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Presented by:

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Filière : **Génie électrique et électrotechnique**

Option : **Electronique**

Title: Power Transformer Protection Improvement

To be defended before the jury composed of :

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ABSTRACT

A power transformer is mostly protected against internal faults using a differential protection which is sensitive and a fast clearing technique. This technique of protection detects nonzero differential current, and then activates a circuit breaker that disconnects the power transformer. However, this nonzero differential current may be produced by transformer magnetization, due to so called inrush current or over-excitation, and may cause the relay to operate unnecessarily. This magnetization current is a transient current that appears only when a transformer is first energized or after clearing external fault. Even though, it can be as great as 8 times the full load current and it contains harmonic components, however, it is harmless due to rapidity. During periodic magnetization condition due to over-excitation the third and fifth harmonic components are largely noticed; however, during the normal apperiodic inrush conditions, the second harmonic is relatively high.

The transformer differential protection scheme has to be improved so that it can distinguish between nonzero differential current produced by magnetization current and that produced by internal fault. Several methods have been proposed to blind the differential protection system during magnetization current where the harmonic components have been used as means of detection. However, the digital computer based protection offers a number of advantages over the conventional ones. So, the security and reliability have been improved; it remains only to develop an efficient algorithm requiring less time consuming calculations.

In this research project, a new approach applied to digital differential protection relay for a large power transformer is proposed.

Key-words: Large power transformer, differential protection, harmonics, inrush-current, over excitation condition.

خلاصة.

محول الكهرباء محمي معظمه ضد إعطاب داخلي باستخدام الحماية التفاضلية التي تعتبر حساسة وسريعة .هذاالنمط من الحماية يعمل بالكشف عن التفاضلية الحالية، ثم ينشط قاطع ليفصل محول الكهرباء من الشبكة الكهربائية في حالة عطب داخلي . ومع ذلك، يمكن أن يكون هذا الفارق الحالي غير صفر ناتج عن مغنطة المحول، وذلك ما يسمى تدفق التيار أو الإفراط في الإثارة، ويمكن أن يتسبب في عمل نظام الحماية دون داع .هذا التيار الممغنط هو تيار عابر الذي يظهر فقط عندما يتم وصلا لمحول لأول مرة أو بعد إزالة عطل خارجي .على الرغم من ذلك، فإنه يمكن أن يكون كبيرا (8 مرات تحميل كامل) وأنه يحتوي على مكونات التوافقي، ومع ذلك، فأنه غير مؤذي بسبب سرعته .خلال مغنطة دورية بسبب الإفراط في الإثارة لحظت المركبات التوافقية الثالثة والخامسة كبيرة .وأما، في ظل الظروف تدفق العادي، فالتوافقي الثاني مرتفع نسبيا.

نظام الحماية التفاضلية للمحول يحتاج إلي تحسين بحيث يمكن التمييز بين التفاضلية الحالية صفرية التي تنتجها مغنطة والتي أنتجت عن طريق العطب الداخلي .وقد اقترحت عدة طرق لتوقيف نظام الحماية التفاضلية من العمل خلال مغنطة الحالية باستخدام المركبات التوافقية كوسيلة للكشف .ومع ذلك، فإن

الحماية باستخدام الحاسوب الرقمي لها عدة مزايا مقارنة بالتقليدية .لذلك، تم تحسين الأمن والموثقية . يبقى فقط تطوير خوارزمية فعالة تستهلك أقل وقت في الحسابات.

في هذا المشروع البحثي، تم اقتراح نهج جديد لمرحل الوقاية التفاضلية الرقمية لمحول الطاقة.

كلمات مفتاحية:محول الطاقة الكبيرة، وحماية التفاضلية، التوافقيات، تدفق التيار، حالة الإثارة.

Résumé

Un transformateur de puissance est principalement protégé contre les défauts internes à l'aide d'une protection différentielle qui est sensible et rapide. Cette technique de protection détecte un courant différentiel (nonzero), puis actionne un disjoncteur qui débranche le transformateur de puissance. Cependant, ce courant différentiel (nonzero) peut être produit par courant d’excitation et peut provoquer un fonctionnement inutile du relais. Ce courant de magnétisation est un courant transitoire qui apparaît seulement lorsque le transformateur est mis sous tension où après l’élimination d’un défaut externe. Il est plus grand que 8 fois le courant nominal qui contient des composantes harmoniques. Cependant, il est sans danger en raison de la rapidité du phénomène de magnétisation. Pendant la magnétisation périodique en raison de la surexcitation les troisième et cinquième composantes harmoniques sont largement remarquées; Cependant, pendant les conditions d'enclenchement apériodiques normales, la seconde harmonique est relativement élevée.

Le système de protection différentielle du transformateur doit être amélioré de manière à pouvoir distinguer entre le courant différentiel (nonzero) produit par courant de magnétisation et celui produit par un défaut interne. Plusieurs méthodes ont été proposées pour bloquer le système de protection différentielle au cours de courant d’excitation, où les composantes harmoniques ont été utilisées comme moyens de détection. Toutefois, la protection numérique offre un certain nombre d'avantages par rapport aux conventionnels. Ainsi, la sécurité et la fiabilité ont été améliorées; il ne reste plus qu'à développer un algorithme efficace nécessitant moins du temps de calculs. Dans ce projet de recherche, une nouvelle approche appliquée au relais de protection différentielle numérique pour un transformateur de puissance modern est proposé.

Mots clés: Transformateur de puissance, Protection différentielle numérique, Fiabilité, courant d’excitation, courant de magnétisation, algorithme.

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Thesis outline

List of Acronyms and Symbols

ADC	Analog/Digital Converter
CB	Circuit Breaker
CT	Current Transformer
BS	Blocking Scheme
UBS	Un-Blocking Scheme
DAC	Data Acquisition Card
DFT	Discrete Fourier Transform
DSP	Digital Signal Processing
GOC	Ground Over-Current relay
HRC	High Rupturing Capacity
HV	High Voltage
k_1, k_2	Constant coefficients
I_{mpu}	Minimum pickup current
I_{op}	Fundamental component of the operating current
I_{2h}	Second harmonics of the operating current,
I_{3h}	Third harmonic of the operating current
I_{rt}	Unfiltered restraint current
NSC	Negative Sequence Compound
OLTC	Over Load Tap Changer
ODF	Optimized Digital Filter
PDC	Phasor Data Concentrator
PLC	Programmable Logic Controller
PMU	Phasor Measurement Unit
PS	Power System
PT	Power Transformer
PT	Potential Transformer
PQA	power quality analyzer
ROCOF	Rate of Change Of Frequency
RTU	Remote Terminal Unit
RWG	Relay Working Group
SLP	Slop
SEL	Schweitzer Engineering Laboratories, Inc.
SOA	Spiral optimization Algorithm
TCR	Thyristor Controlled
TCSC	Thyristor Controlled Switched Capacitor
TT	Grounding system Type
TVE	Total vector error
P_{out}	Out Power
P_{in}	Input power
ϕ_M	Steady state Flux, Wb
ϕ_R	Reminisce Flux, Wb
N_c	Number of corrected trips
N_d	Number of desired trips
N_u	Number of uncorrected trips (false trip

Chapter 1

Introduction

1.1 Context

Power transformer is one of the most important element in the power systems. Therefore, the protection of power transformers is crucial for the continuity of the power supply. A power transformer is mostly protected against internal faults using a differential protection which is sensitive and a fast clearing technique [1]. The differential protection is simple and provides the best protection against phase and ground faults. It compares the currents that enter with the currents that leave a zone or element to be protected. If the net sum of the currents is zero, then the protected equipment is under normal condition. However, if the net sum is different from zero, the differential relay operates due to an existing fault within the equipment and isolates it from the power system.This technique of protection detects nonzero differential current only during the internal faults, and then activates a circuit breaker that disconnects the power transformer from power system. However, this nonzero differential current may be produced by transformer magnetization, due to so called inrush current or over-excitation, and may cause the relay to operate unnecessarily. This magnetization current is a transient current that appears only when a transformer is first energized or after clearing external faults. Even though, it can be as great as ten times the full load current and it contains harmonic components, however, it is harmless due to its rapidity. During a periodic magnetization condition due to over-excitation the third and fifth harmonic components are largely noticed; however, during the normal apperiodic inrush conditions, the second harmonic is relatively high.

The transformer differential protection scheme has to be improved so that it can distinguish between nonzero differential current produced by magnetization current and that produced by internal faults. Several methods have been proposed to blind the differential protection system during magnetization current where the harmonic components have been used as means of detection. However, the digital computer based protection offers a number of advantages over the conventional ones. So, the security and reliability have been improved; it remains only to develop an efficient algorithm requiring less time consuming calculations.

In this research project, a new approach applied to digital differential protection relay for a large power transformer is proposed.

Even differential protection is relatively simple to be implemented, but it has drawbacks. One of these drawbacks as mentioned before is its unnecessary tripping due to the transformer magnetizing current, when the relay considers this situation as an internal fault. Differential relays are prone to mal-operation in the presence of transformer inrush currents. Inrush currents result from transients in transformer magnetic flux [2, 7]. The first solution to this problem has been investigated by introducing an intentional time delay in the differential relay. Another technique has been performed by desensitizing the relay for a given time, to overcome the inrush condition [3, 4]. Others have suggested adding a voltage signal to restrain [5] or to supervise the differential relay [8].

This research work motivation is the need to develop an appropriate blocking technique of differential protection during inrush conditions. This is following a number of questions that has been arisen while applying differential relays for transformer protection. Protection of large power transformers is a very challenging problem in power system relaying. Large transformers are a class of very expensive and vital components of electric power systems. Since it is very important to minimize the frequency and duration of unwanted outages, there is a high demand imposed on power transformer protective relays; this includes the requirements of dependability associated with mal-operation, security associated with no false tripping, and operating speed associated with short fault clearing time [6].

Discrimination between an internal fault and the magnetizing inrush current has long been recognized as a challenging power transformer problem [6]. This research will analyze the problem and its effect on transformer differential protection. Since the magnetizing inrush current generally contains a large second harmonic component in comparison to an internal fault, conventional transformer protection systems are designed to restrain during inrush transient phenomena by sensing this large second harmonic. However, the second harmonic component may also be generated during internal faults in the power transformer [7]. This may be due to current transformer (CT) saturation, presence of shunt capacitance, or the capacitance in long extra high voltage transmission lines to which the transformer may be connected. The magnitude of the second harmonic in an internal fault current can be close to or greater than that present in the magnetizing inrush current [6]. Moreover, the second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers because of the improvements in the power transformer core material. The commonly employed conventional differential protection technique based on the second harmonic restraint will have difficulty in distinguishing between an internal fault current and the inrush current thereby threatening transformer stability [6]. In this work, a new approach has been proposed using two harmonics (second and fourth) for restraining or blocking a differential relay and reducing the blocking time during an internal fault. This technique has been implemented in protection system for a three phase power transformer using Simulink/MATLAB, which ensures security for inrush conditions and provides dependability for internal faults.

Three characteristics generally provide means for detecting transformer internal faults. These characteristics include an increase in phase currents, an increase in the differential current, and gas formation. When transformer internal faults occur, immediate disconnection of the faulted transformer is necessary to avoid extensive damage and preserve power system stability. Three types of protection are normally used to detect these faults: overcurrent protection for phase currents, differential protection for differential currents, and gas accumulator for arcing faults.

Overcurrent protection with fuses or relays provided the first type of transformer fault protection and is used for small transformers. Transformer differential protection is one of the most reliable and popular technique for protecting large power transformers. The percentage differential principle was applied to transformer protection to improve the security of differential protection for external faults with CT saturation.

This research focused primarily on methods of reducing the blocking time of differential protection during inrush. These methods included adjusting the slope of the differential characteristics, adjustment of restraining current, and evaluation of current transformers during saturation.

1.2 The Objectives of this research work

This work was motivated by the need to reduce the blocking time of differential protection during inrush conditions. This is following a number of questions that arise while applying differential relays for transformer protection. Protection of large power transformers is a very challenging problem in power system relaying. Large transformers are a class of very expensive and vital components of electric power systems. Since it is very important to minimize the frequency and duration of unwanted outages, there is a high demand imposed on power transformer protective relays; this includes the requirements of dependability associated with maloperation, security associated with no false tripping, and operating speed associated with short fault clearing time [9].

Discrimination between an internal fault and a magnetizing inrush current has long been recognized as a challenging power transformer problem [9]. This research will analyze the problem and its effect on transformer differential protection. First, the research will review the concept of transformer differential protection and then analyze magnetizing inrush, overexcitation and current transformer saturation phenomena as possible causes of relay maloperation. Since magnetizing inrush current generally contains a large second harmonic component in comparison to an internal fault, conventional transformer protection systems are designed to restrain during inrush transient phenomena by sensing this large second harmonic. However, the second harmonic component may also be generated during internal faults in the power transformer [10].

The second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers because of the improvements in the power transformer core material. The commonly employed conventional differential protection technique based on the second harmonic restraint will have difficulty in distinguishing between an internal fault and an inrush current thereby threatening transformer stability [9].

Transformer overexcitation is another possible cause of power transformer relay mal-operation. The magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency [11]. Overvoltage and/or under frequency conditions can produce flux levels that saturate the transformer core. These abnormal operating conditions can exist in any part of the power system, so any transformer may be exposed to overexcitation. Transformer overexcitation causes transformer heating and increase exciting current, noise, and vibration [11]. Though it is difficult, with differential protection, to control the amount of overexcitation that a transformer can tolerate, transformer differential protection tripping for an overexcitation condition is not desirable.

The research work is mainly concerned with:

Implementation of digital differential Protective relay for transformer: With advanced PC that operates in high speed, an acquisition card may be used for acquiring currents which will be needed by protection elements. The protection elements may be implemented using Simulink/Labview software program..

In order to test this research work results, a testing system relay may be used. The developed approach should provide good discrimination between the magnetizing current and the internal fault current.

Development of a new approach applied to a digital protective relay for large transformers:

A differential relay that is very sensitive relay operating even at its limits may be used for protecting a power transformer. However, this characteristic may lead to unnecessary tripping due to transient currents such as an inrush and over excitation current. In order to avoid this mal-operation of the relay, a second and fifth harmonic blocking technique has been used; however this technique is not reliable if a second harmonic magnitude is weak. In this paper, a new approach is proposed using even harmonics (second and fourth). The test results show that this proposed approach is a good blocking technique associated with the differential relay even for large modern power transformer which has small second harmonic as well; it provides a good discrimination between the transient currents and the internal fault currents during internal fault.

1.3 Thesis Outline

In Chapter 1, the subject and organization of the research are described. The motivation of the work and the problem statement of the research are presented.

In Chapter 2, an overview of power transformer faults is presented.

In Chapter 3, an overview of power system protection and protection philosophy is presented. In this chapter the protection of power transformers with differential relays is discussed. Percentage restraint differential relays are introduced. Finally, the protection of power transformers with differential relays as well as some background on transformer differential protection during inrush conditions is presented.

In Chapter 4, simulations of differential relays as applied to power transformer are presented. Simulations with transformer models are carried out using both theoretical and actual transformer values. Besides, simulations are carried out to set and adjust harmonic restrained differential relay to overcome the effects of the presence of inrush current on a power transformer.

Chapter 5 presents development of a new approach applied to a digital protective relay for large transformers.

A summary of the contributions, implications, and limitations of the study and future research directions is given in Chapter 6.

Some additional information and techniques related to the research are defined in Appendices.

1.4 Publications

The thesis is developed from the peer-reviewed journal and conference papers which are listed below.

Journal papers

1. R. Bouderbala, H. Bentarzi, A. Ouadi, (2011), "Digital Differential Relay Reliability Enhancement of Power Transformer", International Journal of Circuits, Systems and Signal processing, ISSN: 1998-446, Issue 1, Volume 5, pp.263-270, (SCOPUS Indexed)
2. R. Bouderbala, H. Bentarzi, (2013), "A New Computer Based Differential Relay Framework for Power Transformer", Advanced Technologies, Lecture Notes in Electrical Engineering 260, **Springer**, pp 473-481,. DOI: 10.1007/978-94-007-7262-5_54. (SCOPUS Indexed)
3. R. Bouderbala, H. Bentarzi, (2014), "A New Differential Relay Framework for Power Transformer", Applied Mechanics and Materials Vol. 492 pp 426-430 , Online available since 2014/Jan/09 at www.scientific.net, Trans Tech Publications, Switzerland, doi:10.4028/www.scientific.net/AMM.492.426. (SCOPUS Indexed)
4. R. Bouderbala, H. Bentarzi "Differential relay reliability enhancement using fourth harmonic for a large power transformer *DOI 10.1007/s13198-016-0475-6, International Journal of Syst. Assur. Engineering Mang., Springer, (2016)* . (SCOPUS Indexed)
5. A. ABDELMOUMENE, R. BOUDERBALA, and H. BENTARZI, *'' Design and Evaluation of a DSP Based Differential Relay of Power Transformer'', Algerian Journal of Signals and Systems, Vol.1, Issue 1 pp. (2016).*

Conference papers

1. RACHID BOUDERBALA, HAMID BENTARZI and ABDERRAHMANE OUADI, "A New Approach Applied to a Digital Differential Protection of Large Power Transformer", in Proc. 9th WSEAS International Conference on CIRCUITS, SYSTEMS, ELECTRONICS, CONTROL & SIGNAL PROCESSING (CSECS '10), ISBN: 978-960-474-262-2, PP.202-205,December 29-31. 2010.
2. RACHID BOUDERBALA, and HAMID BENTARZI, "A. New Differential Relay Framework for Power Transformer ", ICEEA2013, Oct. 24-25, 2013, Konya, Turkey (best presentation award from IACSIT organization).

Chapter 2

Power Transformer Operating Conditions

The power transformer is one of the most important main elements of the electric power system. The development of modern power systems has been reflected in the advances in transformer design. This has resulted in a wide range of transformers with sizes ranging from a few kVA to several hundred MVA being available for use in a wide variety of applications.

Different faults can occur inside the transformer and at the electrical system during its operation. Transformer faults can be divided into two classes as permanent abnormal conditions (faults) and transient abnormal conditions (inrush).In this chapter; we will cover the basic methods used to distinguish between inrush current and fault current in power transformers. First, the nature of inrush current is presented compared to the fault current. Then, the nature of the magnetizing current due to energizing a power transformer at no-load is explained.

2.1 Permanent abnormal conditions (faults)

Many faults can occur in the power transformer. The protection system must disconnect and isolate the power transformer from power network rapidly and correctly and hence it clears the fault as fast as possible. These faults can be classified as external and internal faults.

2.1.1 Externally applied conditions: The transformer protection has to limit damage to the transformer during overload and low frequency condition. The protection system has to disconnect the consumers if the voltage becomes too high.

2.1.1.1 Overvoltage:

Overvoltage conditions are of two kinds:

- Transient surge voltages,
- Power frequency overvoltage.

Transient overvoltages, switching overvoltages and temporary overvoltages are the most important overvoltages that may damage components of the power system. Transient overvoltages may arise during switching and lightning disturbances. Such overvoltages may cause turn-to-turn short circuit in the power transformer. These overvoltages are usually limited by shunting the high voltage terminals to earth either with a plain rod gap or by surge diverters, which comprise a stack of short gaps in series with a non-linear resistor. Surge arresters connected close to the bushings of the transformer may also reduce overvoltages. The surge diverter, in contrast to the rod gap, has the advantage of extinguishing the flow of power current after discharging a surge, in this way avoiding subsequent isolation of the transformer. Power-frequency overvoltages and resonance conditions cause temporary overvoltages. They can cause an increase in dielectric stress on the insulation and a proportionate increase in the working flux density.

The latter effect causes an increase in the iron loss and a disproportionately large increase in magnetizing current. In addition, the flux is diverted from the laminated core into structural steel parts. The core bolts, which normally carry little flux, may be subjected to a large flux diverted from the highly saturated region of core alongside. This leads to a rapid temperature rise in the bolts, destroying their insulation and damaging coil insulation if the condition continues.

2.1.1.2 Overload: it causes an increase in copper losses and consequently the temperature may rise. Power transformers can be temporarily overloaded. The length of the acceptable overload period depends on the initial temperature and the cooling systems. Overloads can be carried for limited periods. The thermal time constant of naturally cooled transformers lies between 2.5 to 5 hours. Shorter time constants apply in the case of force-cooled transformers.

2.1.1.3 Overexcitation: The transformer core becomes overexcited when the applied voltage is too high or the applied frequency is too low. Overexcitation causes an increase in the iron loss and a substantial increase in the magnetizing current. In addition, flux is diverted from the laminated core. It is forced through surrounding steel parts such as the metal of the tank and other non-laminated parts of the transformer. In particular, the core bolts, which normally carry little flux, may be subjected to a large component of flux. Under such conditions, the bolts may be rapidly heated to a temperature that destroys their own insulation and will damage the coil insulation if the condition continues as the overload situation. It follows that a transformer can operate with some degree of overvoltage with a corresponding increase in frequency. Operation must not continue if the applied voltage is high and frequency is low

2.1.1.4 Low system frequency: Reduction of system frequency has an effect with regard to flux density, similar to that of overvoltage. It follows that a transformer can operate with some degree of overvoltage with corresponding increase in frequency, but operation must not be continued with a high voltage input at a low frequency. Operation cannot be sustained when the ratio of voltage to frequency, with these quantities given values in per unit of their rated values, exceeds unity by more than a small amount, for instance if $V/f > 1.1$. If a substantial rise in system voltage has been catered for in the design, the base of 'unit voltage' should be taken as the highest voltage for which the transformer is designed.

2.1.1.5 System faults: Short circuits produce a relatively intense heating of the feeding transformers, the copper loss increasing in proportion to the square of the per unit fault current. The typical duration of external short circuits that a transformer can sustain if the current is limited only by the self-reactance is shown in Table 2.1. Maximum mechanical stress on windings occurs during the first cycle of the fault. Avoidance of damage is a matter of transformer design.

Table 2.1: Fault withstand levels

Transformer reactance (%)	Permitted Fault current (times of current rating)	Permitted fault duration (seconds)
4	25	2
5	20	2
6	16.6	2
7	14.2	2

2.1.2 External faults: are those faults that happen outside the transformer such as shunt faults. Power system short circuits may produce a relatively intense rate of heating of the feeding transformers. The unit protection of the transformer should not operate for external (through) faults. The transformer must be disconnected during such faults occur only when the faults are not cleared by other relays in pre-specified time.

2.1.3 Internal faults: occur within the transformer protection zone such as incipient fault (overheating, overfluxing, overpressure) and active faults (turn-to-earth, turn-to-turn, tank fault, core fault). These internal faults can be classified into two groups.

Group I: Electrical faults that cause immediate damage but are generally detectable by unbalance of current or voltage. Amongst them are the following:

- Winding failures resulting from short circuits (turn-turn faults, phase-phase faults, phase-ground, open winding) ,
- Short circuit between turns of high-voltage or low-voltage windings,
- Faults to earth on a tertiary winding or short circuit between turns of a tertiary winding Statistics show that winding failures most frequently cause transformer faults (ANSI=IEEE, 1985).

Group II: These include incipient faults, which are initially minor but cause substantial damage if they are not detected and taken care of. These faults cannot be detected by monitoring currents or voltages at the terminals of the transformer. Incipient faults include the following:

- A poor electrical connection between conductors,
- A core faults (core insulation failure, shorted laminations) which causes arcing in oil,
- Terminal failures (open leads, loose connections, short circuits),
- On-load tap changer failures (mechanical, electrical, short circuit, overheating),
- Coolant failure, which causes rise of temperature,
- Bad load sharing between transformers in parallel, which can cause overheating due to circulating currents.

For the group I of faults, the transformer should be isolated as quickly as possible after the occurrence of the fault. The group II faults, though not serious in the incipient stage, may cause major faults in the course of time. Incipient faults should be cleared soon after they are detected. The IEEE Guide for Protective Relay Applications to Power Transformers statistics show that winding failures most frequently cause transformer faults [12, 13].

Figure 2.1 shows summaries of failures in those categories reported by groups of utilities in USA. Winding failures, tap-changer failures and bushing failures represent more than 85% of the transformer failures. The winding failures still represent the majority of transformer failures, with tap-changers being a distant second. Two transformer characteristics causing problems for protection schemes are the low magnitude turn-to-turn faults and the high-magnitude magnetizing inrush current during energizing. Minimum internal faults can result in less than 10% of a transformer rated current. On the other hand, maximum fault current can flow for a high-side transformer bushing failure. For faults within the transformer itself, the approximate proportion of faults due to each of the causes listed above is shown in Figure 2.2.

2.1.3.1 Winding faults

A fault on a transformer winding is controlled in magnitude by the following factors:

- Source impedance,
- Neutral earthing impedance,
- Transformer leakage reactance,
- Fault voltage,
- Winding connection.

Several distinct cases may be arisen and are discussed below.

