ANALYSIS OF INRUSH CURRENT IMPACTS TOWARDS TRANSFORMER PROTECTION CAPABILITY

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ABSTRACT

Inrush current in power transformer is also known as magnetizing inrush current, which the transformer windings are linked magnetically by flux in the transformer core. Magnetizing inrush current in transformer is the current which is drawn by a transformer when transformer is being energized. The inrush current has a large DC-component and rich of harmonics where the fundamental frequency and the second harmonic are dominating. Magnetizing inrush current is not a fault current, and therefore during inrush current event, transformer protection must remain stable. Differential protection is the most widely used methods for protecting power transformer against internal fault. The differential transformer protection can identify the inrush current by detecting the second harmonic content that used in this research. In this project, transformer differential protection has been modeled in PSCAD software. There are four main components in PSCAD library used for modeling of the relay, which are Fast Fourier Transform (FFT), Dual Slope Current Differential Relay, Overcurrent Detection Block, and relay logic components for tripping signal. The FFT component used for extracting the fundamental and second harmonic current, and the Dual Slope Current Differential Relay component for differential current and bias current setting. The OC Detection Block component functions as inrush current blocking. The tripping signal in transformer differential relay used to show the operation of the relay. The analysis has been simulated based on two case studies with different capacities and voltage level of transformers.

ABSTRAK

Arus rempuh-masuk dalam alatubah juga dikenali sebagai arus rempuh-masuk pemagnetan, dimana lilitan alatubah disambungkan secara magnetik oleh fluks yang terdapat di dalam teras alatubah. Arus rempuh-masuk pemagnetan di dalam alatubah ialah arus yang mana dihasilkan oleh alatubah semasa alatubah dihidupkan. Arus rempuh-masuk mempunyai satu komponen DC yang besar dan kaya dengan harmonik. Ia dikuasai oleh frequensi asas dan harmonik yang kedua. Arus rempuh-masuk pemagnetan bukanlah satu arus kerosakan. Oleh itu geganti perlindungan alatubah mestilah kekal stabil semasa arus rempuh-masuk. Geganti perlindungan kerbeda alatubah adalah geganti yang paling banyak digunakan secara meluas untuk melindungi alatubah terhadap arus kerosakan dalaman. Geganti perlindungan kerbeda alatubah boleh mengenalpasti arus rempuh-masuk dengan mengesan harmonik yang kedua, yang juga digunakan di dalam penyelidikan ini. Di dalam projek ini, geganti perlindungan kerbeda alatubah dimodelkan di dalam perisian PSCAD. Terdapat empat komponen utama yang terdapat di dalam PSCAD 'library' digunakan untuk memodelkan geganti perlindungan tersebut, iaitu Fast Fourier Transform (FFT), Dual Slope Current Differential Relay, Overcurrent Detection Block, dan komponen 'relay logic' untuk 'tripping signal'. Komponen FFT digunakan untuk mengesan arus asas dan harmonik yang kedua, dan komponen Dual Slope Current Differential Relay pula untuk penatahan 'differential current' dan 'bias current'. Fungsi komponen OC Detection Block adalah untuk mengesan dan menghalang arus-rempuh masuk ke dalam geganti perlindungan kerbeda alatubah. 'Trip signal' bagi geganti perlindungan kerbeda alatubah digunakan untuk menunjukkan operasi geganti tersebut. Analisis telah dibuat berdasarkan dua kes kajian yang berbeza keupayaan alatubah dan aras voltan.

ACKNOWLEDGEMENTS

In the name of Allah SWT, the Beneficent, the Merciful, all praise to Allah SWT for giving the health and strength to pursue the study and enable me to complete this research.

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LIST OF SYMBOLS AND ABBREVIATIONS

DC	:	Direct current
OC	:	Overcurrent
PSCAD	:	Power system computer aided design
FFT	:	Fast Fourier transform
HV	:	High voltage
LV	:	Low voltage
CT	:	Current transformer
Φ	:	Flux in transformer core

CHAPTER 1: INTRODUCTION

1.1 Background

A power transformer is a very important equipment in a power system. Therefore, high reliability of the transformer is necessity to avoid disruptions in power transmit. A high quality transformer proper is designed and provided with suitable protective devices. Normally, transformer will severely damage when a fault occurs in a transformer. The transformer protection can prevent the faults and to minimize the transformer damage. The selection of transformer protective devices depending on transformer capacity and voltage level.

Power transformers are usually protected by differential protection as a main protection. Differential protection is a fast and selective method of protection against internal fault current in transformers which apply Kirchhoff's current law (R. Hunt, J. Schaefer, & B. Bentert, 2008). Kirchhoff's current law is the sum of the currents entering the transformer and the sum of the currents leaving the transformer should be equal.

1.2 Problem Statement

In a practical power system, transformer will produce high current when a transformer is energized and may trip the circuit breaker. The transformer will draw a heavy magnetizing current that may exceed full load current. It is also known as inrush current. The magnitude of inrush current is initially six to ten times the rated load current. Another major condition for inrush current occurs when the transformer is on at no load with its secondary open (R & Sankar, 2017). The transformer inrush current can be considered as critical problem because it may affect the insulation of transformer, transformer windings, power quality issues, and sensitivity to protection devices. Many researchers analyzed the problem to reduce or avoid the inrush current phenomena as mentioned in (Behrendt, Fischer, & Labuschagne, 2017).

Transformer differential protection as protection device towards transformer inrush currents would normally cause mal-operate if not properly blocked the inrush current. Inrush currents are typically rich in harmonics and the second harmonic is dominating. Therefore, during inrush current conditions, the second harmonic content in transformer differential protection commonly used to block or to increase restrain in the differential current (Hodder, Kasztenny, Fischer, & Xia, 2014). In order to analyze this problem, a model of differential protection relay is required.

1.3 Objectives

The main aims for this research are:

i. To design the behavior of transformer differential protection during energizing transformer in PSCAD software.

ii. To analyze the inrush current and fault current output in tripping signal of transformer differential protection.

iii. To define setting of inrush current detection that can be obtained by second harmonic detection in differential relay.

iv. To improve the protection setting and the design of the transformer differential protection.

1.4 Scope of Project

The research mainly focuses on analysis of inrush current impact towards transformer differential protection. The ratio of second harmonic current to the fundamental current is used to measure the inrush current element in the transformer differential protection.

In this research, power transformer with two different capacities and voltage levels are used for simulation of inrush current and internal fault current during normal operation, no load condition, and during fault condition. The transformer differential protection has been modeled in this research. There are four main components in PSCAD library used for modeling of the relay, which are Fast Fourier Transform (FFT), Dual Slope Current Differential Relay, Overcurrent Detection Block, and relay logic components for tripping signal. The FFT component used for extracting the fundamental and second harmonic current, and the Dual Slope Current Differential Relay component for differential current and bias current setting. The OC Detection Block component function as inrush current blocking. The tripping signal in transformer differential relay used to show the operation of the relay.

1.5 Research Report Outline

The research report is structured as follow:

Chapter 1 includes the background of proposed research followed by the problem statement. The objectives of the research are presented and then the scope of the research is stated. In the end, research outline is stated.

Chapter 2 explains an overview of transformer inrush current and principle of transformer differential protection towards the inrush current. The characteristics of transformer inrush current that impact towards transformer differential protection also discussed in this chapter. Furthermore, this chapter also presents on Fourier series analysis on inrush current.

Chapter 3 discusses about methodology of inrush current analysis impacts towards transformer differential protection. The CT ratio selection of two case studies of power transformers with different rated capacities and voltage levels are show in this chapter. The components use for modeling of transformer differential protection in PSCAD software and the parameters setting of the components are also describe in this chapter.

Chapter 4 presents an analysis of inrush current and fault current during normal operation, no load condition, and during internal fault current condition in transformer differential protection based on two case studies. All the data of power transformers used in this power system modeling also include in this chapter.

Chapter 5 concludes this research report and presents direction of future recommendation related to this research.

CHAPTER 2: LITERATURE REVIEW

The transformer magnetization inrush phenomena have been studied for many years. Common technique used to block the inrush current is second harmonic restraint measurement in transformer differential element during transformer magnetization inrush phenomena. This chapter starts with the overview of transformer inrush current and principle of transformer differential protection towards the inrush current. The differential protection of power transformer is a unit protection scheme that means the relay should operate within the zone of protection and not trip due to external fault and inrush current. To overcome this problem, the characteristic of transformer inrush current that impact towards transformer differential protection are discussed in this chapter.

2.1 Overview of Transformer Inrush Current

Figure 2.1 shows the equivalent circuit of transformer. In an ideal transformer (with a 1:1 turns ratio), the currents I1 and I2 are equal except for the small current flowing through the shunt element of the magnetizing branch. In magnetizing branch, there have small current flowing through the element and increasing the exciting voltage that cause increase in flux. During transformer is being energized, inrush current flows through HV winding. Current at HV winding I1 is more than LV winding. Then, magnetizing inrush current in the inrush event results in a differential current than can cause operation of the differential protection (R. Hunt et al., 2008). An example of magnetizing inrush current and the resulting differential current are shown in Figure 2.2.

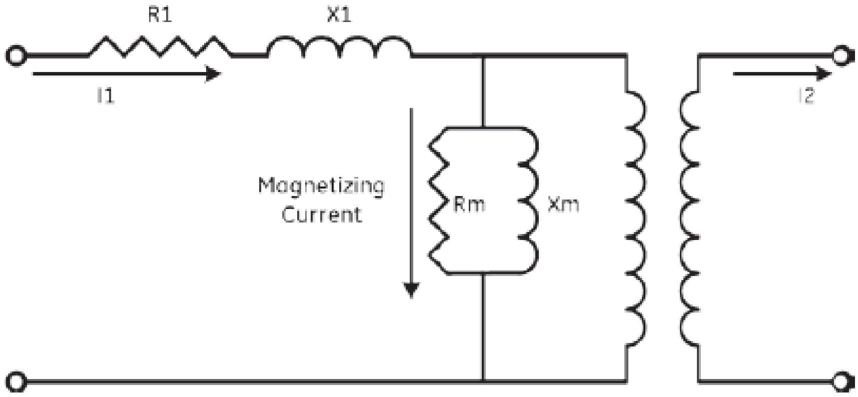

Figure 2.1: Transformer Equivalent Circuit

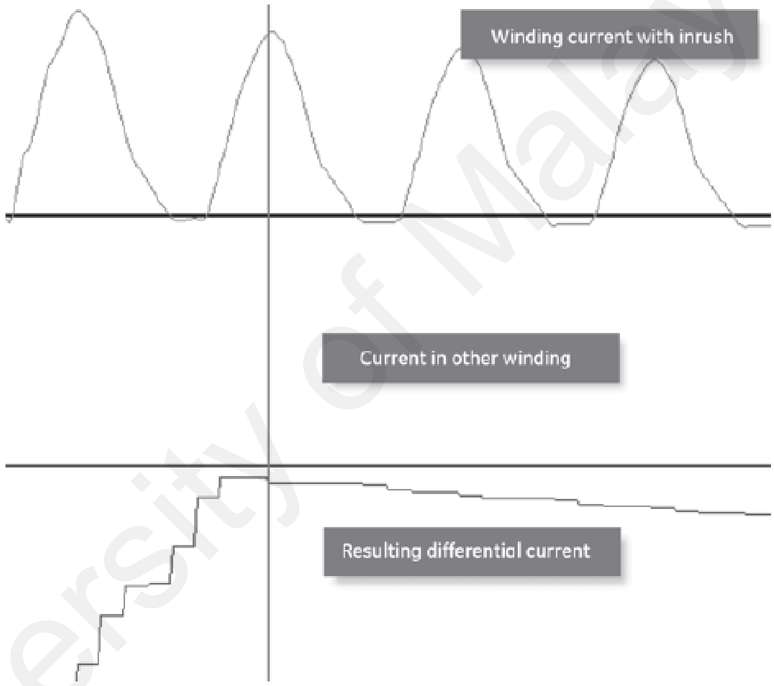

Figure 2.2: Inrush Current and Resulting Differential Current

2.2 Causes of Magnetizing Inrush Current

There are three conditions of transformer inrush current, which are energization or normal inrush, recovery inrush, and sympathetic inrush (Paliwal & Trivedi, 2014). As explained in (R. Hunt et al., 2008), an energization inrush is the magnetizing inrush event that results of the excitation voltage increased to full voltage on one winding. Meanwhile, recovery inrush occurs when excitation voltage returns to normal system voltage level after an external fault is cleared. Sympathetic inrush is a magnetizing inrush that occur in an energized transformer when a nearby transformer is energized.

In (R & Sankar, 2017) stated that there are various factors that affecting the inrush current magnitude in the transformer. The factors are residual flux and characteristics of non-linear magnetizing in the transformer core, the voltage source during energizing the transformer, and the source impedance.

2.2.1 Flux Characteristic of Iron Core

Transformer inrush current is related to flux characteristic of the iron core. Transformer will produce inrush current when the flux is saturated. Figure 2.3 illustrate the approximate magnetization curve of iron core in transformer. At $\Phi < \Phi s$, the slope of magnetization curve is very large and exciting current I_μ is approximately equal to zero. At ($\Phi > \Phi s$), the slope of magnetization curve became very small, when the flux reached saturation. The formation of inrush current is due to increase of flux and exciting current (Chen et al., 2016).

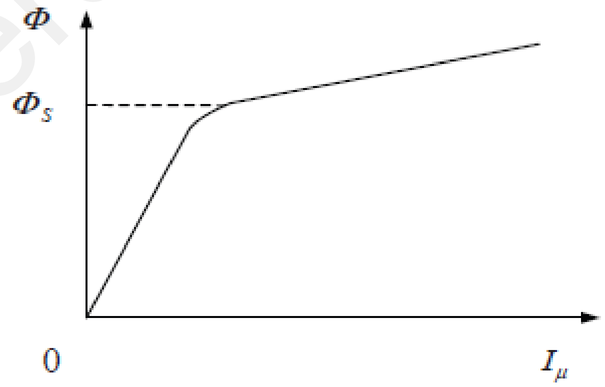

Figure 2.3: The approximation magnetization curve of iron core in transformer

2.2.2 Magnetizing Inrush Current Characteristic

Figure 2.4 shows the magnetizing voltage, core flux, and magnetizing current relationship in transformer as mentioned in (Hodder et al., 2014). The summary of the relationship of the Figure 2.4 was tabulated in Table 2.1.

