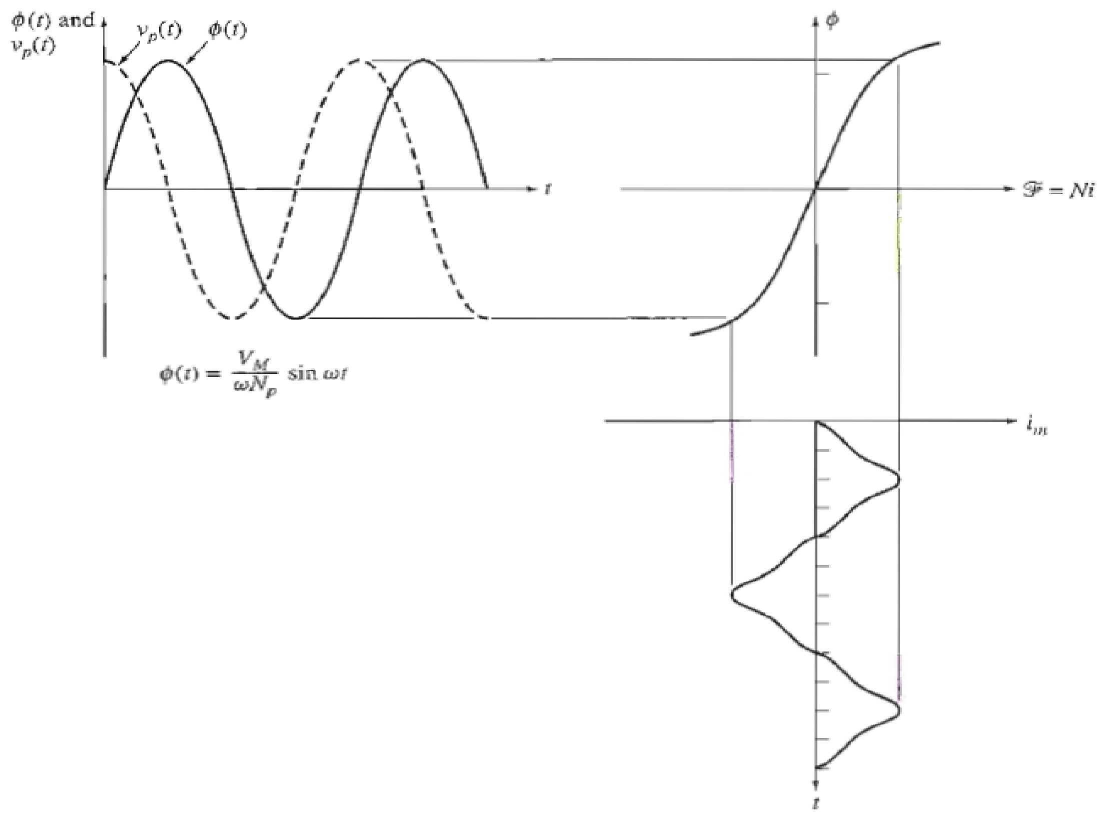

Figure 2-8: (a) The magnetization curve of the transformer core. (b) The magnetization current caused by the flux in the transformer core [12].

2.3.5 Inrush current

The inrush Current is the maximum input current drawn by an electrical device when it is first energized and can last for few cycles of the input waveform. Inrush current occurs in a transformer whenever the residual flux does not match the instantaneous value of the steady-state flux which would normally be required for the particular point on the voltage waveform at which the circuit is closed [15].

Inrush currents even though they are transient they can make transformer differential units to trip because they only flow in one winding [16].

Figure 2-9 shows the current waveform of transformer when the power is turned on. When the power is turned on, current begins to flow, and the initial current flow reaches the peak current value that can be larger than the steady-state current value. Following this, the current value gradually decreases until it stabilizes at the steady-state current. The part during which a large current flows before reaching the steady state current is called the inrush current.

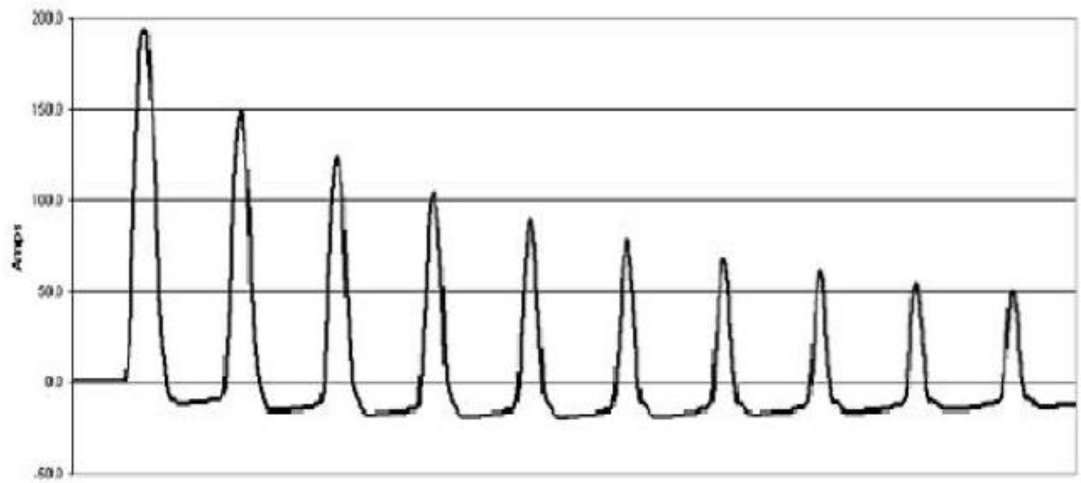

Figure 2-9: transformer magnetizing current on energization [16].

As a result of Faraday's law discussed in the previous section, the flux waveform can be treated as the integral of the voltage waveform. The two waveforms are 90˚ shifted. At steady state condition, when voltage is at zero, the flux waveform will be at its negative peak. This is not the case during energization of the transformer [12].

At t=0s, if the flux is assumed to be zero.

If the primary voltage is of the form: $V_p(t) = V_M \sin(wt + \theta)$, where θ is the voltage phase angel at which the transformer is switch on.

The maximum flux reached on the first half-cycle of the applied voltage depends on the phase of the voltage at the time the voltage is applied.

If θ= 90°, then the maximum flux is the steady state flux.

$$\varphi_{max} = \frac{V_M}{wN} \tag{2-13}$$

Now if θ= 0°, then the maximum flux is twice the steady state flux.

$$\varphi_{max} = \frac{2V_M}{wN} \tag{2-14}$$

Transformers are made up to operate within the limits of the saturation region of their magnetizing curve [17]. By examining the magnetization curve, it is easy to see that doubling the maximum flux in the core results in a very large magnetization current. Actually, the magnitude of inrush current can reach 8 to 10 times the rated load current and up to 50 times the normal exciting current [4]. Consequently, this might cause an undesired false tripping of the differential protective relay.

2.3.5.1 Factors affecting the inrush current

The magnitude and duration of the inrush current can be affected by several factors:

a) Energization voltage angel

For any other phase angle of the applied voltage between 90°, which causes no problem, and 0°, which is the worst case, there is some excess current flow [18]. The applied phase angle of the voltage is not normally controlled on starting, so there can be huge inrush currents during the first several cycles after the transformer is connected to the line [16].

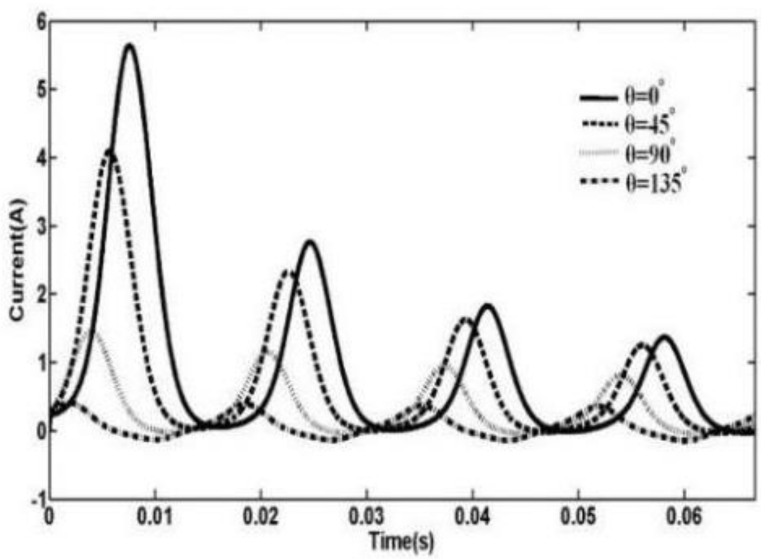

Figure 2-10: Effect of switching angle variation on amplitude of inrush current [18].

b) Residual flux

Since the transforms are made of ferromagnetic material, they are affected by their hysteresis characteristic. Even if the transformer is switched on at 90° voltage phase angel, some remanence flux is probably present depending on the moment of disconnecting the transformer. This residual flux affects the magnitude and duration of the inrush current [16].

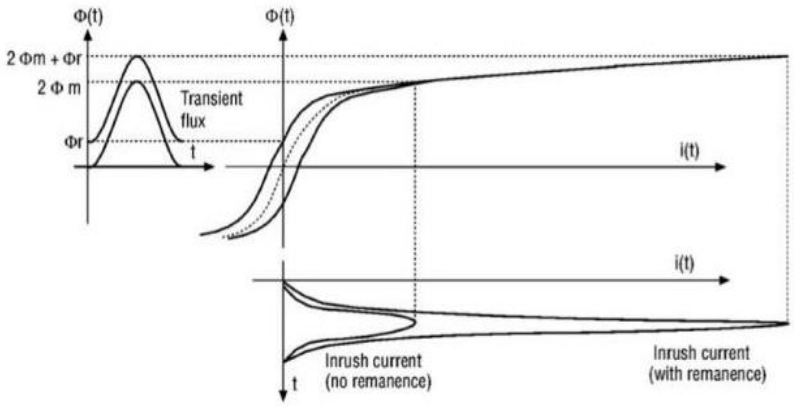

Figure 2-11: inrush current for twice plus residual flux [18].

Other factors like the source resistance, size of the transformer may affect with less degree the inrush current waveform [18] [19].

2.3.5.2 Events resulting in inrush current

a) Energization of the transformer

This is the main event where the inrush current is to be considered because it is considered to be the most severe case. When a transformer is switched-off, the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core. This results in certain remnant flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage, the flux becomes also sinusoidal but biased by the reminisce. The residual flux may be as high as 80% - 90% of the rated flux, and therefore, it may shift the flux-current trajectories far above the knee-point of the characteristic resulting in both large peak values and heavy distortions of the magnetizing current [19].

b) Voltage recovery after an external fault clearing

An external fault may significantly reduce the system voltage, and therefore reduce the excitation voltage of the transformer. When the fault is cleared, the voltage at the terminals of a transformer recovers to its normal level. The return of voltage may force a dc offset on the flux linkages, resulting in magnetizing inrush current. This creates conditions similar to energizing of a transformer [14]. This magnetizing inrush current will be less than that of energization, as usually there is no significant remanence flux in the core and also the voltage change is not the same as switching in except for a three-phase fault [19].

c) Sympathetic inrush

This phenomenon occurs when a transformer parallel to another, already energized transformer is being energized as shown in Figure 2-12. Assume, the transformer T2 has a large positive remanence flux and is switched-in at the unfavorable voltage phase, and obviously, a large inrush current will be drawn by this transformer. The slowly decaying dc component of the inrush current produces a significant voltage drop across the resistance of the equivalent power system. The resulting dc voltage drop shifts abruptly the voltage at the bus bar B. The change of the bus bar B voltage decreases saturation of the transformer T2, and consequently, reduces the inrush current of T2. The transformer T1, in turn, is exposed to this abrupt change of the voltage and may generate its own inrush current but in opposite direction [19]. Because the dc offset of the current in the supplying line is reduced, the damping of this current is also reduced. Consequently, the sympathetic inrush may last much longer as compared to their individual switching-in as shown in figure 2-13 [20].