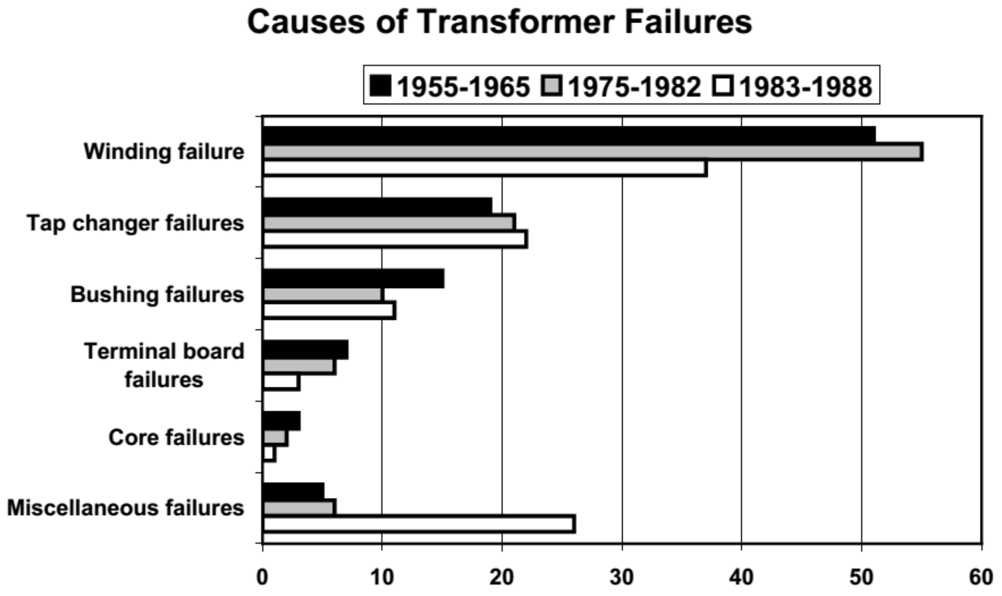


Figure 2.1 IEEE fault statistics

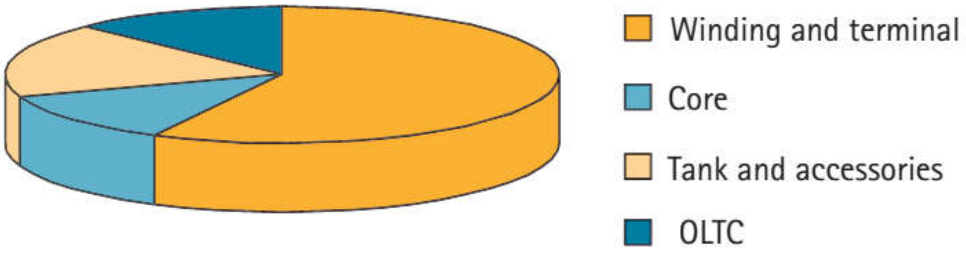


Figure 2.2: Transformer fault statistics

2.1.3.1.1 Star-connected winding with neutral point earthed through impedance

The winding earth fault current depends on the earthing impedance value and is also proportional to the distance of the fault from the neutral point, since the fault voltage will be directly proportional to this distance. For a fault on a transformer secondary winding, the corresponding primary current will depend on the transformation ratio between the primary winding and the short-circuited secondary turns. This also varies with the position of the fault, so that the fault current in the transformer primary winding is proportional to the square of the fraction of the winding that is short-circuited. The effect is shown in figure 2.3. Faults in the lower third of the winding produce very little current in the primary winding, making fault detection by primary current measurement difficult.

2.1.3.1.2 Star-connected winding with neutral point solidly earthed

The fault current is controlled mainly by the leakage reactance of the winding, which varies in a complex manner with the position of the fault. The variable fault point voltage is also an important factor, as in the case of impedance earthing. For faults close to the neutral end of the winding, the reactance is very low, and results in the highest fault currents. The variation of current with fault position is shown in figure 2.4.

For secondary winding faults, the primary winding fault current is determined by the variable transformation ratio; as the secondary fault current magnitude stays high throughout the winding, the primary fault current is large for most points along the winding.

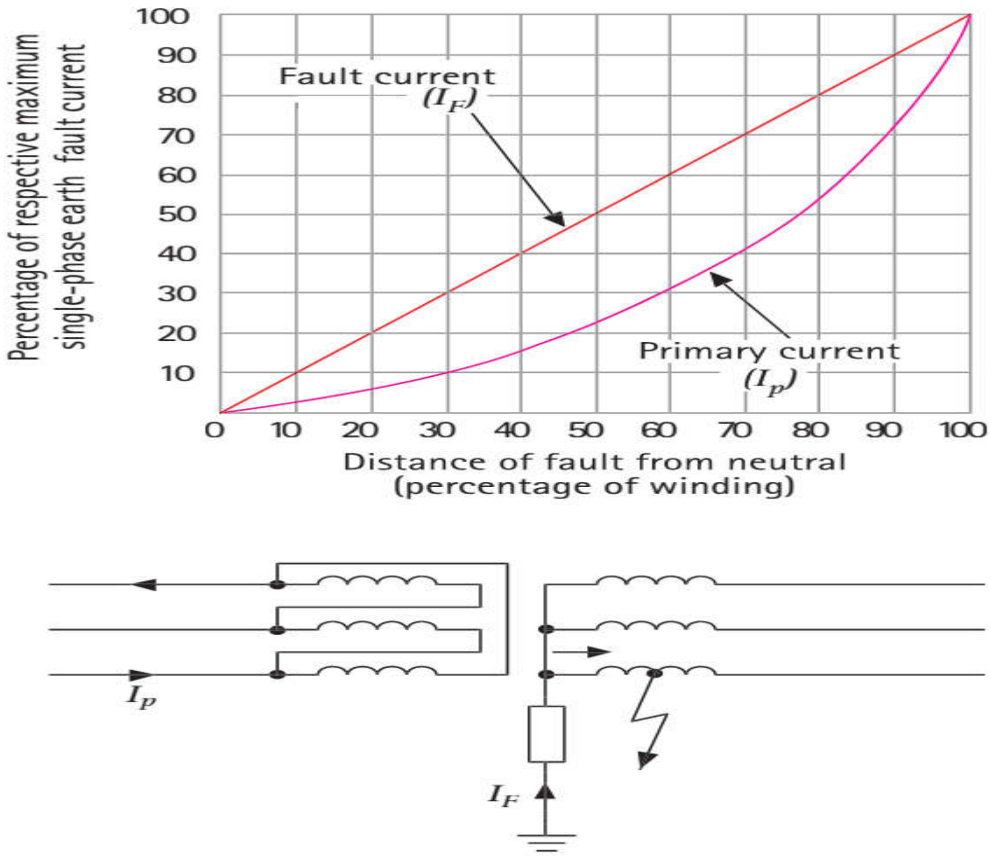


Figure 2.3: Earth fault current in resistance-earthed star winding [19]

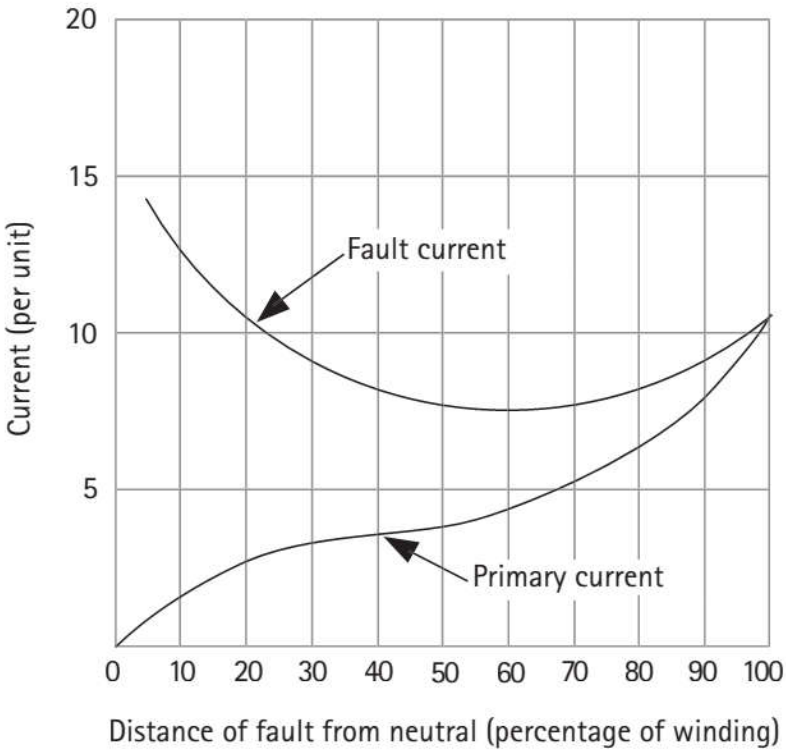


Figure 2.4: Earth fault current in solidly earthed star winding [19]

2.1.3.1.3 Delta-connected winding

No part of a delta-connected winding operates with a voltage to earth of less than 50% of the phase voltage. The range of fault current magnitude is therefore less than for a star winding. The actual value of fault current still depends on the method of system earthing; it should also be remembered that the impedance of a delta winding is particularly high to fault currents flowing to a centrally placed fault on one leg. The impedance can be expected to be between 25% and 50%, based on the transformer rating, regardless of the normal balanced through-current impedance. As the prefault voltage to earth at this point is half the normal phase voltage, the earth fault current may be no more than the rated current, or even less than this value if the source or system earthing impedance is appreciable. The current will flow to the fault from each side through the two half windings, and will be divided between two phases of the system. Therefore, the individual phase currents may be relatively low, resulting in difficulties in providing protection.

2.1.3.1.4 Phase to phase faults

Faults between phases within a transformer are relatively rare; if such a fault does occur it will give rise to a substantial current comparable to the earth fault currents.

2.1.3.1.5 Inter-turn faults

In low voltage transformers, inter-turn insulation breakdown is unlikely to occur unless the mechanical force on the winding due to external short circuits has caused insulation degradation, or insulating oil (if used) has become contaminated by moisture. A high voltage transformer connected to an overhead transmission system will be subjected to steep fronted impulse voltages, arising from lightning strikes, faults and switching operations. A line surge, which may be of several times the rated system voltage, will concentrate on the end turns of the winding because of the high equivalent frequency of the surge front. Part-winding resonance, involving voltages up to 20 times rated voltage may occur. The inter-turn insulation of the end turns is reinforced, but cannot be increased in proportion to the insulation to earth, which is relatively great. Partial winding flashover is therefore more likely. The subsequent progress of the fault, if not detected in the earliest stage, may well destroy the evidence of the true cause. A short circuit of a few turns of the winding will give rise to a heavy fault current in the short-circuited loop, but the terminal currents will be very small, because of the high ratio of transformation between the whole winding and the short-circuited turns.

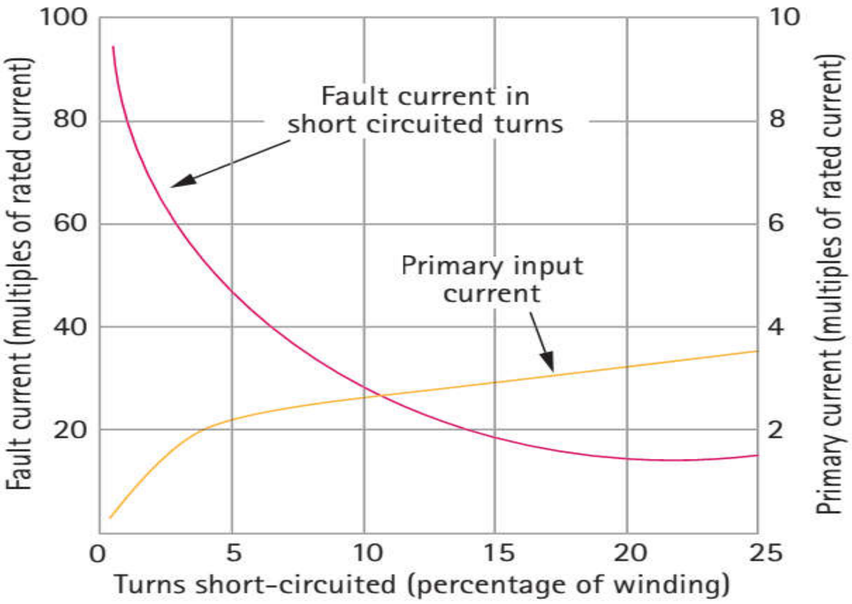


Figure 2.5 Interturn fault current/number of turns short-circuited [21]

The graph in figure 2.5 shows the corresponding data for a typical transformer of 3.25% impedance with the short-circuited turns symmetrically located in the centre of the winding.

2.1.3.2 Core faults

A conducting bridge across the laminated structures of the core can permit sufficient eddy-current to flow to cause serious overheating. The bolts that clamp the core together are always insulated to avoid this trouble. If any portion of the core insulation becomes defective, the resultant heating may reach a magnitude sufficient to damage the winding. The additional core loss, although causing severe local heating, will not produce a noticeable change in input current and could not be detected by the normal electrical protection; it is nevertheless highly desirable that the condition should be detected before a major fault has been created. In an oil-immersed transformer, core heating sufficient to cause winding insulation damage will also cause breakdown of some of the oil with an accompanying evolution of gas. This gas will escape to the conservator, and is used to operate a mechanical relay.

2.1.3.3 Tank faults

Loss of oil through tank leaks will ultimately produce a dangerous condition, either because of a reduction in winding insulation or because of overheating on load due to the loss of cooling. Overheating may also occur due to prolonged overloading, blocked cooling ducts due to oil sludging or failure of the forced cooling system, if fitted.

2.2 Transient abnormal conditions (magnetization)

To properly set a protection function, it is necessary to have a basic understanding of the power system events, the function is intended to detect. To set the inrush restraint function for transformer differential protection requires some understanding of transformer inrush currents, including the causes and characteristics of these events.

2.2.1 Magnetizing inrush current

An inrush current is the surge of transient current that rushes in a transformer when a transformer is energized. Inrush currents are caused by the saturation of a power transformer due to changes in the magnetizing voltage. They can occur during the following situations: transformer energization, post external fault clearing (voltage recovery) and energization of a parallel transformer (sympathetic inrush). Inrush currents can make transformer differential units trip because they only flow in one winding.

For providing a more easy-to-understand image of inrush current, figure 2.6 shows the current waveform 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 is 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 the inrush current. If the size of the inrush current exceeds that allowed by the part in use, depending on the magnitude of the inrush current (difference between the peak current value and the steady-state current value) and length of its duration (the length of time until the peak current value converges with the steady-state current value, hereafter called the pulse width), the part used in the circuit may overheat, potentially causing the electrical device to malfunction or break down.

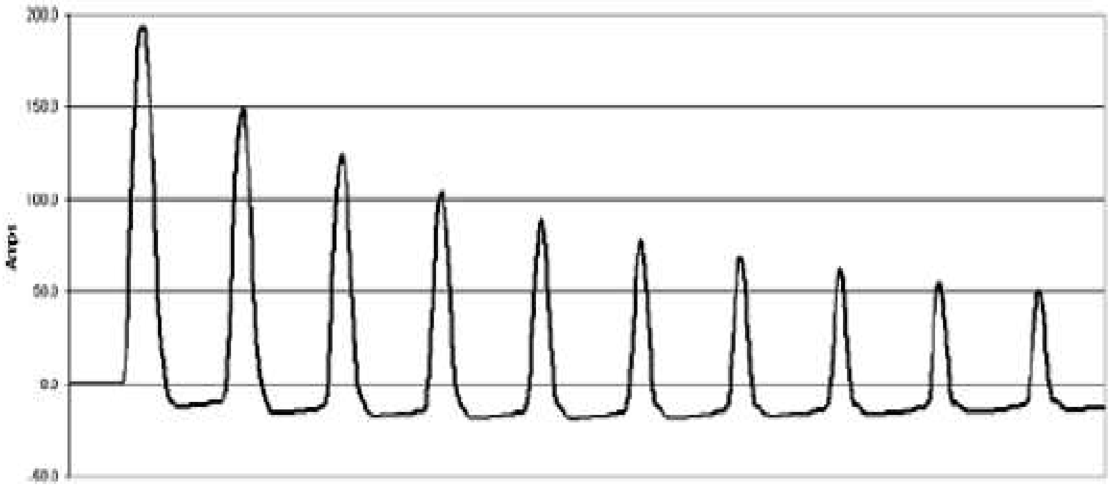


Figure 2.6 Current waveform when the device is powered on

2.2.3 Magnetic flux

A review of AC excitation of magnetic materials helps understand the actual characteristic of magnetizing inrush current. The magnetic steel used in transformers has a large number of regions (known as "domains") with a specific magnetic moment. An external magnetizing force causes all the magnetic moments of the steel to align with the applied magnetic field.

In the case of transformers, the excitation voltage provides this applied magnetic field. The alignment of the magnetic moments causes an increase in flux density greater than that of the external magnetic field. The steel is fully saturated when all the magnetic moments are aligned with the applied field. Once the external field is reduced, the magnetic moments maintain a net magnetization component along by the direction of the field. This effect results in magnetic hysteresis of the steel [16]. Transformers use grain-oriented electrical steel, where the domains tend to produce directions of magnetization with high permeability and low core loss.

If a voltage is applied to the primary winding of a transformer and the leakage inductance and the winding resistance are neglected, the following equation will be fulfilled:

$$v = N1.\frac{d\emptyset}{dt} \qquad (2.1)$$

where v is the instantaneous value of the supply voltage connected to the primary winding; N1 is number of turns of the primary winding; Φ is the instantaneous value of the magnetic flux.

If v =V_m sin (ωt +θ), the flux will be

$$\emptyset = \int_0^t v(t)dt = -\frac{Vm}{N1.\omega}.\cos(\omega t + \theta) + k \qquad (2.2)$$

where k is an integration constant. The term$-\frac{\boldsymbol{Vm}}{\boldsymbol{N1.\omega}}.\boldsymbol{\cos(\omega t + \theta)}$ represents the steady state flux and the integration constant k represents a transient DC flux that is generated when there is a difference between the initial flux and the steady state flux. As it can be seen in figure 2.7, the steady state flux will be lagging the voltage by 90º.

For t=0,

$$\boldsymbol{k = \emptyset_0 + \frac{V_m}{N_1.\omega}.\cos(\theta)} \qquad (2.3)$$

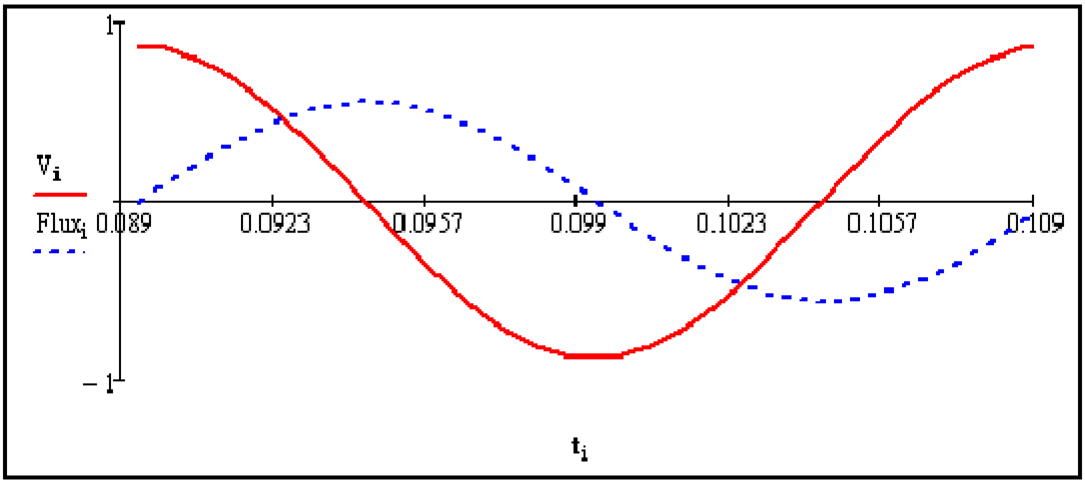


Figure 2.7 Steady state flux and supply voltage.

where $Ø_0$ is the initial total flux (flux at t=0) and θ_0 is the angle of the voltage at t=0. k will be called $Ø_{DC}$.

2.2.4 Events that result in magnetizing inrush currents

Any event on the power system that causes a significant increase in the magnetizing voltage of the transformer core results in magnetizing inrush current flowing into the transformer. The three most common events are:

- Energization of the transformer: This is the typical event where magnetizing inrush currents are a concern. The excitation voltage on one winding is increased from zero to full voltage. The transformer core typically saturates, with the amount of saturation determined by transformer design, system impedance, the ruminant flux in the core, and the point on the voltage wave when the transformer is energized. The current needed to supply this flux may be as much as 40 times the full load rating of the transformer, with typical value for power transformers for 2 to 6 times the full load rating [16]. The waveforms of figure 2.7 were recorded during energization of a transformer,
- Initial magnetizing due to switching a transformer in is considered the most severe case of an inrush. When a transformer is de-energized (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.

Figure 2.8 shows a typical inrush current waveform. The waveform displays a large and long lasting dc component, is rich in harmonics, assumes large peak values at the beginning (up to 30 times the rated value), decays substantially after a few tenths of a second, but its full decay occurs only after several seconds (to the normal excitation level of 1% - 2% of the rated current). In certain circumstances, some small changes of the excitation current are observable even minutes after switching a transformer in [15].

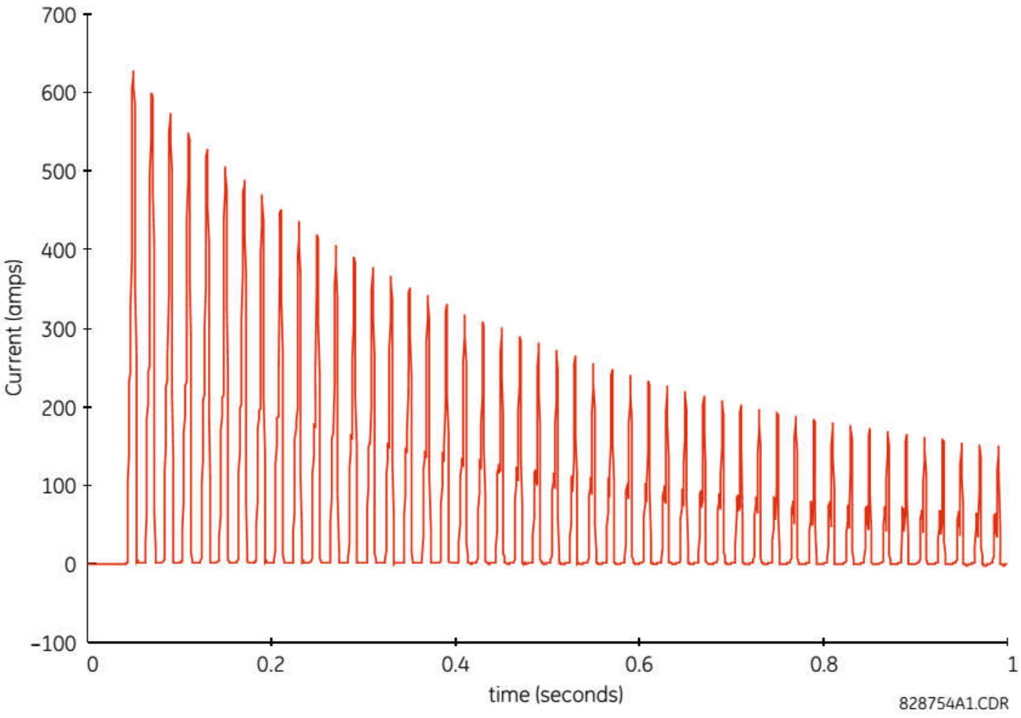


Figure 2.8 Typical inrush current waveform [15]

The shape, magnitude and duration of the inrush current depend on several factors:

1. Size of a transformer,
2. Impedance of the system from which a transformer is energized,
3. Magnetic properties of the core material,
4. Remanence in the core,
5. Moment when a transformer is switched on,
6. Way a transformer is switched on.

The highest values of the inrush current occur when the transformer is switched on at the zero transition of the winding voltage. It is approximated that every fifth or sixth energizing a power transformer result in considerably high values of the inrush current [16].

- **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 this fault is cleared, the excitation voltage returns to the normal system voltage level. The return of voltage may force a dc offset on the flux linkages, resulting in magnetizing inrush current. This magnetizing inrush current will be less than that of energization, as there is no remanent flux in the core [15]. The current measured by the differential relay will be fairly linear due to the presence of load current, and may result in low levels of second harmonic current.
- **Sympathetic inrush:** Energizing a transformer on the power system can cause sympathetic magnetizing inrush currents to flow in an already energized parallel transformer. Energizing the second transformer causes a voltage drop across the resistance of the source line feeding the transformers. This voltage drop may cause a saturation of the already energized transformer in the negative direction. This saturation causes magnetizing inrush current to supply the flux. The magnitude of the magnetizing inrush current is generally not as severe as the other cases [14-16].

Consider the two power transformers, T1 and T2, of figure 2.9. Both transformers are connected in parallel to the busbar B, which is fed by the voltage E. Rs represents the source resistance, Xs the source reactance, R_1 the resistance of the primary winding for transformer T1 and R_2 the resistance of the primary winding for transformer T2. Transformer T1 is already energized and transformer T2 will be energized by closing the breaker B2. In order not to mix the inrush current with the load current we will neglect the load current in transformer T1, so current i_1, just before T2 is energized, will be zero. When the breaker B2 is closed the transformer T2 will experience an inrush. We will assume a negative DC offset for the flux in transformer T2 (see figure 2.10a). This DC offset will be damped because of the voltage drop caused by (i_1+i_2) in Rs and by i_2 in R_2. The following formula defines the flux change in one cycle:

$$\emptyset_{2_t} - \emptyset_{2_{t-T}} = \int_{t-T}^{t} [Rs(i_1 + i_2) + i_2]dt \tag{2.4}$$

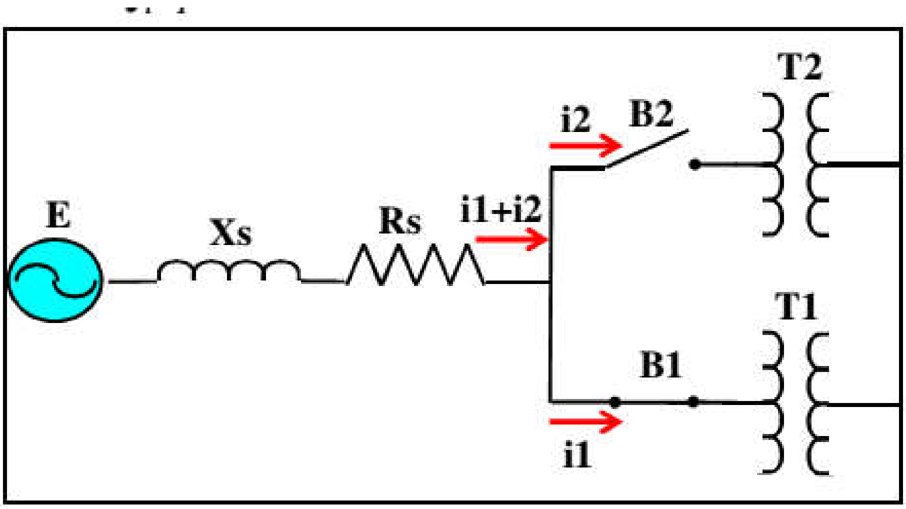


Figure 2.9 System considered for the sympathetic inrush phenomena.