Table 2.1: Summary of the Magnetizing Voltage, Core Flux, and Magnetizing Current Relationship In Transformer

Time	Magnetizing Voltage	Core Flux	Magnetizing Current
t0	Instantaneous voltage is zero	At residual flux value	Low magnetizing current (Due to large inductance at magnetizing branch)
t1	• Instantaneous voltage increase • Instantaneous voltage is positive	Linearly increase	Instantaneous current increase
t2	Instantaneous voltage is positive	Flux increases	Instantaneous current linearly increase
t3	Negative voltage zero crossing	Maximum values of flux	Large source current (Due to lowest value of inductance and impedance at magnetizing branch become zero)

This shows that the energization current drawn by a transformer is determined by the flux, the voltage applied to the transformer and the residual flux. The source impedance also important factor that affecting the inrush current magnitude in transformer.

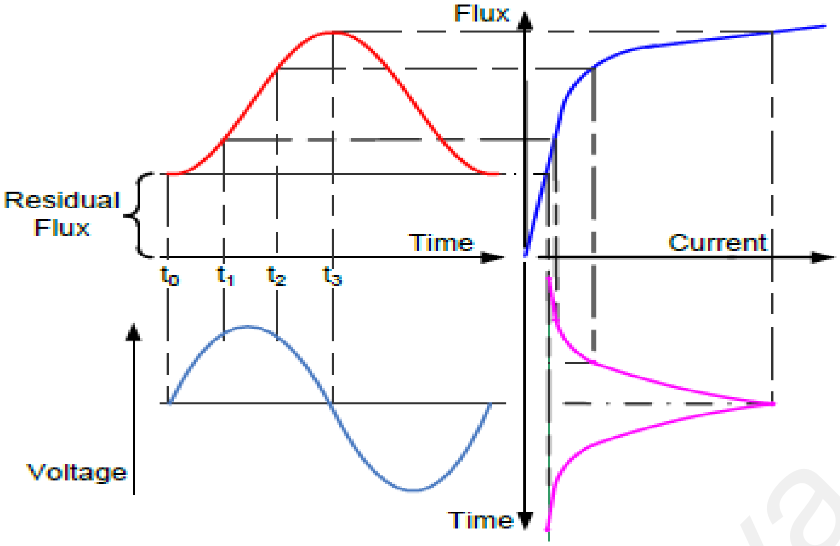

Figure 2.4: Magnetizing voltage, core flux, and magnetizing current relationship in transformer

2.2.3 Voltage Across Winding Transformer

The voltage induced across the winding in transformer is according to Faraday's law of Electromagnetic Induction as Equation (2.1):

$$e = N \frac{d\varphi}{dt} \tag{2.1}$$

Where;

φ: the flux in the core

N: is number of turn

$$e = E \sin \omega t = \frac{d\varphi}{dt} \tag{2.2}$$

$$\varphi = \int e \; dt = E \int \sin \omega t \; dt \tag{2.3}$$

Hence the flux will be integral of the voltage wave as Equation (2.3).

Equation (2.4) shows the flux value at the end of first half cycle of the voltage waveform, if the transformer is switched on at the instant of voltage zero,

$$\varphi_m{}' = \left(\frac{E}{m}\right) \int_0^{\pi} \omega \sin \omega t \;\; dt = \;\varphi_m \int_0^{\pi} \sin \omega t \;\; d(\omega t) = 2\varphi_m \tag{2.4}$$

Where;

φ_m: the maximum value of steady state flux

That means flux become double to its maximum value. Above the maximum steady state value of flux, the transformer core is saturated. But during switching on the transformer the maximum value of flux is twice of its steady state maximum value. To produce the rest of flux, high current is required. So magnetizing inrush current occurs in transformer which is the high source current draw in the transformer primary. (Asizehi, 2013).

The excitation voltage on one winding is increased from zero to full voltage. When transformer is energized, the transformer core is saturated due to transformer design, system impedance, the remnant flux in the core, and the point on the voltage wave. The return of voltage may force a dc offset on the flux linkages, resulting in magnetizing inrush current and there is no remnant flux in the core. Due to presence of load current, the current may consist of low levels second harmonic current in the differential relay (Aibangbee, 2016).

2.3 Fourier Series Analysis on Inrush Current

There are harmonics in the non-linear nature of the magnetizing inrush current. By using Fourier series analysis, the level of harmonics can be estimate in the magnetizing inrush current.

During transformer inrush events, the commonly used as basis for inrush restraint functions is the second harmonic that predominant harmonic in Fourier series analysis. The ratio of second harmonics to fundamental decreases, when the exciting current becomes linear and saturation angle increases. When the transformer core is severely saturated, the magnetizing inrush current become more linear (R. Hunt et al., 2008).

2.4 Principle of Transformer Differential Protection

As mentioned in (López & Guardado, 2015), the differential protection is defined as "the one that operates when the vector difference of two or more similar electrical quantities exceed a predetermined amount". The currents entering and leaving the power transformer are required to calculate the differential current. Figure 2.5 described that the current transformers from both side of transformer windings is usually connected to transformer differential protection as protective device to transformer (Sevov, Khan, & Zhang, 2016).

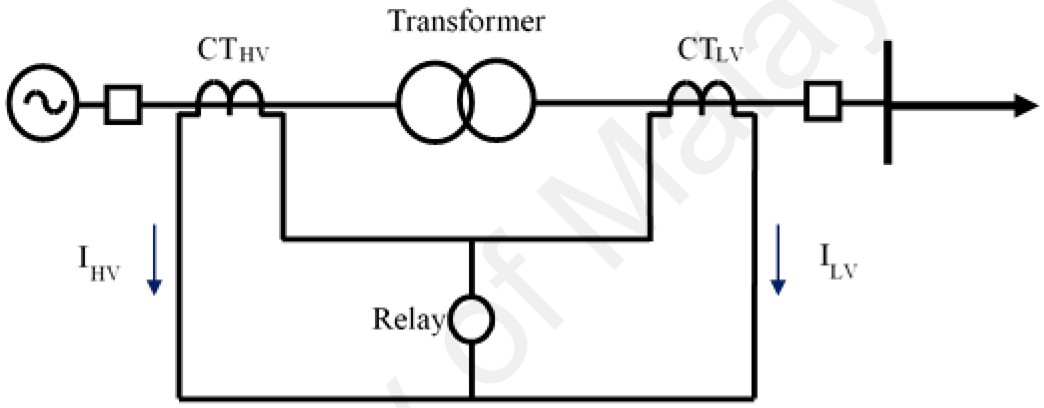

Figure 2.5: Transformer Differential Protection Principle

Differential relay protection operates on the basic theory of Kirchhoff's current law which the sum of the currents entering the node and the sum of the currents leaving the node are equal. There is no fault in the protection zone, if the net sum of the currents entering and leaving a protection zone is zero. However, if there is fault in the zone of protection, the differential protection should operate to isolate the zone from the rest of the system (Aibangbee, 2016). The differential current, I_{diff}, can be obtained from the phasor sum of the current entering the protected element (Behrendt et al., 2017) as shown in Equation (2.5) below:

$$I_{diff} = |I_{HV} + I_{LV}| \tag{2.5}$$

(R. Hunt et al., 2008) presented that there are two common situations where differential protection may wrongly differentiate an internal fault condition. First common situation is Current Transformer (CT) saturation. The second common situation is a transformer inrush event. This event required a large supply of current and the change the operating flux of the transformer core. This inrush current typically occurs in only one winding of the transformer that may produce a differential current in the differential protection. The differential protection should not operate because this type of event is not a fault condition. This research discussed on the second condition, which is analysis of inrush current impacts towards transformer protection capability.

2.5 Summary

In this chapter, an overview of transformer inrush current is illustrated in the equivalent circuit of transformer. The magnetizing inrush current in the inrush event results in a differential current that can cause operation of the differential protection. The energization current drawn by a transformer is determined by the flux, the voltage applied to the transformer and the residual flux. The source impedance also important factor that affecting the inrush current magnitude in transformer. During switching on the transformer the maximum value of flux is twice of its steady state maximum value. By using Fourier series analysis, the level of harmonics can be estimated in the magnetizing inrush current. During transformer inrush events, the commonly used as basis for inrush restraint functions is the second harmonic that predominant harmonic in Fourier series analysis. This inrush current typically occurs in only one winding of the transformer that may produce a differential current in the differential protection. The differential protection should not operate because this type of event is not a fault condition.

CHAPTER 3: RESEARCH METHODOLOGY

Commonly, the power transformer is protected by differential relay. The current input at the transformer primary and secondary side are compared in the differential relay. This chapter firstly present the Current Transformer (CT) selection for both sides of transformer. As stated in (López & Guardado, 2015), the CT ratio mismatch and CT ratio errors need to be considered to avoid unwanted tripping to transformer differential protection. One of the design criteria of transformer protection that must be considered is the security to the power system, which in this research the transformer differential protection schemes should dependent on detecting the magnetizing inrush currents. The differential operation due to inrush should operate properly for faults during inrush conditions. Refer to (Aibangbee, 2016), the fundamental current in the faulted phase easily override the sum of the second harmonic currents associated with energizing the un-faulted phases. By using PSCAD software, the analysis of the inrush current during normal condition, no load condition, and during internal fault condition have been simulated. The transformer differential protection has been modeled using components in PSCAD software are described in this chapter. In this chapter also indicate the parameters setting of the components.

3.1 Inrush Current Simulation

In this research, there are presented two case studies with different capacities and voltage levels of power transformers. The inrush current was simulated in transformer differential protection that has been modeled in PSCAD software. The selection of CT ratio for power transformers based on CT calculation in Equation (3.1) and Equation (3.2). There are four main components in PSCAD library used for modeling of the relay, which are Fast Fourier Transform (block 1), Dual Slope Current Differential Relay (block

2), Overcurrent Detection Block (block 3), and relay logic components for tripping signal (block 4) as shown in Figure 3.1. For developing transformer differential protection, Fast Fourier Transform (FFT) component in PSCAD is used for extracting of fundamental and second harmonic current, and Dual Slope Current Differential Relay component for differential current and bias current setting. The Overcurrent Detection Block component used as inrush current blocking, where in this research was set the overcurrent limit value to 2 Amps, which is more than experimental inrush current value. The trip signal in the relay will mal-operate if the detection is setting below the peak up value.

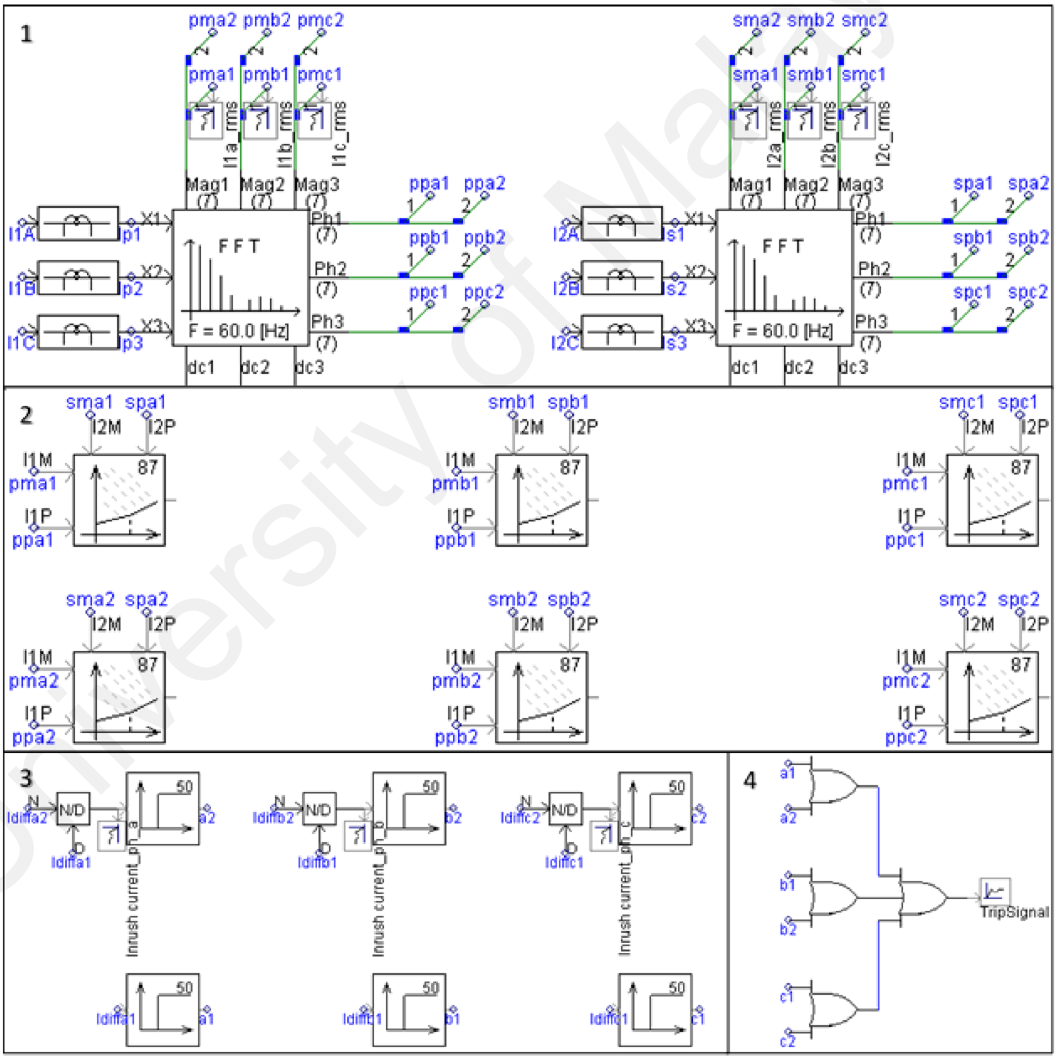

Figure 3.1: Circuit For Transformer Differential Protection

3.1.1 CT Calculation

CT ratio for primary and secondary side of transformer must be choose carefully. The selection of CT ratings based on transformations ratio of transformers. As explained in (Aktaibi & Rahman, 2012), the transformation ratio of transformers is the ratio between the number of turns in the primary side N_1 to the number of the turns in the secondary side N_2. Therefore, the turn ratio of the primary current transformer is $\frac{1}{N_1}$ and the turn ratio of the secondary side current transformer is $\frac{1}{N_2}$. The secondary current of the CT located in the primary side of the power transformer is:

$$I_1 = \frac{I_p}{N_1} \tag{3.1}$$

Where;

I_p: the primary side current of the power transformer

I_1: the secondary side current of CT_1

N_1: the number of turns in the secondary side of CT_1

In the same manner or the CT located at the secondary side of the power transformer, the CT secondary current is:

$$I_2 = \frac{I_s}{N_2} \tag{3.2}$$

Where;