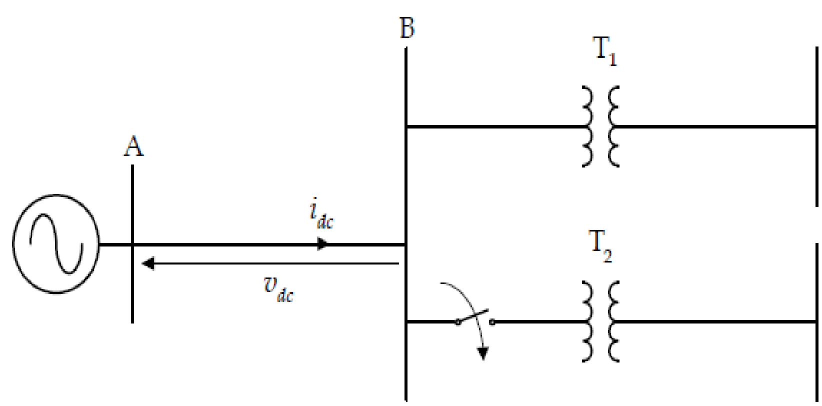

Figure 2-12: Conditions leading to the sympathetic inrush [19]

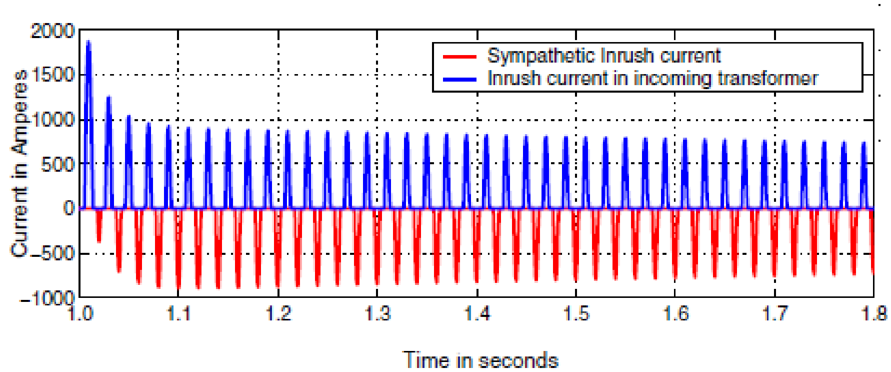

Figure 2-13: Typical waveforms of sympathetic inrush current [20]

2.3.5.3 Inrush current characteristics

Magnetizing inrush current in transformers results from any abrupt change of the magnetizing voltage. The magnetizing inrush currents that follow may be several times higher than the rated currents of the transformer. The waveform of transformer magnetizing current contains a proportion of harmonics that increases as the peak flux density is raised to the saturating condition. This current is high magnitude, harmonic-rich current generated when transformer cores are driven into saturation. The inrush current might reach 50 times the normal exciting current and few times the rated current of the power transformer. The inrush current starts very large and it decays in mill seconds to its steady state value. Since the inrush current is present in only one side of the transformers it may cause an unwanted tripping of the differential protection [4].

The current demanded by the transformer during the magnetization contains all orders of harmonics. The 2nd harmonic is the most significant harmonic present in the inrush current, it represents no less than 17% of the fundamental followed by the third the fourth and so on [15]. The dc component can also be significant during the first cycles depending on the residual flux. Higher order harmonics have small values and can be neglect.

Table 2-1: Percentage of harmonics in typical magnetizing inrush current [21].

Harmonic components in Magnetizing Inrush Current	*Amplitude (% of Fundamental)*
DC	55
2nd Harmonic	63
3rd Harmonic	26.8
4th Harmonic	5.1
5th Harmonic	4.1
6th Harmonic	3.7
7th Harmonic	2.4

2.3.6 Over-excitation

According to equation (2-12), the magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency. Overvoltage or under frequency conditions can take the transformer core to saturation.

Transformers might not tolerate more than a small amount of increase in the voltage over frequency ratio, a 10% increase of voltage in the limits of the saturation region may lead to a much higher increase in the magnetizing current [12].

Transformer over excitation causes transformer heating, increase of the exciting current, noise, vibration and may lead to an undesirable tripping the differential protection [22]. Over excitation of a power transformer is a typical case of ac saturation of the core that produces odd harmonics in the exciting current. Figure 2-14 shows the exciting current recorded during a real test of a 5kVA, 230/115 V, single-phase laboratory transformer [23].

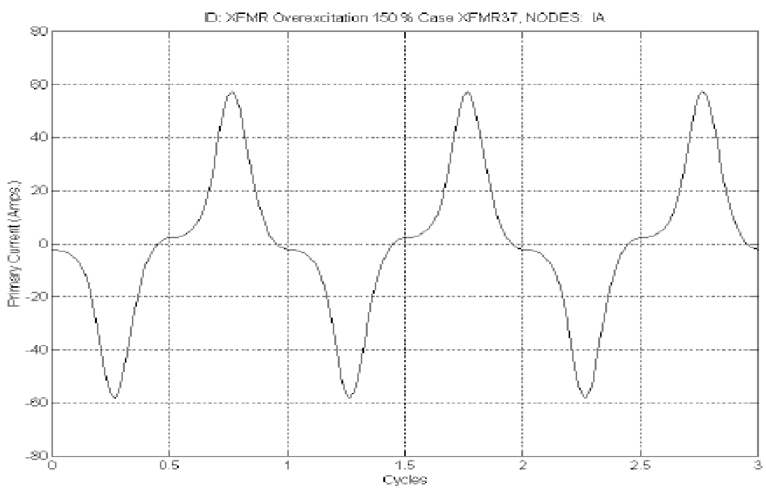

Figure 2-14: Phase Current from Transformer Testing. 150% Overvoltage on the Low Side of the transformer [23].

Table 2-2 shows the odd-harmonic content of the current signal shown in Figure 2-14. The third and fifth harmonics provide reliable quantities to detect over excitation conditions. However, the third harmonic can be filtered out with the delta connection compensation of the differential relay or the delta connection of the CTs. The fifth harmonic, is still a reliable quantity for detecting over excitation conditions.

Table 2-2: Harmonics of the Excitation Current under over excitation condition [23].

Frequency Component	**Magnitude (Primary Amps)**	**Percentage of Fundamental**
Fundamental	22.5	100.0
Third	11.1	49.2
Fifth	4.9	21.7
Seventh	1.8	8.1

2.3.7 Ct saturation

Since the first use of differential protection schemes, CTs have been part of the architecture of the differential relay. One of the main problems for differential transformer protection is CTs saturation. Although the CTs used in protection systems are designed to work properly until 20 times of their rated full load current, sever external faults or even internal faults might lead the CTs to saturate. Saturation leads to inaccurate measurement of primary currents that may cause relay malfunction. CTs saturation can affect both the protection system security and dependability. For external faults, double sides or single side CTs saturation may provide false differential current that causes undesired trip of the system. At the same time, the harmonics generated in the differential current due to the CTs saturation during an in-zone fault may cause a time delay or even block the operation of the harmonics based differential relays [24].

CTs saturation secondary current are characterized by the presence of dc component and harmonics. However, only odd harmonics can be observed on the waveform as the even harmonics are transient (figure 2-15) [22].

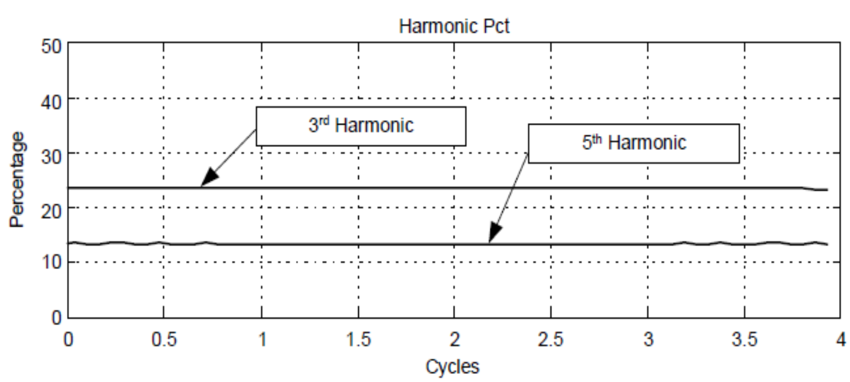

Figure 2-15: Typical Harmonic Content of a Secondary Current under CT Saturation [22].

Differential Relay Improvement

3.1 Introduction

Transformers belong to a class of vital and expensive components of the electric power systems. If a power transformer experiences a fault, it is necessary to take the transformer out of service as soon as possible so that the damage is minimized.

Accordingly, high demands are imposed on power transformer protective relays. The requirements include dependability (no missing operations), security (no false tripping), and speed of operation (short fault clearing time).

The operating conditions of power transformers, however, do not make the relaying task easy. Protection of large power transformers is a challenging problem in the area of power system relaying.

Numerical relays capable of performing sophisticated signal processing enable the relay designer to re-visit the classical protection principles and discrimination techniques and enhance the relay performance, facilitating faster, more secure and dependable protection for power transformers.

3.2 Differential protection improvement domains

3.2.1 Reliability

A relaying system has to be as reliable as possible with the minimum possible coast. Reliability can be achieved by redundancy which can be an expansive choice. Other way to improve reliability is to improve the used relay performances.

A protection system reliability is characterized by following parameters [25]:

- Dependability
- Security

3.2.1.1 Dependability

A relay is said to be dependable if it trips only when it is expected to trip. However, false tripping of relays or tripping for faults that is either not within its jurisdiction, or within its purview, compromises system operation. The power system may get unnecessarily stressed or else there can be loss of service. Dependability is the degree of certainty that the relay will operate correctly.

To be dependable the differential relay must trip for each internal fault. For internal faults, dependability of the harmonic restraint type relays could be negatively affected if current harmonics generated in the CT secondary circuit due to CT saturation are high enough to restrain the relay.

3.2.1.2 Security

On the other hand, security is a property used to characterize false tripping on the relays. A relay is said to be secure if it does not trip when it is not expected to trip. It is the degree of certainty that the relay will not operate incorrectly.

Transformer False tripping impact the power system security, availability and also the transformer and circuit breakers life duration due to the electrical and mechanical stresses produced by the switching in and off.

Security in differential relay is a challenging field. Inrush, over excitation and CTs saturation for external fault are the most security affecting operation condition.

3.2.2 Speed

Electrical components are sometimes very expansive. Fast clearing of faults is essential to avoid important damage on equipment. Designing a fast relaying system depends on many factors like CBs tripping speed or the algorithm decision making fastness.

3.3 Discrimination techniques

Many particular conditions that the transformers can undergo may lead to differential relay mal operation. Inrush current, over excitation and CTs saturation are common situation where wrong decisions can be taken by the differential protection.

One of the oldest solutions, was to introduce an intentional time delay in the differential relay or desensitize the relay for a given time at the energization of the transformer [26]. Adding a voltage signal to restrain the differential relay was also a suggested solution [27].

Harmonic based restrain methods were introduced later. Those methods are based on the fact that differential current harmonic content provides helpful information on the transformer operating conditions. Kennedy and Hayward were the first to propose differential relay with 2^{nd} harmonic restrain [28], then Sharp and Glassburn introduced the idea of harmonic blocking instead of restraining [29].

Einval and Linders proposed the use of an additional fifth-harmonic to prevent mal operations due to transformer over excitation [30]. Others method based on wave shape recognition [31], were they make benefits of the waveform shape of the inrush current was found to provide good results. Differential active power can also be used to distinguish internal faults from inrush [32].

3.3.1 Percentage restrain differential protection scheme

As discussed in the previous chapters, differential protection is supposed to operate for the internal faults or for the zone of protection that is intended for, and should not operate for a through fault. Through fault means a fault outside the zone of protection. Thus, as discussed, for a through fault the differential current through the overcurrent element of the differential protection relay is zero while there is some definite value of differential current for internal faults. But actually, there are many limitations due to which a differential current flow in the differential relay in normal operation also.

A practical transformer and CTs pose some challenge to differential protection. They are as follows:

- The primary of transformer will carry no load current even when the secondary is open circuited. This will lead to differential current on which the protection scheme should not operate.
- It is not possible to exactly match the CT ratio as per equation. This would also lead to differential currents under healthy conditions.
- If the transformer is used with an off-nominal tap, then differential currents will arise as the CT ratio calculated for a particular tap (Nominal Tap) will be different for different taps, even under healthy conditions.

Therefore, because of the above reasons a differential current will flow through the differential protection relay. So, the differential relay will operate which is not expected to operate for the above said reasons [33].

To prevent the differential protection scheme from picking up under such conditions, a percentage differential protection scheme is used. It improves security at the cost of sensitivity.

Percentage restrained differential protection is one of the oldest forms of adaptive protection algorithms. It requires that the differential current be greater than a percentage of the through (restraint) current. The percentage restraint characteristic operates on the ratio of operate-to-restraint current in the zone of protection. The operate quantity (Iop) is universally defined as the magnitude of the differential current in the zone of protection. However, many different methods have been developed to quantify the restraint quantity (Irst). The definition of the restraint magnitude has an impact on the effective sensitivity and security of a given slope setting. This characteristic is demonstrated by the use of a slope.