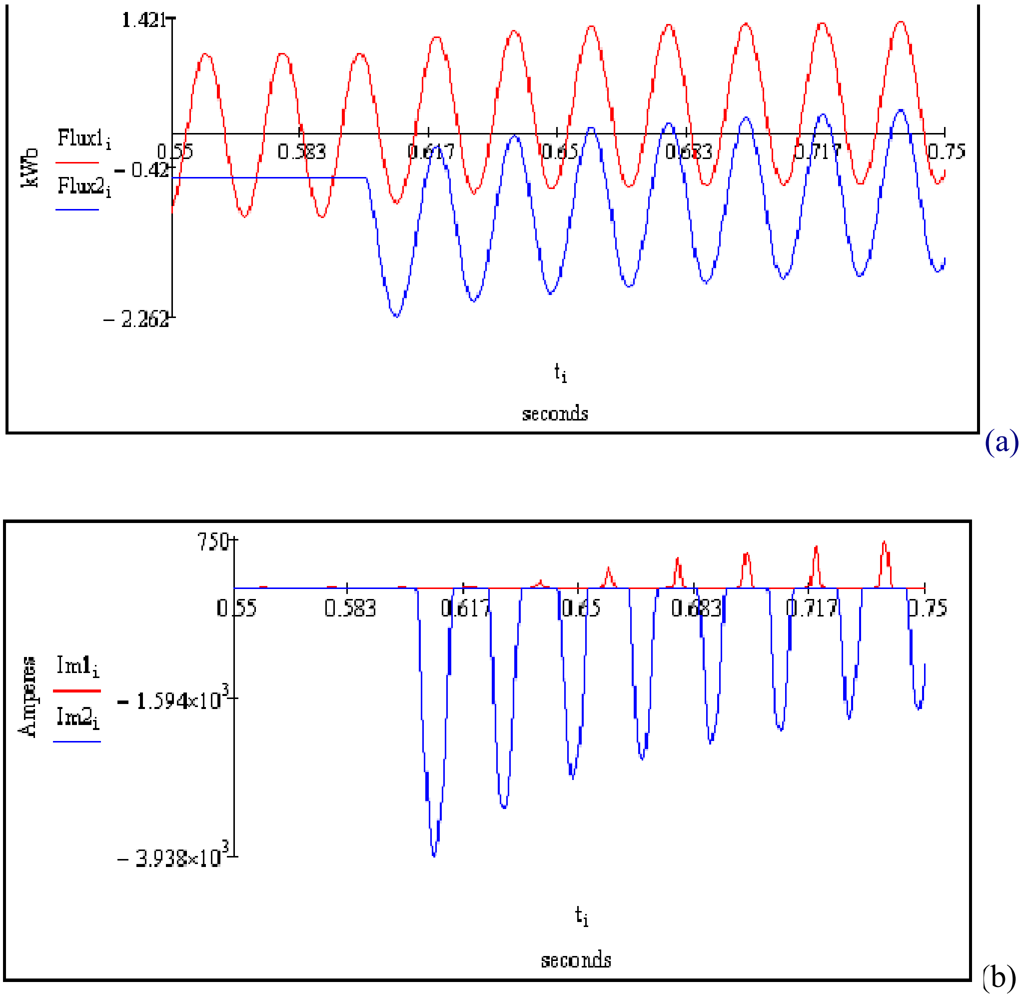


Figure 2.10 Currents in transformers T1 and T2 during the first cycles of a sympathetic inrush.

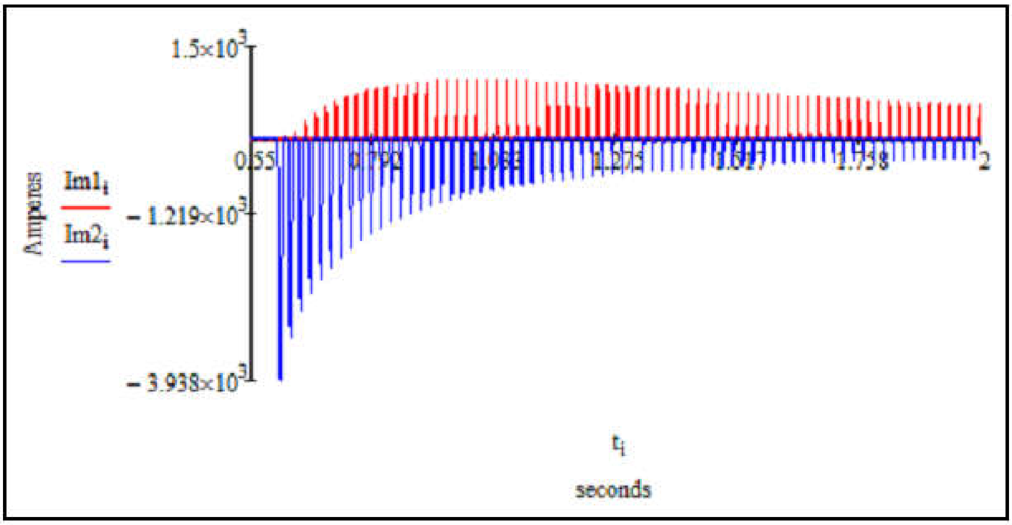


Figure 2.11 Currents in transformers T1 and T2 during 2 seconds of the sympathetic inrush.

The voltage drop created by the current (i_1+i_2) in the source resistance (there is no voltage drop in the winding resistance as i_1 is considered zero at the beginning of this phenomena) will also modify the DC flux at transformer T1, which initially was zero, creating a positive DC flux, which makes transformer T1 saturate:

$$\emptyset_{1_t} - \emptyset_{1_{t-T}} = \int_{t-T}^{t} [Rs(i_1 + i_2) + R_1 \, . \, i_1] dt \tag{2.5}$$

The steady state component of both fluxes, Φ_1 and Φ_2, can be considered equal, as both transformers will be supplied from the same voltage. Flux Φ_2 has a negative DC offset and flux Φ_1 has a positive DC offset. This makes the saturation periods of T1 and T2 happen at opposite half-cycles. T2 is saturated during the negative half-cycles of the steady state flux and T1 is saturated during the positive half-cycles of the steady state flux. The currents i1 and i_2 will therefore have opposite polarity and their peaks will occur at alternate half-cycles. The consequence is that the flux changes created by the voltage drop in the source resistance (caused by the sum current, i_1+i_2) changes its sign every half-cycle (until the instant that T1 saturates the flux change was always positive, for every half-cycle, as i_1 was null): i_1 tends to create a negative flux change (tending to get T1 out of saturation and, on the other hand, tending to maintain T2 saturated) while i_2 tends to create a positive flux change (tending to get T2 out of saturation and, at the same time, tending to maintain T1 saturated). At the beginning of the sympathetic inrush, as i_2 is higher (in absolute value) than i_1 its effect is bigger, so, due to the positive flux change, it will make i_2 decrease (in absolute value) and i_1 increase, until its absolute value is equal. When both currents are equal the flux change for a cycle in both transformers due to the voltage drop in the source resistance will be zero (the flux change in every half-cycle will be equal and with opposite polarity). The only flux change is created by the voltage drop of each current in the winding resistance of the corresponding transformer. This generates a very slow damping making the inrush currents in both transformers be present for a long time. Figure 2.11 represents the currents i_1 and i_2 during 2 seconds of the phenomena. Note that when both currents get equal (in absolute value) the damping reduces very much.

2.3 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 for 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. These currents are high magnitude; harmonic-rich currents generated when transformer cores are driven into saturation, and may erroneously trigger transformer overcurrent protections. 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. The inrush current [14] is composed of harmonics of multiples of the fundamental frequency. (As given in Table 2.2)

The second harmonic is very significant where it represents 63% of the amplitude of the total inrush current. The fault current is composed of the fundamental frequency and it lasts until the fault is removed. The magnitude of the fault current depends on the type of the fault and location. Protective relays schemes used to prevent relays from tripping power transformers during inrush current based on the knowledge of the nature of the inrush current signal and its difference from the fault current where power transformer should be tripped.

Magnetizing inrush current in transformers results from any abrupt change of the magnetizing voltage. Generally, the magnetizing inrush current may be caused by the following [15, 16]:

- Energizing a power transformer;

- Occurrence of an external fault;

- Voltage recovery after clearing an external fault;

- Change of the character of a fault (for example when a phase-to-ground fault evolves into a phase-to-phase-to-ground fault), and

- Out-of-phase synchronizing of a connected generator.

Since the magnetizing branch representing the core appears as a shunt element in the transformer equivalent circuit model, the magnetizing current upsets the balance between the currents at the transformer terminals, and is therefore experienced by the differential relay, the main protection of power transformers, as a “false” differential current. The relay, however, must remain stable during inrush conditions. In addition, from the standpoint of the transformer life-time, tripping-out during inrush conditions is a very undesirable situation since breaking a current of a pure inductive nature generates high over voltage that may jeopardize the insulation of a transformer and be an indirect cause of an internal fault.

Table 2.2 Percentage of harmonics in typical magnetizing inrush current.

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

The magnetizing current of a transformer contains a third harmonic and progressively smaller amounts of fifth and higher harmonics. If the degree of saturation is progressively increased, not only will the harmonic content increase as a whole, but the relative proportion of fifth harmonic will increase and eventually exceed the third harmonic. At a still higher level the seventh would overtake the fifth harmonic but this involves a degree of saturation that will not be experienced with power transformers.

The energizing conditions that result in an offset inrush current produce a waveform that is asymmetrical. Such a wave typically contains both even and odd harmonics. Typical inrush currents contain substantial amounts of second and third harmonics and diminishing amounts of higher orders. The second harmonic is very significant where it represents 63% of the amplitude of the total inrush current. The fault current is composed of the fundamental frequency and it lasts until the fault is removed. The magnitude of the fault current depends on the type of the fault and location.

As with the steady state wave, the proportion of harmonics varies with the degree of saturation, so that as a severe inrush transient decays, the harmonic makeup of the current passes through a range of conditions.

Problems caused by inrush:

Power quality problems: 1) unbalance, 2) harmonics.

Other disturbances caused by inrush:

1. Incorrect operation and failures of electrical machines and relay systems,
2. Irregular voltage distribution along the transformer windings,
3. High amount of voltage drop at the power system at energization times,
4. Electrical and mechanical vibrations among the windings of the transformer.

The schemes currently used to distinguish between magnetizing Inrush and fault current are based on:

1. Second harmonic restraint principle,
2. Voltage restraint principle,
3. Restraint principle based on currents and voltages of the transformers,
4. But the second harmonic component is widely used for the detection of inrush current in power transformer.

Problems in identifying inrush condition using second harmonics component are:

1. The magnitude of the second harmonic in fault current can be close to or greater than that present in the magnetizing inrush current,
2. The second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers,
3. Consequently, differential protection technique based on the second harmonic restraint may fail.

2.3.1 Harmonic content of the inrush current

In order to analyze the harmonic content of the inrush current the simplified waveform of figure 2.12 is considered. This waveform results from assuming a simplified B-H curve consisting of a vertical line in the non-saturated region and a straight line with a low slope in the saturated region. The transformer will be saturated during the angular span of 2α (which is normally called base angle), during this angle the magnetizing current will be an offset sine wave. The rest of the period the magnetizing current will be zero [5].

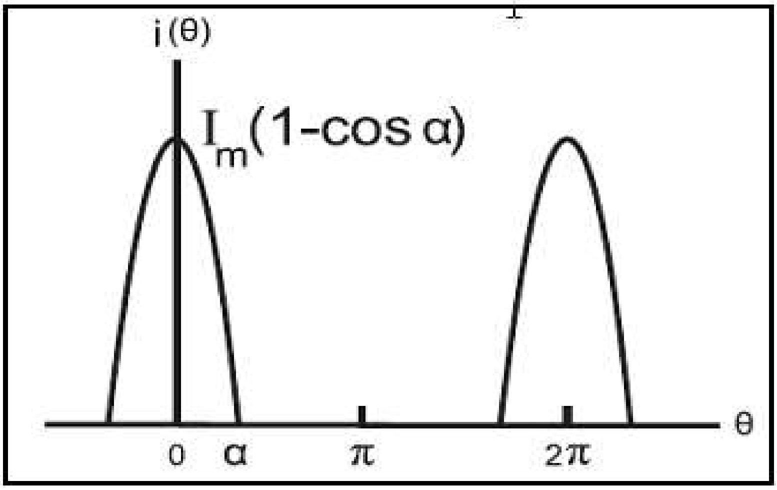


Figure 2.12 Simplified waveform for the inrush harmonic analysis.

The equation for the simplified waveform will be:

$$i(\theta) = I_m(\cos\theta - \cos\alpha), 0 \le \theta \le \alpha,\ (2\pi - \alpha) \le \theta \le 2\pi \qquad (2.5)$$

$$0, \alpha \le \theta \le (2\pi - \alpha)$$

The harmonic content of this waveform can be calculated with a cosine Fourier series. The harmonic content of this waveform for α values of 60º, 90º and 120º is given in table 2.3 [5]. It can be observed that the higher the α angle is the lower the second harmonic content is.

Table 2.3 Harmonic content in the inrush current

Harmonic	**a_n/a_1**		
	$\alpha = 60°$	$\alpha = 90°$	$\alpha = 120°$
2	0.705	0.424	0.171
3	0.352	0.000	0.086
4	0.070	0.085	0.017
5	0.070	0.000	0.017
6	0.080	0.036	0.019
7	0.025	0.000	0.006
8	0.025	0.029	0.006
9	0.035	0.000	0.008
10	0.013	0.013	0.003
11	0.013	0.000	0.003
12	0.020	0.009	0.005
13	0.008	0.000	0.002

As explained in reference [3], the closer the residual flux is to the saturation density the larger the base angle 2α is.

In this reference a 90% residual flux and a 140% saturation density was considered, resulting in a base angle (2α) of 240º. Modern transformers can operate closer to the knee point allowing higher residual fluxes, reducing the difference between the saturation density and the residual flux [6]. This results in lower second harmonic contents than the ones obtained in reference [3] which talked about a 17.1%. Modern transformers can have second harmonic contents as low as 7% [7]. The low second harmonic content will only be present in the first 4-5 cycles of the inrush [6]. This occurs because the damping reduces the DC offset of the flux so it reduces the time the flux is above the saturation density, decreasing the base angle of the magnetizing current.

2.4 Transformer Over-excitation

Over-excitation can also be caused by an increase in system voltage or a reduction in frequency. It follows, therefore, that transformers can withstand an increase in voltage with a corresponding increase in frequency but not an increase in voltage with a decrease in frequency. Operation cannot be sustained when the ratio of voltage to frequency exceeds more than a small amount. The magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency. Overvoltage and/or under-frequency conditions can produce flux levels that saturate rapidly the transformer core. These abnormal operating conditions can exist in any part of the power system, so any transformer may be exposed to over-excitation. Transformer over-excitation causes transformer heating and increases exciting current, noise, and vibration. A severely overexcited transformer should be disconnected to avoid transformer damage. Because it is difficult, with differential protection, to control the amount of over-excitation that a transformer can tolerate, transformer differential protection tripping for an over-excitation condition is not desirable. Protection against over-flux conditions does not require high-speed tripping. In fact, instantaneous tripping is undesirable, as it would cause tripping for transient system disturbances, which are not damaging to the transformer.

An alarm is triggered at a lower level than the trip setting and is used to initiate corrective action. The alarm has a definite time delay, while the trip characteristic generally has a choice of definite time delay or inverse time characteristic. Use separate transformer over-excitation protection instead, and the differential element should not trip for these conditions. One alternative is a V/Hz relay that responds to the voltage/frequency ratio.

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 2.13 shows the exciting current recorded during a real test of a 5 kVA, 230/115V, single-phase laboratory transformer [22]. The current corresponds to an overvoltage condition of 150 percent at nominal frequency. For comparison purposes, the peak value of the transformer nominal current is 61.5A, and the peak value of the exciting current is 57.3A. Table 2.3 shows the most significant harmonics of the current signal depicted in figure 2.13. Harmonics are expressed as a percentage of the fundamental component. The third harmonic is the most suitable for detecting over-excitation conditions, but either the delta connection of the CTs or the delta connection compensation of the differential relay filters out this harmonic. The fifth harmonic, however, is still a reliable quantity for detecting over-excitation conditions.

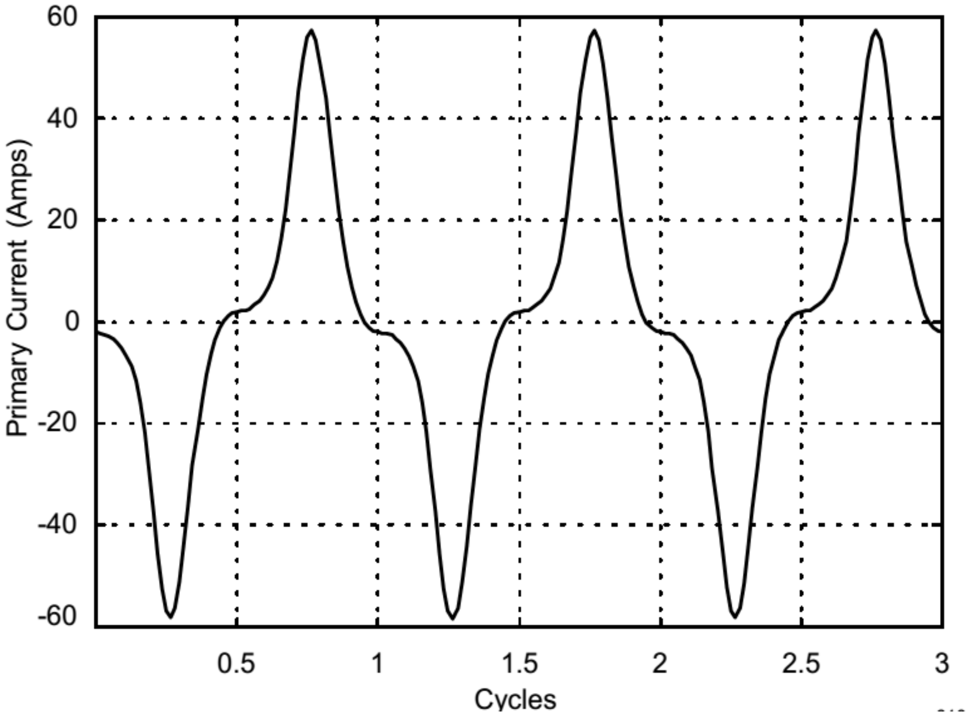


Figure 2.13 Exciting Current of an Overexcited Transformer

Chapter 3

Protection System of Power Transformer

Power transformers are one of the most important elements in power systems. Therefore, the protection of power transformers and the prevention of tripping power transformer unnecessarily due to inrush current are crucial for the continuity of the power supply.

The first generation of methods used to block the protective relay system during inrush current, namely the Desensitizing and Tripping Suppressor, is introduced. The second generation, the harmonic restraint method and the waveform-based restraint method with their different versions, is explained. Then we will explore thoroughly the fictitious equivalent resistance method as an example of the third generation of model type restraining or blocking methods. Finally, a comparison among these methods and conclusion is carried out.

3.1Transformer Protection Overview

Transformers are a critical and expensive component of the power system and should be protected properly. The type of protection for the transformers varies depending on the application and the size of the transformer. Transformers are protected primarily against faults and overloads. The type of protection used should minimize the time of disconnection for faults within the transformer and to reduce the risk of catastrophic failure to simplify eventual repair. Any extended operation of the transformer under abnormal condition such as faults or overloads reduces the life of the transformer, which means adequate protection should be provided for quicker isolation of the transformer under such conditions. However as long as a possibility of failure exists, protection must be provided. Therefore, when internal faults occur in the transformer, immediate disconnection of the faulted transformer is necessary to avoid extensive damage and/or preserve power system stability and hence power quality. The purpose of the transformer fault protection is to:

a) Remove any secondary overload faults from the transformer before it gets damaged,

b) Isolate the transformer before it gets totally out of control,

c) Remove the damaged transformer from the system to continue the function.

Table 3.1 summarizes the problems and the possible forms of protection that may be used. The following sections provide more details on the individual protection methods. In a modern relay, all the required protection functions can be provided in a single package, in contrast to electromechanical types that would require several relays complete with interconnections and higher overall CT burdens.

3.1.1 Transformer Protection System Requirements

A protective system should be designed to recognize certain system abnormalities which, if undetected, could lead to damage equipments or extended loss of service. The design and specification of the system components is an important part of the protective strategies and power system are designed to withstand the usual operating contingencies that accompany load changes and line switching operation. There is several design consideration that must be weighed against cost in devising a protection strategy, the following fundamental requirements that are considered in designing the protective systems with a good performance of a relay are [2, 3]:

Table 3.1: Transformer faults/protection

Fault type	**Protection functions to be provided**
Primary winding Phase-Phase fault	Differential; Overcurrent
Primary winding Phase-Earth fault	Differential; Overcurrent
Secondary winding Phase-Phase fault	Differential
Secondary winding Phase-Earth fault	Differential; Restricted Earth Fault
Interturn fault	Differential, Buchholz
Core fault	Differential, Buchholz
Tank fault	Differential, Buchholz; Tank-earth
Overfluxing	Volts/Hz
Overloads	Thermal
External system short circuits	Time overcurrent, Instantaneous overcurrent

Reliability: it is the ability of the relay system to operate under the predetermination condition. Without reliability, the protection will be rendered largely ineffective and could even become a liability. The reliability of a relay depends directly on the concepts of dependability and security. A relay is said to be dependable when it operates in the occurrence of a fault relevant to its protection zone. In other words, dependability is a measure of the relay ability to operate when it is supposed to operate. Security is defined as "the degree of certainties that a relay or relaying system will not operate incorrectly". Security is reached either when the relay will not operate for a fault outside its operating zone, or when the system is in a healthy state.

Selectivity: is the ability of the protective system to select correctly that part of the system in trouble and disconnect the faulty part without disturbing the rest of the system. Selectivity discrimination can be achieved by time grading or by unit protection. Selectivity by time grading means that different zones of operation are graded by time and that in the occurrence of a fault, although a number of protections equipment respond, only those relevant to the faulty zone complete the tripping function. Selectivity by unit protection means that the relay will only operate under certain fault conditions occurring within a clearly defined zone.

Speed: the relay system should disconnect the faulty section as fast as possible for the following reasons. In the occurrence of a fault, the greater the time in which the fault is affecting the power system, the greater is the risk that the power system falls into an unstable operation point. Relays are therefore required to clear the fault as quickly as possible.

1. Electrical apparatus may be damaged if they are made to carry the fault current for a long time.
2. A failure on the system leads to a great reduction in the system voltage. If the faulty section isn't disconnected quickly, then the low voltage created by the fault may shut down the customers' motors and the generations on the system may be unstable.
3. The high speed relay system decreases the possibility of development of one type of fault into more sever types.

Sensitivity: it is the ability of the relay system to operate with low value of actuating quantity. In other words, the relay is said to be sensitive if the relay operates to the minimum value of faulted input signals.

Simplicity: the relaying system should be simple so that it can be easily maintained. Reliability is closely related to the simplicity. The simpler the protection scheme the greater will be its reliability.

Economy: the most important factor in the choice of a particular protection scheme is the economic aspect. Sometimes it is economically unjustified to use an ideal scheme of protection and compromise methods have to be adopted. As a rule, the protective gear should not cost more than 5% of total cost. However, when the apparatus to be protected is of utmost importance, economics considerations are often subordinate to the reliability.

3.1.2 Protective Relays performance and technology

The relay application for protection of power system date back nearly 100 years ago. Since then, the technology employed to construct relays have improved dramatically relay size, weight, cost and functionality. Based on the technology employed for their construction, relays can be classified as follows:

Electromechanical relays: The first relays employed in the electric industry were electromechanical devices. These relays have worked based on creating a mechanical force to operate the relay contacts in response to a fault. The mechanical force has established by the flow of a current that reflected the fault current through windings mounted in magnetic cores. Due to the nature of its principle of operation, electromechanical relays are relatively heavier and bulkier than relays constructed with other technologies. Besides, the burden of these relays can be extremely high, affecting protection purposes. However, electromechanical relays were so largely employed, tested and known that even modern relays employ their principle of operation, and still represent a good choice for certain conditions of application.

Solid-state relays: With the advances on electronics, the electromechanical technology presented in the relays of the first generation started to be replaced by static relays in the early 60's. Static relays defined the operating characteristic based in analog circuitry rather than in the action of windings and coils. The advantages of the static relays with respect with electromechanical relays are a reduced size, weight and electrical burden. However, static relays have showed some disadvantages since analog circuitry is extremely affected by electromagnetic interference and the ranges of current and voltages values are strongly restricted in analog circuits, affecting the sensitivity of the relay.

Digital relays: Incorporating microprocessor into the architecture of relay to implement relay and logic functions started in the 80's. Digital relays incorporated analog-to-digital converter (ADC) to sample the analog signals incoming from instrument transformers, and used microprocessor to define the logic of the relay. Digital relays have presented an improvement in accuracy and control over incoming signals, and the use of more complexes relay algorithms, extra relay functions and complementary task.

Numerical relays: The difference between numerical relays and digital relays lies in the kind of microprocessor used. Numerical relays use digital signal processors (DSP) cards, which contain dedicated microprocessors especially designed to perform digital signal processing.

3.2 Non electrical protection

The non electrical protection operates independently from the current and the voltage of the transformer. Its operations are based on the physical and the chemical condition of the transformer or insulation media of the transformer (oil).

Buchholz relay: This relay is actuated by gas and oil inside the transformer bank. The turn-to-earth fault, turn-to-turn fault or other internal fault inside the transformer will generate gases in sufficient quantities to operate this protection device and actuate the operating of circuit breaker. When a fault occurs inside the oil-filled transformer tank, the fault arc produces gases, which create pressure inside the oil. In the conservator type of tank construction, the pressure created in the oil is detected by a pressure vane in the pipe which connects the transformer tank with the conservator. The movement of the vane is detected by a switch, which can be used to sound an alarm or send the trip contact to the circuit breaker.

Temperature relay: it works based on the temperature of the transformer. When the temperature is high, then this relay will give the alarm signal. If the temperature is extremely high, then this relay will send a trip command to the circuit breaker.