Is: the secondary side current of the power transformer

I_2: the secondary side current of CT_2

N_2: the number of turns in the secondary side of CT

Two different capacity of transformer are studied in this research. For case study-1, the existing model of power transformer in PSCAD library with 230/25kV 50MVA YNyn0 and frequency 60Hz is used for simulation of inrush current. Equation (3.3) shows the ratio of CT primary and secondary is selected to 130:1 and 1200:1 based on Equation (3.1) and Equation (3.2):

$$\frac{230\ kV}{25\ kV} = \frac{1200}{130} = 9.2 \qquad (3.3)$$

For case study-2, with the transformer capacity of 132/33kV 90MVA and frequency 50Hz, the ratio of CT primary is selected to 400:1 and 1600:1 for CT ratio secondary. By using Equation (3.1) and Equation (3.2), the CT calculation as shown in Equation (3.4) below:

$$\frac{132\ kV}{33\ kV} = \frac{1600}{400} = 4.0 \qquad (3.4)$$

3.1.2 Harmonic Detection Using FFT

Fast Fourier Transform technique is used for preventing the mal-operation. The secondary current signals from the CTs are sampled at a regular interval. This is an online Fast Fourier Transform (FFT), which can determine the harmonic magnitude and phase of the input signal as a function of time. The input signals first sampled before they are decomposed into harmonic constituents (Mayurdhvajsinh & Bhalja, 2013). In this research, FFT used for extracting fundamental and second harmonic current during normal condition, no load condition, and fault condition. PSCAD software includes the online FFT block which is shown in Figure 3.2 below:

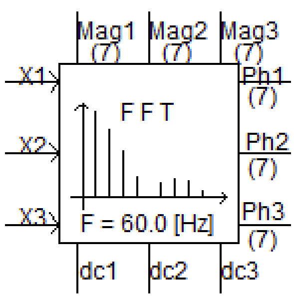

Figure 3.2: FFT Block In PSCAD

3.1.3 Dual Slope Differential Relay Component

The dual slope differential relay component in PSCAD software used for computing of differential current, I_{diff} and biased current, I_{bias} in the system. The dual slope percentage biased restraint characteristics can be determined by the following four settings:

- I_{S1}: The basic differential current setting
- K_1: The lower percentage bias setting
- I_{S2}: The bias current threshold setting
- K_2: The higher percentage bias setting

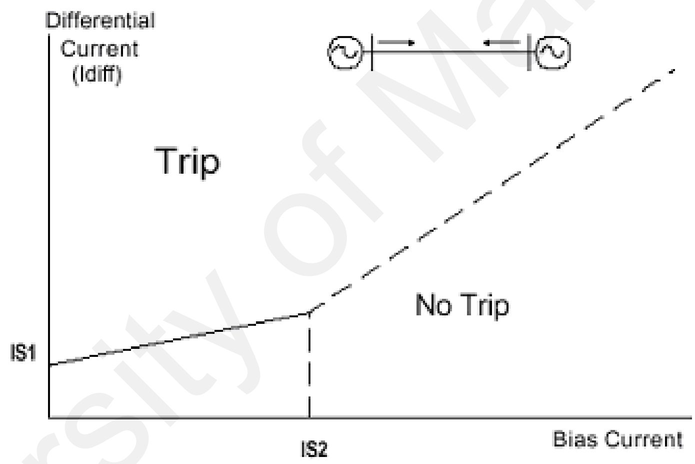

Figure 3.3: Characteristic of Dual Slope Differential Relay In PSCAD

The tripping criteria can be formulated as:

CASE 1:

$|I_{bias}| < I_{s2}$

If $|I_{diff}| > K_1|I_{bias}| + I_{s1}$ then trip

CASE 2:

$|I_{bias}| \geq I_{s2}$

If $|I_{diff}| > K_2|I_{bias}| - (K_2 - K_1).I_{s2} + I_{s1}$ then trip

In this research, the parameters setting of the slope were set as Table 3.1:

Table 3.1: Parameters Setting of Dual Slope

Parameter	Setting
I_{S1}	0.2 A
K_1	0.3 (30%)
I_{S2}	2.0 A
K_2	0.6 (60%)

3.2 Comparison Between Inrush Current & Fault Current

The differential relay will determine the transformer inrush, by comparing the differential current of fundamental and second harmonic content. The trip signal of a differential relay must be accurately operated. Overcurrent detection block in PSCAD library used to set overcurrent limit for inrush current blocking and further to avoid unwanted tripping to power system. The overall flow of inrush current simulation is illustrated in Figure 3.4.

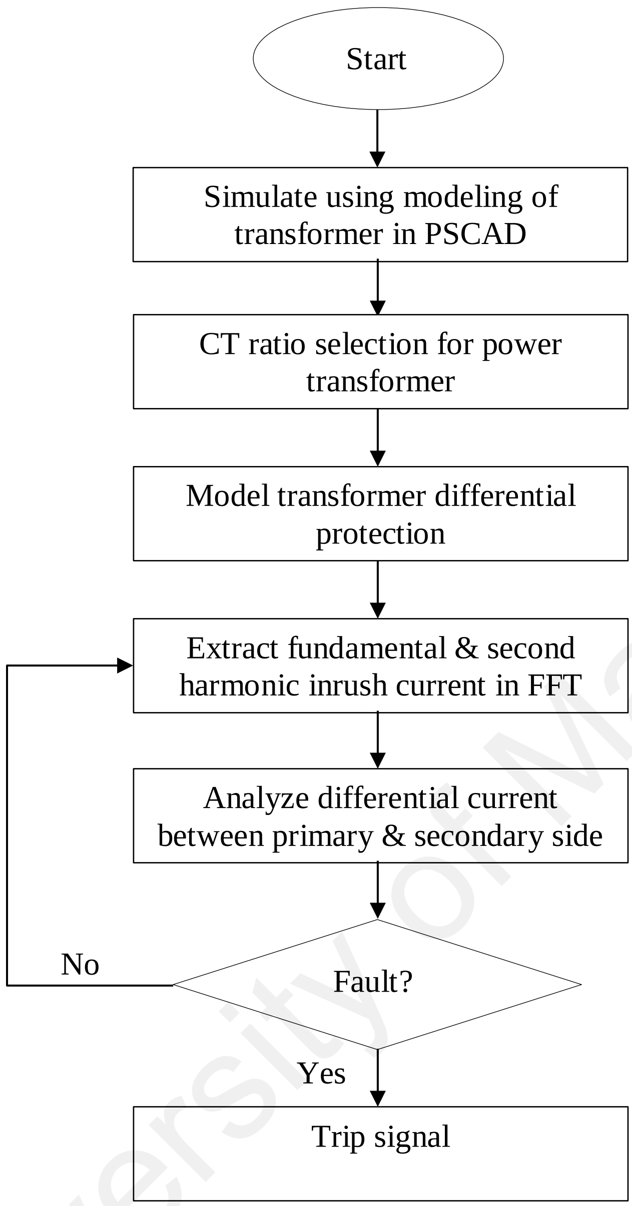

Figure 3.4: Flowchart of Inrush Current Simulation

3.3 Summary

This chapter discussed about methodology of inrush current analysis impacts towards transformer differential protection. The power transformers with different rated capacity is analyze using PSCAD software and selection of CT ratio based on CT calculation. For developing transformer differential protection, FFT component in PSCAD is used for extracting of fundamental and second harmonic current and Dual Slope Current Differential Relay component for differential current and bias current setting. The differential relay will determine the transformer inrush, by comparing the differential current of fundamental and second harmonic content. The trip signal of a differential relay must be accurately operated. Overcurrent detection block in PSCAD used to set overcurrent limit for inrush current blocking and further to avoid unwanted tripping to power system.

CHAPTER 4: RESULTS AND DISCUSSION

The methodology proposed in the research for analysis of inrush current impacts towards transformer protection capability consists of two case studies where the simulations based on two different capacities and voltage levels of transformers. All the data of power transformers used in this power system modeling presented in this chapter.

4.1 Case Study-1: 230/25kV YNyn0 50MVA Power Transformer

In this case study, existing model of power transformer in PSCAD library is used. The parameters for case study-1 are as follows:

Table 4.1: Parameters Setting Case Study-1

Equipment	Parameter	
Substation 1 Three Phase Voltage Source	Base MVA	100MVA
	Base voltage	230kV
	Base frequency	60Hz
	Positive sequence impedance	52.9 Ω, 80º
	Zero sequence impedance	52.9 Ω, 80º
3 Phase 2 Winding Transformer	Transformer capacity	50MVA
	Base operation frequency	60Hz
	Winding	YNyn0
	Voltage level	230/25kV
Substation 2 Three Phase Voltage Source	Base MVA	100MVA
	Base voltage	25kV
	Base frequency	60Hz
	Positive sequence impedance	52.9 Ω, 80º
	Zero sequence impedance	52.9 Ω, 80º
3 Phase Resistive Load	Three phase load	20MW
	Three phase RMS voltage	14.4kV
3 Phase Inductive Load	Three phase load	5.0 MVAR
	Three phase RMS voltage	14.4kV
	Rated frequency	60Hz
HV Side Current Transformer	Primary turns	1
	Secondary turns	130
	Secondary resistance	0.5Ω
	Secondary inductance	0.8mH
	Area	$6.5\text{x}10^{-3}\text{m}^2$
	Path length	0.5m
	Frequency	60Hz

<u>LV Side</u> Current Transformer	Primary turns	1
	Secondary turns	1200
	Secondary resistance	0.5Ω
	Secondary inductance	0.8mH
	Area	$6.5x10^{-3}m^2$
	Path length	0.5m
	Frequency	60Hz

4.1.1 Single Line Diagram for 230/25kV YNyn0 50MVA Transformer

Figure 4.1 shows single line diagram for 230/25kV YNyn0 50MVA of power transformer that using for simulation.

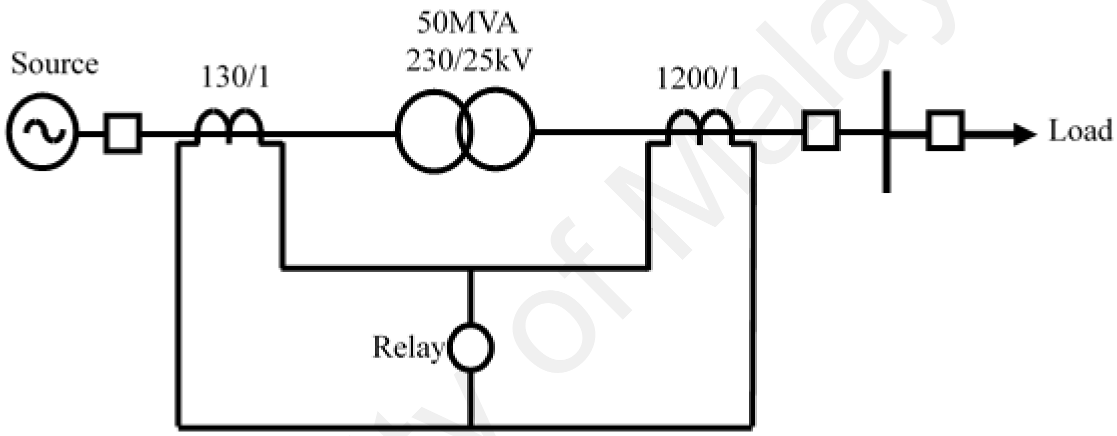

Figure 4.1: Single Line Diagram For Case Study-1

4.1.2 Analysis of Inrush Current for Case Study-1

In this research, the inrush current of transformer is analyzed when the power transformer of case study-1 is energized during normal condition, no load condition, and during internal fault condition. The voltage and current of primary and secondary side of transformer are indicated in the simulation results. The simulation results also showed the differential current of fundamental and second harmonic content. The trip signal of the differential transformer protection shows the operation of the relay, where ‘1’ is trip and ‘0’ is not trip.

(a) ***Energize transformer during normal condition***

Figure 4.2 and Figure 4.3 show the instantaneous voltage and RMS voltage during normal condition. While the instantaneous current and RMS current at HV side of transformer and LV side of transformer during normal condition illustrated in Figure 4.4 to Figure 4.7 respectively. When the transformer is energized in normal operation, the differential current of fundamental and second harmonic content that show in Figure 4.8 is below the setting peak up value as explained in previous chapter. The relay does not issue any trip signal as shown in Figure 4.9. It is the correct operation of the relay. The relay will mal-operate if the overcurrent limit value in OC detection block component of transformer differential protection is set less than the differential current of fundamental and second harmonic content. The analysis of inrush current that impacts towards the relay is shown in Figure 4.10.