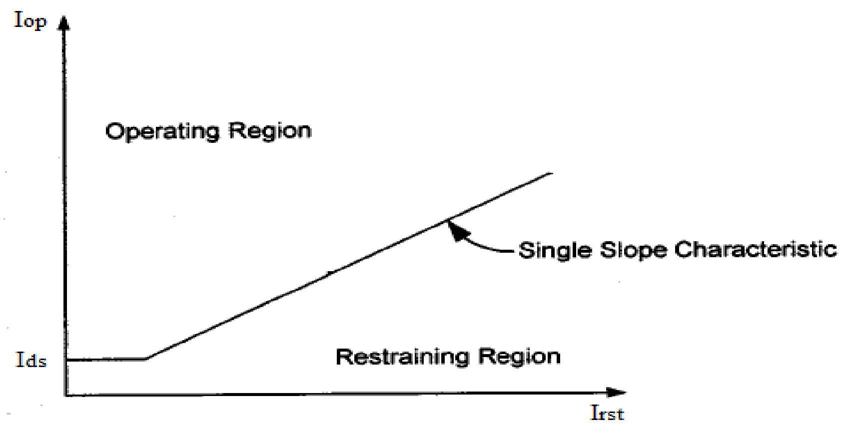

Figure 3-1: One slope percentage differential protection scheme [33].

It can be also achieved by dual-slope characteristic which implies improved sensitivity over the linear operating range but less stability. It also compensates for current transformer (CT) ratio mismatches, CT ratio errors, CT saturation, and errors due to tap changing [33].

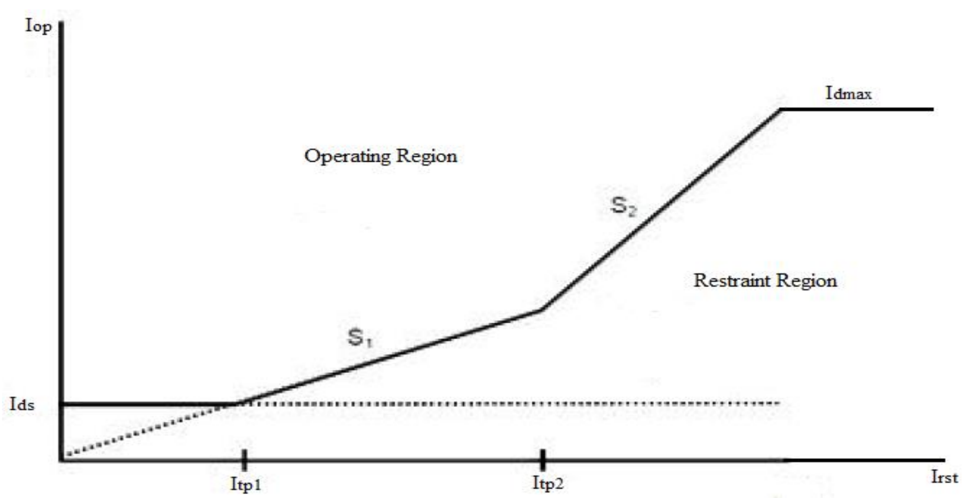

Figure 3-2: Dual slope percentage differential protection scheme.

3.3.1.1 Analysis and setting of the slopes

The slope characteristic can provide high sensitivity when low levels of current are flowing in the zone of protection but has less sensitivity when high levels of current are flowing.

In order to set the percentage of the slope one, we consider the following:

- Relay tap mismatch (this can be 0 with the proper CT ratio selection).
- Power transformer ratio (nominal tap to minimum tap). No-load taps can be up to 5 percent, and autotransformers are typically 10 percent.
- Protective relay error (up to 5 percent).
- CT ratio error (3 to 5 percent).
- Magnetizing inrush (up to 5 percent).

This improves security because CTs are more prone to saturation when they have to reproduce high levels of current in the primary circuits [34].

For the second slope it is set to the range of 50 to 90 percent to avoid problems with CT saturation for high fault currents.

From the figures of slopes, we Notice an offset to account for the no load current of transformer. If we do not provide this offset then the differential protection will operate during no load of transformer and will trip the transformer primary side breaker which is not desired.

The current on the X-axis is the average current of primary and secondary winding referred to primary. It indicates the restraining current called the Biasing Current, $I_{b.}$ While the corresponding difference on Y-axis represents the differential current. The differential protection relay will pick up if magnitude of differential current is more than a fixed percentage of the restraining current [33].

3.3.1.1.1 Setting of the threshold current

As a first step to set the differential protection curve, a low set point is defined. It is considered as the maximum differential current that exists in normal transformer operation. This low set point is named also Ids threshold. It is expressed as a percentage of the primary nominal current In1 [34]. The percentages of threshold current include:

- Differential current induced by the relay, I_{drelay} = 1%
- Magnetizing current of the core which creates a differential current, I_{dm} = 3%
- A safety margin is also taken: typically, 5%.

As a standard value, from 30% to 40% of the nominal current is taken as a value for I_{ds}.

3.3.1.1.2 Setting of the first segment

The part that follows the threshold current is the first segment of the slope. It starts by the first turning point Itp1, which a standard value and it is conventionally set to I_{tp1}= 45% of I_n, where In is the nominal current of transformer [35].

The first segment of the slope is used to prevent tripping due to high fault currents of external origin, because when a high external fault occurs, a high through current circulates. The differential current due to the transformer and its accessories (measurement CT, on-load tap changer and auxiliary winding) is also higher than in normal operation, so the Ids set point is exceeded. However, the protection should not trip, since the fault is external. With the first slope, the higher the through current, the higher the differential current tripping threshold will be, thereby ensuring that the function will not trip in the event of external faults [34].

The setting of the slope should be sufficient to compensate for measurement errors caused by current with low but significant amplitude. This is achieved by the following computations: [35]

$$Slope1 = \frac{\text{Ids1}}{\text{Irst}} \times 100\% + 5\% \text{ (of errors)} \quad (3\text{-}1)$$

Where:

$$\text{Ids1} = |\text{I1} - \text{I2}| \times \text{Ids} \quad (3\text{-}2)$$

$$I_{rst} = \frac{\text{I1}+\text{I2}}{2} \quad (3\text{-}3)$$

3.3.1.1.3 Setting of the second segment

The second slope starts by the second turning point I_{tp2}, which depends on the CT's capacity to give a correct image of the primary currents during external faults. This value could be set up to 200% of rated current for large transformers and from 100% to 200% of rated current for smaller transformers. I_{tp2} depends on type of formula used to calculate I_{rst}. For type A ($I_{rst} = \frac{I1+I2}{2}$, the one used) the value of this turning point will be twice the rated current.

The second segment of the slope ensures additional restraint with severe external fault current that could cause at least one CT to saturate. If only the primary CTs saturate, not the secondary CT, a very high differential current is created. To prevent unwanted tripping in these conditions, the percentage-based curve includes the slope2.

The curve should be set sufficiently high to compensate for the worst case in which only the CTs at one end saturates. Typically, the slope is set between 60 and 90% [34] [35].

3.3.1.1.4 Setting of high set point

The high set point allows faults inside the protected zone to be detected by the rise in differential current. If the differential current exceeds a predetermined set point (I_{dmax}), the protection function trips faster than an overcurrent protection relay would. In addition, there is no restraint on the high threshold, meaning that once it is activated, it is not affected by any restraint.

The high set point is set above the closing current, typically with a margin of 40% so that the protection function will not be tripped by transformer energizing [34].

$$I_{dmax} = 140\% \times I_n \quad (3\text{-}4)$$

Where I_n is the transformer rated current.

3.3.2 Harmonic based methods

The harmonic content of the differential current might be used to restrain or block the relay. The relay is provided information that help to differentiate between different operating conditions (inrush, over excitation, internal fault,...). Two main approaches with slight differences are used. Those techniques are harmonic restrain and harmonic blocking.

3.3.2.1 Harmonic blocking

Harmonic blocking is the simplest harmonic based method. Sharp and Glassburn [29] were first to propose harmonic blocking method in 1958. Harmonic blocking method calculates the ratio between the harmonic content and the fundamental content of the differential current. When this ratio is above a predefined threshold set the harmonic blocking operates.

$$\frac{I_{diff-harm-n}}{I_{diff-fund}} \geq Kn \qquad (n=2,3,4\ldots.) \qquad (3\text{-}5)$$

$I_{diff-harm-n}$ is the nth harmonic component of the differential current.

$I_{diff-fund}$ is the fundamental component of the differential current.

Kn is the ratio set.

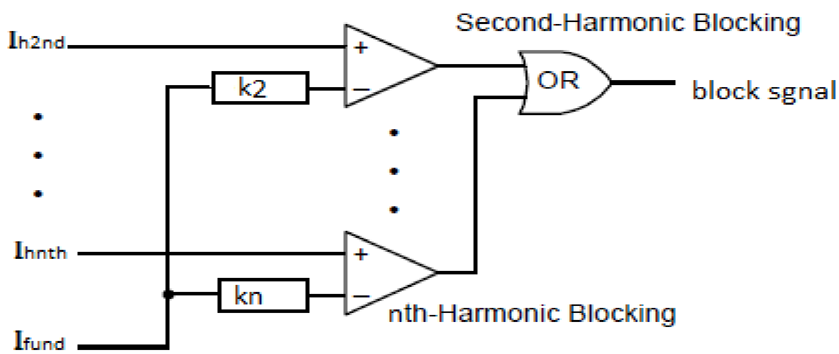

Figure 3-3: harmonic blocking operation logic.

The condition for the differential relay to operate in the presence of the harmonic blocking is:

$$(I_{op} > I_{rst} \cdot f(SLP1, SLP2))\ \&\ (\frac{I_{diff-harm-n}}{I_{diff-fund}} < Kn\ ) \qquad (n=2,\ 3,\ 4\ldots.) \qquad (3\text{-}6)$$

So, the operating current (differential current) must exceed the percentage restrain current and the harmonic level of the selected harmonic must be less than the fundamental of the differential current.

Several logics and combinations have been used to increase the precision of the deferential relay [36].

a) Per phase method

This is the earliest and simplest harmonic blocking method. The algorithm is applied to each phase separately. The relay makes the comparison and output a response for each phase depending on the harmonic level present in the phase. The phase satisfying the blocking condition is restrained independently of the other phases. However, in a three-phase transformer it is possible that one of the phases experience a harmonic level below the blocking settings at the same time that the other phases are above the settings due to the fact that each phase has a different switch angel and residual flux. This case may result in a false tripping of the relay. The per-phase method is most dependent but least secure.

b) Cross blocking method

In this method, the blocking signal for one phase is used to inhibit other phases.

- One out of three logic

If one phase of the three phases is blocked due to the presence of high harmonic content the blocking is activated in the other phases, no matter their harmonic content. This logic has the drawback that if there is an internal fault in one phase or two phases, the high harmonic ratio in a healthy phase may block the percent differential protection. The differential protection with per phase cross blocking harmonic method is very secure but least dependable.

- Two out of three logic

The blocking of differential operation needs at least two phases to have sufficient harmonic level. If two phases out of three have enough harmonic content the blocking is activated in the other phase, no matter its harmonic content. This logic provides a better balance between security and dependability than the “one out of three” logic but still face the same drawback as it can prevent the relay from correctly tripping if an internal fault occurs in one phase.

- Average logic

The average blocking method uses the average of the harmonic ratio of the each of the phases to obtain a common harmonic ratio, i.e :

$$\text{harm-ratio} = \frac{1}{3}\left(\frac{I_{diff-harm-n-A}}{I_{diff-fund-A}} + \frac{I_{diff-harm-n-B}}{I_{diff-fund-B}} + \frac{I_{diff-harm-n-C}}{I_{diff-fund-C}}\right) \quad (3\text{-}7)$$

Compared to the cross-blocking method, this method improves the security of differential protection to a certain degree. The differential operation may be restrained when there is a single-phase fault during energization, provided that there are large harmonic ratios in the remaining healthy phases. This would cause a concern on the dependability in the differential protection.

- Summing (sharing) logic

The harmonic ratio is computed using the sum of the harmonic content of all the phases in the following manner:

$$I_{diff-harm-n-sum} = I_{diff-harm-n-A} + I_{diff-harm-n-B} + I_{diff-harm-n-C} \quad (3\text{-}8)$$

$$I_{ratio-harm-n-A} = \frac{I_{diff-harm-n-sum}}{I_{diff-fund-A}} \quad (3\text{-}9)$$

$$I_{ratio-harm-n-B} = \frac{I_{diff-harm-n-sum}}{I_{diff-fund-B}} \quad (3\text{-}10)$$

$$I_{ratio-harm-n-C} = \frac{I_{diff-harm-n-sum}}{I_{diff-fund-C}} \quad (3\text{-}11)$$

This method provides a good balance between security and dependability. The shared harmonic content compensates for any low harmonic level phase. At the same, in case of an internal fault in one phase, the differential large fundamental current will result in a low harmonic ratio.