The temperature sensors are also commonly used to start and stop the cooling system of the transformer.

Sudden Pressure Relay: The sudden pressure relay operation is based on the rate of rise of gas in the transformer. It can be applied to any transformer with the sealed air or gas chamber above the oil level. It will not operate on static pressure or pressure changes resulting from normal operation of the transformer. This sudden pressure relay is usually found at the transformer with a gas cushion at the top of the bank. Just the same with Buchholz relay, a pressure wave created by a fault is detected by this relay.

There are two types of sudden pressure relay, membrane type and pressure relief valve type. For membrane type, the membrane will break when the pressure is above its design. For pressure relief valve type, the valve will open and remove the pressure with the oil when the pressure inside the transformer exceeds the spring pressure. The valve is pressed by the spring in the normal condition.

Faults on the bushings do not create an arc in the insulating oil and must be protected by other protection system. The combination of the pressure relay (sudden pressure relay and Buchholz relay) and differential relay provides an excellent protection system for a power transformer.

3.3 Electrical protection

The type of protection for the transformers varies depending on the application and the importance of the transformer.

Transformers are protected primarily against faults and overloads. The type of protection used should minimize the time of disconnection for faults within the transformer and to reduce the risk of catastrophic failure to simplify eventual repair.

Any extended operation of the transformer under abnormal condition such as faults or overloads compromises the life of the transformer, which means adequate protection should be provided for quicker isolation of the transformer under such conditions.

The electrical protection means the working principle of the protection based on the current, the voltage, or the frequency of that appear on the protected zone. The electrical protection of the Transformer comprises of the following and each is elaborated further.

- Over Current Protection,
- Fused Protection,
- Over Voltage Protection,
- Over Excitation Protection,
- Differential Current Protection.

3.3.1 Transformer over current protection

The philosophy of transformer over current protection is to limit the fault current below the transformer through fault with stand capability. The fault withstand capability in turn is based on the possibility of mechanical of the windings due to the fault current, rather than on the thermal characteristics of the transformer.

Overcurrent protection provides the first type of transformer protection and is commonly used for protection for phase and ground faults [10]. It's used as primary protection where differential protection is not used; also it is used to backup protection if differential protection has been used. The protection zone of over current devices is normally more than the transformer. Hence they are part of the system protection and need to be coordinated with the other system protection devices. Instantaneous over current relays are also used for back up where differential relays have been used. Typically they are set to 150% to 200% of the maximum of:

1. Magnetizing current inrush (if harmonic restraint is not used),
2. Short time load – Cold Pickup,
3. Maximum 3 phase short circuit current.

Overcurrent protection with fuses or relays provided the first type of transformer fault protection [20]; it continues to be applied in small size transformers. Fuses may adequately protect small transformers, but larger ones require overcurrent protection using a relay and Circuit Breaker, as fuses do not have the required fault breaking Capacity.

a) Fuses

Fuses commonly protect small distribution transformers typically up to ratings of 1MVA at distribution voltages level. In many cases, no circuit breaker is provided, making fuse protection the only available means of automatic isolation. The fuse must have a rating well above the maximum transformer load current in order to withstand the short duration overloads that may occur. Also, the fuses must withstand the magnetizing inrush currents drawn when power transformers are energized. High Rupturing Capacity (HRC) fuses, although very fast in operation with large fault currents, are extremely slow with currents of less than three times their rated value.

It follows that such fuses will do little to protect the transformer, serving only to protect the system by disconnecting a faulty transformer after the fault has reached a dangerous stage. Table 3.2 shows typical ratings of fuses for use with 11kV transformers.

Table 3.2 Typical fuse ratings

Transformer rating		**Fuse**	
kVA	Full load current (A)	Rated current (A)	Operating time at 3 x rating(s)
100	5 ,25	16	3
200	10,5	25	3
315	15,8	36	10
500	26,2	50	20
1000	52,5	90	30

b) Overcurrent relays

Overcurrent relays are used for larger transformers provided with standard circuit breaker control. Improvement in protection is obtained in two ways; the excessive delays of the HRC fuse for lower fault currents are avoided and an earth-fault tripping element is provided in addition to the overcurrent feature. The time delay characteristic should be chosen to discriminate with circuit protection on the secondary side. A high-set instantaneous relay element is often provided, the current setting being chosen to avoid operation for a secondary short circuit. This enables high-speed clearance of primary terminal short circuits.

3.4 Over-flux protection

Transformer over-fluxing can be a result of:

- Overvoltage
- Low system frequency

A transformer is designed to operate at or below a maximum magnetic flux density in its core. Above this design limit, the eddy currents in the core and nearby conductive components cause overheating which within a very short time may cause severe damage. The magnetic flux in the core is proportional to the voltage applied to the winding divided by the impedance of the winding. The flux in the core increases with either increasing voltage or decreasing frequency. During startup or shutdown of generator-connected transformers, or following a load rejection, the transformer may experience an excessive ratio of volts to hertz, that is, become overexcited.

When a transformer core is overexcited, the core is operating in a non-linear magnetic region, and creates harmonic components in the exciting current. A significant amount of current at the 5th harmonic is characteristic of overexcitation.

Transformer cores are normally subjected to flux levels approaching the knee point in their magnetizing characteristic. Typically, the rated voltage at rated frequency may be 10% below the saturation level. If the core flux should exceed the saturation level, the flux patterns in the core and the surrounding structure would change, and significant flux levels may be reached in the transformer tank and other structural members. As these are not laminated, very high eddy currents are likely to result, producing severe damage to the transformer. Therefore, it is desirable to provide a protection package which will respond to the flux level in the transformer. As the flux is proportional to the voltage, and inversely proportional to the operating frequency, the significant relaying quantity is the ratio of the per unit voltage to the per unit frequency. This is known as volts/hertz protection.

This protection is specially needed in the case of unit-connected generator transformers. If the turbine–generator is shut down with the voltage regulator in service, the volts/hertz limit of the transformers (and indeed of generators as well) could be easily exceeded. Similar conditions could also be reached by load rejection with voltage regulators disconnected, or in manual position, or with faulty instrumentation in the regulator circuits. The volts/hertz capability of transformers is specified by manufacturers. A typical capability curve is shown in figure 3.1. Many volts/hertz relays have two settings, a lower setting for alarm and a higher setting which may be used for tripping.

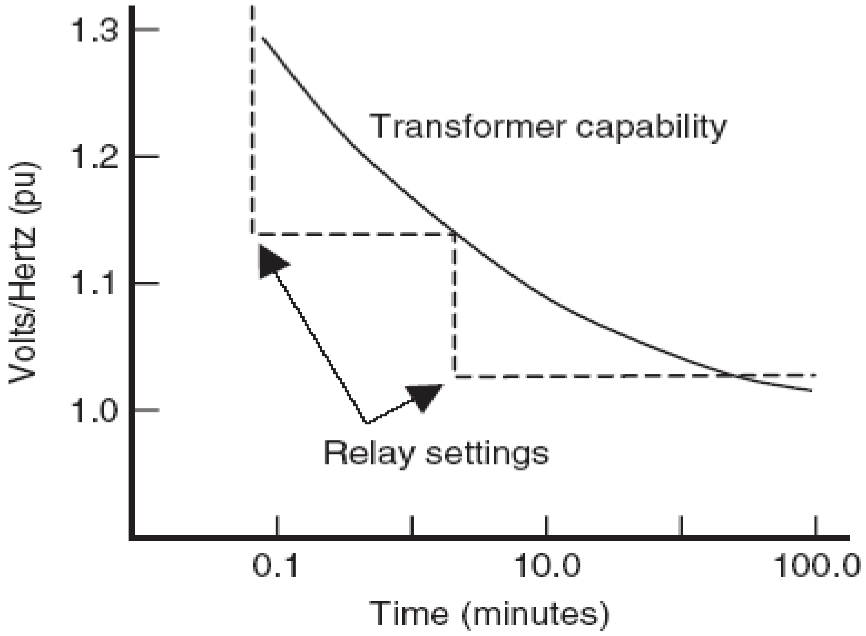


Figure 3.1 Volts/hertz capability of transformers, and relay settings.

3.5 Differential protection

Differential protection replaces overcurrent protection as the main protection for large power transformers.

A typical differential protection system is shown in figure 3.2. Multiple circuits may exist, but the example is sufficient to explain the basic principle of differential protection [2]. It can be observed from figure 3.2 that the protection zone is delimited by current transformers. Due to its very nature, differential protection does not provide backup protection to other system components. For this reason, differential protection is categorized as a unit protective scheme. The conductors bringing the current from the current transformers to the differential relay are in some situations called pilot wires.

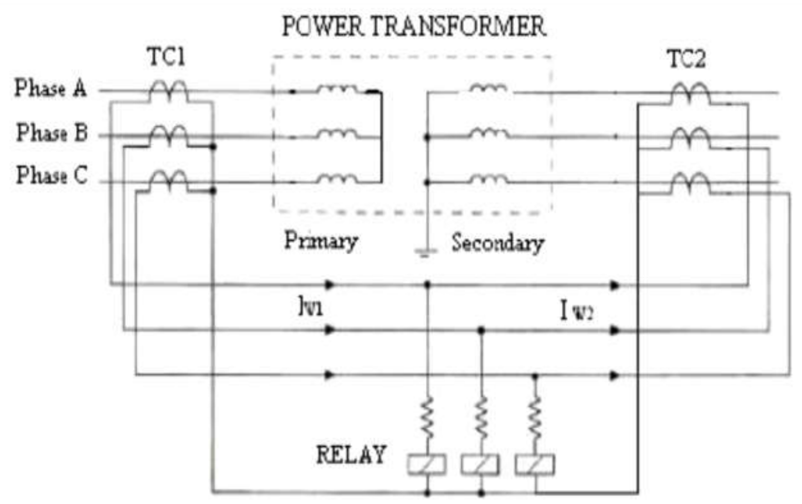


Figure 3.2 Typical differential power transformer protection relay

Figure 3.3 shows a diagram illustrating the principle of the differential relay protection. Current transformers with similar characteristics and ratio are connected on the both sides of the transformer and a relay is connected between the two current transformers by using pilot wires. Under healthy or external fault conditions, the current distribution as shown in figure 3.3 (a), no current flowing in the relay. When the internal fault occurs as shown in figure 3.3 (b), the conditions of balance are upset and current flows in the relay to cause operation. It can be noted also that the protected zone of this differential relay is between the two current transformers. If the fault had occurred beyond, as shown in figure 3.3 (a), than the operation will not occur as the fault current would then flow through both current transformers thus maintaining the balance. Differential relays perform well for external faults as long as the current transformers reproduce the primary currents correctly [19].

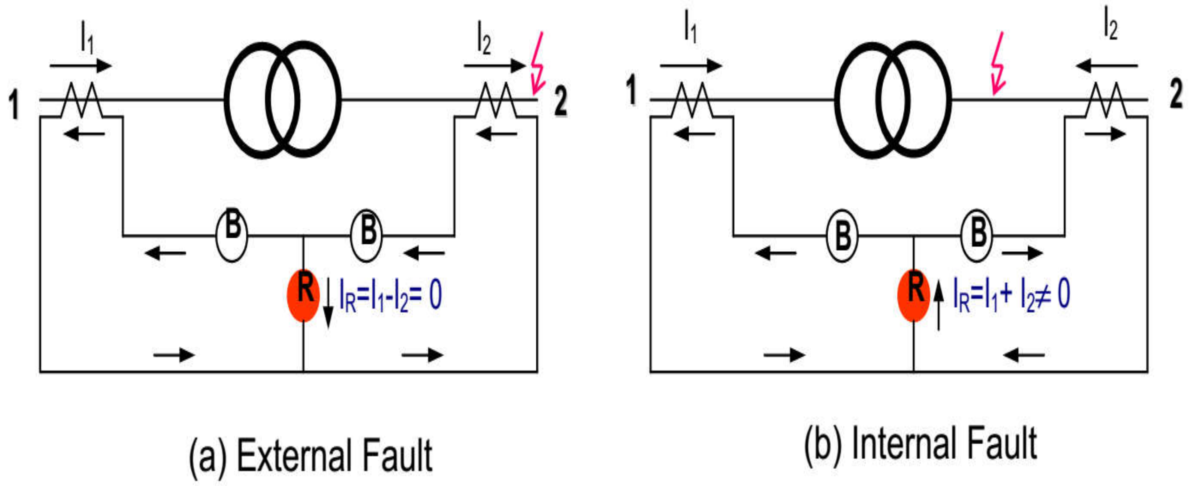


Figure 3.3 Principle of Differential Relay Protection.

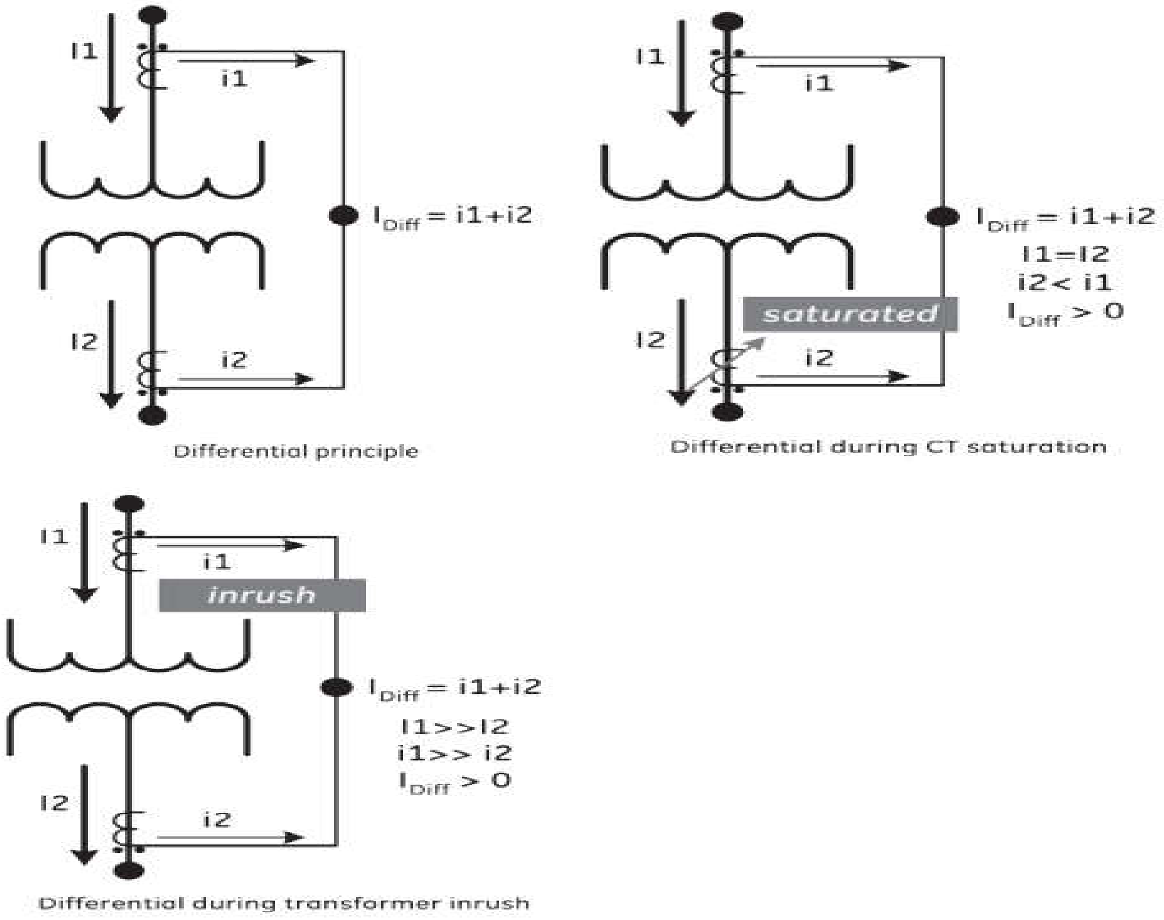


Figure 3.4 Transformer Differential Protection Principle

When one of the current transformers saturates, or if both current transformers saturate at different levels, false operating current appears in the differential relay and causes relay mal-operation. Some relays use the harmonics caused by the current transformer saturation for added restraint [19].

With the ideal transformer of figure 3.4, and assuming ideal CTs, the differential current is zero when current is flowing through the transformer. A differential current greater than zero indicates an internal fault condition. In practice, the differential current for a normally operating transformer is always greater than zero due to CT measurement error, the position of the load tap changer, and other factors introducing noise into the measurement signals. Therefore, the sensitivity of the protection is reduced slightly to account for these errors.

There are two common situations where differential protection may incorrectly declare an internal fault condition. One condition is CT saturation for a fault outside of the transformer zone of protection. The error in the measurement signal of the saturated CT results in a significant error in the differential current. The erroneous differential current may result in undesired operation of the differential element for an external fault condition.

- The second common situation is a transformer inrush event.
- Some operating situations instantly change the operating flux of the transformer core, requiring a large supply of current.

This inrush of current typically occurs in only one winding of the transformer. Therefore inrush currents may produce a differential current that results in the operation of the differential protection. This type of event is not a fault condition, so the differential protection should restrain from operating for this condition.

3.5.1 Modelling

Under normal conditions, the current I_p entering the protected unit would be equal to the current leaving it at every instant as shown in figure 3.5. Consider current transformer A. The secondary current of current transformer A is equal to,

$$I_{AS} = \alpha_A I_P - I_{Ae} \tag{3.1}$$

where, α_A : is the transformation ratio of current transformer A, and I_{Ae} : is the excitation current of current transformer A on the secondary side.

For current transformer B, the equation is similar and is as follows.

$$I_{BS} = \alpha_B I_P - I_{Be} \tag{3.2}$$

where, α_B : is the transformation ratio of current transformer B, and I_{Be} : is the excitation current of current transformer B on the secondary side.

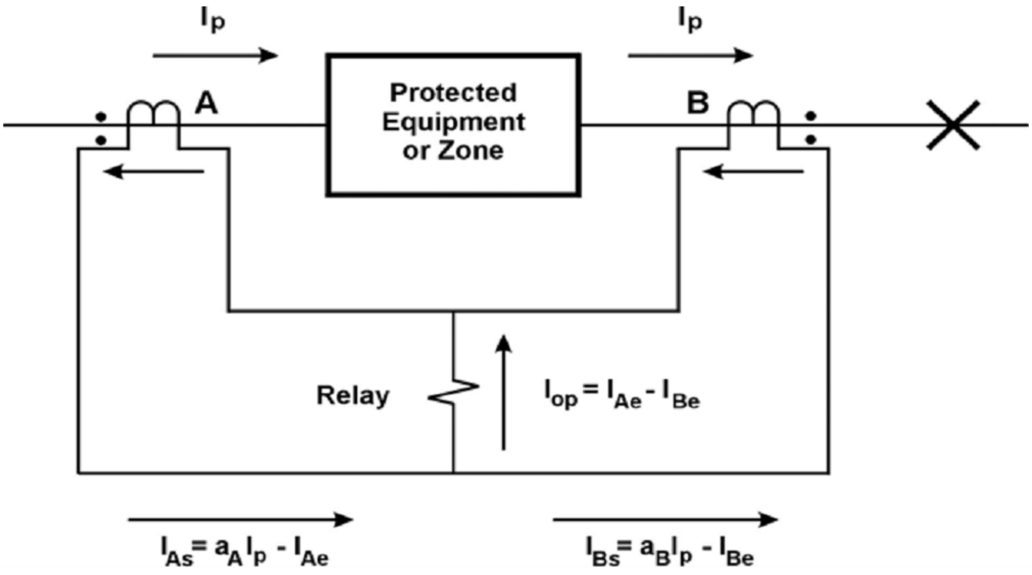


Figure 3.5 Differential relay currents during normal operation or external fault.

Assuming equal transformation ratios, $\alpha_A = \alpha_B = \alpha$, the relay operation current I_{op} is given by:

$$I_{op} = I_{Ae} - I_{Be} \tag{3.3}$$

During normal system operation and during external faults, the relay operating current I_{op} is small, but never zero ($I_{op} \neq 0$).

In the event of a fault in the protection zone, the input current is no longer equal to the output current. The operating current of the differential relay is now the sum of the input currents feeding the fault as shown in figure 3.6.

$$I_{op} = \alpha(I_{F1} + I_{F2}) - I_{Ae} - I_{Be} \qquad (3.4)$$

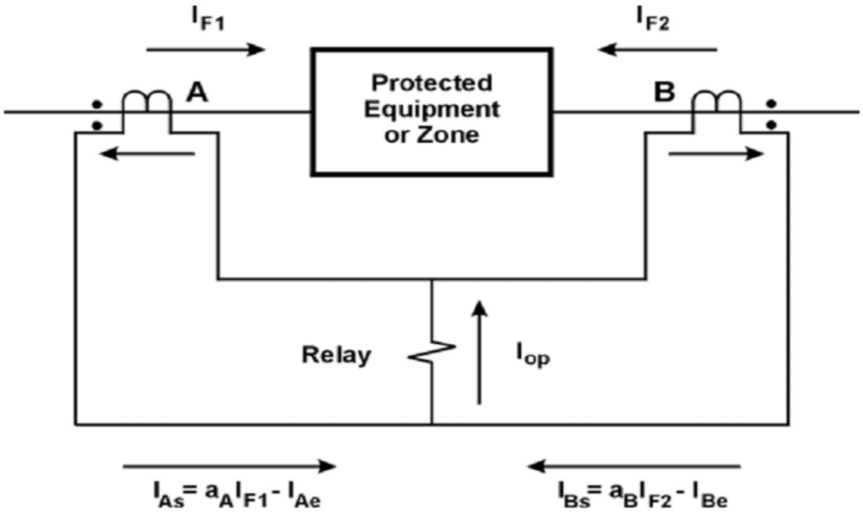


Figure 3.6 Differential relay currents during internal fault

Transformer differential relay are subject to several factors that can cause maloperation such as: different voltage level, including tap changer, which result in different currents in the connecting circuits, ratio mismatch between current transformers, mismatch that occur on the taps, phase-angle shift introduced by transformer wye (star)-delta connections, and magnetizing inrush currents, which differential relay sees as internal faults.

Those above factors can be accommodated by the design of current transformer and combination of relay with proper connection and applications. The connection of differential relay, current transformers, interposing current transformer, and auxiliary current transformers (ACT) is used to overcome the above factor for the older/electromechanical differential relay protection. For the newer/numerical differential relay, the information of the transformer and current transformer connection must be included correctly to the relay setting without any auxiliary connections.

In general, the current transformers on the wye side must be connected in delta and the current transformers on delta side connected in wye. These arrangements will compensate the phase angle shift introduced by wye delta bank and blocks the zero sequence current from the differential circuit on external ground faults. The zero sequence current will flow in the differential circuit for external ground fault on the grounded wye side; if the current transformer connected in wye, the relay would misoperate. With the current transformers connected in delta, the zero sequence current circulates inside the current transformers, preventing relay mal-operation.

3.5.2 Blocking methods during inrush conditions

The transformer energization resembles the condition of an internal fault. If no inhibiting mechanism (blocking function) is provided, the differential element will trip. The magnetizing inrush currents have high component of even and odd harmonics.

The most common methods included in modern relays are based either on the measurement of the harmonic content of the differential current or on a wave shape recognition of this current. Wave shape recognition techniques represent another alternative for discriminating internal faults from inrush conditions. However, these techniques fail to identify transformer over-excitation conditions.

This section will focus on the first method and its implementation by means of the so-called harmonic restraint / blocking. The methods based on the harmonic measurement of the waveform do not only use the second harmonic but also other harmonics. The magnetizing inrush current has significant second harmonic content. The level of second harmonic current can be used to differentiate between inrush and a fault condition. The fourth harmonic is also present in the inrush currents so it can also be used to restraint the operation. The third and fifth harmonics are normally used to detect an over-excitation condition of the power transformer. This situation occurs when the power transformer saturates with a symmetrical flux (the flux during an inrush condition was asymmetrical) because of an overvoltage or / and an under-frequency condition. The symmetrical flux originates a symmetrical magnetizing current that does not contain even harmonics but odd harmonics. The third harmonic is a good indicator for an over-excitation condition but, as it is a zero-sequence component (the three phase currents are equal), it is filtered by the delta windings or by the zero-sequence filters included in the differential relays so it will not be reliable in many transformer configurations. The fifth harmonic is normally used.

Traditional Second harmonic blocking: The traditional second harmonic restraint responds to the ratio of the magnitudes of the second harmonic and the fundamental frequency currents.

Adaptive Second harmonic blocking: The adaptive second harmonic blocking responds to both magnitudes and phase angles of the second harmonic and the fundamental frequency currents.

The differential element correctly distinguishes between faults and transformer energization, when the second harmonic current is less than the entered second harmonic setting. While levels of second harmonic during inrush often do not go below 20%, many transformers are susceptible of generating lower second harmonic current during energization. Setting the second harmonic restraint below 20% may result in incorrect inhibit of the differential element during some internal fault events. The adaptive second harmonic blocking allows settings in the traditional 20% range, while maintaining the security of the differential element against inrush.

Many modern transformer differential relays use either harmonic restraint or blocking methods. These methods ensure relay security for a very high percentage of inrush and overexcitation cases. However, these methods do not work in cases with very low harmonic content in the operating current. Common harmonic restraint or blocking, introduced by Einval and Linders [20], increases relay security for inrush, but could delay operation for internal faults combined with inrush in the nonfaulted phases. Transformer overexcitation may also cause differential relay misoperation. Einval and Linders proposed the use of an additional fifth-harmonic restraint to prevent such misoperations [20].