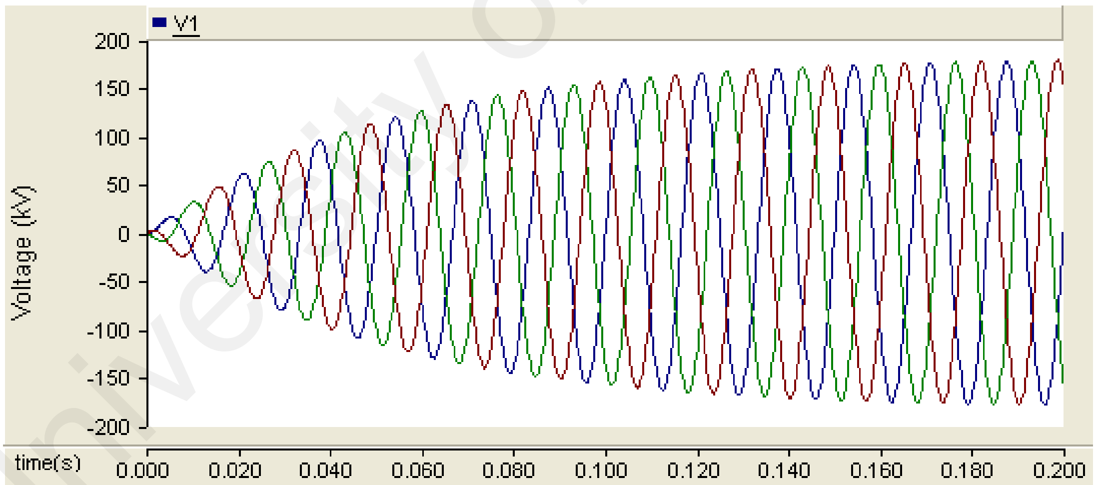

Figure 4.2: Case Study-1 Voltage at HV Side During Normal Condition

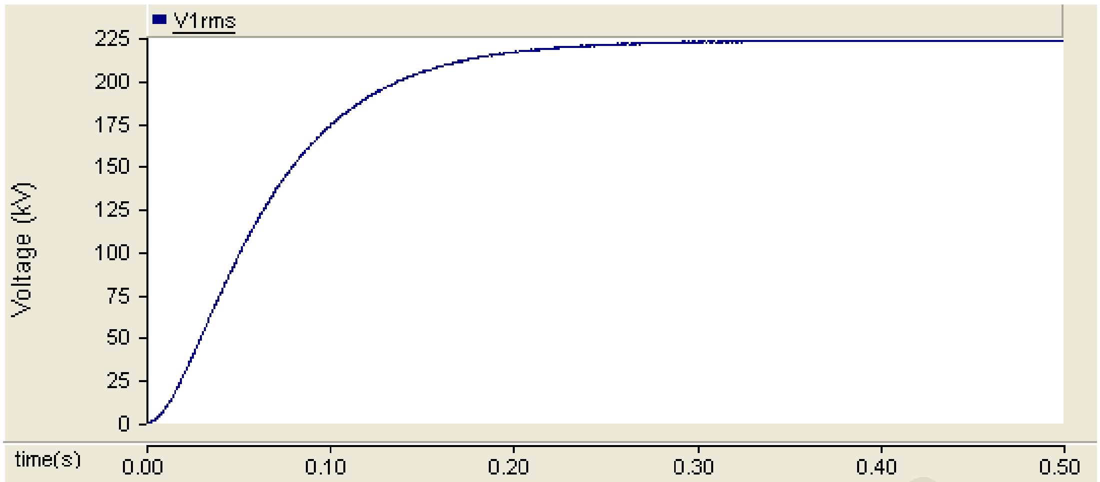

Figure 4.3: Case Study-1 RMS Voltage at HV Side During Normal Condition

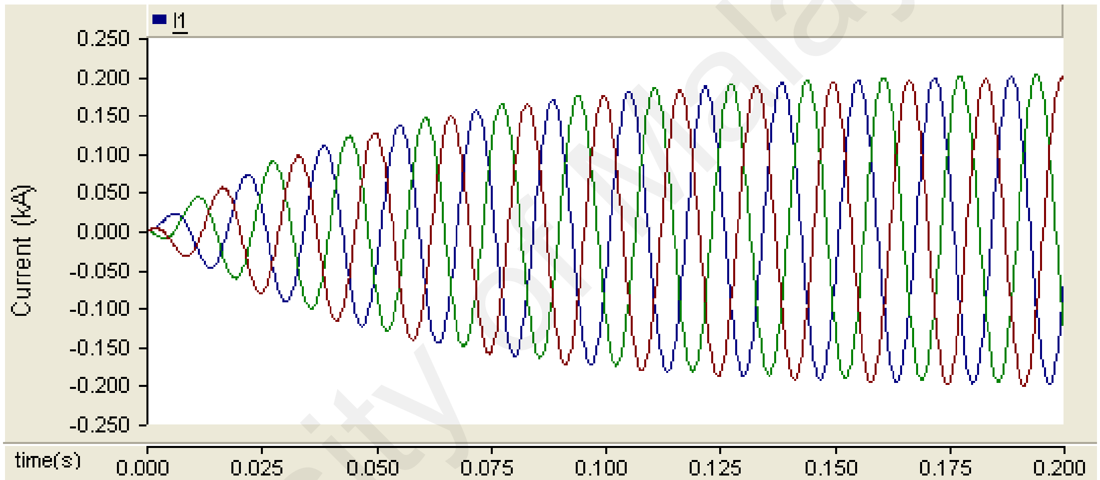

Figure 4.4: Case Study-1 Current at HV Side During Normal Condition

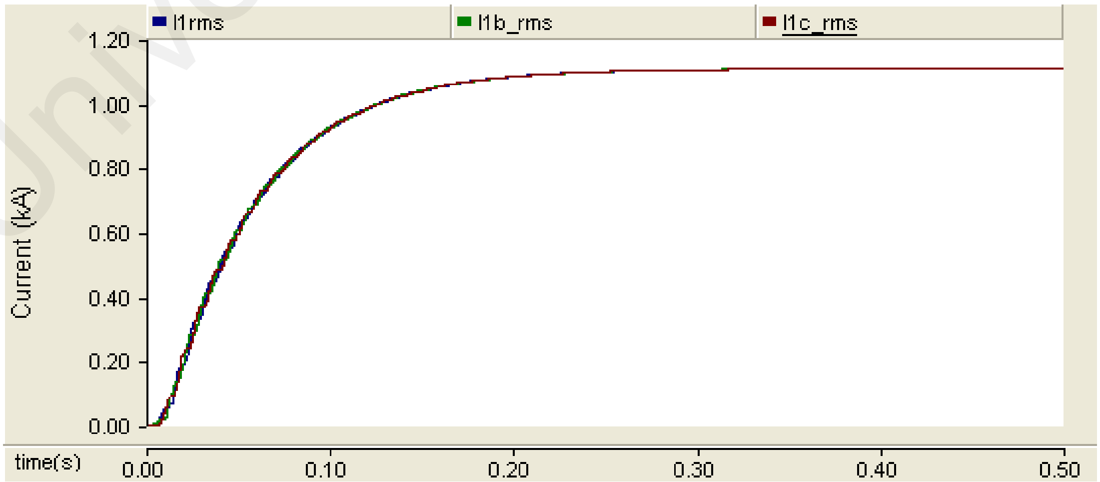

Figure 4.5: Case Study-1 RMS Current at HV Side During Normal Condition

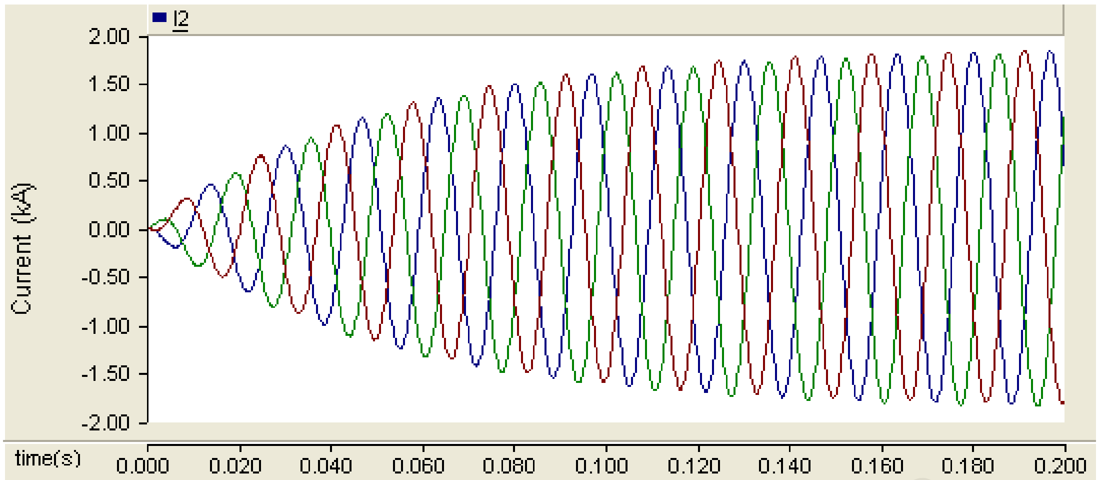

Figure 4.6: Case Study-1 Current at LV Side During Normal Condition

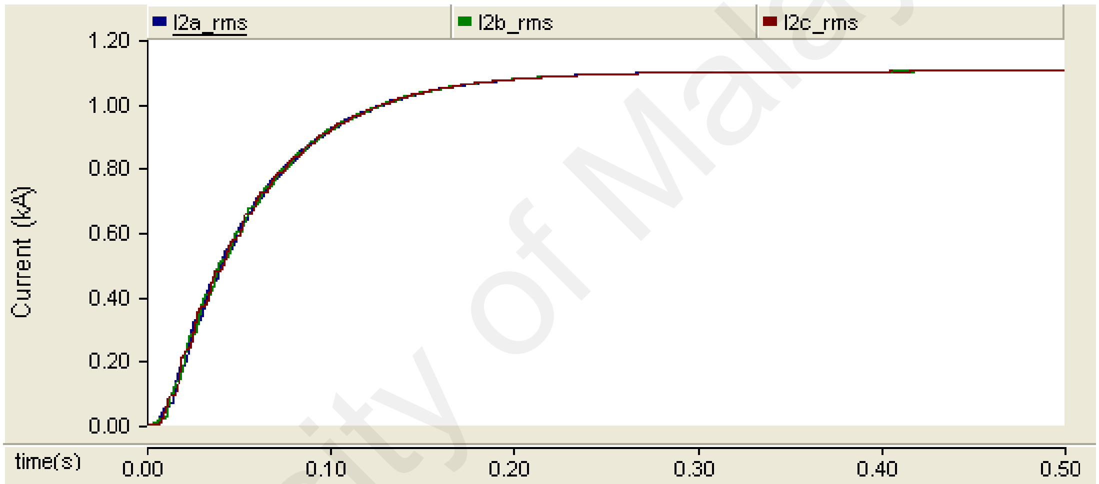

Figure 4.7: Case Study-1 RMS Current at LV Side During Normal Condition

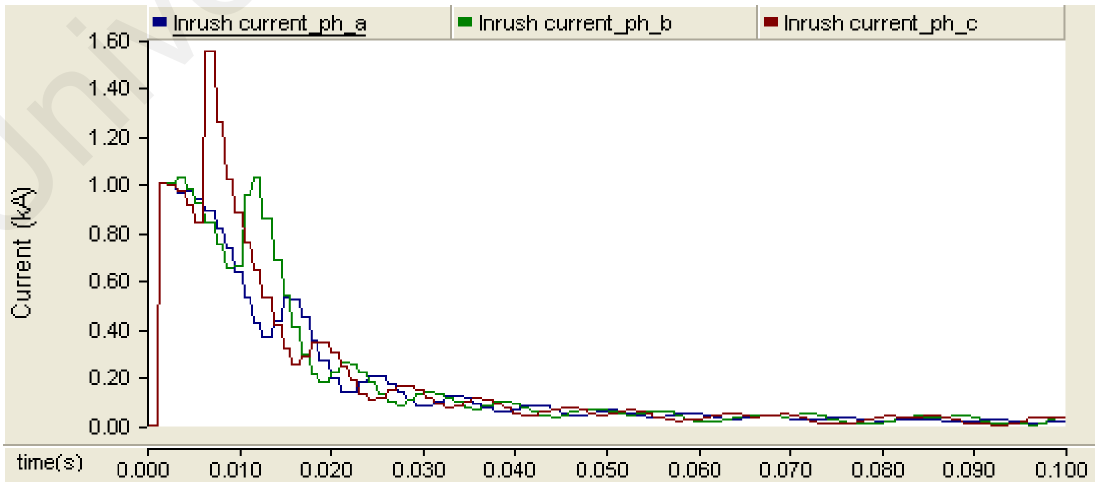

Figure 4.8: Case Study-1 Differential Current of Fundamental & Second Harmonic Content During Normal Condition

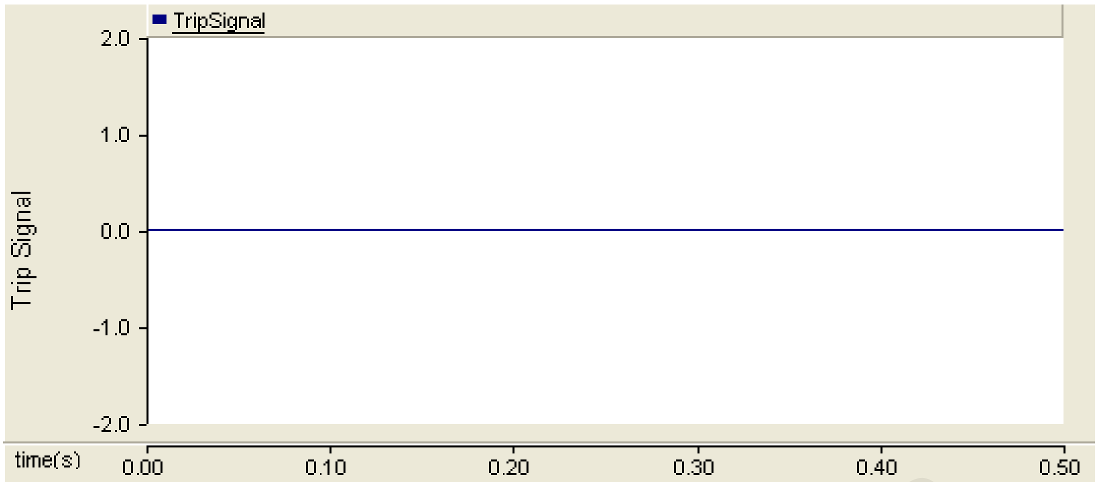

Figure 4.9: Case Study-1 Trip Signal During Normal Condition

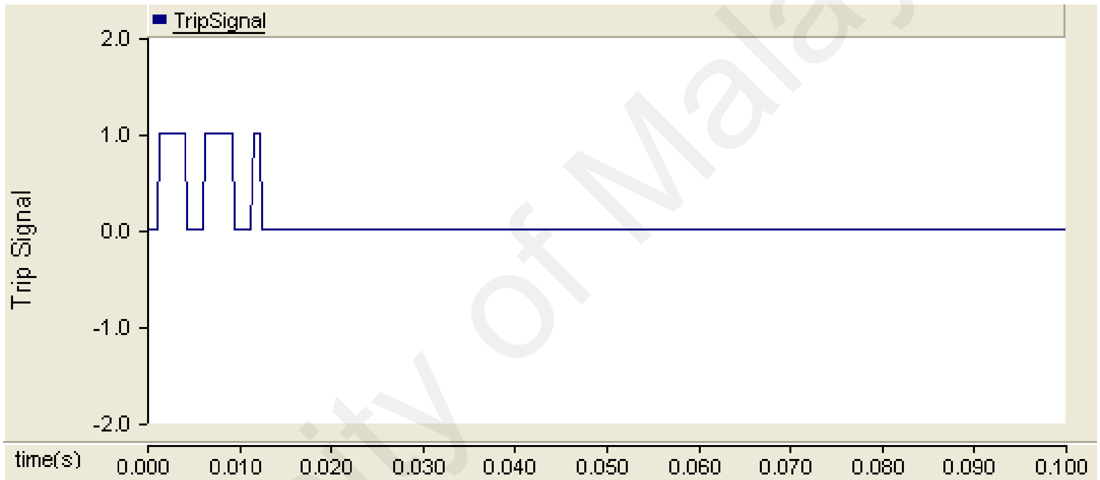

Figure 4.10: Case Study-1 Mal-Operation of Trip Signal

(b) ***Energize transformer during no load condition***

Figure 4.11 and Figure 4.12 show the instantaneous voltage and RMS voltage during no load condition. While the instantaneous current and RMS current at HV side of transformer and LV side of transformer during normal condition illustrated in Figure 4.13 to Figure 4.16 respectively. When the transformer energized with circuit breakers of loads is opened, the inrush current as shown in Figure 4.17 is higher than the inrush current during normal condition, but less than the peak up value setting. Figure 4.18 shows the trip signal of the differential relay. The relay operation does not issue any trip signal and it is the correct operation of the relay.