3.3.2.2 Harmonic restraint

Harmonic restraint is the earliest harmonic based discrimination method. It was introduced in electromechanical relays in 1938 by Kennedy and Hayward [28]. The harmonic restraint method uses the harmonic content of the differential current to increase the theoretical differential current required to trip (obtained from the percentage restrained characteristic). This concept is expressed in the following equation:

$$I_{op} > I_{rst} \cdot f(SLP1, SLP2) + \sum_{x=2}^{n} \frac{I_{diff-harm-x}}{kx} \quad (3\text{-}12)$$

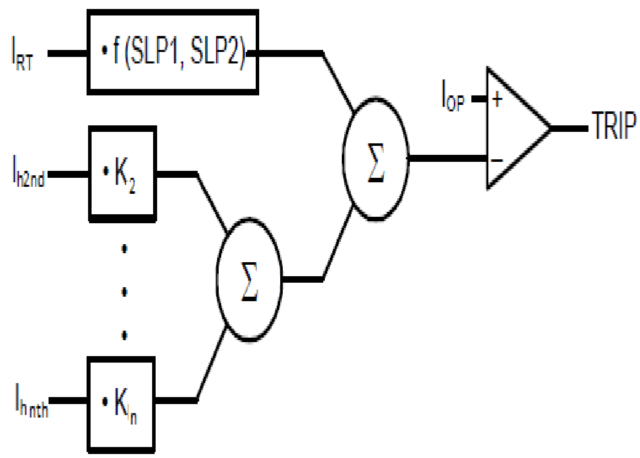

Figure 3-4: harmonic restrain operation logic.

The harmonic restraint principle elevates the percentage current characteristic by adding additional current extracted from the differential current selected harmonic content [37].

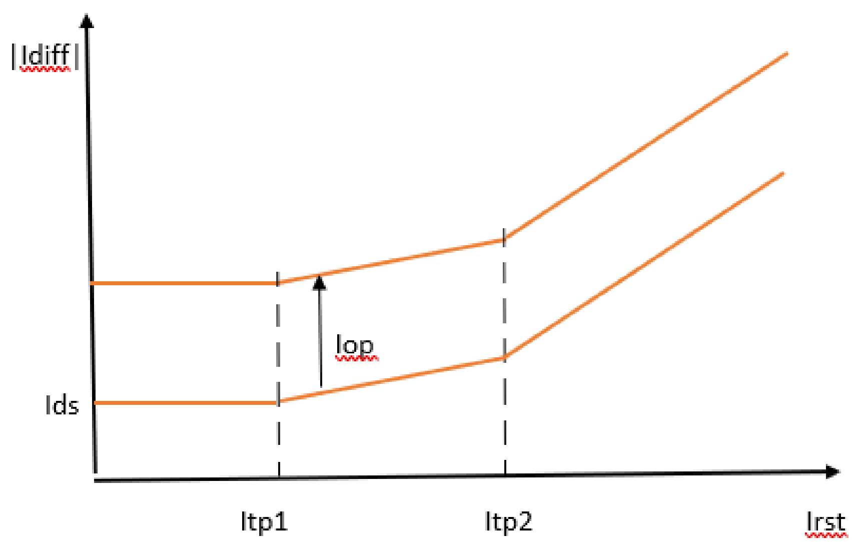

Figure 3-5: Rise in the percent differential characteristic due to harmonic restrain.

3.3.2.3 Even harmonic restrain/blocking

Even harmonics are a clear indicator of magnetizing inrush. The 2nd harmonic was the first used harmonic in harmonic restraint/blocking [28], as it is the most dominant harmonic during inrush condition. Restrain settings around 20% are found to provide good results [29]. It was found that the inrush current can have values of second harmonic, being as low as 7%. Changing the settings to 7% decreases the dependability as an internal fault may contain such level of second harmonic. Reference [38] suggested the use even harmonics (and not only the second harmonic) to obtain better discrimination between inrush and internal fault currents.

The use of even harmonics (second and fourth) in a restraint scheme ensures security for inrush currents having very low second-harmonic current. The operation equation for second and fourth harmonic restraint differential element is:

$$I_{op} > I_{rst} \cdot f(SLP1, SLP2) + \frac{I_{diff-harm-2}}{k2} + \frac{I_{diff-harm-4}}{k4} \qquad (3\text{-}13)$$

3.3.2.4 Odd harmonic restraint/blocking

Over excitation and CTs saturation are characterized by the presence of odd harmonics. The third and fifth harmonics are normally used to detect such condition. The third harmonic even though it is a good indicator for an over excitation condition but it is filtered by the delta windings since it is a zero-sequence component. The fifth harmonic is normally used [30]. Studies showed a 35% setting provides good discrimination [39].

Implementation of the Improved Numerical Differential Relay

4.1 Introduction:

Due to the high requirements and needs on the transformer differential protection, new methods and algorithms are continuously proposed and tested. Numerical relays capable of performing sophisticated signal processing enable the relay designer to enhance the relay performance.

In this chapter an advance differential protection algorithm, based on percentage differential characteristic and both harmonics restraint and harmonics blocking, was modelled, implemented, simulated and tested for different conditions.

4.2 Description of the implemented algorithm:

In order to improve the differential protection performances several algorithms and methods have been proposed and tested. Each of those methods showed different results and limitations in term of discrimination and fastness. Since each of the techniques has its advantage and limits, it is a wise choice to combine multiple techniques in a way that allow to take benefits and overtake limitations of the single methods.

The implemented algorithm is a combination of three performant techniques: Dual slop percentage differential characteristic method, even (second and fourth) harmonic restraint and odd (fifth) harmonic blocking.

4.2.1 Percentage differential method:

Transformer differential relay are subject to several factors that can cause incorrect operation such as: ratio mismatch between current transformers, mismatch that occur on the taps, which differential relay sees as internal faults. Those factors can be accommodated by using percentage differential protection scheme.

The percentage restrained differential protection is one of the oldest forms of adaptive protection algorithms. It requires that the differential current be greater than a percentage of the through (restraint) current. This characteristic is illustrated by the use of a slope which compensates for current transformer (CT) ratio mismatches, CT ratio errors and errors due to tap changing.

The proposed algorithm for this discrimination technique works with dual slope percentage differential protection scheme. The setting of each part was calculated apart and then combined the suitable slope to be implemented.

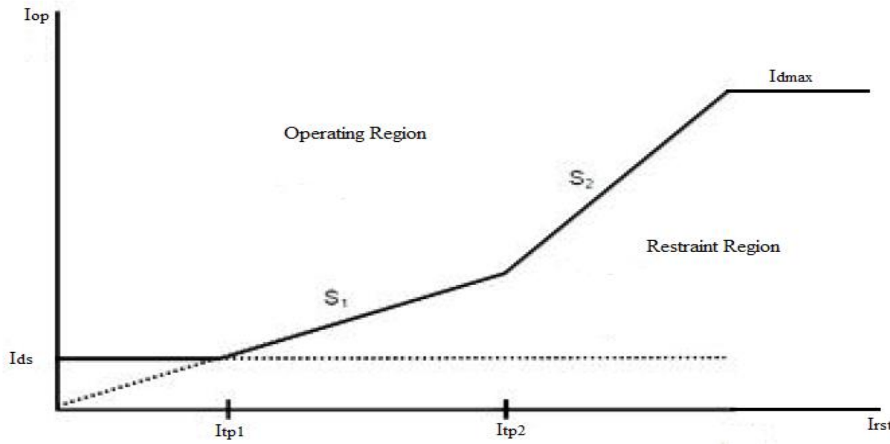

Figure 4-1: Dual slope percentage differential protection scheme.

The dual slope percentage differential protection is composed of four parts with two turning points. The first part is the maximum differential current that exists in normal transformer operation and at the same time the minimum current at which the differential relay starts to work. This low set point is named Ids threshold current. It is expressed as a percentage of the primary nominal current In1. As a standard value, 30% of the nominal current is taken as a value for Ids.

The part that follows the threshold current is the first segment of the slope. It starts by the first turning point Itp1, which a standard value and it is conventionally set to Itp1= 45% of In, where In is the nominal current of transformer. Then, the first slope which is used to prevent tripping due to high fault currents of external origin, because when a high external fault occurs, a high through current circulates.

The setting of the slope should be sufficient to compensate for measurement errors caused by current with low but significant amplitude. This is achieved by the following computations:

$$Slope1 = \frac{\mathrm{Ids1}}{\mathrm{Irst}} \times 100\% + 5\% \text{ (of errors)} \quad (4\text{-}1)$$

Where:

$$\mathrm{Ids1} = |\mathrm{I1} - \mathrm{I2}| \times \mathrm{Ids} \quad (4\text{-}2)$$

$$\mathrm{Irst} = \frac{\mathrm{I1}+\mathrm{I2}}{2} \quad (4\text{-}3)$$

The second slope starts by the second turning point Itp2. This value could be set up to 200% of rated current for large transformers and from 100% to 200% of rated current for smaller transformers. Itp2 depends on type of formula used to calculate Irst. For type A (Irst $= \frac{I1+I2}{2}$, the one used) the value of this turning point will be twice the rated current. After that, the curve of the second slope should be set sufficiently high to compensate for the worst case in which only the CTs at one end saturate and not the others. Typically, the slope is set between 60 and 90%, for our algorithm it is set to 85%.

At the end of the slope a high set point is defined which protect the zone for a high fault current. The high set point is set above the closing current, typically with a margin of 40% so that the protection function will not be tripped by transformer energizing.

$$I_{dmax} = 140\% \times I_n \quad (4\text{-}4)$$

Where: In is the transformer rated current.

4.2.2 Even harmonic restraint

Inrush current is one of the most challenging problems for the differential protection. The inrush current is present in one side of the transformer and can reach several times the transformer rated current. Such transient current can operate unnecessarily the differential relay. Inrush condition can result from the transformer energization, parallel transformers switching in or even external fault clearing and is characterized by the presence of even harmonics. The second harmonic is the most dominant one with values rarely below 17% of the fundamental component. However, due to the fact that the inrush current is different from one phase to another depending on multiples factors such as the energization angle and the residual flux, transformer can undergo an inrush current with much lower second harmonic content ratio. To overcome this situation not only the second harmonic restraint is used but both the second and fourth harmonic are used. The principal of working of the second and fourth harmonic restraint is illustrated by the following equation:

$$I_{op} > I_{rst} \cdot f(SLP1, SLP2) + \frac{I_{diff-harm-2}}{k2} + \frac{I_{diff-harm-4}}{k4} \quad (4\text{-}5)$$

Where:

I_{op} is the operating (differential) current.

$I_{rst} \cdot f(SLP1, SLP2)$ is the percentage characteristic.

K_2 and K_4 are the ratio settings.

For the second harmonic setting values, studies showed that ratios around 15% and 20% provides good results. The fourth harmonic, being a secondary indicator of the inrush current, has a setting less than the second harmonic. Settings around 7% and 15% are considered to be effective.

4.2.3 Odd harmonic blocking

Transformer can undergo an over excitation condition if the ratio of the voltage over frequency (V/Hz) increases due to an over voltage or an under frequency. It is not desirable to disconnect instantaneously the transformer when facing an over flux but if the situation persist transformer tripping is necessary to avoid damage. The majority of power transformers are provided with a protection against over excitation. However, an increase in flux leads to an increase in the magnetizing current which may appear to be an internal fault and causes differential relay tripping. Transformer over excitation is characterized by the presence of odd harmonics. The fifth harmonic is commonly used to detect the over excitation since the third harmonic is greatly present if CTs are saturated.

The fifth harmonic is desirable to be used in a blocking mode where the harmonic content is compared separately with the fundamental of the operating current. Such method ensures security for over excitation condition and dependability for internal faults with CTs saturation.

The relay tripping with fifth harmonic blocking required the fulfilment of the following equation:

$$(I_{op} > I_{rst} \cdot f(SLP1, SLP2))\ \&\ \left(\frac{I_{diff-harm-5}}{I_{diff-fund}} < K5\right) \tag{4-6}$$

The setting ratio of 35% is used in the tests since it was found to provide good discrimination according to several studies.

4.3 Algorithm flowchart and working procedure

The algorithm is implemented according to the following steps:

Step 1: Reading the predefined stings and the currents I_1 and I_2 from the CTs.

Step 2: Calculation of the following parameters: The differential current Idiff and the through current Irst, measuring the fundamental and the second, fourth and fifth harmonic component of the differential current and then calculating the even harmonic restraint current I_{heven}.