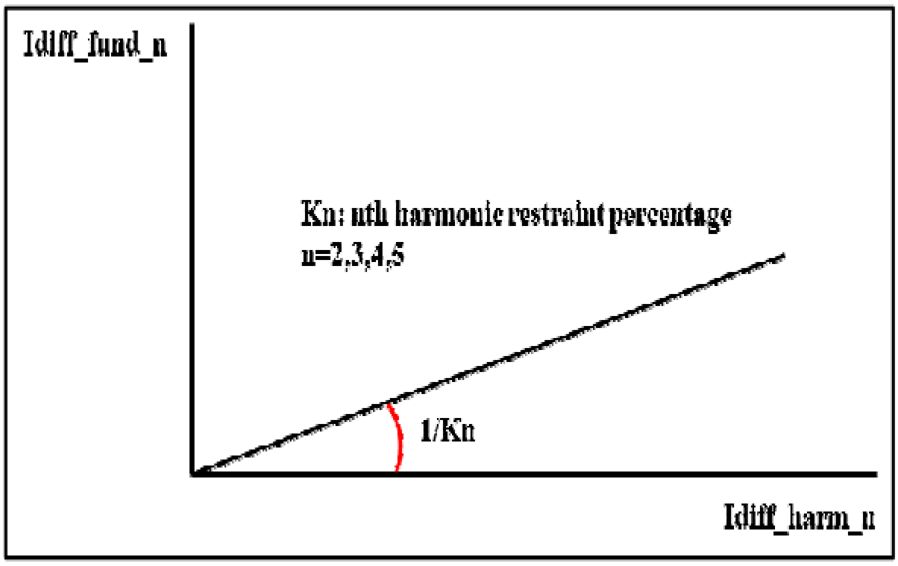


Figure 3.7 Characteristic for the extraction of the fundamental differential current based on the harmonic content.

3.5.2.1 Harmonic restraint

The harmonic restraint method uses the harmonic content of the differential current to increase the theoretical fundamental differential current required to trip (obtained from the restrained differential characteristic). The effect is a rise in the differential characteristic. Based on the nth (n = 2, 3, 4, 5) harmonic restraint percentage set (kn) and on the harmonic content of the differential current (Idiff_harm_n, n=2, …, 5) a fundamental differential current is obtained (Idiff_fund_n, n=2,…, 5) (see figure 3.7). Note that the slope of the characteristic will be the inverse of the setting, α=1/kn.

The four fundamental differential currents calculated (Idiff_harm_n, n=2,…, 5) are summed to obtain a total fundamental differential current (Idiff_fund_total). The latter current will be added to the operating fundamental differential current calculated from the through current restrained differential characteristic (see figure 3.8).

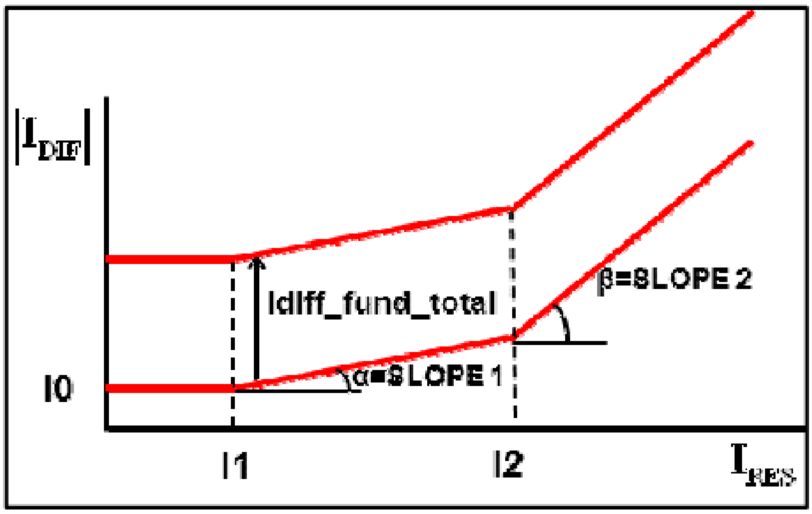


Figure 3.8 Rise in the current restrained differential characteristic due to the harmonic restraint.

The operating condition for the differential unit working with harmonic restraint will be:

$$I_{diff\_fund} > I_{\substack{diff\\ through\\ current\\ restraint}} + I_{\substack{diff\\ harmonic\\ restraint}} = I_{rest}.f(\alpha,\beta) + \sum_{2}^{5} \frac{I_{diff\,harm_n}}{K_n} \tag{3.6}$$

with n having values for the harmonics selected to restrain; α and β are the first and the second slopes of the differential characteristic.

3.5.2.2 Harmonic blocking

Harmonic blocking calculates the ratio between the harmonic content and the fundamental content of the differential current. When this ratio is above the threshold set the harmonic blocking operates:

$$\frac{I_{diff\_harm\_n}}{I_{diff\_fund}} > K_n \tag{3.7}$$

(n=2,…,5), with n having values for the harmonics selected to block.
The operating condition for the differential unit working with harmonic blocking will be:

$$\left\{ I_{diff\_fund} > I_{\substack{diff \\ through \\ current \\ restraint}} \cdot f(\alpha,\beta) \right\} \tag{3.8}$$

Reorganizing the terms:

$$\left(I_{diff\_fund} > I_{rest} \cdot f(\alpha,\beta)\right) \times \left(I_{diff\_fund} > \frac{I_{diff\_harm\_n}}{Kn}\right) \cdot \tag{3.9}$$

From equations (3.6) and (3.9) we can see that harmonic restraint is more secure than harmonic blocking.

3.5.2.3 Crossed harmonic blocking

As mentioned in the section 2.3 the inrush current can have low values of second harmonic, being as low as 7%.The settings normally used both for the second harmonic restraint and blocking were around 20%. Changing to a 7% will increase the security very much but, on the other hand, it will decrease the dependability. A setting around 15%-20% is normally used for both harmonic restraint and blocking and crossed logics are enabled in order to increase the security. These logics take advantage of the fact that the low harmonic content will normally occur only in one of the phases. The harmonic content of the other phases will be used to increase the restraint. Crossed logics are normally only applied in harmonic blocking but not in harmonic restraint.

3.5.2.3.1 Crossed logics for harmonic blocking

“1 out of 3”: if one phase has a high second harmonic content the blocking is activated in the other two phases, no matter their harmonic content. This logic is very secure but it can block the operation with internal faults occurring during the transformer energization as the healthy phases can have a high second harmonic percentage.

“2 out of 3”: if two phases have a high second 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 **“1 out of 3”** logic as it will not operate for internal phase faults that occur during the transformer energization. On the other hand, if the transformer is wye-delta and it is energized from the wye side, on a single phase to ground fault happening during the transformer energization, fault current will flow in the healthy phases due to the coupling with the delta winding. The same will happen in a three-legged wye-wye transformer due to the phantom tertiary effect. If the zero-sequence filter is applied from the phase currents on the wye winding there will be an increase of the fundamental current in the healthy phases making the **“2 out of 3”** logic more dependable. However, if the zero-sequence filter is applied from the ground current, the currents in the healthy phases will be pure inrush currents making the **“2 out of 3”** logic block the trip [21].

Average: the second harmonic ratio used for blocking the three phases is the average of the second harmonic ratio for each phase

$$average_{2nd_{harm_{ratio}}} = \frac{1}{3}\cdot\left(\frac{I_{diff_{harm_{2nd_A}}}}{I_{diff_{fund_A}}} + \frac{I_{diff_{harm_{2nd_B}}}}{I_{diff_{fund_B}}} + \frac{I_{diff_{2nd_C}}}{I_{diff_{fund_C}}}\right) \quad (3.10)$$

This logic provides a good security due to the increase of the average ratio provided by the phases with a high second harmonic content. However it does not provide a good dependability as for an internal fault the average ratio can still be high due to the high ratio of the healthy phase/s.

Sum: this logic calculates a three-phase second harmonic ratio with the following formula:

$$3phase_{2nd_{harm_{ratio}}} = \left(\frac{I_{dif_{harm_{2nd_A}}} + I_{diff_{harm_{2nd_B}}} + I_{diff_{harm_{2nd_C}}}}{I_{diff_{fund_A}} + I_{diff_{fund_B}} + I_{diff_{fund_C}}}\right) \quad (3.11)$$

This logic provides good security during energization because the phase/s with high second harmonic content increase the value of the ratio. On the other hand the logic will normally provide a good dependability as during internal faults the faulted phases have a high fundamental current that decreases the value of the ratio.

3.5.2.3.2 Time for the application of the crossed logics

As the low content of the harmonic current only lasts for 4-5 cycles (see point 1.2) the cross-blocking will only be necessary during this time.

3.5.2.4 Dynamic harmonic blocking / restraint

Harmonic blocking / restraint tends to operate not only when the power transformer saturates (for an inrush or an over-excitation condition) but also for faults with CT saturation due to the harmonic content of the waveform during such conditions. When the fault with CT saturation is external the operation of the harmonic blocking / restraint units will increase the security. However, if the fault is internal the activation of these units will reduce the dependability. DC CT saturation (with an asymmetrical current) is characterized by odd and even harmonics, while AC CT saturation (with a symmetrical current) is characterized by odd harmonics. Reference [22] recommends the use of second and fourth harmonic restraint and fifth harmonic blocking. The aim is not to add the odd harmonics restraint to increase the dependability during internal faults with CT saturation. A normal setting for the percentage of fifth harmonic blocking is 35% which is larger than the 15%-20% used for second harmonic blocking / restraint. This makes the fifth harmonic blocking less susceptible to operate during DC CT saturation than the second harmonic blocking / restraint. An unrestrained differential unit set above the maximum inrush current is normally used to increase the dependability. However, internal faults with CT saturation could happen for current values lower than the ones for the inrush currents.

An algorithm that inhibits the harmonic blocking /restraint is therefore necessary. References [25-27] describe an external fault detector based on three units that discriminate between external and internal faults:

Differential unit with instantaneous values: This unit is based on the ratio between the differential and restraint currents. It detects an external fault condition when a fault detector, based on a current change, activates and the mentioned ratio is below a threshold during a number of consecutive samples. More detailed information can be found in references [23] and [21].

Directional comparison units: Reference [24] describes a directional comparison unit that uses the angle between the currents measured at each end of the protected element (a transformer, in this case) in order to determine if the fault is internal or external. When this angle is lower than 90º the fault is considered internal; on the contrary, if the angle is higher than 90º the fault is considered external. The angular comparison requires that the currents are above a minimum threshold.

Two directional comparison units are described, one that operates with phase currents and another one that operates with positive-sequence pure fault current. The removal of the pre-fault current allows this unit compensates the load flow effect. The pre-fault current is taken two cycles before the activation a fault detector, based on current changes. The fault detector supervises the operation of the two directional comparison units.
The external fault detector will be used to inhibit the harmonic blocking / restraint.

3.5.2.4.1 Second and fourth harmonic restraint / blocking inhibit logic

Once the transformer has been energized a combination of the three mentioned units, the external fault detector will be used to inhibit the second and fourth harmonic restraint/blocking.
The inhibit logic for the second / fourth harmonic restraint / blocking will be enabled after a settable time since the detection of the energization of the transformer. When all the currents in the transformer are below a threshold and any of them changes above this threshold the energization is detected and a timer is started. Until this timer expires the second/fourth harmonic restrain / blocking is always enabled. When the timer expires the following logic will be applied:

If a fault detector activates, based on current changes, during a window time of three cycles, the second / fourth harmonic restraint / blocking will be inhibited if **“2 out of 3”** units comprising the external fault detector indicates an internal fault condition.
After the three cycles, the application of the even harmonic restraint / blocking will be latched during a settable time, no matter if the fault detector activates again.

The three cycle window allows accelerating the trip during an internal fault. If the fault is external any of the units will activate the external fault condition. In this case the application of the second / fourth harmonic restraint / blocking is latched at this moment, without waiting for the three cycles. The units comprising the external fault detector operate very fast indicating the internal fault condition in less than a cycle. When a transformer is already energized the only inrush condition can occur during an external fault clearing or during the energization of a parallel transformer (sympathetic inrush).

External fault clearing: When there is an external fault, during the three cycle window, the internal fault conditions will not be fulfilled. As an external fault condition will be activated, the second and fourth harmonic restraint / blocking will be applied and latched during the settable time. This latching assures that during the inrush condition generated by the clearing of the external fault the harmonic restraint / blocking will be enabled.

Sympathetic inrush: When a parallel transformer is energized there will be a change in the current in the already energized transformer that makes the fault detector activate. During these conditions and before the loaded transformer gets saturated any of the units comprising the external fault detector will activate the external fault condition. In this case the harmonic restraint / blocking will be latched during the settable time. If the current change due to the inrush of the parallel transformer is not enough to activate the fault detector, when the inrush in the loaded transformer starts, the current change in one of the windings (in the one not energizing the transformer) will also be very small, preventing the activation of the two directional comparison units, so the **"2 out of 3"** logic will never be fulfilled.

3.5.2.4.2 Third and fifth harmonic restraint / blocking inhibit logic

The inhibit logic for odd harmonic restraint / blocking will be based on an "underexcitation" unit that measures the ratio **V/f** and compares it against a rated ratio $\mathbf{V_{rated}/f_{rated}}$.

When $\mathbf{V/f < V_{rated}/f_{rated}}$ the underexcitation unit operates. There will be three underexcitation units, one per phase. If any of them activates the odd harmonic restraint / blocking will be inhibited.

Inrush current phenomena have been explained in detail for three different conditions: energization, external fault recovery and sympathetic inrush. Harmonic restraint is more secure than harmonic blocking however it does not normally allow the application of crossed logics, which are needed due to the low second harmonic content of modern transformers. For transformers with a delta winding energized from the wye winding/s the **"2 out of 3"** logic provides good balance between security and dependability. For other type of transformer connection group or in a wye-delta transformer if the energization is done from the delta side the harmonic three-phase "sum" logic is considered the best one. The logic that inhibits the harmonic restraint / blocking allows accelerating the trip for an internal fault that occurs once the transformer is energized. It is based on an external fault detector consisting of three units: differential unit with instantaneous values, the phase directional comparison unit and the positive-sequence directional unit. The original harmonic-restrained differential relay used all the harmonics to provide the restraint function [22], [25, 26]. The resulting high level of harmonic restraint provided security for inrush conditions at the expense of operating speed for internal faults with current transformer saturation. As a result, the harmonic-restrained differential relay compares the fundamental component of the operating current with a restraint signal consisting of the unfiltered restraint current plus the harmonics of the operating current.

The differential relay operation condition can be expressed as;

$$I_{op} \geq SLP_i \times I_{rt} + k_2 I_{2h} + k_3 I_{3h} + \cdots \tag{3.12}$$

where,

I_{op} : is the fundamental component of the operating current

I_{2h}, I_{3h} : are higher harmonics of the operating current

I_{rt} : is the unfiltered restraint current

k_1, k_2 : are the constant coefficients

A more recent set of techniques use only the second harmonic to identify currents and the fifth harmonic to avoid mal-operation for transformers due to over-excitation [21]. The basic operating equation for one phase can be expressed as follows:

$$I_{op} \geq SLP_i \times I_{rt} + k_2 I_{2h} + k_5 I_5 + \cdots \tag{3.13}$$

Common harmonic restraint for three-phase transformer differential protection is a technique where the harmonic restraint quantity is proportional to the sum of the second and the fifth-harmonic components of the three relay elements. The relay operation is of the following form:

$$I_{op} \geq SLP_i \times I_{rt} + \sum_{n=1}^{3} k_2 I_{2hn} + k_5 I_{5n} \qquad (3.14$$

3.6 Percentage restraint differential protection

Percentage restraint differential protective is more sensitive and secure than traditional differential [5], [6] have been in service for many years.
Figure 3.9 shows a typical differential relay connection diagram. Differential elements compare an operating current with a restraining current. The operating current (also called differential current), I_{OP}, can be obtained as the phasor sum of the currents entering the protected element:

$$I_{op} = \left|\vec{I}w_1 + \vec{I}w_2\right| \qquad (3.15)$$

where I_{w1}, I_{w2} are the currents on the pilot wires of the current transformers,

I_{OP} is proportional to the fault current for internal faults and approaches zero for any other operating (ideal) conditions [35].

Following are the most common ways to obtain the restraining current:

$$I_{RT} = k\left|\vec{I}w_1 - \vec{I}w_2\right| \qquad (3.16)$$

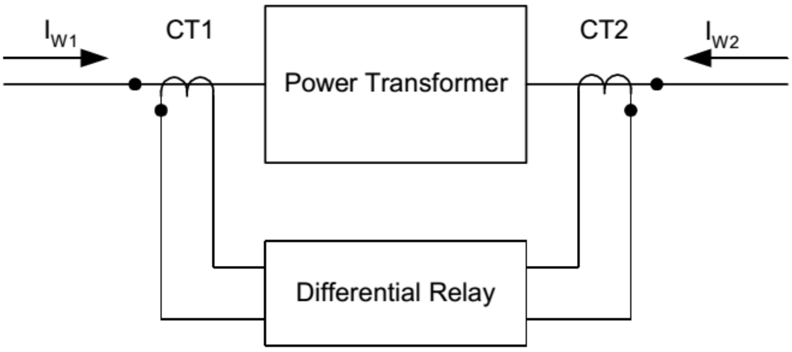


Figure 3.9 Typical Differential Relay Connection Diagram

$$I_{RT} = k(|I_{w1}| + |I_{w2}|) \tag{3.17}$$

$$I_{RT} = Max(|I_{w1}|, |I_{w2}|) \tag{3.18}$$

where k is a compensation factor, usually taken as 1 or 0.5

Equations 3.17 and 3.18 offer the advantage of being applicable to differential relays with more than two restraint elements. The differential relay generates a tripping signal if the operating current, I_{OP}, is greater than a percentage of the restraining current, I_{RT}.

$$I_{op} > SLP_i \times I_{rt} \tag{3.19}$$

where, SLPi is the slope of the ith characteristic of the differential relay.

Figure 3.10 shows a typical differential relay operating characteristic. This characteristic consists of a straight line having a slope equal to SLP and a horizontal straight line defining the relay minimum pickup current, I_{mpu}. The relay operating region is located above the slope characteristic (equation 3.19), and the restraining region is below the slope characteristic. Typical characteristic of differential relays present a small slope for low currents to allow sensitivity to light internal faults. At higher currents, the slope of the characteristic is much higher, which requires that the operating current, I_{op}, be higher in order to cause operation of the differential relay. The current in the differential relay will not exactly zero at the normal operating condition or when external fault occur. It is normal because the tap of the transformer, the current transformer (CT) error, mismatch, and the excitation current.

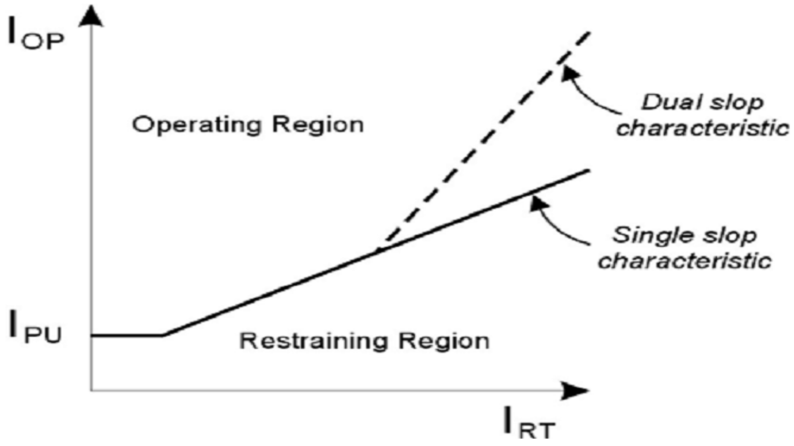


Figure 3.10: Typical characteristic of a percentage differential relay.

The minimum pickup restraint setting, $_{\text{Impu}}$ adjusts the sensitivity of the relay. In non-numerical relays, the Ip.u(min) was fixed at a typical value of 0.35 of the relay tap [32]. Selecting a lower Ip.u(min) setting needed an increase in the slope setting to maintain a given margin at the knee-point of the differential tripping characteristic. Conversely, it is sometimes necessary to accommodate unmonitored loads in the differential zone. In that case, the Ip.u(min) setting may be higher. A setting of 0.25 per unit of transformer full load rating is recommended for typical installations where no unmonitored load needs to be considered. This value is well above the magnetizing current and provides a safe margin at the knee point of the slope characteristic.

Typical differential relay operating characteristic is shown in figure 3.11. The characteristic consists of two slopes, S1 and S2 and a horizontal straight line defining the relay minimum pickup current, I_{Dmin}. The relay operating region is located above the slope characteristic and the restraining region is below the slope characteristic [21].

We can set the characteristic as either a single-slope, percentage differential characteristic or as a dual-slope, variable-percentage differential characteristic.

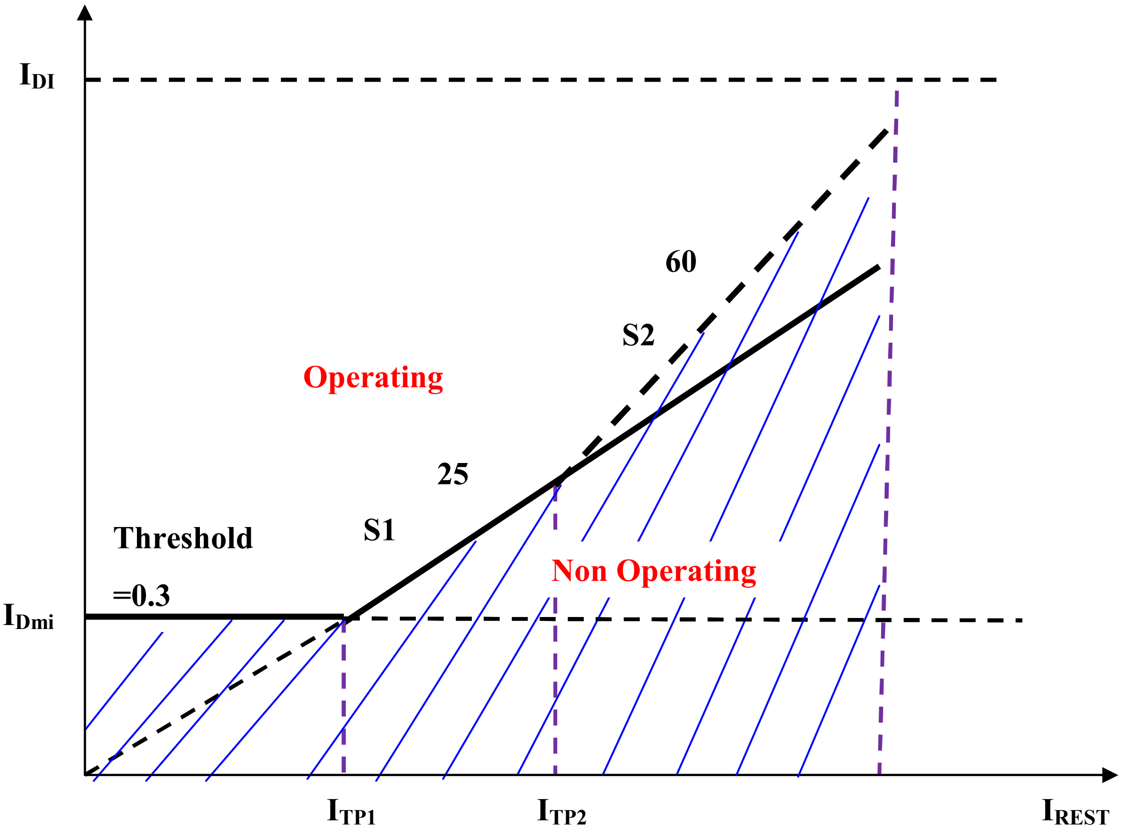


Figure 3.11 Differential relay with dual slope characteristics

Differential relays perform well for external faults, as long as the CTs reproduce the primary currents correctly. When one of the CTs saturates, or if both CTs saturate at different levels, false operating current appears in the differential relay and could cause relay mal-operation. Some differential relays use the harmonics caused by CT saturation for added restraint and to avoid mal-operations [33]. In addition, the slope characteristic of the percentage differential relay provides further security for external faults with CT saturation. A variable-percentage or dual slope characteristic originally proposed by Sharp and Glassburn [25], further increases relay security for heavy CT saturation. Figure 3.11 shows this characteristic as a dotted line. CT saturation is only one of the causes of false operating current in differential relays. In the case of power transformer applications other possible sources of error are:

- Mismatch between the CT ratios and the power transformer ratio,

- Variable ratio of the power transformer caused by a tap changer,
- Phase shift between the power transformer primary and secondary currents for delta-wye connections,
- Magnetizing inrush currents created by transformer transients because of energization, voltage recovery after the clearance of an external fault, or energization of a parallel transformer
- High exciting currents caused by transformer overexcitation.

The relay percentage restraint characteristic typically solves the first two problems. A proper connection of the CTs or emulation of such a connection in a digital relay (auxiliary CTs historically provided this function) addresses the phase shift problem. A very complex problem is that of discriminating internal fault currents from the false differential currents caused by magnetizing inrush and transformer overexcitation.

3.7 Others techniques:

Probably every utility has experienced a false operation of a differential relay when energizing a transformer bank. Over the years, many different methods of preventing differential relay operation on inrush have been implemented.

1. Power differential method: Another relaying principle uses the differential active power to discriminate between internal faults and other conditions. This method is based on the idea that the average power drawn by a power transformer is almost zero on inrush, while during a fault the average power is significantly higher [28].

Instead of the differential currents, the differential power is computed and monitored. The operating signal is a difference between the instantaneous powers at all the transformer's terminals. This approach calls for measuring the voltages at all the terminals, but pays back by enabling avoiding the vector group (angular displacement between the current and voltages at different windings) and ratio compensation. The dependability of this method may be further enhanced by compensating for the internal active power losses — both in copper, and in iron. In addition, having the active power available, the method enables one to compute the energy released in the tank and to emulate the back-up protection — both the accumulated and sudden pressure gas relays.

2. Rectifier relay: This method is based on the fact that magnetizing inrush current is in effect a half-frequency wave. Relays based on this method use rectifiers and have one element functioning on positive current and one on negative current. Both elements must operate in order to produce a trip. On inrush, the expectation is that one element only will operate, while on an internal fault, the waveform will be sinusoidal and both elements will operate [29].

3. Waveform recognition: is the method of measuring “dwell-time” of the current waveform, that is, how long it stays close to zero, indicating a full dc-offset, which it uses to declare an inrush condition. Such relays typically expect the dwell time to be at least ¼ of a cycle, and will restrain tripping if this is measured.

4. Flux-current: A new simple and efficient technique for inrush current reduction based on the calculated flux in the core. As its advantage, this approach tides together the cause of the problem (saturation of the core as a source of the current unbalance) with the phenomenon used for recognition (flux in the core). Flux reduction can be achieved by applying a voltage to the core with the help of a tertiary winding [30].