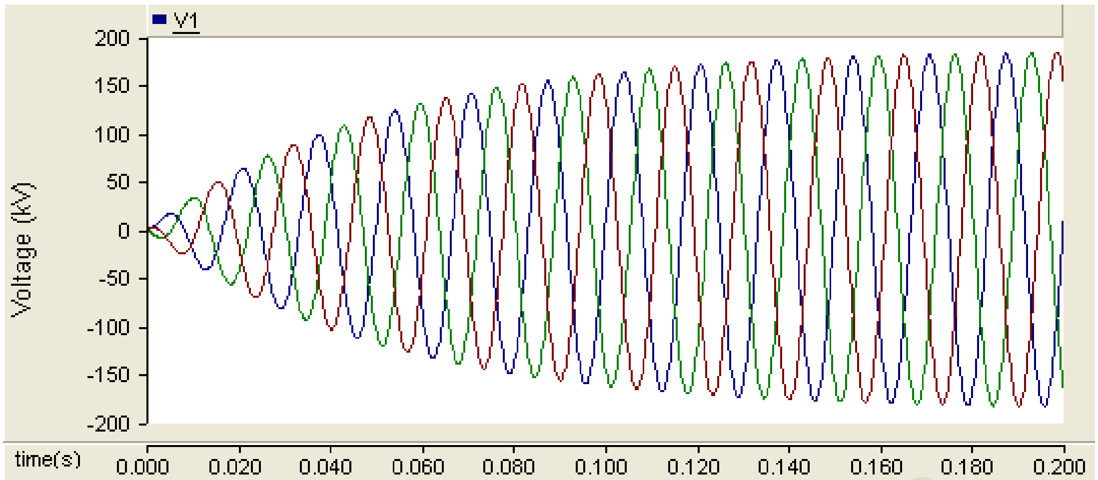

Figure 4.11: Case Study-1 Voltage at HV Side During No Load Condition

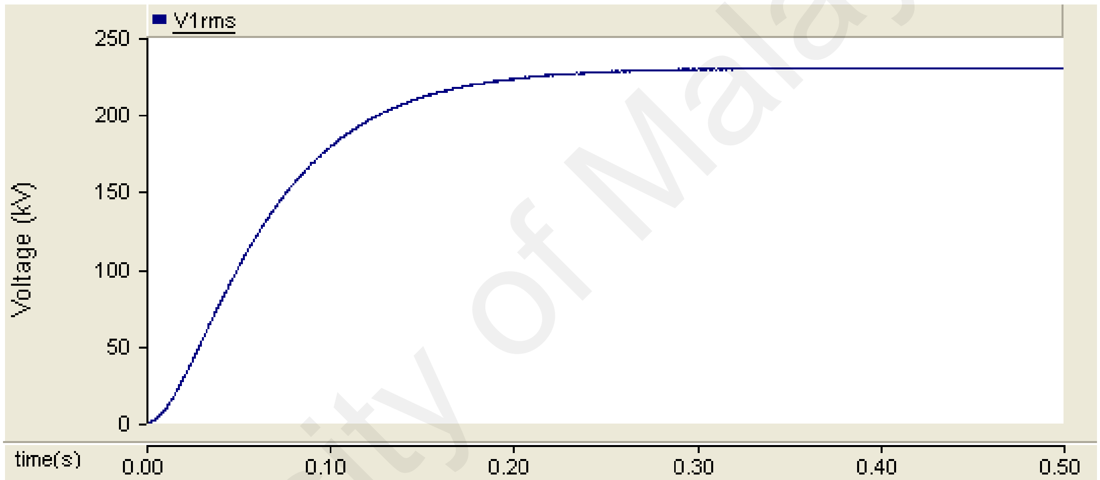

Figure 4.12: Case Study-1 RMS Voltage at HV Side During No Load Condition

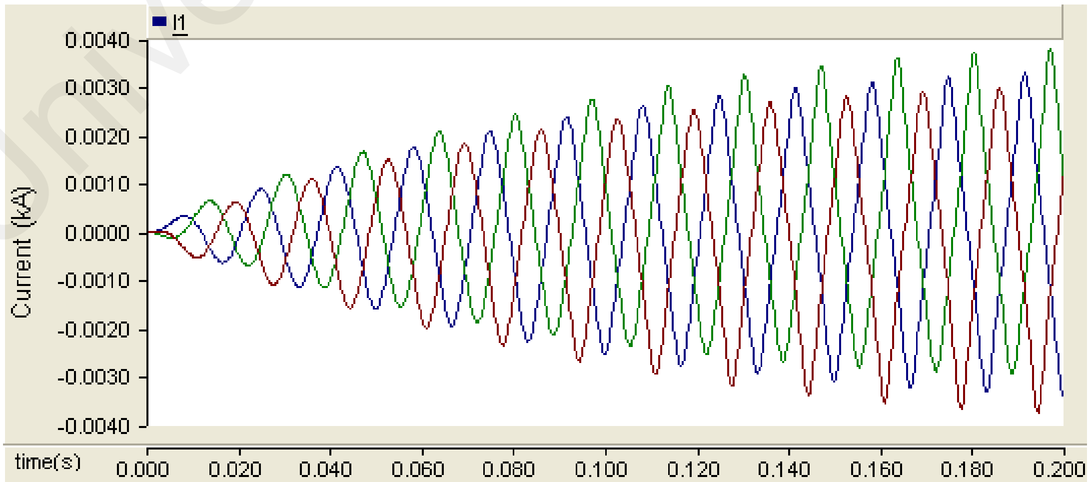

Figure 4.13: Case Study-1 Current at HV Side During No Load Condition

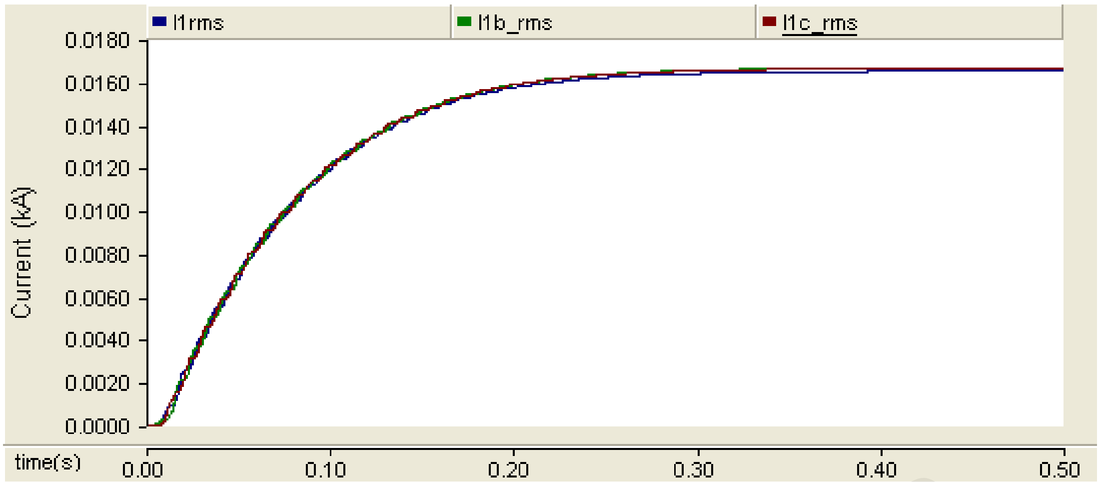

Figure 4.14: Case Study-1 RMS Current at HV Side During No Load Condition

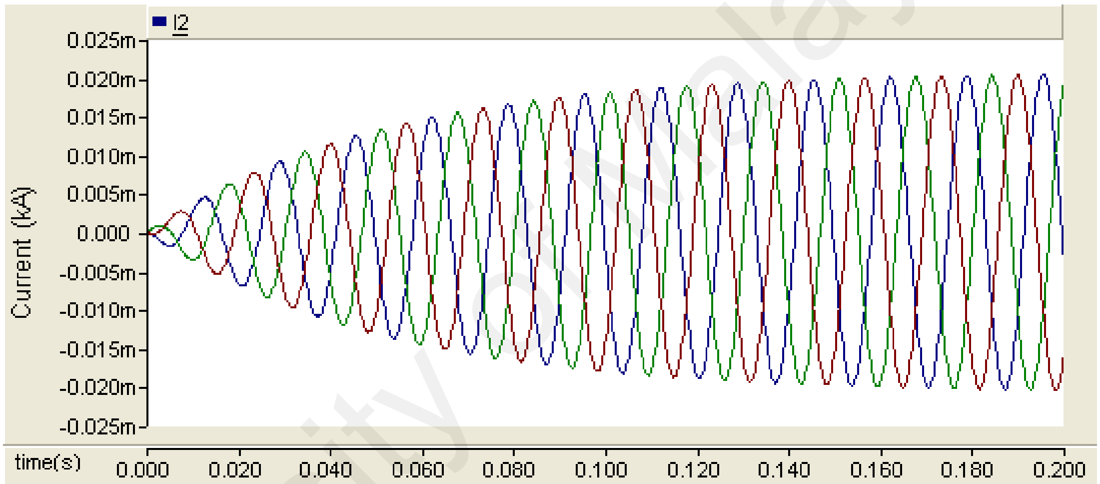

Figure 4.15: Case Study-1 Current at LV Side During No Load Condition

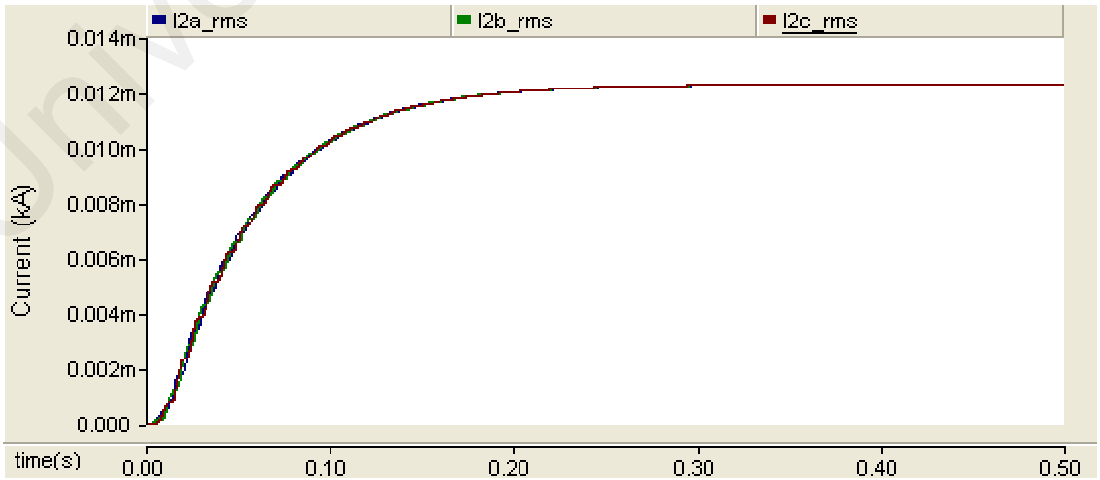

Figure 4.16: Case Study-1 RMS Current at LV Side During No Load Condition

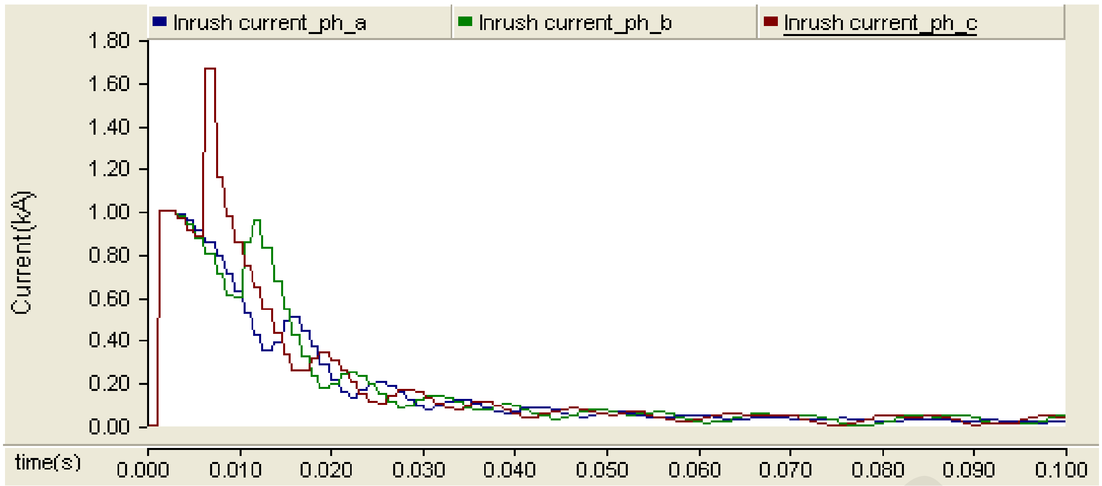

Figure 4.17: Case Study-1 Differential Current of Fundamental & Second Harmonic Content During No Load Condition

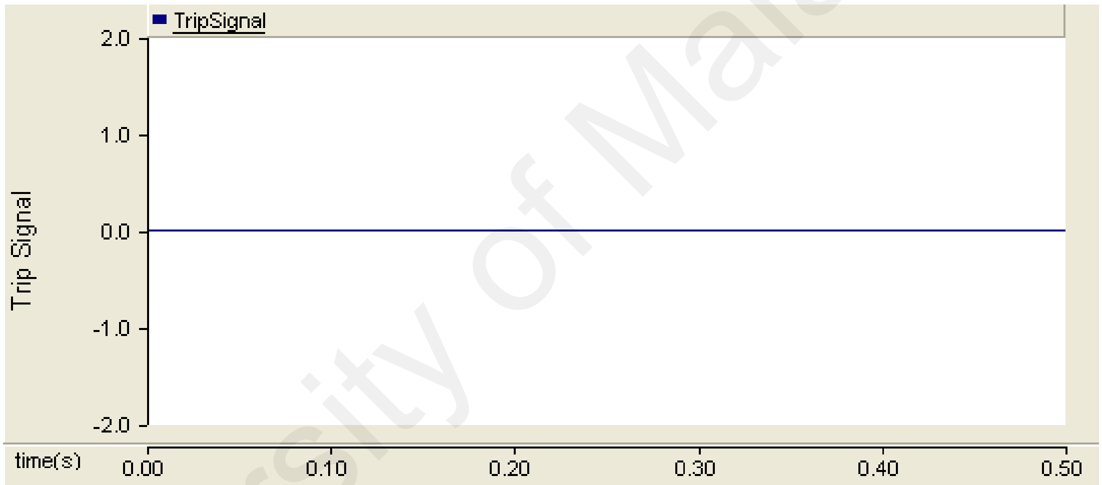

Figure 4.18: Case Study-1 Trip Signal During No Load Condition

(c) Energize transformer during internal fault condition (A-G fault)

Waveforms in Figure 4.19 and Figure 4.20 show the current at HV side of transformer during single-phase-to-ground A-G fault is applied to the power system between 0s to 0.05s. The instantaneous and RMS current at LV side illustrated in Figure 4.21 and Figure 4.22 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.23 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.24, where the relay only trips during fault duration.