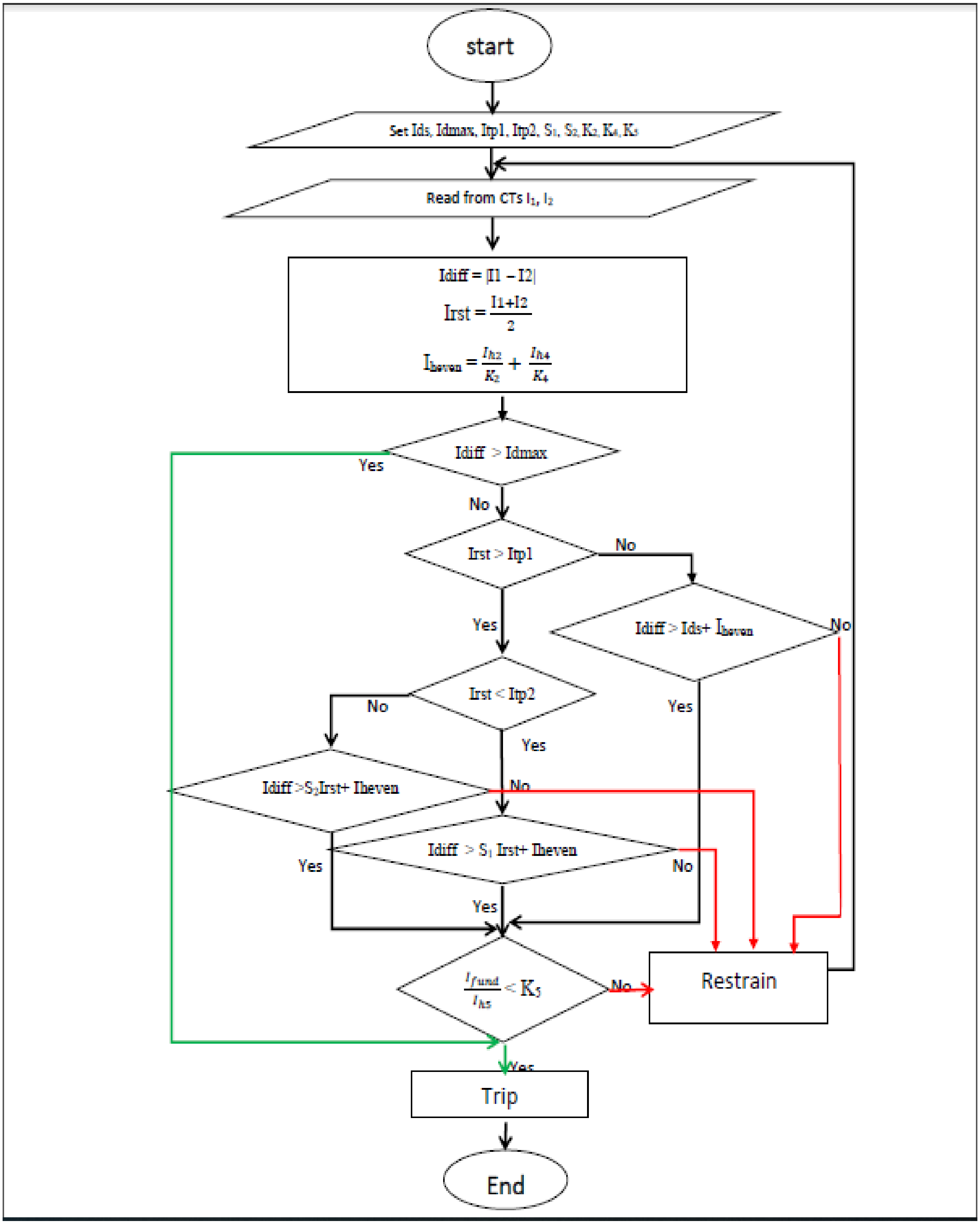

Figure 4-2: Differential protection Algorithm flowchart.

Step 3: Comparison and decision taking:

The proposed algorithm starts by comparing Idiff and Idmax. If Idiff is greater than Idmax an unrestrained trip signal is sent to the CB. This step provides a good protection against heavy internal faults which that may lead to CTs saturation.

Then If Idiff is found to be less than Idmax successive comparisons of the differential current and the percentage differential characteristic take place. If the differential current exceeds the restrain current (S×Irst+ Iheven) of the corresponding operating region of the percentage curve an initial trip signal is sent. Finally, the fifth harmonic ratio is compared to the predefined setting K_5, if an initial trip signal is sent and the ratio is less than K_5 a trip signal is sent to the CB.

4.4 Differential relay implementation

4.4.1 Hardware implementation

An attempt to implement the previous algorithm has been made using an Altera DE2-115 FPGA. The system is composed mainly of current transformer used as a sensor to measure the current at both sides of the transformer, a signal conditioning and filtering circuit, an FPGA board and a circuit breaker. The diagram of the implemented circuit is shown in figure 4-3.

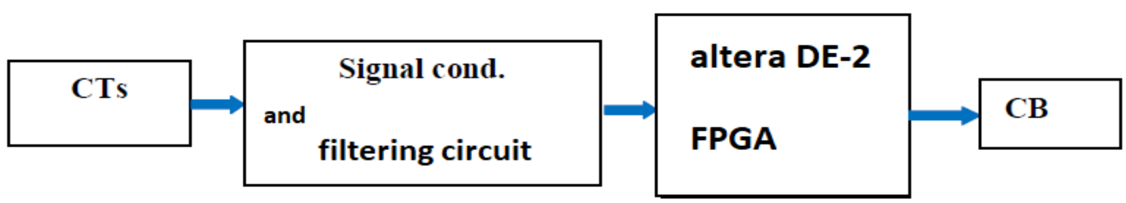

Figure 4-3: Block diagram of FPGA based numerical differential relay.

The FPGA code generated by Quartus ll software is composed of two part the first part is the percentage curve code and the second one is the harmonic restrain/blocking code. The altera DE-2 generation FPGAs are provided with a fast Fourier transform (fft) IP core [40]. The fft IP core was used to extract the selected harmonics order magnitudes which are used with the percentage characteristic to distinguish between the internal faults and the other confusing operating conditions (inrush current, over excitation …).

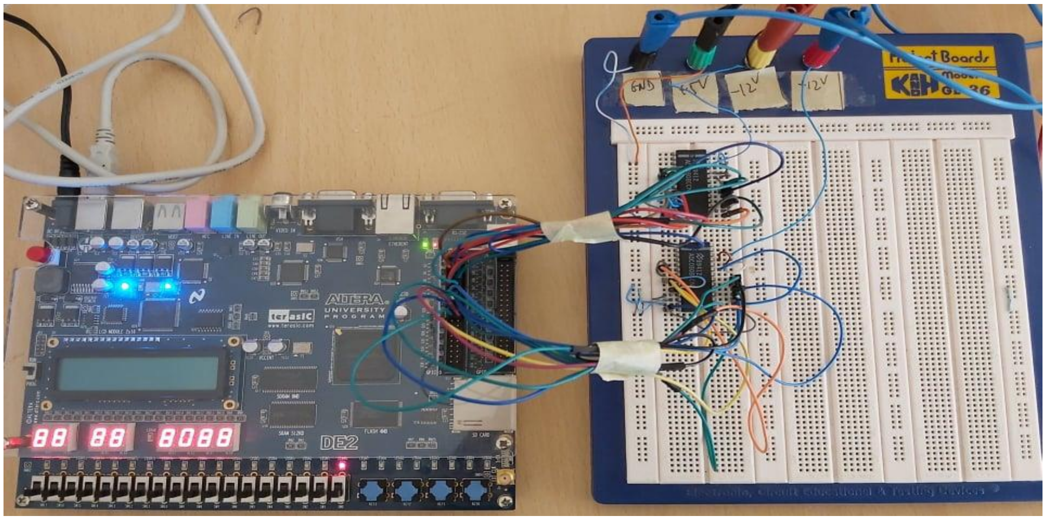

Figure 4-4: FPGA based numerical differential relay.

4.4.2 MATLAB/Simulink model

The proposed algorithm was modelled using MATLAB/Simulink interface. The model is composed of two main part. The first part is the percentage differential characteristic bloc. This part is composed of several if else blocs which compare the differential current to the different curves of the percentage characteristic.

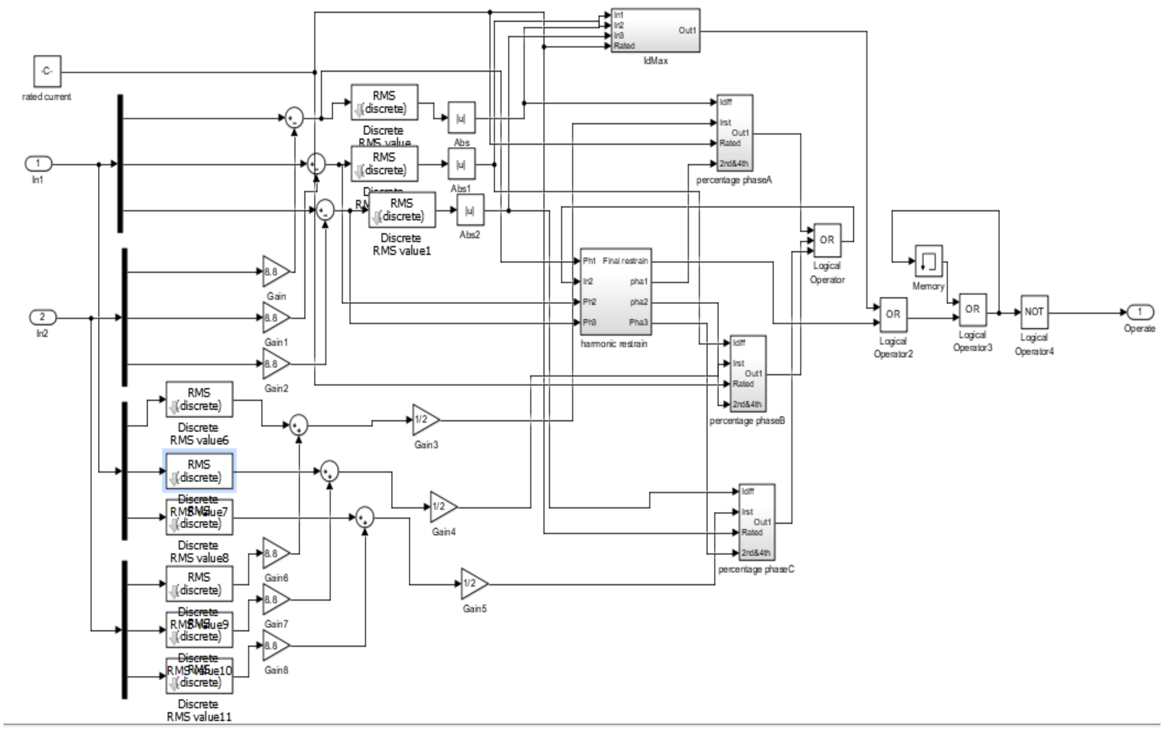

Figure 4-5: differential relay Simulink model

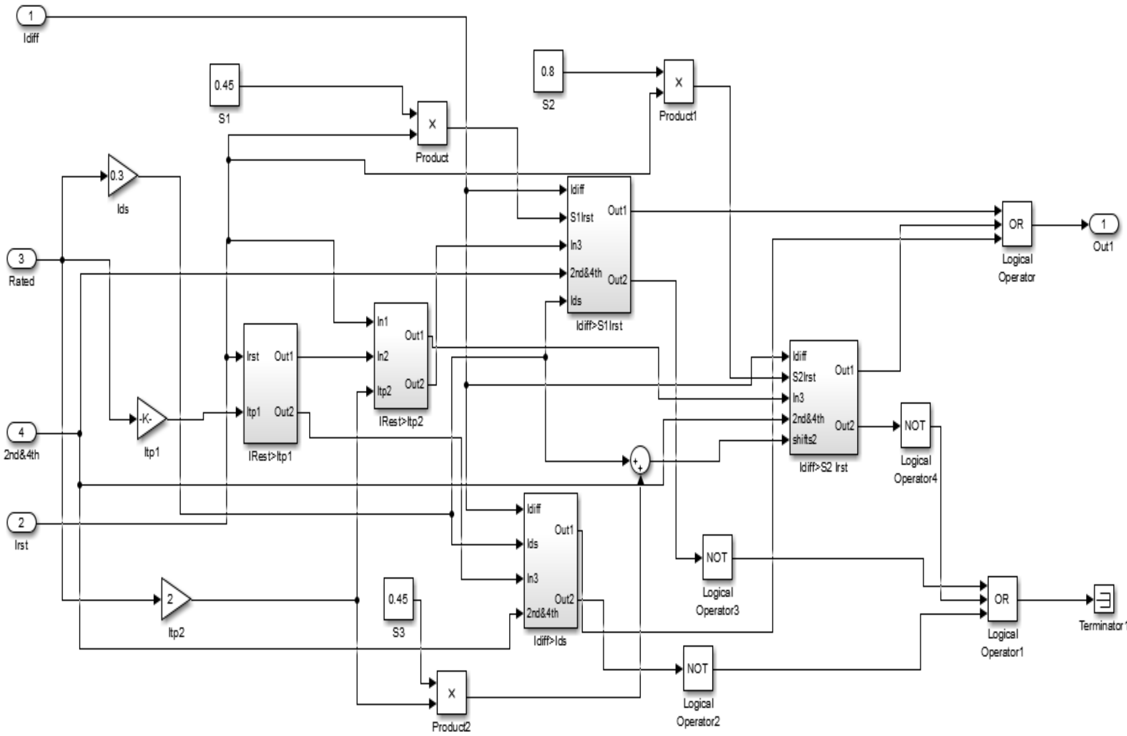

Figure 4-6: Single phase percentage differential relay model

The second part is the harmonic restrain/blocking bloc. In this bloc, used harmonic order (2^{nd} ,4^{th} and 5^{th}) content of each phase are extracted using the Simulink Fast Fourier Transform and processed to provide the restrain when it is needed.