5. Cross blocking: It is not a **“method”** of detecting inrush but a choice made to block all tripping if any relay detects inrush. Any of the relays that use single-phase inrush detection methods can utilize cross blocking.

6. Harmonic current restraint: This is the most common method and widely used for the detection of inrush current in power transformer.

Different schemes currently used to distinguish between magnetizing Inrush and fault current are based on:

Second harmonics restraint principle, Voltage restraint principle, Restraint principle based on currents and voltages of the transformer. But the second harmonic component is widely used for the detection of inrush current in power transformer and is discussed in more detail below.

Simple Second harmonic restraint: This method has been in use for many years and simply looks for a percentage level of second harmonic content (or THD in some relays) in the differential current. If the second harmonic content present in the waveform is above a set threshold (typical thresholds are between 15 and 35% of fundamental) the relay is restrained. This is simply a per-phase calculation of second harmonic current (in Amps) divided by fundamental current (in Amps).

For example, if the waveform has 4A of second harmonic and 10A of fundamental it has a second harmonic level of 40%.

Shared Second harmonic restraint: It is the same method as described above with the exception that the numerator is the sum of the second harmonic current (in Amps) all three differential currents. For example, if the sum of second harmonic current from all three differential currents is 9A and the particular phase of interest (this calculation is performed for each phase) has 10A of fundamental its restraining quantity is 90%. This method attempts to avoid mal-operating on the lack of second harmonic content in one phase that commonly occurs on bank energization.

However, some problems for identifying inrush using the second harmonics component result in:

- The magnitude of the second harmonic in fault current can be close to or greater than that present in the magnetizing inrush current.
- The second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers
- Consequently, differential protection technique based on the second harmonic restraint may fail.

One study reported the minimum possible level of second harmonic content in magnetizing inrush current was about 17% [2]. That being the case, it would appear that a 15% threshold would be a good choice. However, newer transformer designs are producing transformers that can have inrush current with second harmonic levels as low as 7% [18].

In that case, other methods will need to be considered to provide secure, dependable transformer differential protection and be able to distinguish between fault and inrush.

Some of these methods easy to implement and do not rely on the presence of harmonic components to identify inrush are:

1. Rectifier relay

2. Waveform recognition or Dwell-time

3. Power differential method

The developments in digital technology led to the incorporation of microprocessors in the construction of relays. Digital and numerical relays offer an economical and feasible alternative to investigate the performance of relays and protection systems with the capacity to record signals during faults, monitor themselves and communicate with their peers.

3.8 Differential scheme reliability

A relaying system reliable can be achieved by redundancy i.e. duplicating the relaying system. Obviously redundancy can be a costly proposal. However, it is important to realize that back-up protection for safe operation of relaying system. Redundancy in protection also depends upon the criticality of the power apparatus.

A quantitative measure for reliability is defined as follows:

$$R = \frac{N_C}{N_d + N_u} \tag{3.20}$$

Where, N_c : Number of corrected trips, N_d: Number of desired trips, N_u : Number of uncorrected trips (false trip).

Protection system reliability is characterized by the following two important terms:

- Dependability
- Security

3.8.2 Dependability (percentage, threshold, types of connections)

A relay is said to be dependable if it trips only when it is expected to trip. This happens either when the fault is in its primary control (primary protection) or when it is called upon to ensure the back-up protection. However, false tripping of relay due to faults that are either not within its jurisdiction or within its purview may lead to power system instability. Power system may get unnecessarily stressed or else there can be loss of service. Dependability (D) is the degree of certainty that the relay will operate correctly:

$$D = \frac{N_c}{N_d} \tag{3.21}$$

For simplicity, consider the case of overcurrent protection. The protective system must have ability to detect the smallest possible fault current. The smaller the current that it can detect, the more sensitive it is. One way to improve sensitivity is to determine characteristic signature of a fault. It is unique to the fault type and it does not occur in the normal operation. For example, earth faults involve zero sequence current. This provides a very sensitive method to detect earth faults. Once, this signature is seen, abnormality is rightly classified and hence appropriate action is initialized.

CT saturation could have a negative impact on the ability of the transformer protection to operate for internal faults (dependability) and not to operate for external faults (security). 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. With a saturated CT, second and third harmonics predominate initially, but the even harmonics gradually disappear with the decay of the DC component of the fault current. The relay may then operate eventually when the restraining harmonic component is reduced. These relays usually include an instantaneous overcurrent element that is not restrained by harmonics, but is set very high (typically 20 times transformer rating). This element may operate on severe internal faults.

For external faults, security of the differentially connected transformer protection may be jeopardized if the current transformers' unequal saturation is severe enough to produce error current above the relay setting. Relays equipped with restraint windings in each current transformer circuit would be more secure. The security problem is particularly critical when the current transformers are connected to bus breakers rather than the transformer itself. External faults in this case could be of very high magnitude as they are not limited by the transformer impedance

3.8.3 Security (harmonics restraint: inrush, over-excitation)

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 during a given time interval according to the IEEE/PSRC Working Group [6].

$$S = \frac{N_c}{N_t} \qquad (3.22)$$

Where S: security, and Nt =Nc+Nu : total number of trips.

False trips do not just create trouble. They can even compromise system security. For example, tripping of a tie-line in a two area system can result in load-generation imbalance in each area which can be dangerous. Even when multiple paths for power flow are available, under peak load conditions, overloads or congestion in the system may result. Dependability and security are contrasting requirements. Typically, a relay engineer biases his setting towards dependability. This may cause some nuisance tripping, which can in the worst case, trigger partial or complete blackout! Security of the relaying system can be improved by improving selectivity of the relaying system. Like sensitivity, selectivity also implies an ability to discriminate. A relay should not confuse some peculiarities of an apparatus with a fault. For example, transformer when energized can draw up to 20 times rated current (inrush current) which can confuse, both overcurrent and transformer differential protection. Typically, inrush currents are characterized by large second harmonic content. Even-numbered harmonics (second and fourth) provide security during energization, while fifth-harmonic blocking provides security for overexcitation conditions.

This discriminant is used to inhibit relay operation during inrush, thereby, improving selectivity in transformer protection. Also, a relay should be smart enough, not just to identify a fault but also be able to decide whether fault is in its jurisdiction or not. In a differential protection, the CT location provides 'crisp' demarcation of zone of protection of CT as shown in figure 3.12. The fault F1 is in the relay's zone of protection, but fault F2 is not in its jurisdiction. Because differential protection scheme do not require time discrimination to improve selectivity, they are essentially fast.

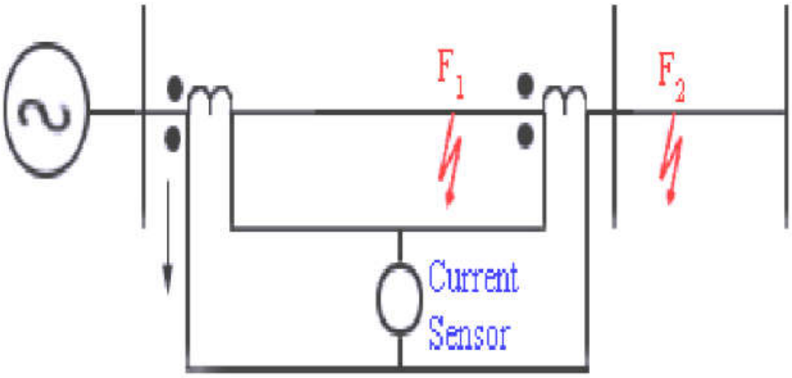


Figure 3.12 Differential protection scheme

Table 3.3 reviews the basic problems of transformer differential relaying from the perspective of magnetizing inrush, stationary overexcitation of a core, internal and external faults, all in the context of measurements, security, dependability and speed of operation [38-40].

Table 3.3: Problems related to protective relaying of power transformers

Disturbance	**Measurement**	**Security**	**Dependability**	**Speed**
Inrush	Accurate estimation of the 2nd and the 5th harmonics takes around one cycle. Off-nominal frequencies create extra measuring errors in harmonic ratio estimation harmonic during overexcitation may be very low jeopardizing relay security	In modern power transformer, due to the magnetic properties of the core, the 2nd harmonic during inrush and the 5th.	The presence of higher harmonics does not necessarily indicate inrush. The harmonics may block a relay during severe internal faults due to saturation of the CTs	It usually takes one full cycle to reject the magnetizing inrush and stationary overexcitation hypotheses if an internal fault is not severe enough to be tripped by the unrestrained differential element.
Overexcitation			The 5th harmonic may be present in internal fault currents due to saturation of the CTs, and due to rotor asymmetry of generators and/or power electronic devices.	
External faults	The measured currents display enormous rate of change and are often significantly distorted.	External fault current when combined with ratio mismatch may generate a false differential signal. The CTs, when saturated during external faults, may produce an extra differential signal.	All the means of preventing false tripping during external faults reduce to a certain extent the dependability of the relay.	The means of restraining the relay from tripping during external faults may limit the relay speed of operation.
Internal faults		The internal fault current may be as low as few percent of the rated value. Attempts to cover such faults jeopardize relay security.	The internal fault current may be as low as a few percent of the rated value. The security demands under inrush, overexcitation and external faults may limit relay dependability.	The means of restraining the relay from tripping during inrush, overexcitation and external faults may limit the relay speed of operation.

Chapter 4

Digital Differential Protective Relay of Power Transformer

In this chapter, an improvement of digital differential relay reliability for protecting a large power transformer is discussed. First, the Fourier sine and cosine coefficients required for fundamental, second, third and fifth harmonics determination have been calculated using rectangular transfer technique. Then, these harmonics have been used in harmonics restrain and blocking techniques used in differential protection system. Simulation testes have been carried out on a variety of magnetizing conditions (normal apperiodic inrush and over excitation conditions) using Simulink/MATLAB. The obtained results shows that the implemented digital differential relay provides good discrimination between the magnetizing current and the internal fault current.

4.1 Introduction

A power transformer is mostly protected against internal fault using a differential protection which is sensitive and a fast clearing technique. This technique of protection detects nonzero differential current, and then activates a circuit breaker that disconnects the transformer. However, this nonzero differential current may be produced by transformer magnetization, due to so called inrush current or over-excitation, and may cause the protective system to operate unnecessarily. This magnetization current is a transient current that appears only when a transformer is first energized or after clearing external fault. Even though, it can be as great as 8 times the full load current, however, it is harmless and it contains harmonic components. During periodic inrush condition due to over-excitation the third and fifth harmonic components are largely seen; however, during the normal apperiodic inrush conditions, the second harmonic is relatively high.

The transformer differential protection scheme has to be improved so that it can distinguish between nonzero differential current produced by magnetization current and that produced by internal fault. Several methods have been proposed to blind the differential protection system to magnetization current where the harmonic components have been used as means of detection [41-44]. However, the digital computer based protection offers a number of advantages over the conventional ones. So, the security and reliability have been improved; it remains only to develop an efficient algorithm requiring less time consuming calculations.

The alternative approaches to the digital protection of power transformer have been proposed to date; one using a digital filtering approach [38, 39] and the other [40] using sine and cosine wave correlations to yield the fundamental and higher harmonic components required for protection. This paper presents a new approach in which the sine and cosine Fourier coefficients are expressed in terms of rectangular transfer coefficients that are obtained from the data samples by only additions and subtractions. This method leads to a more accurate expression for the fundamental and harmonic components compared with those obtained from digital filter techniques. Furthermore, it offers faster computational speed compared with sine and cosine correlation. Besides, these harmonic components have been used in restrain and blocking techniques.

4.2 Magnetization current algorithm

In a large power transformer, any switching actions can produce a large current peak due to the saturation of the transformer iron core. Owing to this core saturation, the inrush current contains, in addition to the harmonic components, a decaying dc current. Therefore, the inrush current can be modeled as follows [41]:

$$i(t)=I_o \exp(-\lambda t)+\sum_{k=1}^{n} I_k \sin(k\omega_1 t+\theta_k) \tag{4.1}$$

where k determines the order of harmonic, and ω_1 is the frequency of the fundamental component. The decaying dc current can be represented by a Taylor expansion of two terms:

$$I_o \exp(-\lambda t) \approx I_o - I_o \lambda t \tag{4.2}$$

If it is assumed that the inrush current does not contain more than five harmonics, equation (4.1) becomes,

$$i(t)=I_o - I_o \lambda t+ \sum_{k=1}^{5} I_k \cos\theta_k \sin(k\omega t) \tag{4.3}$$

Let X(t) denotes a stationary random process with a zero mean and suppose that one record X(t), of length T, is available. It shall be assumed that the record is sampled at equispaced intervals Δt of time tj, so that there are $n=\frac{T}{\Delta T}$ samples (in this case n=12). From the samples, Fourier sine and cosine coefficients X(tj) can be defined by usual relations given by:

$$S_k=\sum_{j=0}^{n-1} X(t_j)\sin(\omega_k j\Delta t) \tag{4.4}$$

$$C_k=\sum_{j=0}^{n-1} X(t_j)\cos(\omega_k j\Delta t) \tag{4.5}$$

where $\omega_k=\frac{2\pi k}{T}$.

If the sine and cosine terms of equations (4.5) and (4.4) are replaced by their equivalent rectangular functions, then the corresponding rectangular transform term will be denoted by:

$$S_k^{'}=\sum_{j=0}^{n-1} X(t_j)\operatorname{sgn}[\sin(\omega_k j\Delta t)] \tag{4.6}$$

$$C_k^{'}=\sum_{j=0}^{n-1} X(t_j)\,\mathrm{sgn}[\cos(\omega_k j\Delta t)] \qquad (4.7)$$

Considering that X(tj) are the last 12 differential currents with sampling frequency of 600 Hz [46]. Thus, the Fourier coefficients can be obtained from the rectangular coefficients as,

$$S_k=A^{-1}S_k^{'} \qquad (4.8)$$

$$C_k=B^{-1}C_k^{'} \qquad (4.9)$$

where A and B are sparse matrices, more details about this theory are given in [47]. So assuming no aliasing, the Fourier coefficients can be expressed as follows:

$$S_1=S_1^{'}-\left(\frac{1}{3}\right)S_3^{'}-\left(\frac{1}{5}\right)S_5^{'} \qquad (4.10)$$

$$C_1=C_1^{'}-\left(\frac{1}{3}\right)C_3^{'}-\left(\frac{1}{5}\right)C_5^{'} \qquad (4.11)$$

$S_2 = S'_2$, $S_5 = S'_5$, and $C_5=C'_5$

In order to improve the processing speed, the quantities 1/3 and 1/5 may be generated by arithmetic shifts rather than hardware divisions. The modified formulations of the above quantities are implemented under the following form [43]:

$$S_1=S_1^{'}-\left(\frac{1}{2}-\frac{1}{16}\right)S_3^{'}-\left(\frac{1}{4}-\frac{1}{32}\right)S_5^{'} \qquad (4.12)$$

$$C_1=C_1^{'}-\left(\frac{1}{2}-\frac{1}{16}\right)C_3^{'}-\left(\frac{1}{5}\right)C_5^{'}$$

$$S_2=\left(1+\frac{1}{16}\right)S_2^{'}$$

$$C_2=\left(1-\frac{1}{16}\right)C_2^{'}$$

$$S_5 = \left(1 + \frac{1}{16}\right) S_3^{'}$$

$$C_5 = \left(1 - \frac{1}{16}\right) C_5^{'}$$

The harmonic components are found to be:

$$I_1 = \frac{2}{12}\left[S_1^2 + C_1^2\right]^2 \qquad (4.13a)$$

$$I_2 = \frac{2}{12}\left[S_2^2 + C_2^2\right]^2 \qquad (4.13b)$$

$$I_5 = \frac{2}{12}\left[S_5^2 + C_5^2\right]^2 \qquad (4.13c)$$

After extraction of the fundamental, the second and the fifth harmonic components, these harmonic components will be used to produce restraining signal that may be used to block the relay. Otherwise, for internal fault case, the relay operates.

4.3 Digital Differential Protection System Implementation

The above discussed approach has been implemented using Matlab/Simulink with the necessary tool box. The Matlab/Simulink which is powerful software program has been used for implementation as well as for testing and simulation.

4.3.1 Software Structure

Differential protection algorithm, which has been implemented using Simulink/ Matlab, its flow chart is shown in figure 4.1. Besides, Graphical User Interface (GUI) has been developed using the same software tool, the user can select and set his wanted parameters, and makes a test by running simulation and displaying the tripping signal (see figure 4.2).

4.3.2 Hardware Architecture

In protection field, current transformers are used to sense the current and provide the measured quantity as voltage signal to the input of relay. Circuit breaker is used as actuator.

The differential protection hardware whose block diagram shown in figure 4.2 consists of:

- **Signal transformation:** current transformer (CT) transform currents of the power system to low safe values.

- **Data acquisition boards:** the measured values of the power system parameters fed from CTs in analog forms are passed through an anti-aliasing filter amplifier (low pass filter). Sample and hold circuits and analog multiplexed are used to sample the three different signals supplied by instrument transformers at the same time. The sampled signals are converted into digital form.

- **PC:** the digital signals are fed from data acquisition board to the PC where they will be processed.

The developed differential protection has been implemented in PC associated with acquisition card AD 622 using Real time tool box with Simulink as shown in figure 4.3 [6 - 7].

4.3.3 Differential Relay Settings

Low impedance differential protection systems typically have 3 to 5 settings required to properly define the restraint characteristic of the relay (see figure 4.4). The ensuing discussion will mainly focus on differential protection for power transformers.

Where, I_{Dmin} = minimum differential current (secondary) required to operate the relay.

I_{TP1} = turning point 1.

I_{TP2} = turning point 2.

S_1 = Slope 1 setting.

S_2 = Slope 2 setting.

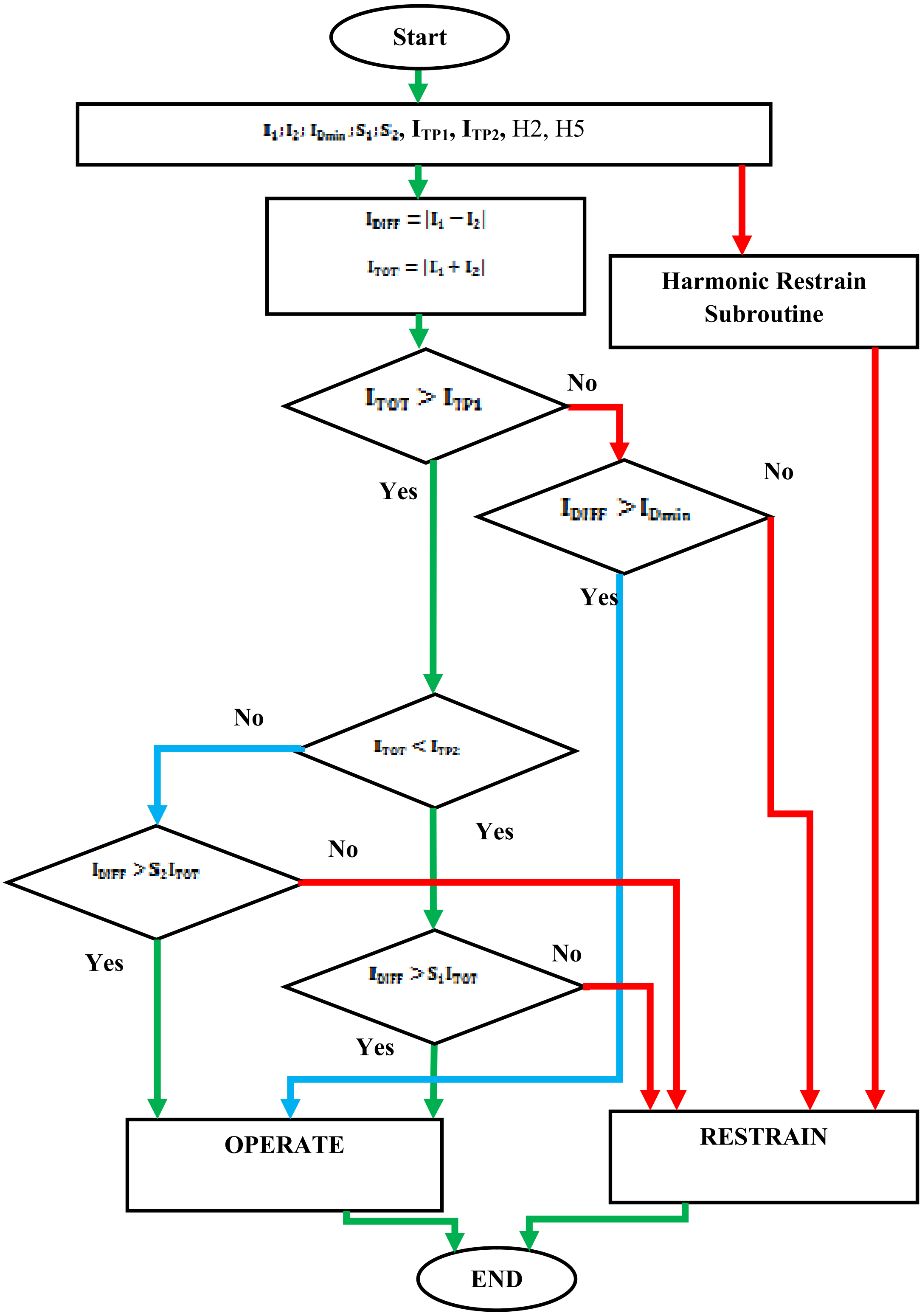


Figure 4.1 Differential protection Algorithm flowchart

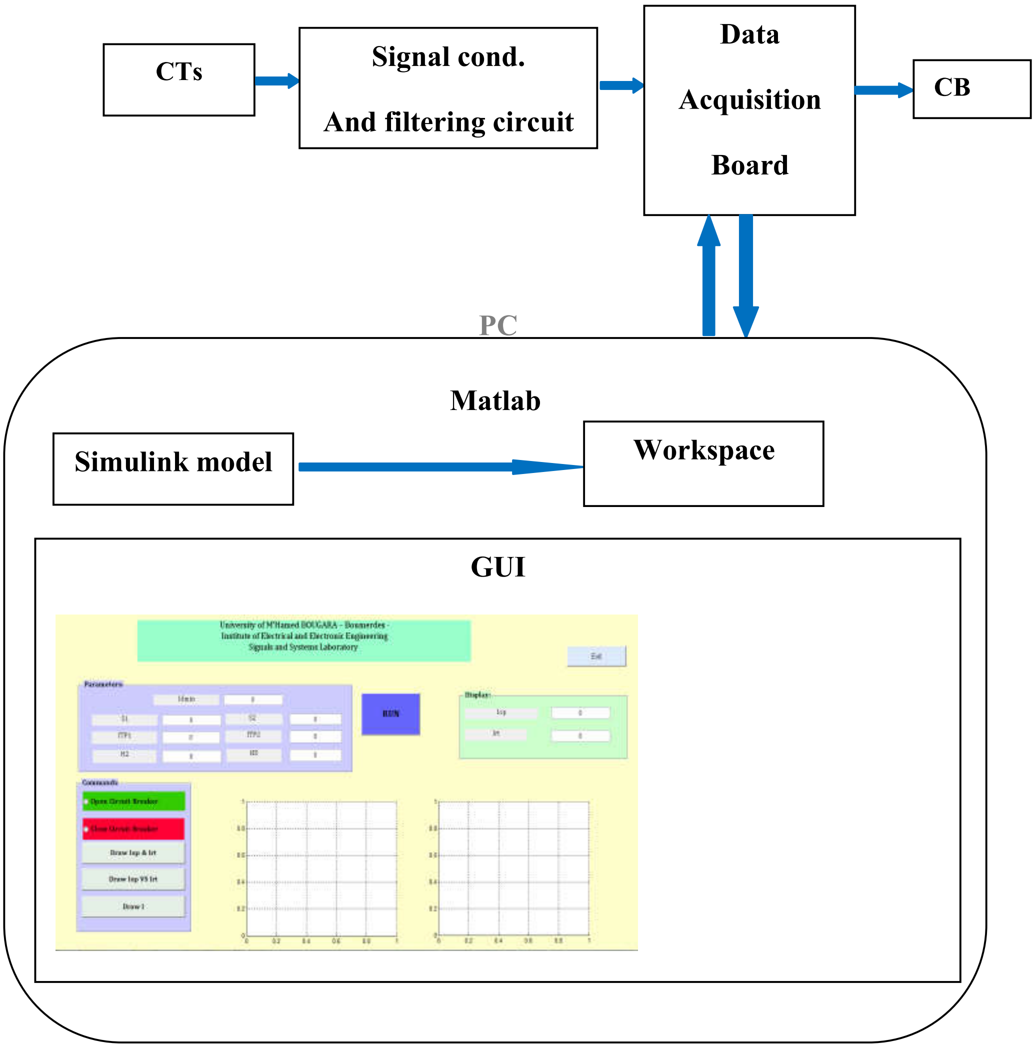


Figure 4.2 General block diagram of PC Based Differential relay

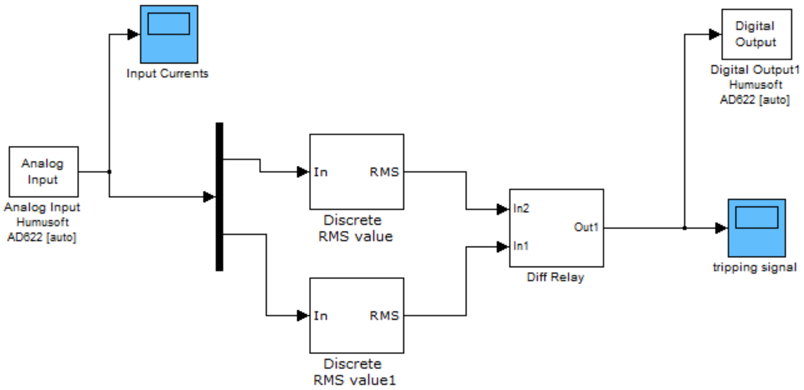


Figure 4.3 Differential relay Real time Simulink Model.