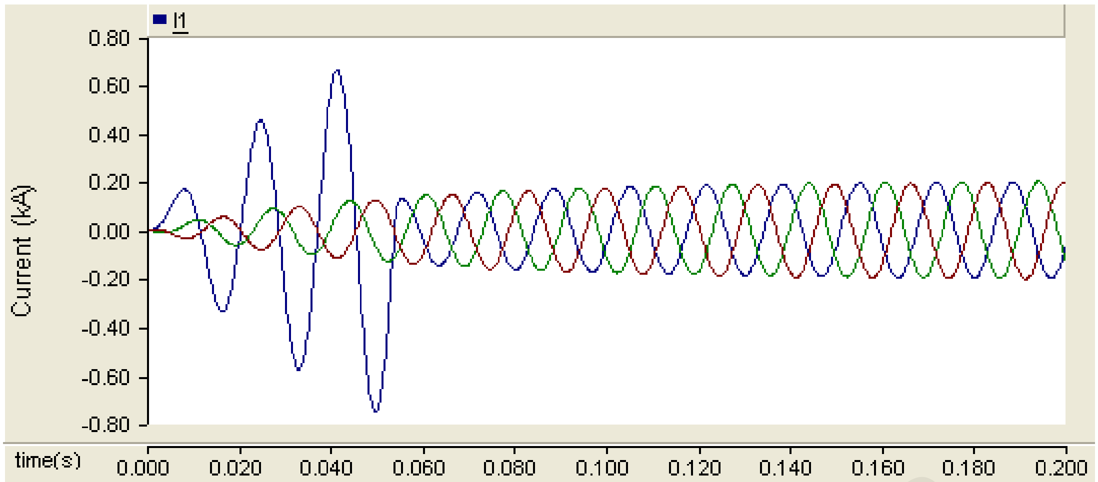

Figure 4.19: Case Study-1 Current at HV Side During A-G Fault

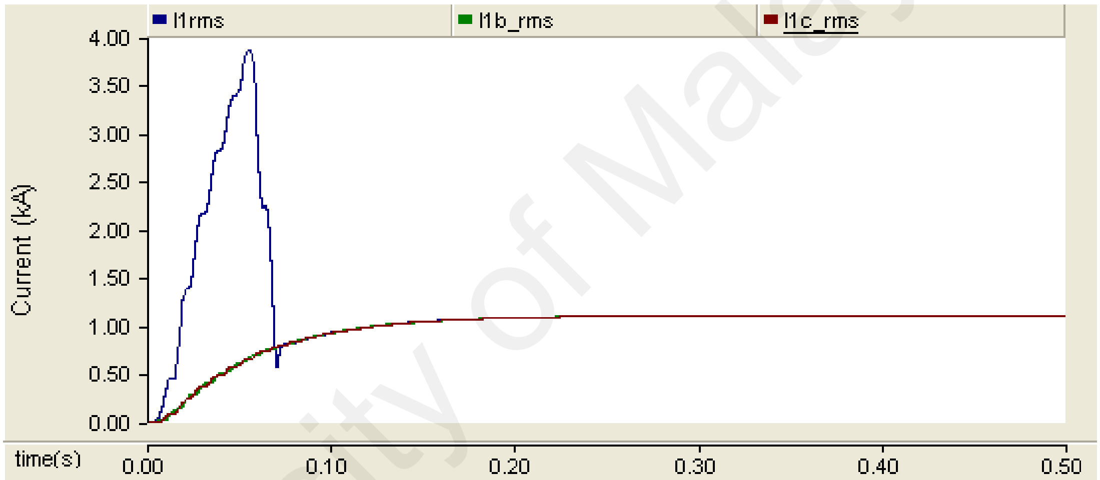

Figure 4.20: Case Study-1 RMS Current at HV Side During A-G Fault

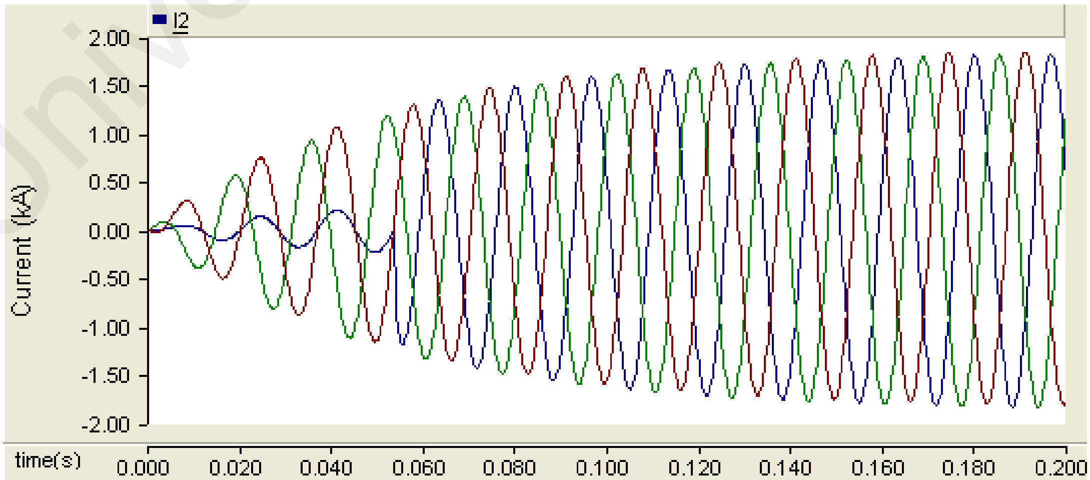

Figure 4.21: Case Study-1 Current at LV Side During A-G Fault

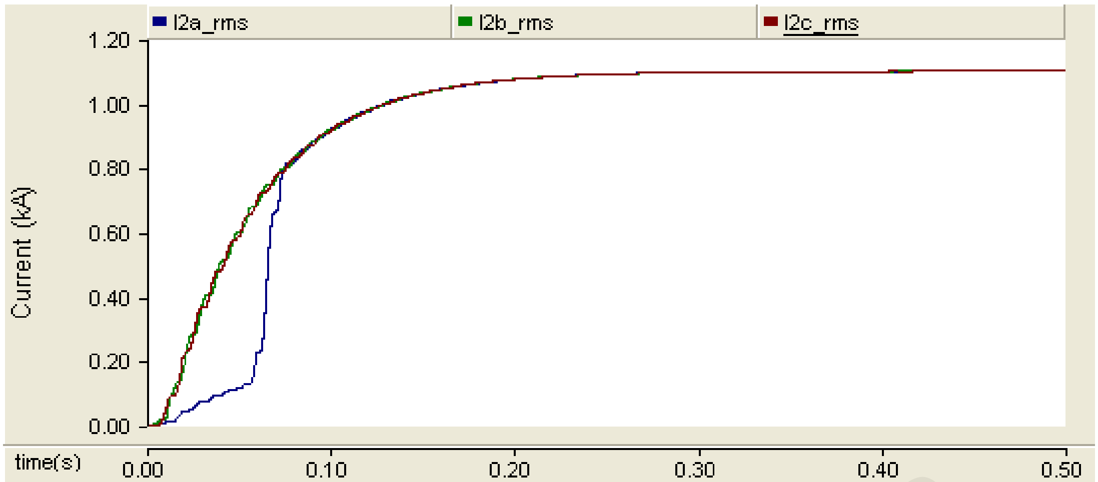

Figure 4.22: Case Study-1 RMS Current at LV Side During A-G Fault

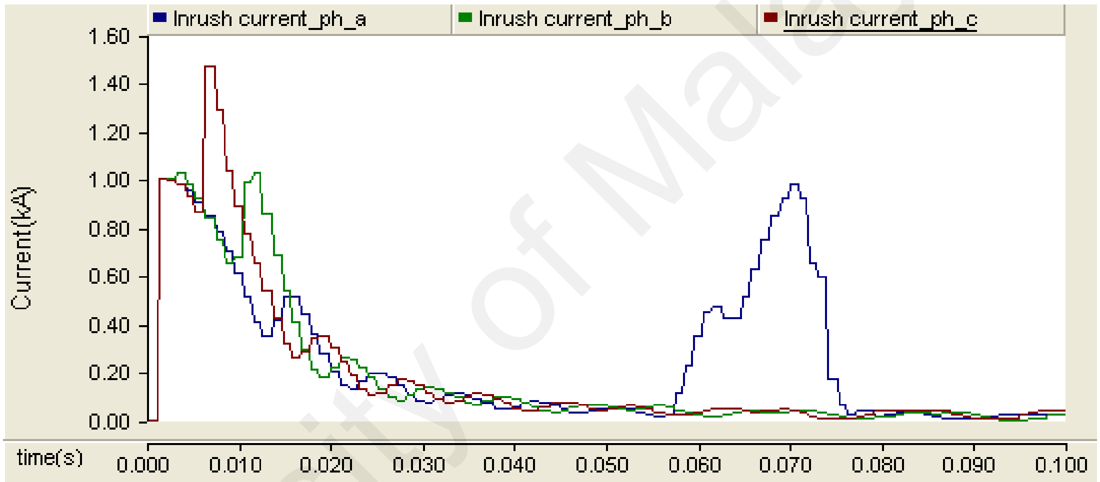

Figure 4.23: Case Study-1 Differential Current of Fundamental & Second Harmonic Content During A-G Fault Condition

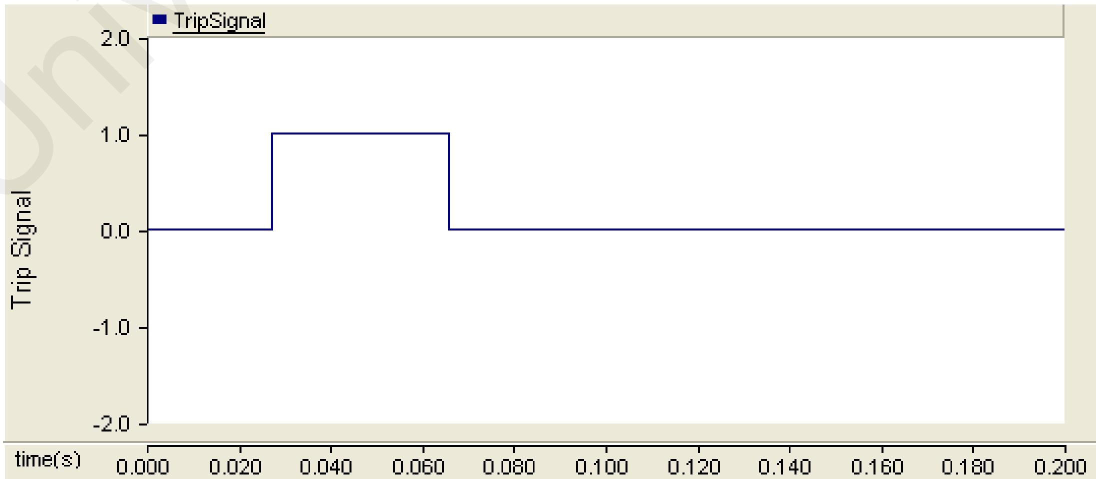

Figure 4.24: Case Study-1 Trip Signal During A-G Fault

(d) ***Energize transformer during internal fault condition (A-B-G fault)***

Waveforms in Figure 4.25 and Figure 4.26 show the current at HV side of transformer during phase-to-phase-to-ground A-B-G fault is applied to the power system between 0s to 0.05s. The instantaneous and RMS current at LV side illustrated in Figure 4.27 and Figure 4.28 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.29 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.30, where the relay only trips during fault duration.