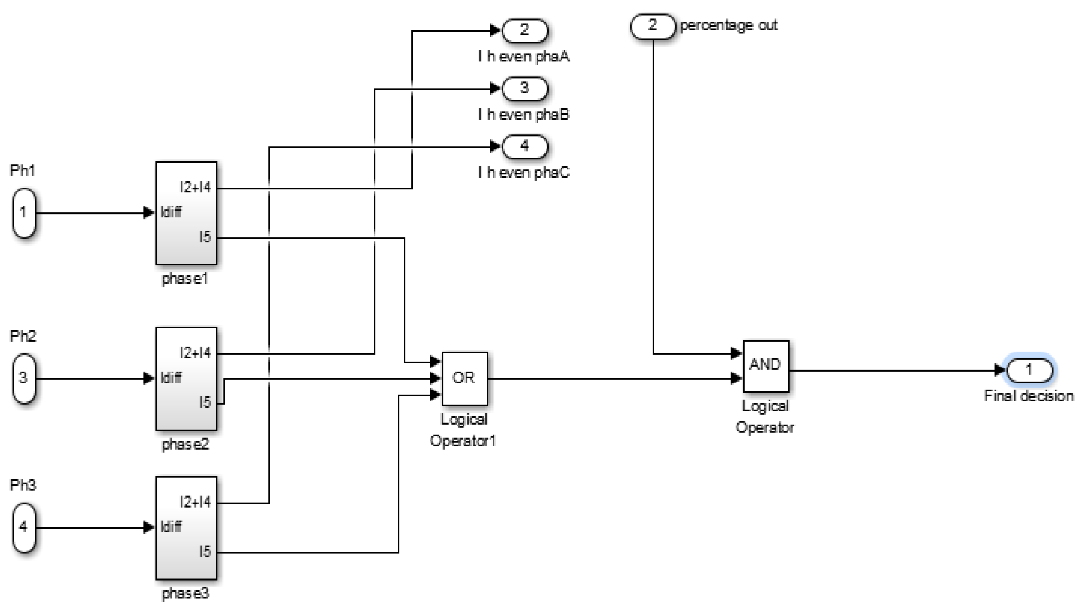

Figure 4-7: Harmonic restrain/blocking differential relay model

4.4.3 Tested system description

The implemented model on MATLAB/Simulink was tested on the system illustrated in figure 4-8. The system under study consists of a three-phase 25 kV voltage source feeding a three-phase 100 kW through a three-phase Y/Y transformer rated 250 MVA, 25 kV/220 kV, and 50Hz. Each phase of the transformer consists of two windings both connected in wye with a grounded neutral.

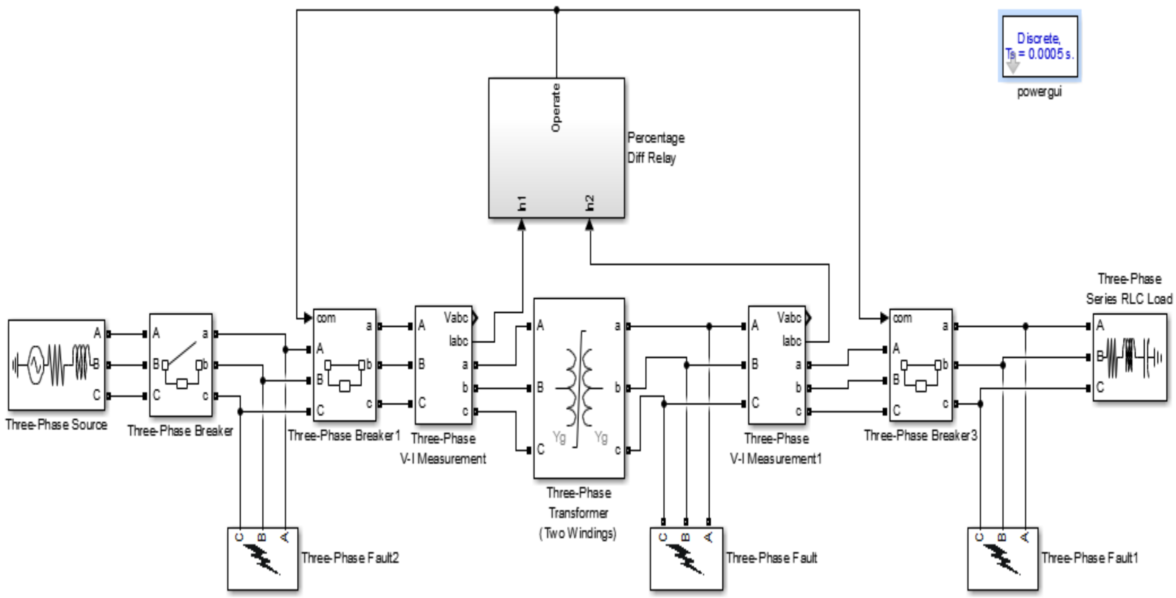

Figure 4-8: Simulink model of the tested system

The simulated transformer parameters are shown in table 4-1.

Table 4-1: Simulated transformer main parameters.

Transformer connection	Y/Y
Rated power	250 MVA
Voltage ratio	25kV/220 kV
Rated frequency	50 HZ
Primary winding resistance/phase	0.002 pu
Primary winding inductance/phase	0.08 pu
Secondary winding resistance/phase	0.002 pu
Secondary winding inductance/phase	0.08 pu
magnetization resistance	500 pu

Measurement are taken to the differential relay from both transformer ends (primary and secondary) to the differential relay where the tripping signal is generated when needed. The disconnection action is performed by the mean of the two CBs placed between the source and the transformer and between the load and transformer.

4.5 Tests, results and discussion

The system modelled in MATLAB/Simulink with the proposed algorithm was simulated and tested for various operating conditions of power transformer.

To test the effectiveness of the proposed algorithm, four essential cases have been simulated.

- Behavior of the relay versus the magnetizing inrush current.
- Behavior of the relay versus an internal fault.
- Behavior of the relay versus an upper side and down side external fault.
- Behavior of the relay when the transformer is energized with an existing internal fault.

Case one: The magnetizing inrush current

In this section of simulation, the primary side CB is closed at t=0.1 sec, a high current flows in the primary of the power transformer. At t=1 sec, the secondary CB is closed and the current starts to flow through the transformer to the load, as shown in figure 4-9 and figure 4-10.

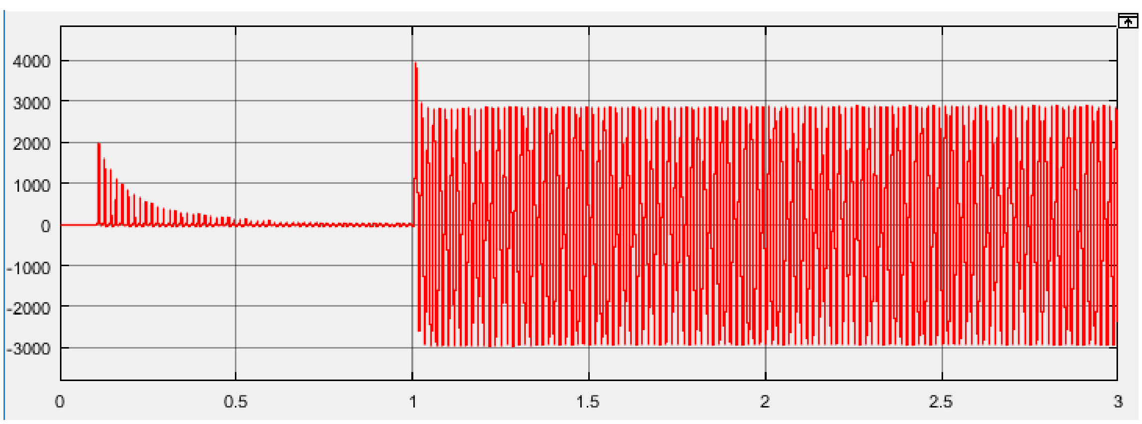

Figure 4-9: Phase A current waveform of the transformer primary side

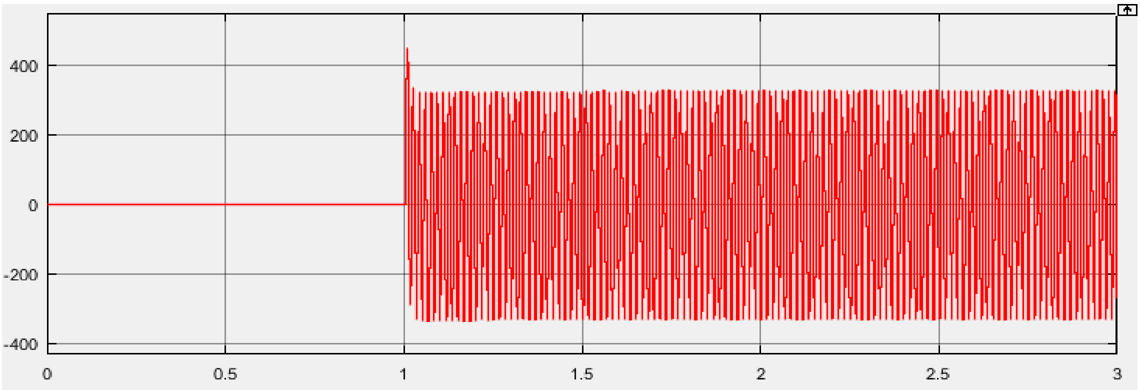

Figure 4-10: Phase A current waveform of the transformer secondary side.

Figure 4-11 shows that the currents caught by the CTs at the transformer terminals are greatly different. Consequently, the relay detects a differential current which reached 2000A.

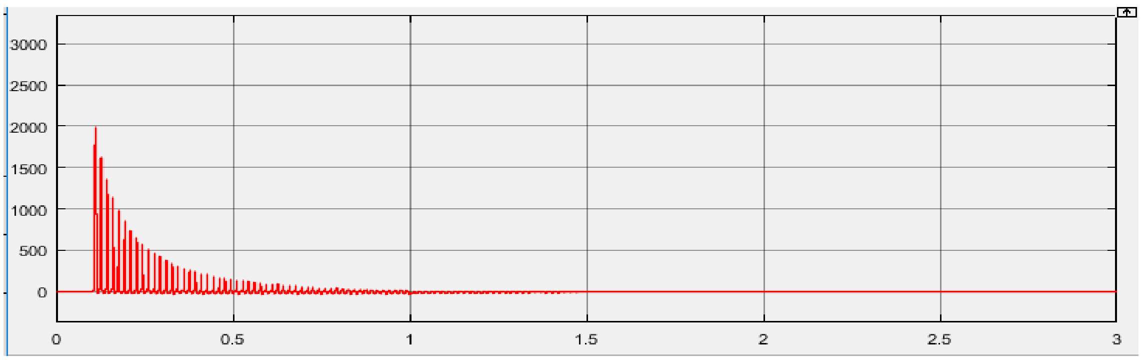

Figure 4-11: Differential current at magnetization of transformer

Even though the differential current is significantly high during the magnetization of the transformer, the figure 4-12 shows that the relay was restrained and hence no tripping signal was generated. The harmonic content of the inrush current illustrated in figure 4-13 provides sufficient additional current to restrain the CBs tripping.