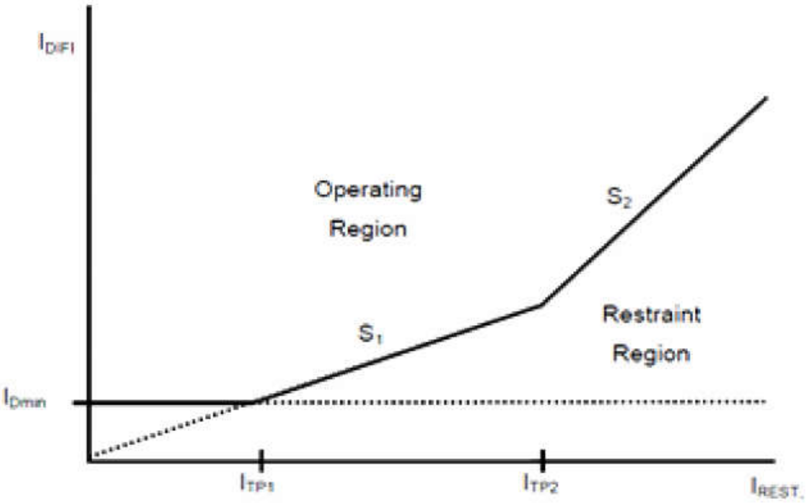


Figure 4.4 Typical restraint and operating characteristic of a differential relay.

I_{RST} = Total current through the differential system, measure of system loading.

I_{DIF} = For a given value of I_{TOT}, this is the restraint current applied by the relay or alternatively the minimum differential current required to operate the relay.

The settings to be considered are I_{Dmin}, I_{TP1}, I_{TP2}, S_1, and S_2. Besides, second harmonic (H2) and fifth harmonic (H5) may be used when harmonic restrain technique. These are generic representations of the settings. They will differ from one manufacturer to the other.

Where there are two straight lines given with a slope of $S_1 = 0.25$ and a slope of $S_2 = 0.6$, which range from I_{rt0} to I_{rt1} and from I_{rt1} to I_{rt2}, respectively, and a horizontal straight line defining the relay minimum pickup current, $I_{Dmin} = 0.3A$. The relay operating region is located above the slope, and the restraining region is below the slope.

The dual-slope percentage pattern adds a restraint area and avoids mal-operation caused by saturation. In comparison with a single-slope percentage scheme, the dual-slope percentage current differential protection can be regarded as a better curve fitting of transformer operational principles [33, 44].

4.4 Simulation

4.4.1 System Description

The whole system Simulink model as illustrated in figure 4.5 consists of a three-phase transformer rated 225kVA, 2400V/600V, 60Hz, connected to a 1MVA, 2400V power network. A 112.5 kW resistive load (50 % of transformer) nominal power) is connected on the 600V side. Each phase of the transformer consists of two windings both connected in wye with a grounded neutral. In a system relaying block, the currents that have been measured on buses B1 and B2 pass through a second order Butterworth low pass filter with a cut off frequency of 600 Hz, which offers a maximum flat response in the pass band and a quite good attenuation slope. After that, the differential and restrain currents using blocks included in Simulink library and our algorithm have been calculated. The generated signals are used in the relay operational principles [45].

The system under study is composed of a three-phase voltage source in series with RL branch feeding a load through a three-phase power transformer; the transformer is protected by a protection differential system. One circuit breaker is connected to the primary side of the transformer and takes its signal from the proposed differential relay so that it may trip the circuit in faulty condition. The inputs to the proposed relay are the difference between the current taken from the primary side of the transformer and the current taken from the secondary side. A simple technique is used, and the system is used to check the validity of the proposed algorithm and it is assumed to be composed of:

- Three phase 25 kV voltage source in series with RL branch.

- Three phase circuit breaker on the primary side of the transformer.

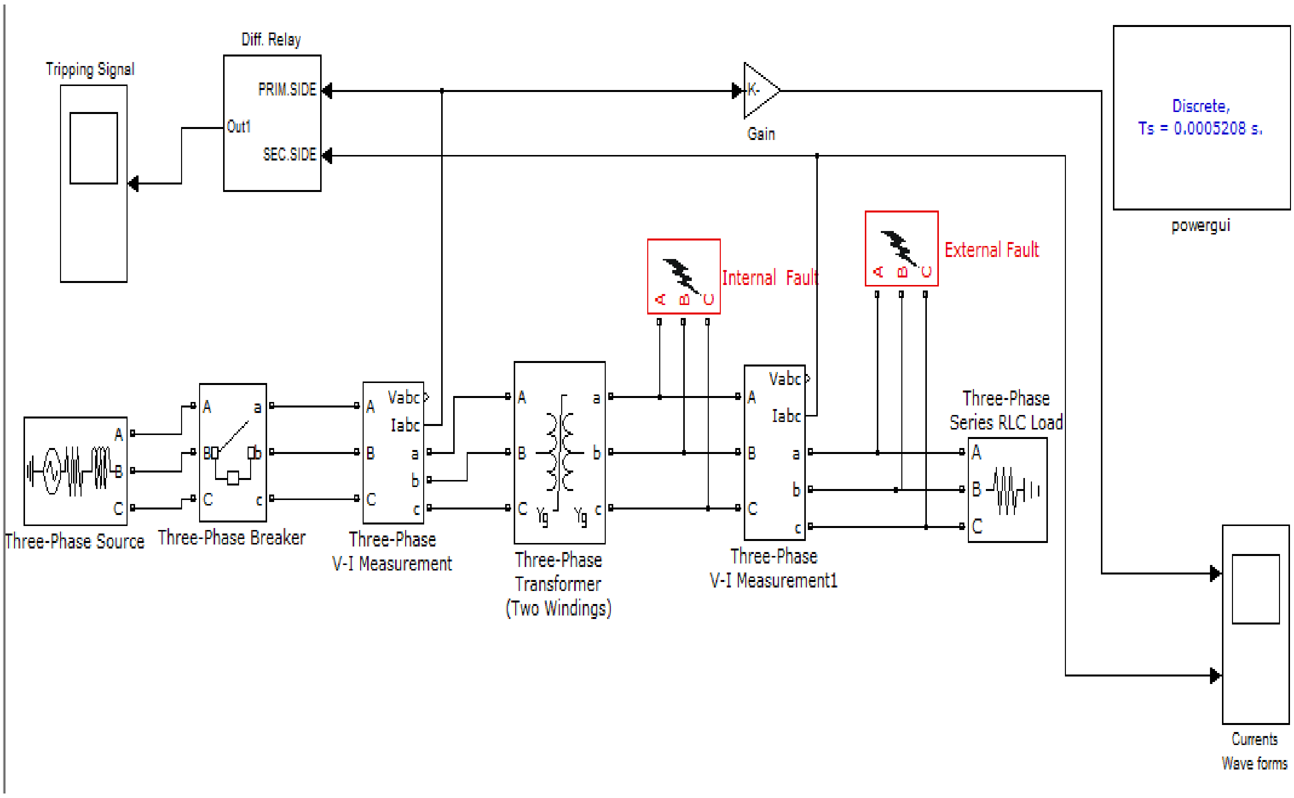


Figure 4.5 Simulink model of the three phase transformer with its protection.

- Three phase star / star 250 MVA, 25000/250 V transformer with saturable core and initial fluxes.

- Two three phase faults.

- Three phase series RLC load of 100 KW

Figure 4.5 shows the presentation for the system configuration used for testing the developed differential relay where table 4.1 presents the main parameters for the simulated power transformer.

Table 4.1 Simulated transformer main parameters.

Transformer connection	Y/Y
Rated power	250 MVA
Voltage ratio	25000/250 V
Rated frequency	60 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	500.02 pu

4.4.2 Test Results and Discussion

The above system was tested in MATLAB using the Simpower system toolbox of SIMULINK.

In the beginning, when the transformer is connected at time 1 s, it can be noticed that the magnetizing current appears only in the primary side shown in figures 4.6 and 4.7 which produces a great difference in current. But since this differential relay contains blinder for avoiding the unnecessary tripping it will not operate as shown in figure 4.8.

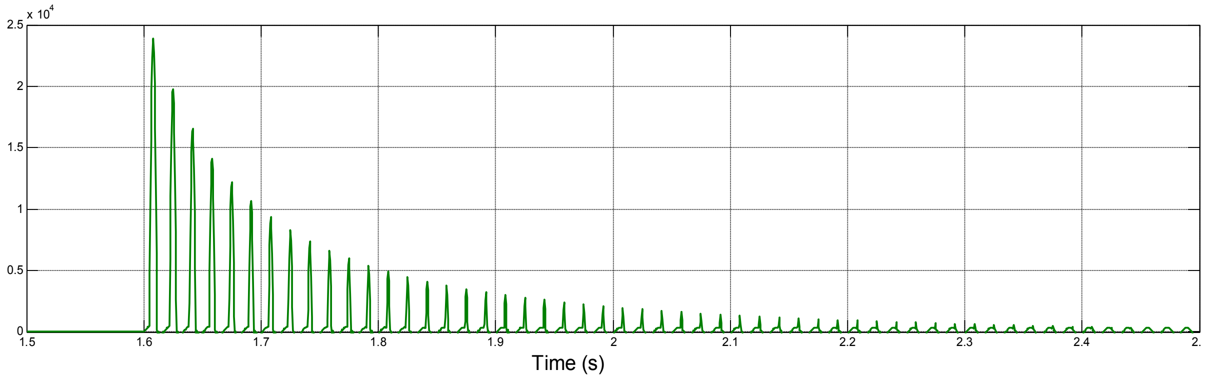
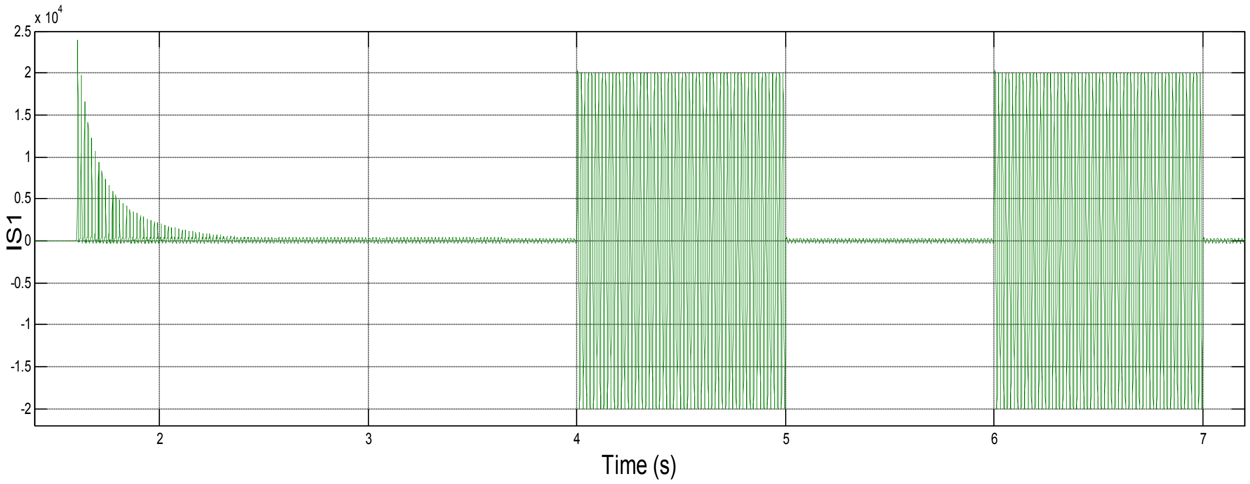
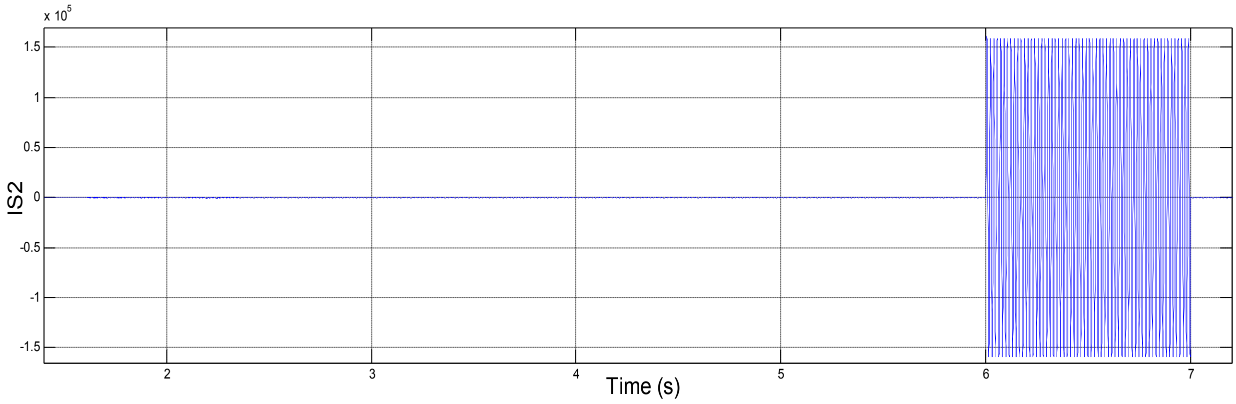


Figure 4.6 The magnetization inrush current of the power transformer.



(a)



(b)

Figure 4.7 The currents of (a) the primary side and (b) the secondary side under applying internal and external faults.

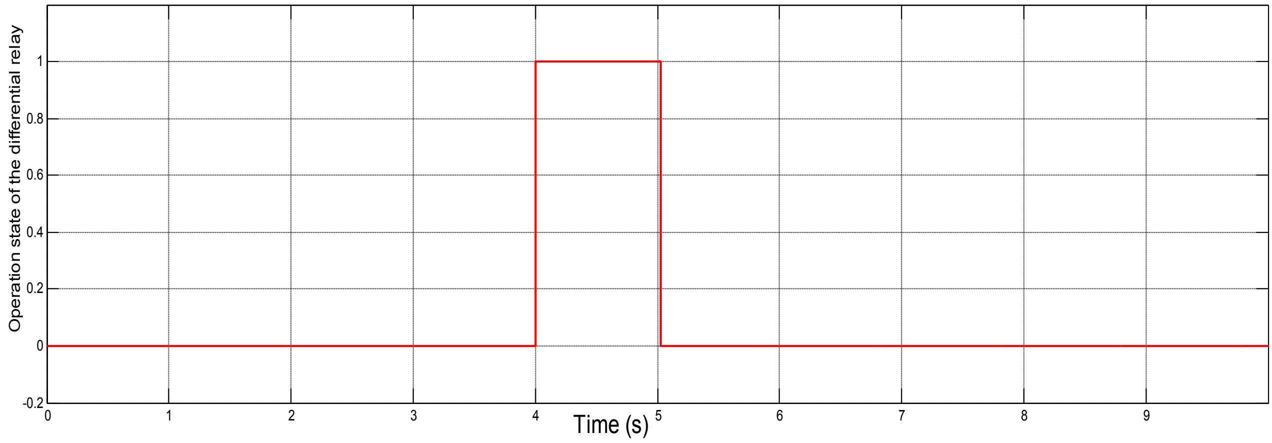


Figure 4.8 The differential relay trip signal.

By applying an internal fault during a transition time from$t_1 = 4s$ to $t_2 = 5s$, we observe a big difference in the current amplitude of both sides of the power transformer as shown in figure 4.7 and thus the differential relay operates in this period as shown in figure 4.8.

On the other hand, when we apply an external fault at the time $t_1 = 6s$, we observe the increase of the current amplitude for the both sides of the power transformer as shown in figure 4.8, this difference appear very small and in this case the differential relay not operate even if there is a big difference in the current amplitudes.

Then, the digital protection scheme developed in previously has been tested by simulation for magnetization currents and internal fault cases. These currents are generated when the circuit breaker is closed to connect the transformer and external fault appears as shown in figure 4.5. The currents are measured by current transformers on buses B1 and B2 and then introduced to the relay. Some parameters have been made variable to allow performing all possible cases of test. Two test cases have been performed:

a) Switching on the transformer and then applying an external fault as shown in figure 4.9.

b) Switching on the transformer and then applying an internal fault as shown in figure 4.10.

Figure 4.9 shows the plots of the differential currents when the transformer is switched on at t=0.08 sec and then an external fault at 0.25 sec and finally this fault cleared at 0.65 sec. In figure 4.7, the differential current as well the restrain current are shown for case (b) switching on the transformer at t=0 and then applying an internal fault at t=0.6 sec. However, figure 4.11 shows the plots of test case (b) for the relay trips. The output and response time of the relay are shown in this figure. However, the trip times that have been found, include the waiting time of one cycle of the power frequency. This delay has been introduced to prevent false trip conditions. It is possible to reduce the time delay to achieve faster tripping. It can be noted that the relay exhibits a good response in all considered cases.

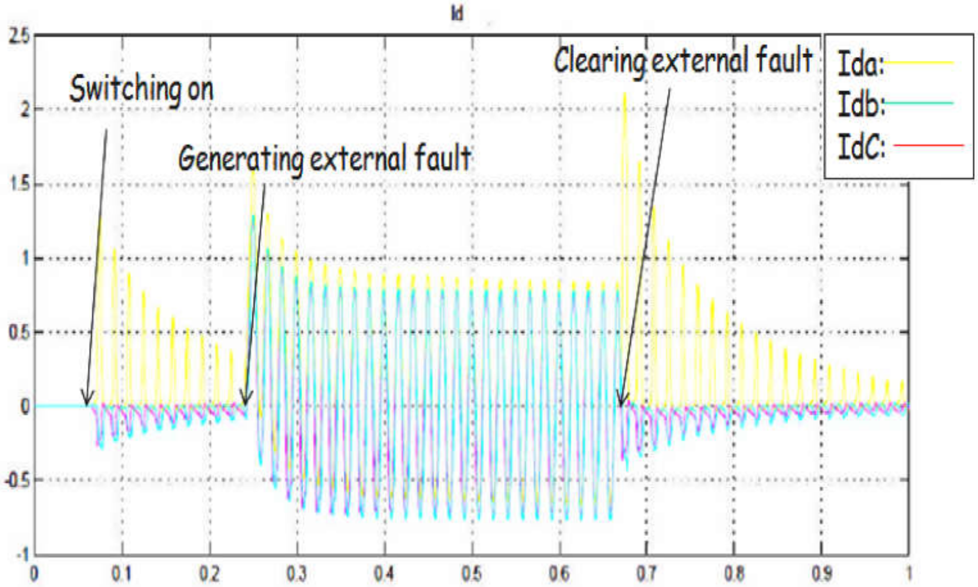


Figure 4.9 Differential currents during switching on the transformer and an external fault.

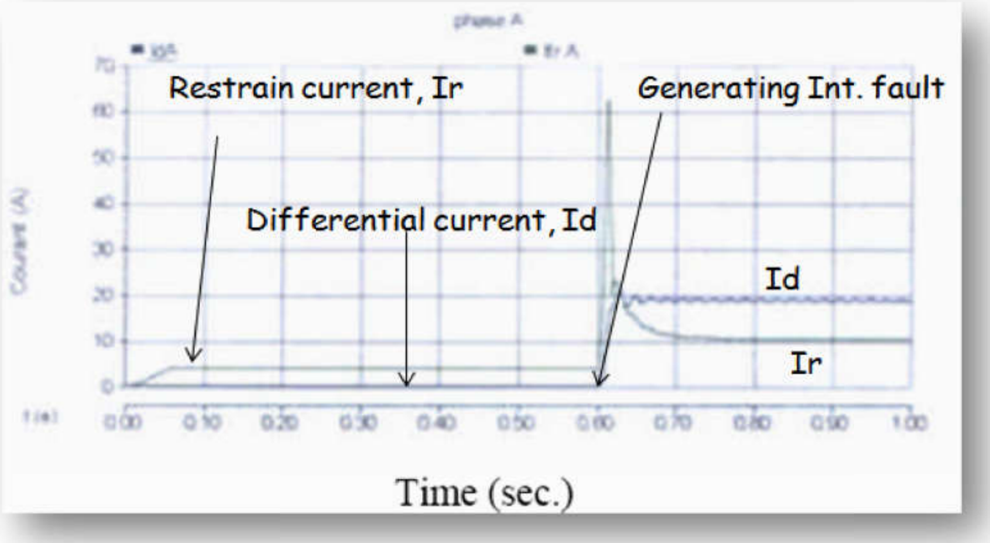


Figure 4.10 Differential and restrain current signals

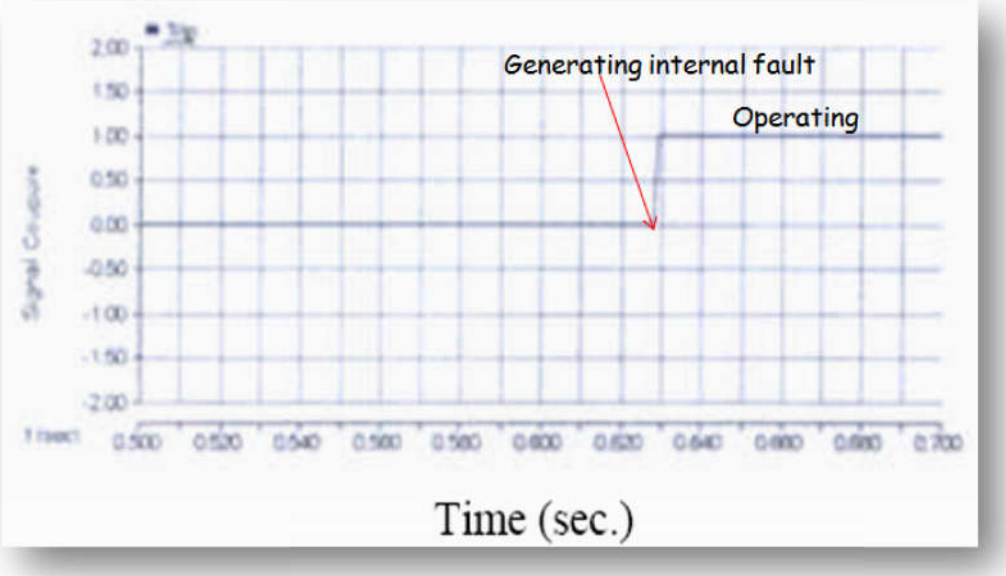


Figure 4.11 Relay response

Moreover, it provides a good discrimination between the inrush and internal fault current.

4.5 Conclusion

In this work, an attempt has been made through the use of MATLAB/SIMULINK to test a new approach applied to digital differential protection relay for a large power transformer.

First, the Fourier sine and cosine coefficients required for fundamental, second, third and fifth harmonics extraction have been calculated using rectangular transfer technique. Then, these harmonic components have been used in harmonics restrain and blocking techniques which may be utilized in differential protection system. Testes have been carried out on a variety of magnetizing conditions (normal aperiodic inrush and over excitation conditions due to external fault) as well as internal fault. It can be noted that, from the obtained simulation results using Simulink/MATLAB, the developed scheme provides good discrimination between the magnetizing current and the internal fault current [47, 48].

Chapter 5

Differential Relay for a Modern Large Power Transformer

A differential relay that is very sensitive relay operating even at its limits may be used for protecting a power transformer. However, this characteristic may lead to unnecessary tripping due to transient currents such as an inrush and over excitation current. In order to avoid this mal-operation of the relay, a second and fifth harmonic blocking technique has been used; however this technique is not reliable if a second harmonic magnitude is weak. In this chapter, a new approach is proposed using even harmonics (second and fourth). The test results show that this proposed approach is a good blocking technique associated with the differential relay even for large modern power transformer which has small second harmonic as well; it provides a good discrimination between the transient currents and the internal fault currents during internal fault.

5.1. Introduction

The differential protection is simple and provides the best protection against phase and ground faults. Differential relay is generally used for protecting the power transformer from internal faults [2]. It compares the currents that enter with the currents that leave a zone or element to be protected. If the net sum of the currents is zero, then the protected equipment is under normal condition. However, if the net sum is different from zero, the differential relay operates due to an existing fault within the equipment and isolates it from the power system.

Even differential protection is relatively simple to be implemented, but it has drawbacks. One of these drawbacks is its unnecessary tripping due to the transformer magnetizing current, when the relay considers this situation as an internal fault. Differential relays are prone to mal-operation in the presence of transformer inrush currents. Inrush currents are produced from transformer magnetic flux [3]. The first solution to this problem has been investigated by introducing an intentional time delay in the differential relay. Another proposal has been performed by desensitizing the relay for a given time, to overcome the inrush condition [4, 5]. Others have suggested adding a voltage signal to restrain [12].

This research work motivation is the need to develop an appropriate blocking technique of differential protection during inrush conditions. This is following a number of questions that has been arisen while applying differential relays for transformer protection. Protection of large power transformers is a very challenging problem in power system relaying. Large transformers are a class of very expensive and vital components of electric power systems. Since it is very important to minimize the frequency and duration of unwanted outages, there is a high demand imposed on power transformer protective relays; this includes the requirements of dependability associated with mal-operation, security associated with no false tripping, and operating speed associated with short fault clearing time [10].

Discrimination between an internal fault and the magnetizing inrush current has long been recognized as a challenging power transformer problem [10]. This research will analyze the problem and its effect on transformer differential protection. Since the magnetizing inrush current generally contains a large second harmonic component in comparison to an internal fault, conventional transformer protection systems are designed to restrain during inrush transient phenomena by sensing this large second harmonic. However, the second harmonic component may also be generated during internal faults in the power transformer [6]. This may be due to current transformer (CT) saturation, presence of shunt capacitance, or the capacitance in long extra high voltage transmission lines to which the transformer may be connected. The magnitude of the second harmonic in an internal fault current can be close to or greater than that present in the magnetizing inrush current [10]. The second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers because of the improvements in the power transformer core material. The commonly employed conventional differential protection technique based on the second harmonic restraint will have difficulty in distinguishing between an internal fault and the inrush current thereby threatening transformer stability [10]. In this work, a new approach is proposed using two harmonics (second and fourth) for restraining or blocking a differential relay and reducing the blocking time during an internal fault. This technique has been implemented in protection system of a three phase power transformer using Simulink/MATLAB, which ensures security for inrush conditions and provides dependability for internal faults.