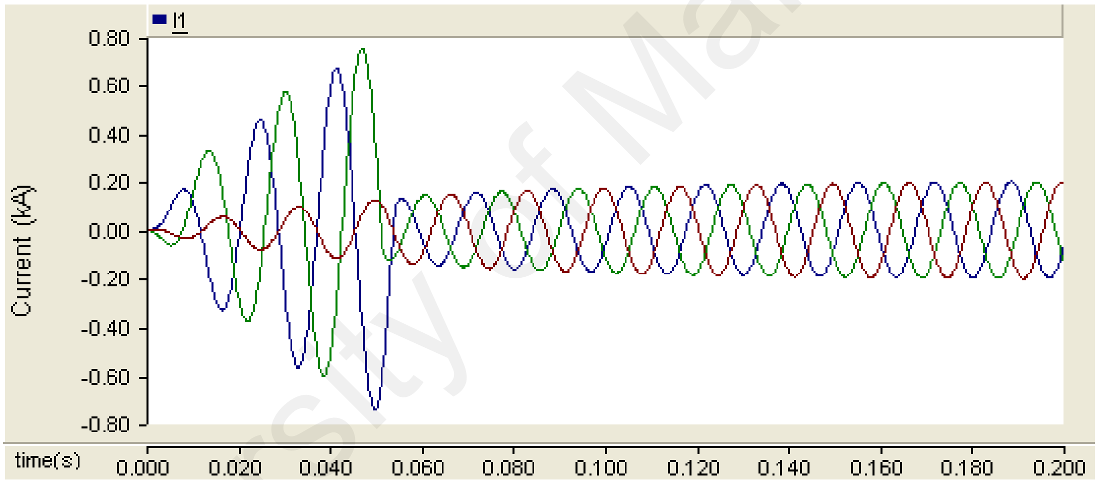

Figure 4.25 : Case Study-1 Current at HV Side During A-B-G Fault

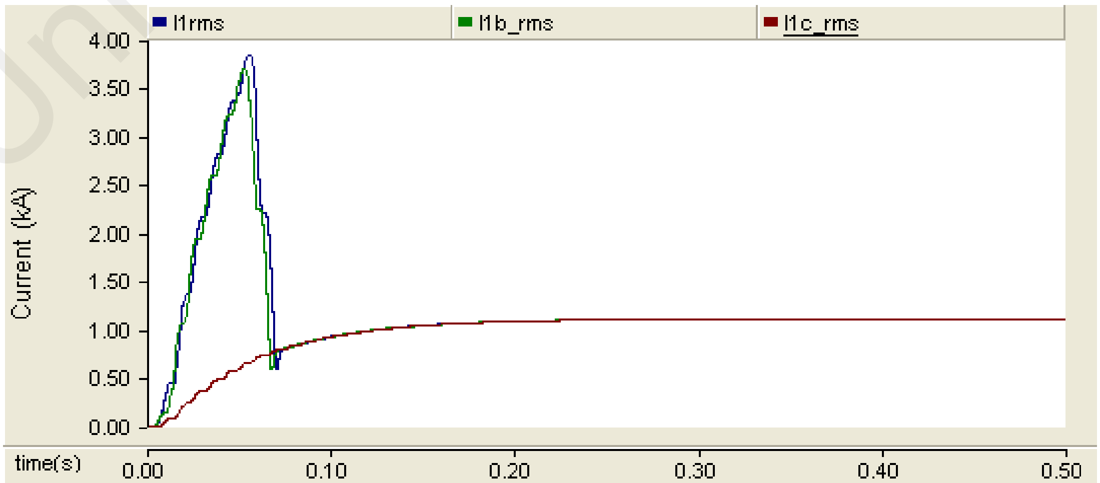

Figure 4.26: Case Study-1 RMS Current at HV Side During A-B-G Fault

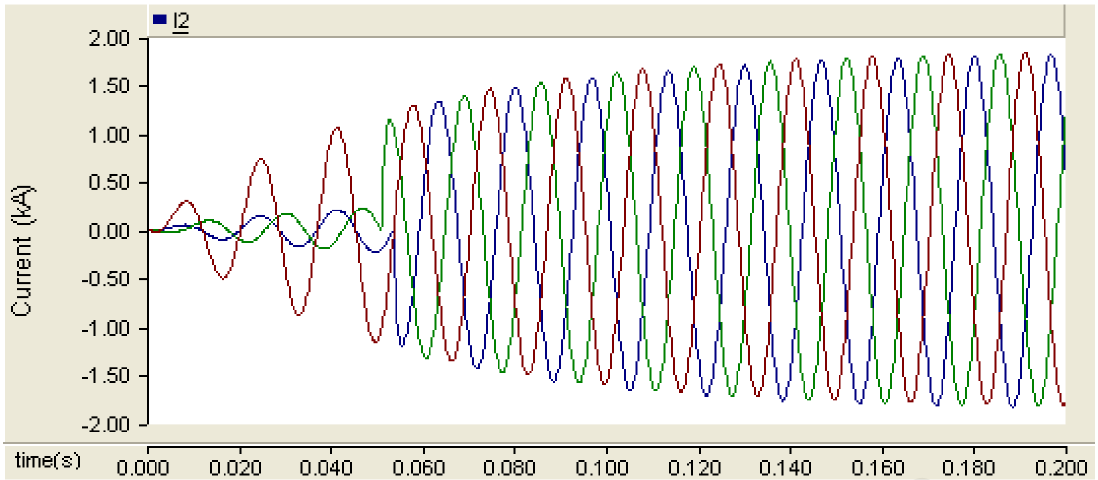

Figure 4.27: Case Study-1 Current at LV Side During A-B-G Fault

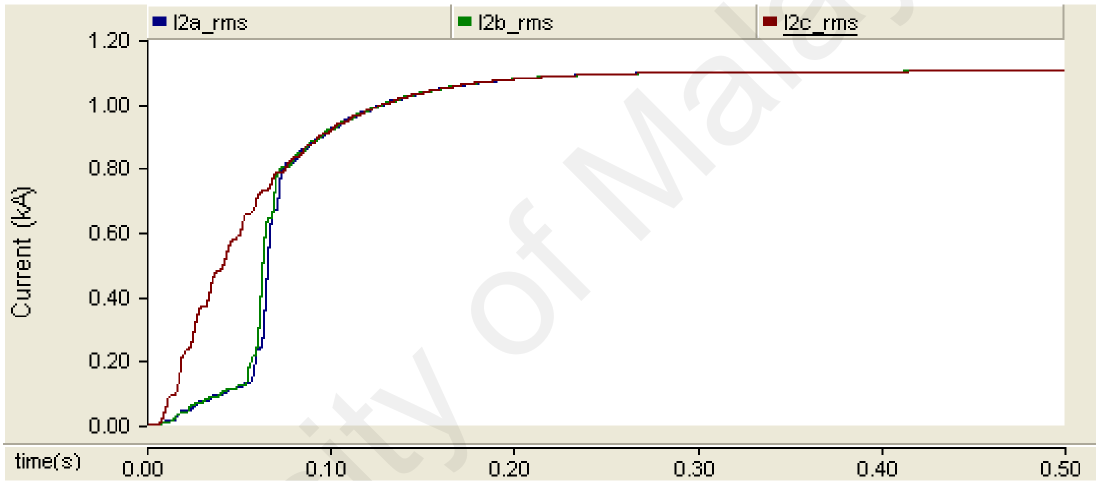

Figure 4.28: Case Study-1 RMS Current at LV Side During A-B-G Fault

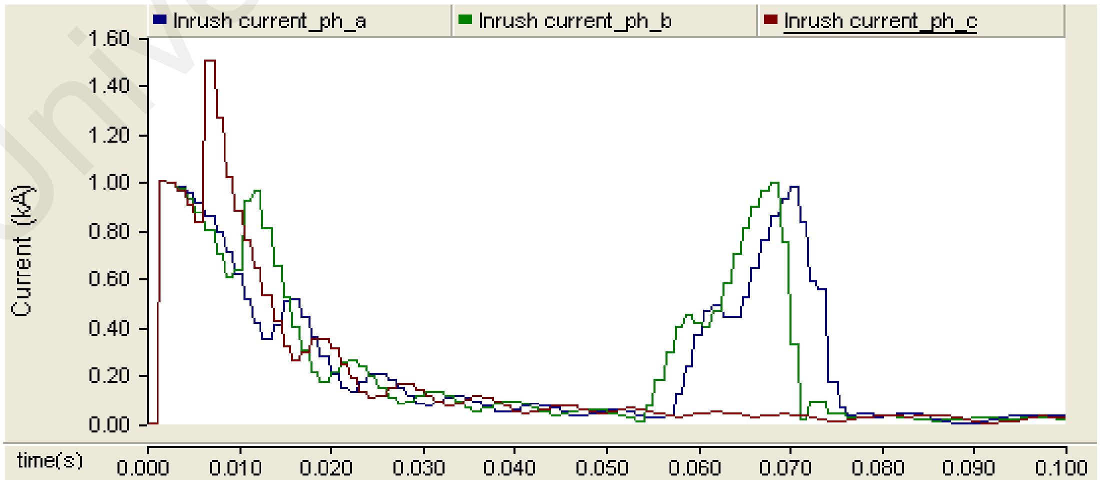

Figure 4.29: Case Study-1 Differential Current of Fundamental & Second Harmonic Content During A-B-G Fault Condition

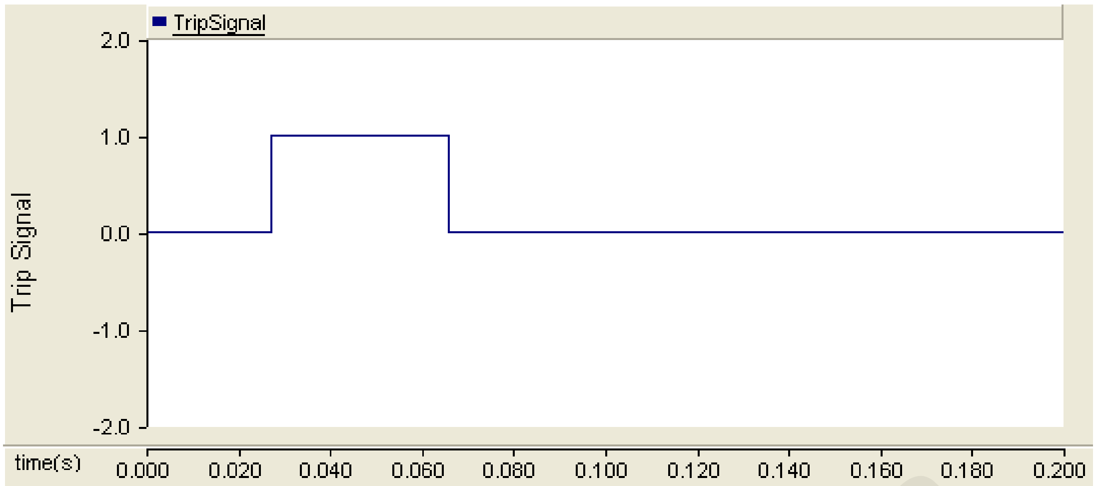

Figure 4.30: Case Study-1 Trip Signal During A-B-G Fault

*(e) **Energize transformer during internal fault condition (A-B-C-G fault)***

Waveforms in Figure 4.31 and Figure 4.32 show the current at HV side of transformer during three-phase-to-ground A-B-C-G fault is applied to the power system between 0s to 0.05s. The instantaneous and RMS current at LV side illustrated in Figure 4.33 and Figure 4.34 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.35 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.36, where the relay only trips during fault duration.