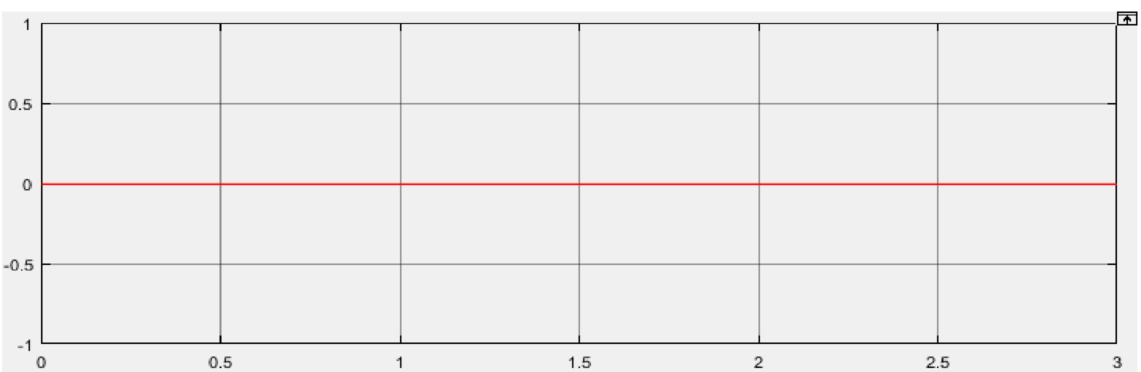

Figure 4-12: Trip signal during magnetizing inrush current

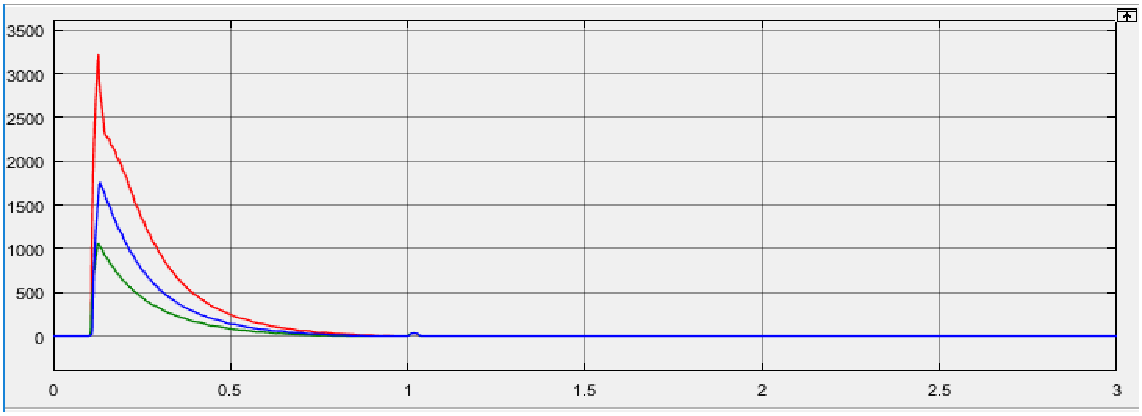

Figure 4-13: Per phase even harmonic content of the inrush current.

Case Two: Internal fault

In this case, the primary side CB is closed at 0.1 sec and the one of the secondary side is closed at 1s sec. At t = 2 sec, a three-phase to ground internal fault is applied to the transformer.

As a result of that, the figures 4-14 and 4-15 shown from the scopes give:

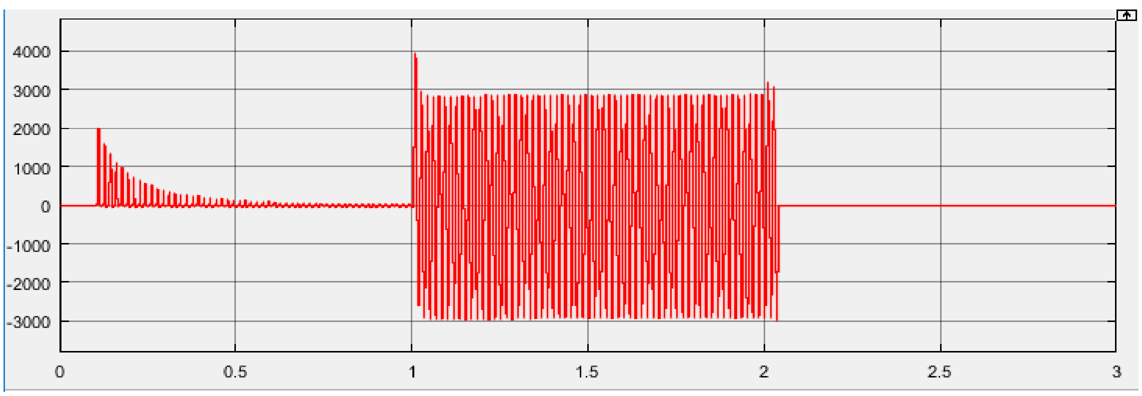

Figure 4-14: The primary current in case of internal fault

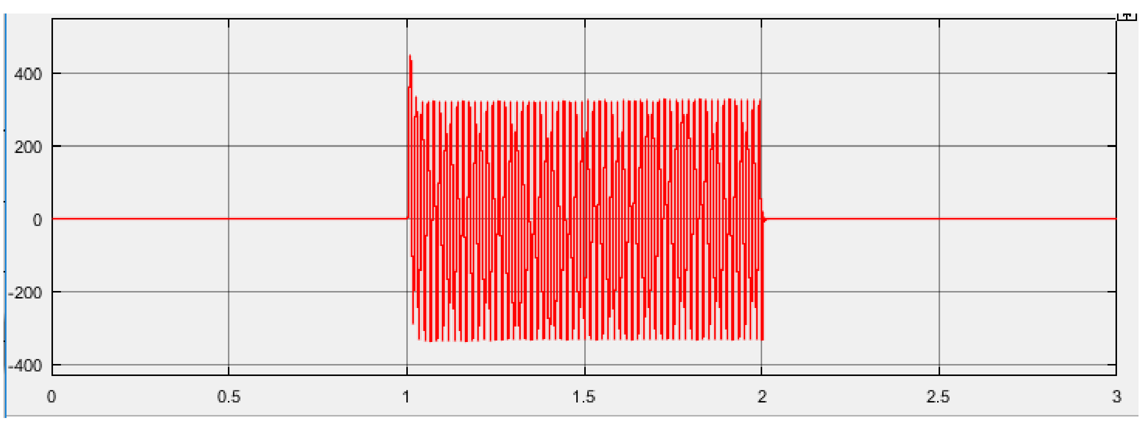

Figure 4-15: The secondary current in case of internal fault

At that moment of applying the internal fault, a significant increase of the differential current (more than 2000A) takes place due to the fault occurring inside the protected zone.

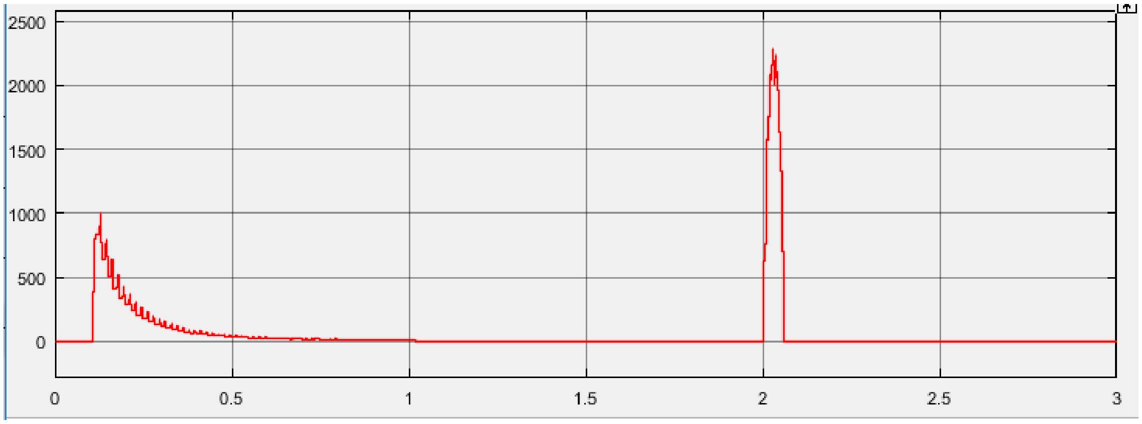

Figure 4-16: Differential current at internal fault

The significant amount of differential current (figure 4-16) is detected by the relay and causes it to release a trip signal. The transformer is hence disconnected.

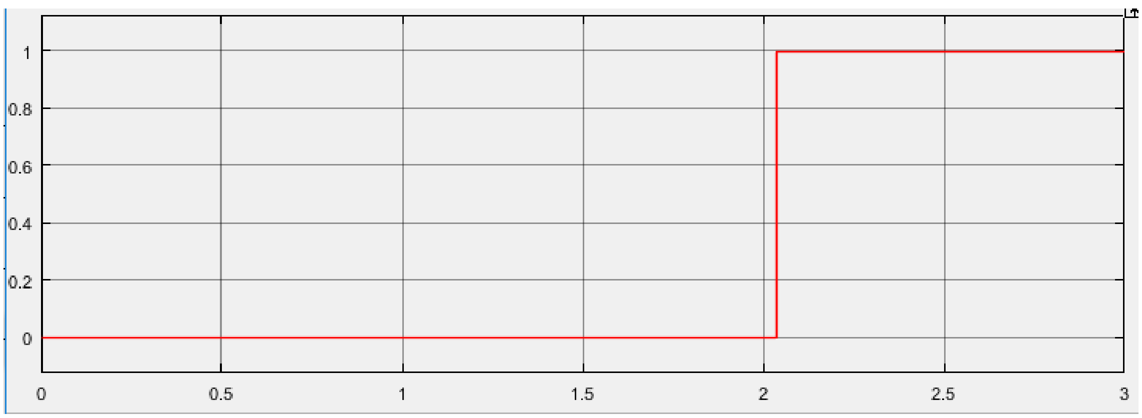

Figure 4-17: Trip signal due to internal fault

The trip signal is generated after 35 msec (figure 4-17) which is an acceptable time according to the IEEE standard for transformer protection (100 msec) [41].

This delay is due to the time taken to execute the needed computation by the relay.

Similarly, the relay is tested for all other cases of different types of faults such as single line to ground, line to line, line to line to ground. In all cases the relay has successfully released a trip signal in each case.

Case three: External upper side fault at 2s and externa down side fault 4s

In this case two three phase to ground external faults have been simulated. The first fault is an upper side fault. It was applied at t=2 sec and cleared at t=4 sec, the occurrence of the second fault which is a down side fault is from t=4 sec to t=5 sec.

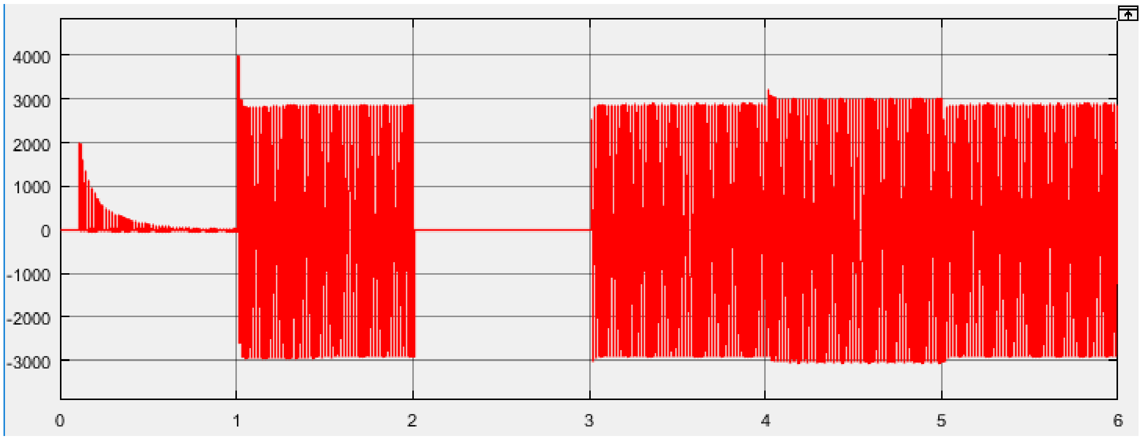

Figure 4-18: Primary current due to the external faults.