5.2 Inrush Current

An inrush current is the surge of transient current that appears in a transformer due to inrush and over excitation conditions. The exciting voltage applied to the primary of the transformer forces the flux to build up to a maximum theoretical value of double the steady state flux plus reminisce,

$$\phi_{MAX}=2\phi_M+\phi_R \tag{5.1}$$

Therefore, the transformer is greatly saturated and draws more current which can be higher than the full load rating of the transformer windings. Even though it is generally considered as a result of the transformer energizing, the magnetizing inrush current may be also caused by:

- Occurrence of an external fault,
- Voltage recovery after clearing an external fault,
- Change of the type of a fault,
- Energizing of a transformer in parallel with a transformer that is already in service.

One of the most important type of the transformer differential protection is percentage differential protection which is based on the comparison of the transformer primary and secondary currents. When these currents deviate from a predefined relationship, an internal fault is detected and the transformer is de-energized. However, during transient primary magnetizing inrush conditions, the transformer can carry very high primary current and no secondary current appears. The resulting differential current can falsely trip the circuit breaker of the transformer.

Probably every utility has experienced a false operation of the differential relay when energizing a power transformer. Over the years, many different methods for preventing differential relay operation during inrush have been developed such as:

- Cross blocking: It is a method that blocks all tripping signal if any relay detects inrush current. Any of the relays that use single-phase inrush detection methods can utilize cross blocking.
- Harmonic current restraint: This is the most common method and widely used for the detection of inrush current in power transformer. A scheme currently used is based on second harmonics restraint principle.

The most common technique used for preventing from false tripping during the above condition is the use of second and fifth harmonic restraint. If the second and fifth harmonic of the differential current exceed pre-defined percentages of the fundamental, inrush current is detected and the relay is blocked from tripping [11]. The magnitude of the second harmonic in fault current can be close to or greater than that present in the magnetizing inrush current. The magnetizing inrush currents have high component of even and odd harmonics. The magnetization inrush current signal form of the power transformer is shown in figure 5.1. Table 5.1 gives typical amplitudes of the harmonics compared with the fundamental [17].

However, some problems may be arisen during the identification of the inrush condition using the second harmonic components. The second harmonic component in the magnetizing inrush currents tend to be relatively small in modern large power transformers. Consequently, differential protection technique based on the second harmonic restraint may fail.

The minimum possible level of second harmonic in magnetizing inrush current is about 17% as reported in the literature [18]. For this case; a 15% threshold would be a good choice. However, modern transformer designs produce inrush current with second harmonic levels as low as 7% [46].

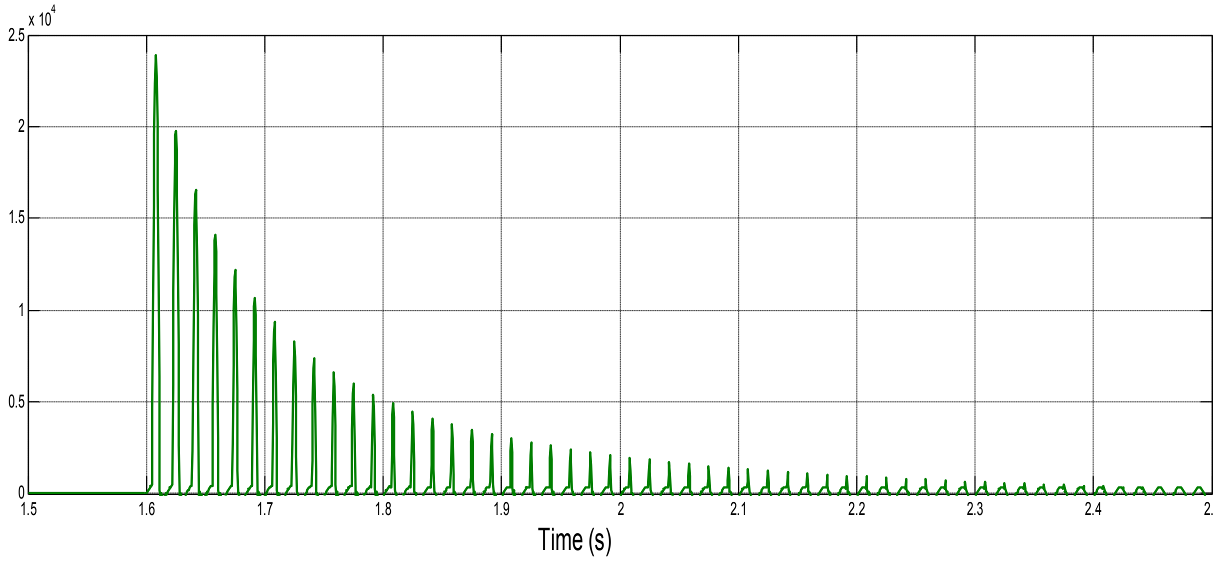


Figure 5.1. Magnetizing inrush current of the power transformer.

Table 5.1 Percentage of harmonics in typical magnetizing inrush current.

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

5.3 Harmonics Restrain

Harmonics restrain is based on the fact that the inrush current has a large second-harmonic component of the differential current which is much larger in the case of inrush than for a fault (see Table 5.1). The over-excitation current has also a larger fifth-harmonic component. Therefore, these harmonics may be used to restrain the relay from tripping during those two conditions. In contrast to the odd harmonics that ac CT saturation generates, even harmonics are a clear indicator of magnetizing inrush. As even harmonics resulting from dc CT saturation which are transient in nature, then it is important to use them (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 which have very low second-harmonic current. The operating equation is:

$$I_{op} \geq SLP_i \times I_{rt} + \textstyle\sum_{n=1}^{3}(k_2 I_{2hn} + k_4 I_{4hn}) \tag{5.2}$$

Where k_2, k_4 are constant coefficients. SLPi is the slope of the ith characteristic of the differential relay. I_2, I_4 are the second and fourth harmonic components of differential current. It is a common practice to use harmonic restraint in three-phase transformer differential protection which is a technique where the harmonic restraint quantity is proportional to the sum of the second and the fifth-harmonic components of the three relay elements. The relay operation is of the following form [69]:

$$I_{op} \geq SLP_i \times I_{rt} + \sum_{n=1}^{3}(k_2 I_{2hn} + k_5 I_{5hn}) \tag{5.3}$$

Where I_5 is the fifth harmonic of the operating current, and K_5 is a constant coefficient.

In a fifth harmonic restraint scheme, a given setting may represent different over-excitation conditions, depending on the other harmonics that may be present. Relay tripping in this case requires fulfillment of equations (5.2) and (5.3) for taking into consideration inrush and over-excitation conditions.

5.4 Simulation Results and Discussion

The power system that has been used for testing the developed differential relay associated with harmonic restrain is composed of a 15 MVA three-phase voltage source in series with a three-phase power transformer feeding a resistive load 10 MW. One circuit breaker is connected to the primary side of the transformer and takes its tripping signal from the differential relay, so that it may open the circuit during faulty condition. The inputs to the relay are the primary side current of the transformer and the current of the secondary side. A simple system is used to check the validity of the proposed algorithm, and it is mainly composed of three phase wye/wye transformer with saturable core and initial fluxes. The main parameters of the used power transformer are given in Table 5.2. A block set of three phase fault may be applied to the terminals of secondary side, which is considered as internal fault. Figure 5.2 shows the Simulink model of power system which contains the three phase transformer.

Simulations were performed with the Simulink software for two cases which are:

1. Case of inrush current; where the simulation results are presented in figure 5.3 for the three phases (phase A, B and phase C).
2. Case of the three phase short circuit located at the terminal end of the secondary side of the power transformer (internal fault) as shown in figure 5.4.

The three phase source is connected at the instant t=0.18s in the first case. Since the restraining signal is higher than the operating one thus the relay is blocked in this case as shown in figure 5.3. However, the three phase source is connected at the instant t=0.05s and the fault is applied at the instant t=0.2s in the second case. Figure 5.4 shows that the restraining signal is higher than the operating one at beginning but when the fault occurs the operating signal is higher than the restraining one then the relay is unblocked. The time taken by the protection to detect the fault is 0.012s as illustrated in figure 5.5.

Table 5.2 Main parameters of power transformer

Transformer connection	**Y/Y**
Rated power	10 MVA
Voltage ratio	33/11 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	500.02 pu

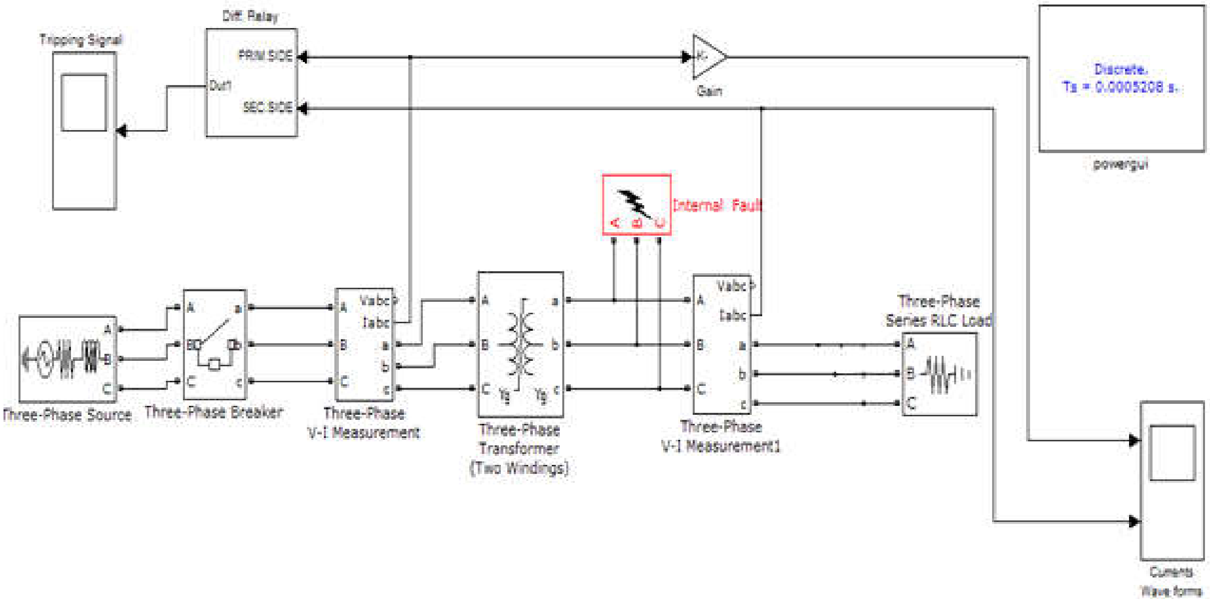
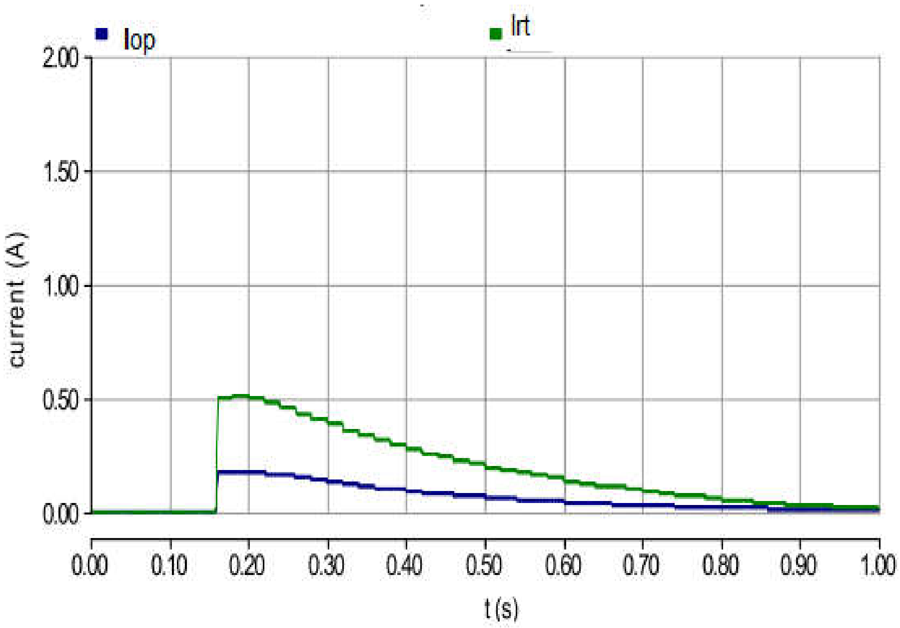
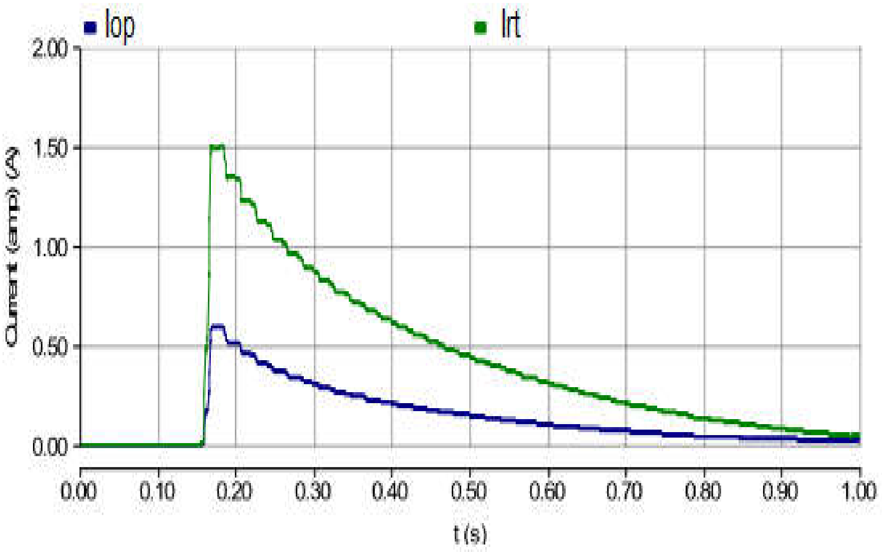


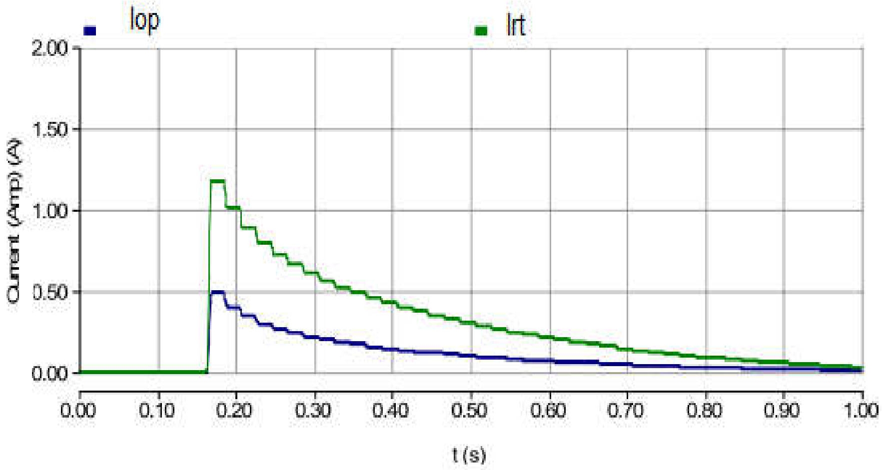
Figure 5.2 Simulink model of the power system including three phase transformer.



Phase A

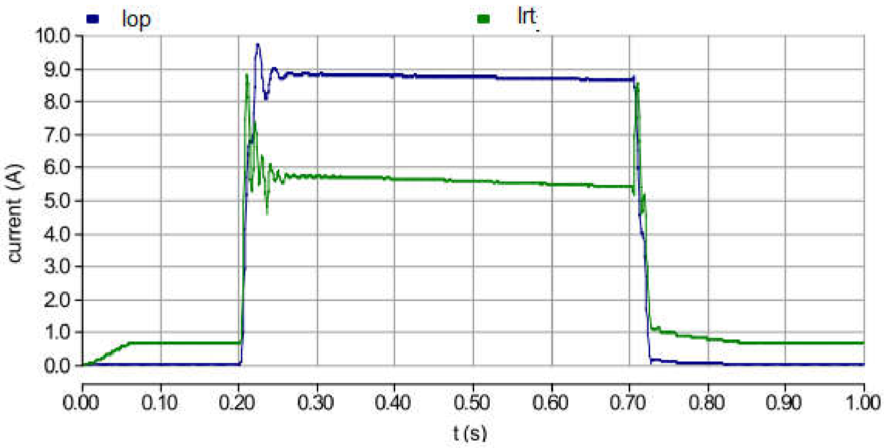


Phase B

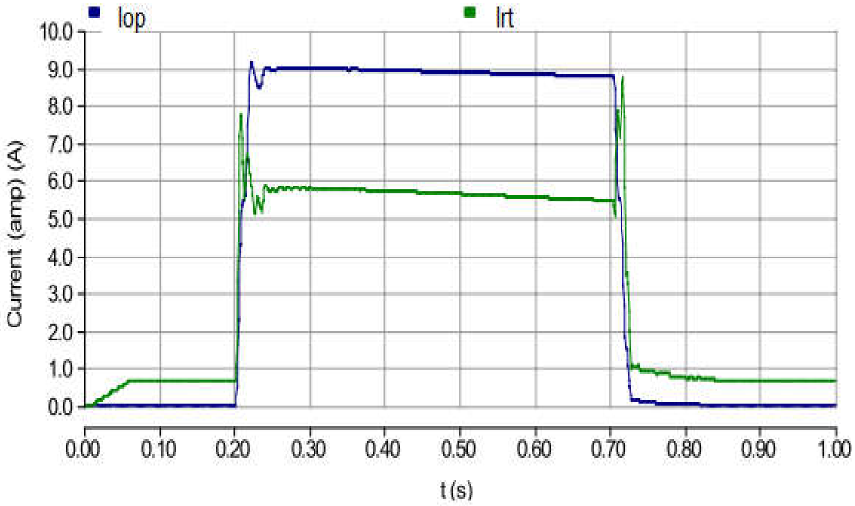


Phase C

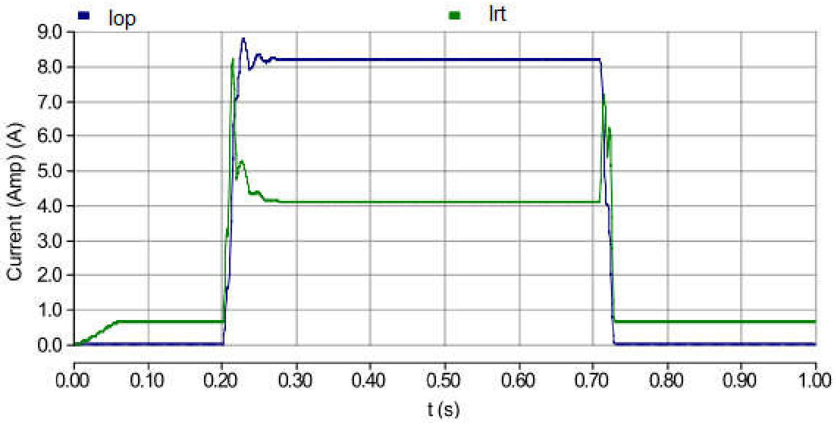
Figure 5.3 Restraining scheme using the harmonics (2nd and 4th) in the case of inrush current (Switching on at t= 0.18s), where I_{op}:operation current and I_{rt}: restraining current.



Phase A



Phase B



Phase C

Figure 5.4. Restraining scheme using the harmonics (2nd and 4th) in the case of internal fault applied at t= 0.2s.

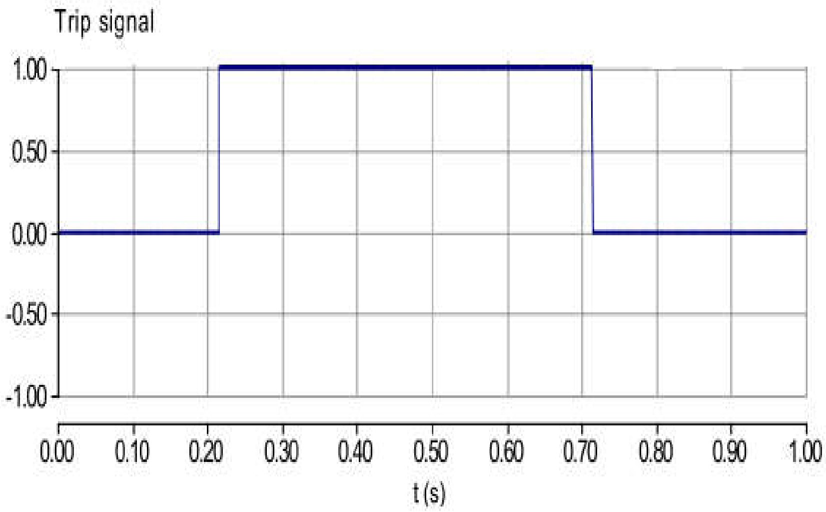


Figure 5. 5 Trip signal initiated by the differential relay.

The simulation shows that the protection based on the second and the fourth harmonics gives a good results in term of discrimination between the normal state of the transformer and the inrush conditions (figure 5.3 A, B, C) and at the same time it is very sensitive to the internal faults, as it can be seen for the case of three phase short circuit at the terminal of the transformer in the secondary winding (figure 5.4 A, B, C). The fault is applied at the instant t=0.18s, the time taken by the protection to detect the fault is 0.012s as illustrated in figure 5.5.

5.5 Conclusion

In this chapter, it can be noticed that the inrush current has a second harmonic component of the differential current which is much larger in the case of magnetization condition. Then, the use of the second harmonic for restraining and blocking in the differential protection gives a possibility to unnecessary tripping during this condition. However, the second harmonic components in the magnetizing inrush currents are relatively small in the modern large power transformers.

Thus, even harmonics (second and fourth) have been used in the restraint scheme to enhance security and hence the reliability of the differential relay during inrush currents conditions. The simulation results show that this proposed approach can block the differential relay even for the large power transformer which has small second harmonic. Besides, it provides good discrimination between the transient magnetizing inrush currents and the internal fault currents as well, the blocking time is small during the internal fault [49].

Chapter 6

Conclusion

A differential protection is simple and provides the best protection for phase and ground faults of power transformer. The differential relay is generally used for protecting the power transformer against internal faults [1]. It compares the currents that enter with the currents that leave a zone or element to be protected. If the net sum of the currents is zero, then the protected equipment is under normal condition. However, if the net sum is different from zero, the differential relay operates due to a fault existing within the equipment and isolates it from the power system. Even differential protection is relatively simple to be implemented, but it has limitations due to its low security. For removing these drawbacks many techniques have been developed which needs more calculations.

Digital relays are a result of the application of microprocessor technology in the protection field. These relays are in an extensive use in modern protection schemes and are also a very active area of research. A particular emphasis has been given to the development of algorithms that allow obtaining the most accurate decision in the fastest speed. Also, the low reliability level of digital relays is regarded as a dark point that hovers about them and considered as major worry stated by many specialists in the field.

In this research project, we have reviewed the developments of different techniques of the differential protective relays for power transformer, then we have developed and implemented performing algorithms for digital differential relay, the obtained results are very encouraging in term of sensitivity and rapidity as well as in term of reliability. The project has presented also a new approach allowing the reliability improvement of digital differential protective relay when it is used for a modern large power transformer which has small second harmonic components.

In Chapter 1 are described the context and organization of the thesis. The importance of protective relays and their developments is emphasized. The objectives and outline of the thesis are also established in this chapter.

Chapter 2 provides a comprehensive approach allowing the distinction efficiently among the different electrical operating abnormal conditions removes some ambiguities causing confusions and difficulties for the accurate classification of faults and abnormal inrush conditions, while indicating the definition limits of each fault.

In Chapter 3, a review of protective relays a large power transformer has been presented. The latest developments and trends of different technique for improving the reliability of the differential relay have been also introduced and discussed whether for hardware and technology aspect.

In Chapter 4, a Digital differential relay has been developed and simulated. The logic used to distinguish between the inrush current and the internal fault is based on the theory of harmonic analysis. In this chapter, it can be noticed that the inrush current has a second harmonic component of the differential current which is much larger in the case of magnetization condition. Then, the use of the second harmonic for restraining and blocking in the differential protection gives a possibility to unnecessary tripping during this condition. The behavior of the presented relay has been simulated versus various situations (inrush current, internal fault and external fault). The obtained results show that the proposed algorithm provides a good discrimination and a fast action.

In Chapter 5, a new approach with high reliability for numerical differential relay has been developed. Since, the second harmonic components in the magnetizing inrush currents are relatively small in the modern large power transformers. Thus, even harmonics (second and fourth) have been used in the restraint scheme to enhance security and hence the reliability of the differential relay during inrush currents conditions. The simulation results show that this proposed approach can block the differential relay even for the large power transformer which has small second harmonic. Besides, it provides good discrimination between the transient magnetizing inrush currents and the internal fault currents as well, the blocking time.
The work reported in this thesis shows that the objectives have been fulfilled successfully. Specifically, the project has made the following contributions:

- An exhausting review which resumes the main highlights in differential protective relay's developments and trends.

- An enhanced algorithm based on the theory of harmonic analysis to discriminate between the internal fault and the inrush current created during the switching of the power transformer. The simulation results of the proposed differential relay gave very satisfactory results in term of discrimination as well as in term of rapidity (operating time).

- A new approach allowing the reliability improvement of digital differential protective relay when it is used for a modern large power transformer which has small second harmonic components.
- A PC-based differential relay prototype has been developed in this work, where we have implemented the algorithm using the Simulink/Matlab and interfaced with the real world via a data acquisition card AD622. This card is used to allow acquiring real time signals, which will be processed in PC, and the trip signal to be outputted to the circuit breaker.

After testing, it can be noticed that the obtained results satisfy the principle of operation of numerical differential relay and its characteristics using new frame work.

Moreover as future scope, this work may be extended to include the Phasor Measurement Unit (PMU) which is considered to be one of the most important part that can provide phasor measurements of currents in digital form [50, 51]. These PMU's should be associated with a reliable high speed algorithm generally using DSP. Besides, an implementation of PC based digital protective relay associated with DSP card may be investigated. The Fourier sine and cosine coefficients required for fundamental, second, third and fifth harmonic extraction have been generated using rectangular transfer technique. Then, these harmonics have been used in harmonics restrain and blocking techniques applied to differential protection system. Testes will be carried out on a variety of magnetizing conditions (normal aperiodic inrush and over excitation conditions).

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