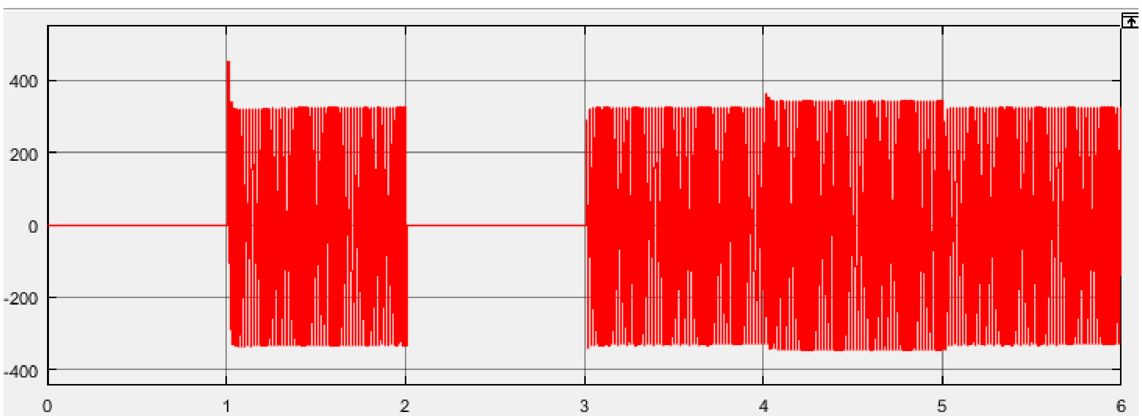

Figure 4-19: Secondary current due to the external faults

As it is shown from figures 4-18 and 4-19, the upper side external fault caused a null current to flow in the transformer. Meanwhile, the down side external fault, leaded to the increase of the phases currents in both sides of the power transformer.

However, the differential current (figures 4-20) at both upper and down side faults was not affected and was nearly null, even though there was a rise in the phase current at the occurrence of down fault. Consequently, the differential relay did not release a trip signal (figure 4-21) to CBs.

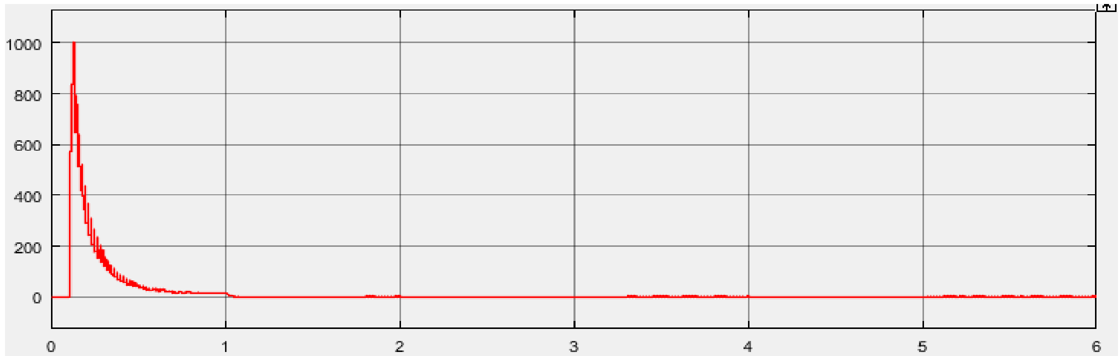

Figure 4-20: Differential current in the presence of external faults

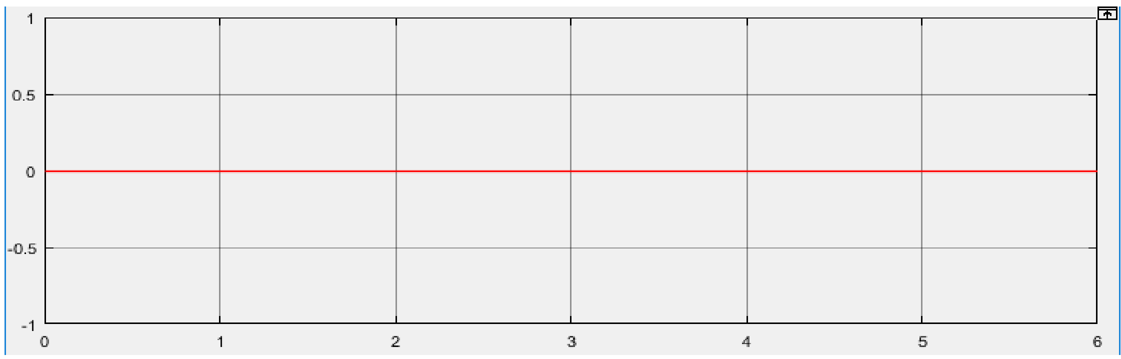

Figure 4-21: Trip signal in the presence of external faults.

Case four: Energizing a transformer with an existing internal fault.

This section tests the relay dependability for the case of existing internal fault followed by the energization of the transformer. A three phase to ground fault is applied at t=0.1 sec and the switching in the transformer at t=0.5 sec. Significant increase of the primary current takes place due to both the internal fault occurrence and the inrush current as shown in figure 4-22).

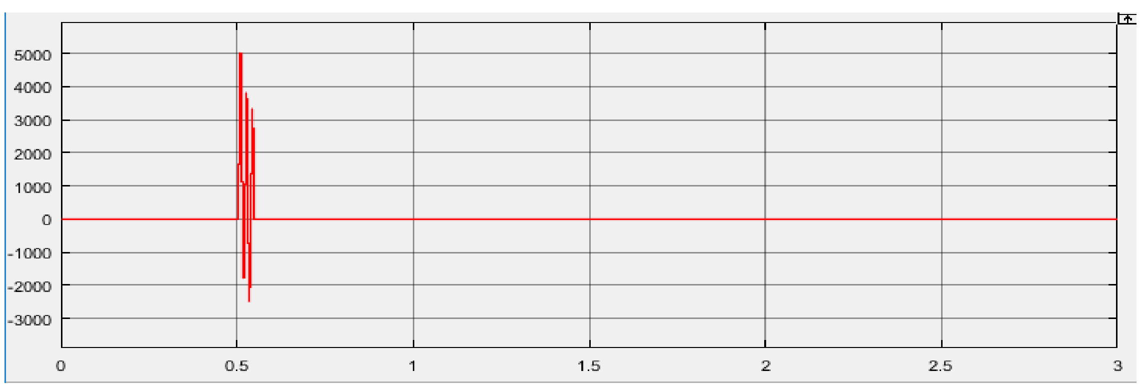

Figure 4-22: Primary current for energizing the transformer under existing internal fault.

The increase in differential current (near to 3000A in figure 4-23) is detected by the relay and considered as an internal fault.

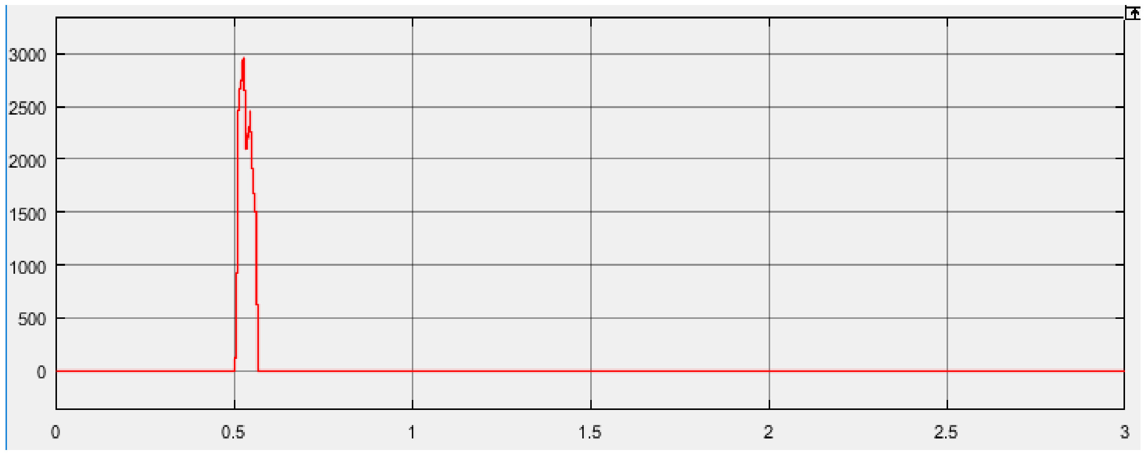

Figure 4-23: Differential current for energizing the transformer under existing internal fault.

Consequently, the transformer is isolated from the grid by the trip signal that is released from the differential relay at t=53 msec (figure 4-24). The high fundamental component in the fault current reduced significantly the even harmonic ratio allowing the relay to operate correctly without restrain.

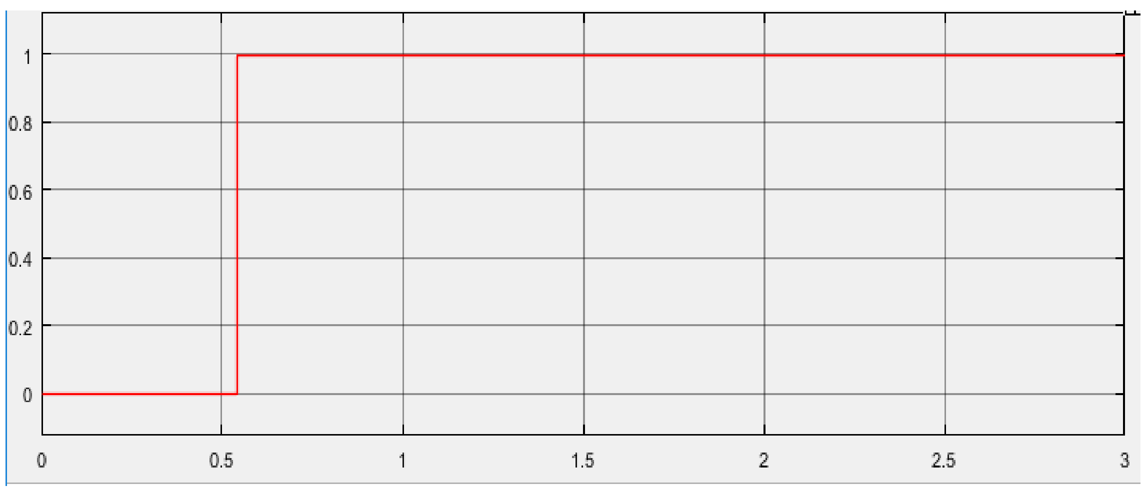

Figure 4-24: Trip signal for energizing the transformer under existing internal fault.

4.6 Conclusion

In this chapter a differential protection algorithm has been introduced. The algorithm was implemented and tested using MATLAB/Simulink software. The model consisting of a percentage differential characteristic and a harmonic restrain and blocking techniques has been tested versus several operating conditions.

The tests showed good performances in terms of dependability, security and speed. The relay provided good security against external faults and against the magnetizing inrush current. Although high differential current was flowing, the harmonic restraint has inhibited the relay tripping.

In term of dependability, the differential protection has been tested under internal fault condition and under inrush current condition with an existing internal fault. Disconnection of the transformer occurred in both cases due to the high differential current caused by the internal fault. Being present at the transformer energization moment, the internal fault current high fundamental content reduced drastically the high even harmonic content of the inrush current allowing the CBs to disconnect the transformer. The speed of the tripping was around 35 msec. Such speed is considered to be acceptable according to the IEEE standards which is 100 msec [41].

The performances expected by the proposed differential relay were highly reached. For all the tested cases, the proposed algorithm model provided good discrimination and gave satisfactory results

General conclusion

Differential protection is used for protecting important equipment of the power system. It is an in-zone protection technique that compares the current entering and the current leaving the protected equipment or the zone of protection, at the ideal case, if the difference is found to be not zero the protective relay sends a trip signal to isolate the faulted part from the rest of the system. However, some external factors can deviate the differential current from zero causing unwanted tripping of the differential relay.

This project, focused on the differential protection as a power transformer main protection. The differential protection was presented and its principle of working explained for both general case and transformer protection case. The importance of the power transform differential protection was highlighted and the issues facing the differential protection were stated. The main techniques used to overcome those issues were explained. An efficient algorithm for numerical differential relay has been proposed. Typically, transformer protection is focused on discriminating the internal faults from the magnetizing inrush currents in the power transformers and overcoming the CTs related issues. For these reasons, the proposed algorithm is composed of two parts. The first one consists of a percentage differential protection curve combined with even harmonic restrain analysis (2^{nd} and 4^{th} harmonic). The second approach is based on harmonic blocking technique (5^{th} harmonic). That algorithm was implemented, modeled and simulated using MATLAB/Simulink software. The Simulink model was tested successfully versus various operating condition. The results of the proposed differential relay gave very satisfactory results in term of discrimination as well as in term of speed.

An attempt to implement the proposed numerical relay using FPGA Altera DE-2 board has been made. The percentage characteristic was successfully built. However, the implementation of the harmonic restrain/blocking part faced some complications due to the fact that the old versions of FPGA are not provided with a simple mean to compute the FFT. As future scoop, this problem can be solved by using recent FPGAs or DSPs that can be programmed by the mean of MATLAB/Simulink software.

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