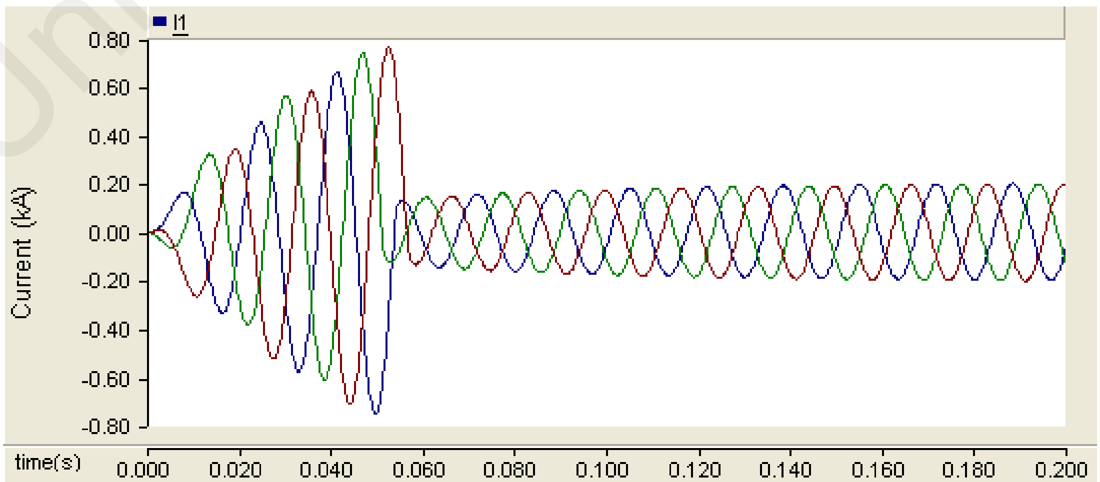

Figure 4.31: Case Study-1 Current at HV Side During A-B-C-G Fault

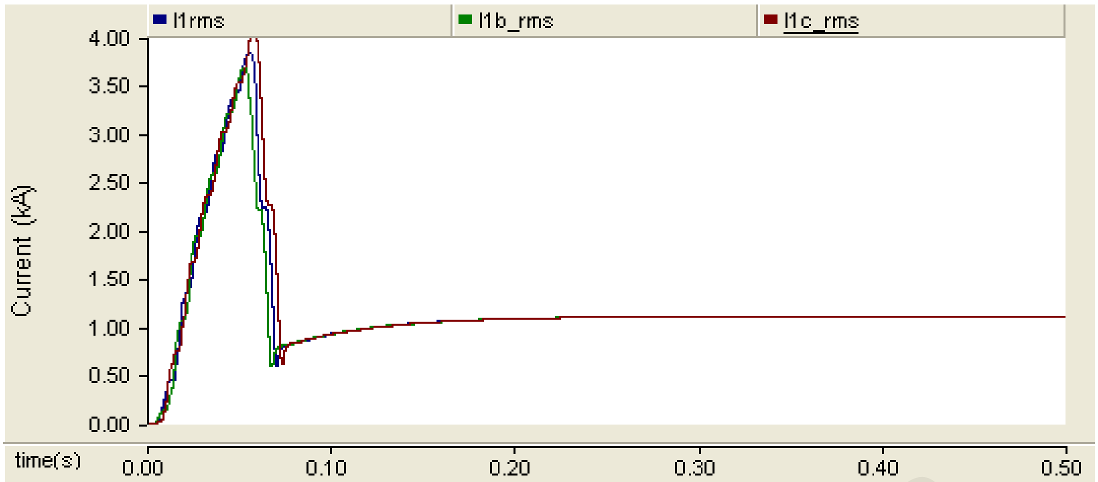

Figure 4.32: Case Study-1 RMS Current at HV Side During A-B-C-G Fault

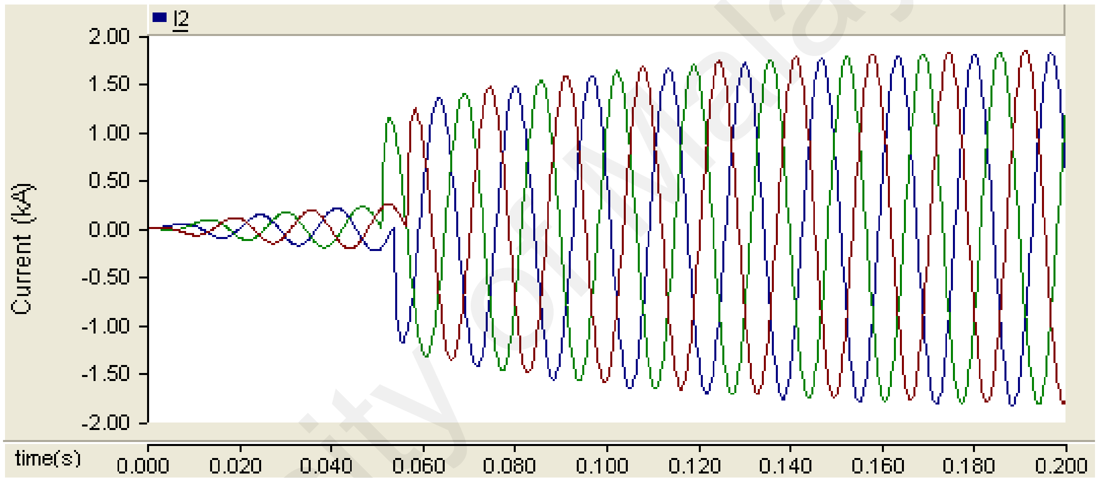

Figure 4.33: Case Study-1 Current at LV Side During A-B-C-G Fault

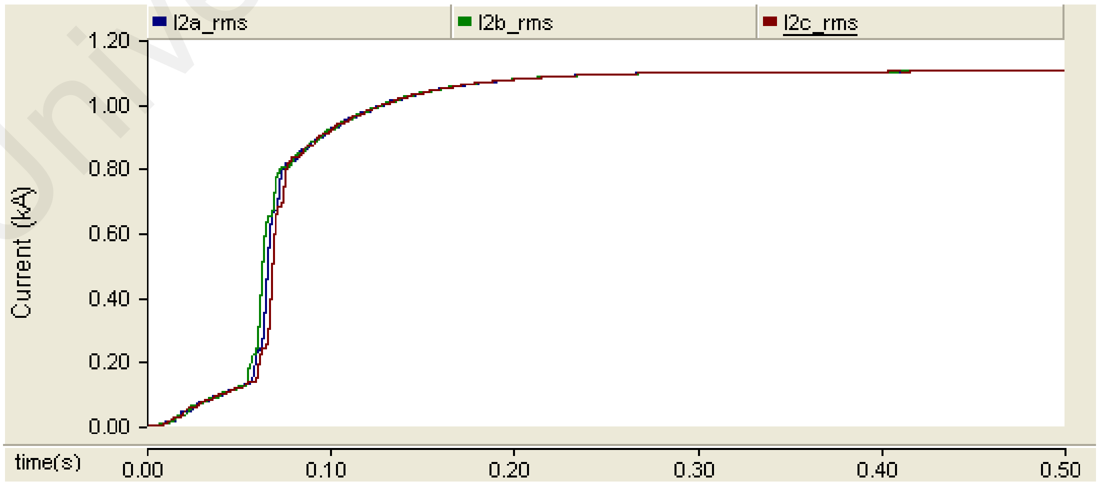

Figure 4.34: Case Study-1 RMS Current at LV Side During A-B-C-G Fault

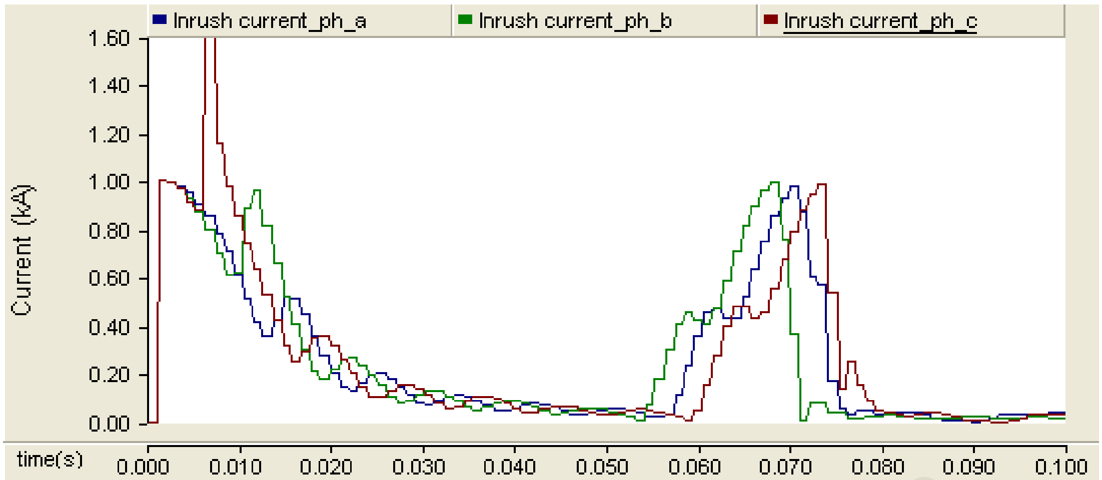

Figure 4.35: Case Study-1 Differential Current of Fundamental & Second Harmonic Content During A-B-C-G Fault Condition

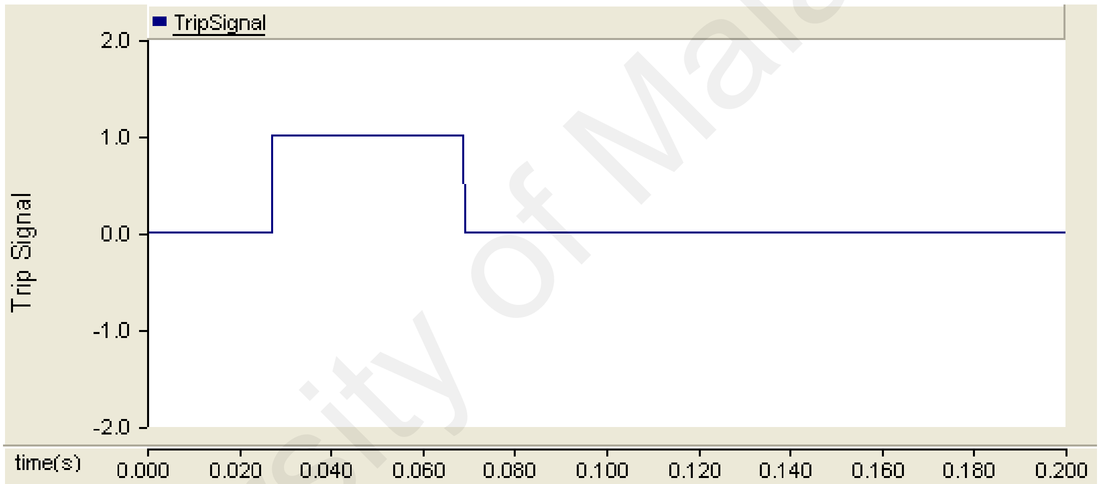

Figure 4.36: Case Study-1 Trip Signal During A-B-C-G Fault

4.2 Case Study-2: 132/33kV YNyn0 90MVA Power Transformer

In case study-2, the modeling power transformer 132/33kV 90MVA with frequency of 50Hz power system used the parameters as follows:

Table 4.2: Parameters Setting Case Study-2

Equipment	Parameter	
Substation 1 Three Phase Voltage Source	Base MVA	100MVA
	Base voltage	132kV
	Base frequency	50Hz
	Positive sequence impedance	52.9 Ω, 80º
	Zero sequence impedance	52.9 Ω, 80º
3 Phase 2 Winding Transformer	Transformer capacity	90MVA
	Base operation frequency	50Hz
	Winding	YNyn0
	Voltage level	132/33kV
Substation 2 Three Phase Voltage Source	Base MVA	100MVA
	Base voltage	33kV
	Base frequency	50Hz
	Positive sequence impedance	52.9 Ω, 80º
	Zero sequence impedance	52.9 Ω, 80º
3 Phase Resistive Load	Three phase load	20MW
	Three phase RMS voltage	11kV
3 Phase Inductive Load	Three phase load	5.0 MVAR
	Three phase RMS voltage	11kV
	Rated frequency	50Hz
HV Side Current Transformer	Primary turns	1
	Secondary turns	400
	Secondary resistance	0.5Ω
	Secondary inductance	0.8mH
	Area	$6.5\text{x}10^{-3}\text{m}^2$
	Path length	0.5m
	Frequency	50Hz
LV Side Current Transformer	Primary turns	1
	Secondary turns	1600
	Secondary resistance	0.5Ω
	Secondary inductance	0.8mH
	Area	$6.5\text{x}10^{-3}\text{m}^2$
	Path length	0.5m
	Frequency	50Hz

4.2.1 Single Line Diagram for 132/33kV YNyn0 90MVA Transformer

Figure 4.37 shows single line diagram for 132/33kV YNyn0 90MVA of power transformer that using for simulation.

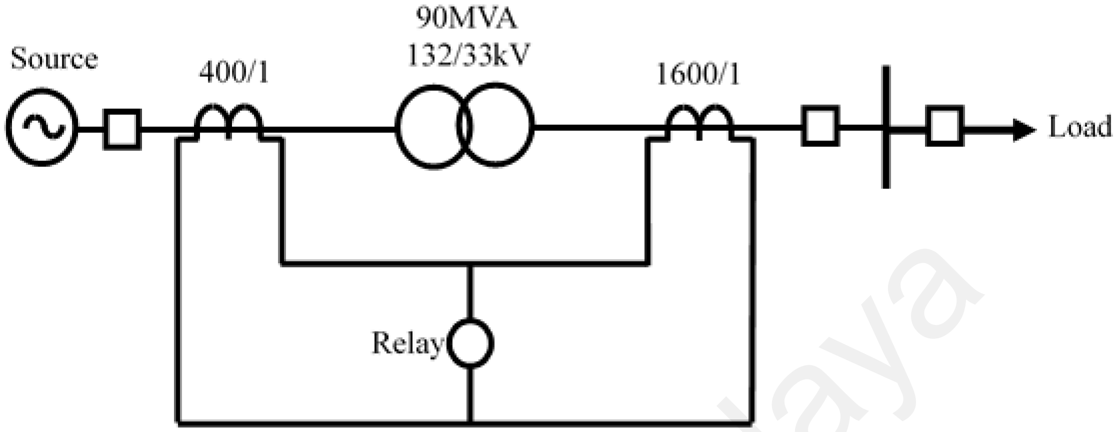

Figure 4.37: Single Line Diagram For Case Study-2

4.2.2 Analysis of Inrush Current for Case Study-2

In this research, the inrush current of transformer is analyzed when the power transformer of case study-2 is energized during normal condition, no load condition, and during internal fault condition. The voltage and current of primary and secondary side of transformer are indicated in the simulation results. The simulation results also showed the differential current of fundamental and second harmonic content. The trip signal of the differential transformer protection shows the operation of the relay, where ‘1’ is trip and ‘0’ is not trip.

*(a) **Energize transformer during normal condition***

Figure 4.38 and Figure 4.39 show the instantaneous voltage and RMS voltage during normal condition. While the instantaneous current and RMS current at HV side of transformer and LV side of transformer during normal condition illustrated in Figure 4.40 to Figure 4.43 respectively. When the transformer is energized in normal operation, the differential current of fundamental and second harmonic content that show in Figure 4.44 is below the setting peak up value and the relay does not issue any trip signal as shown in

Figure 4.45. It is the correct operation of the relay. The relay will mal-operate if the overcurrent limit value in OC detection block component of transformer differential protection is set less than the differential current of fundamental and second harmonic content. The analysis of inrush current that impacts towards the relay is shown in Figure 4.46.

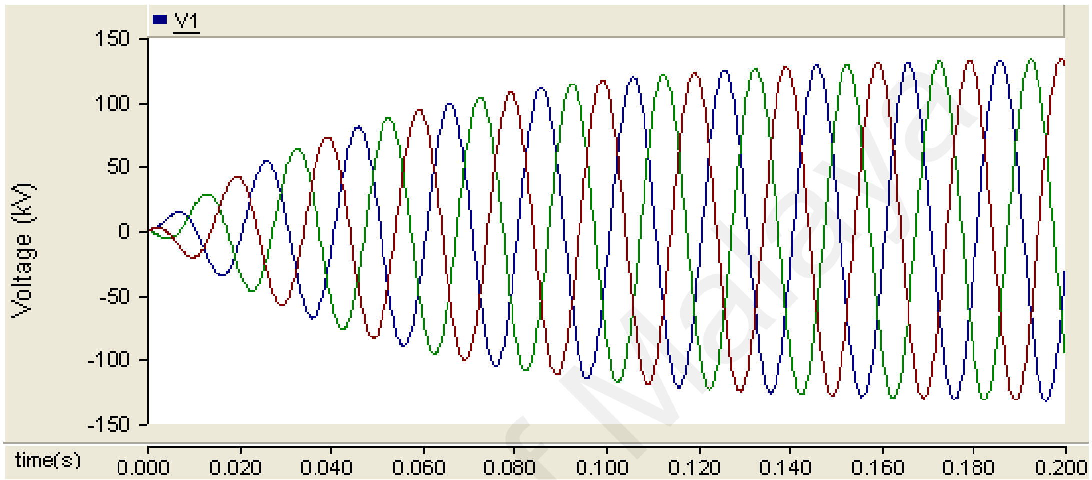

Figure 4.38: Case Study-2 Voltage at LV Side During Normal Condition

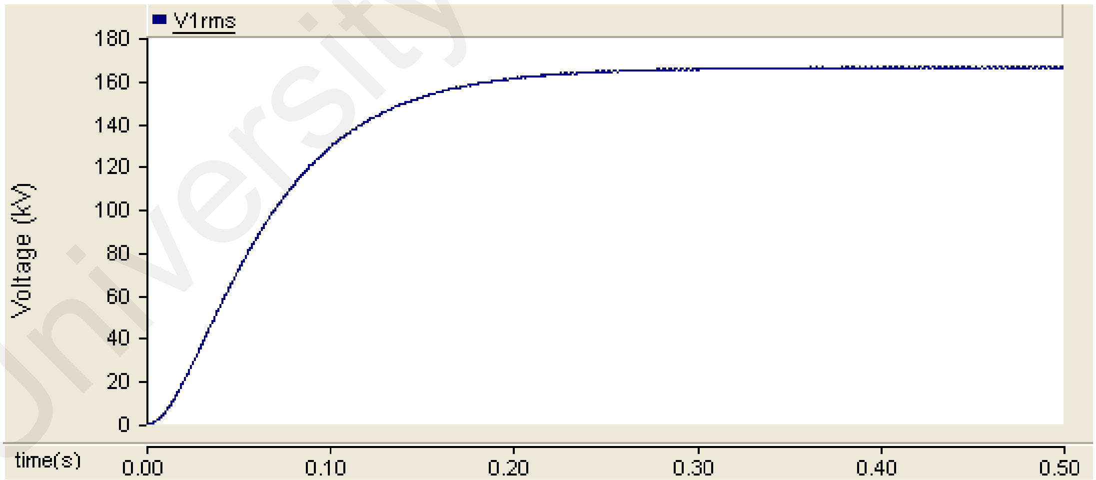

Figure 4.39: Case Study-2 RMS Voltage at LV Side During Normal Condition

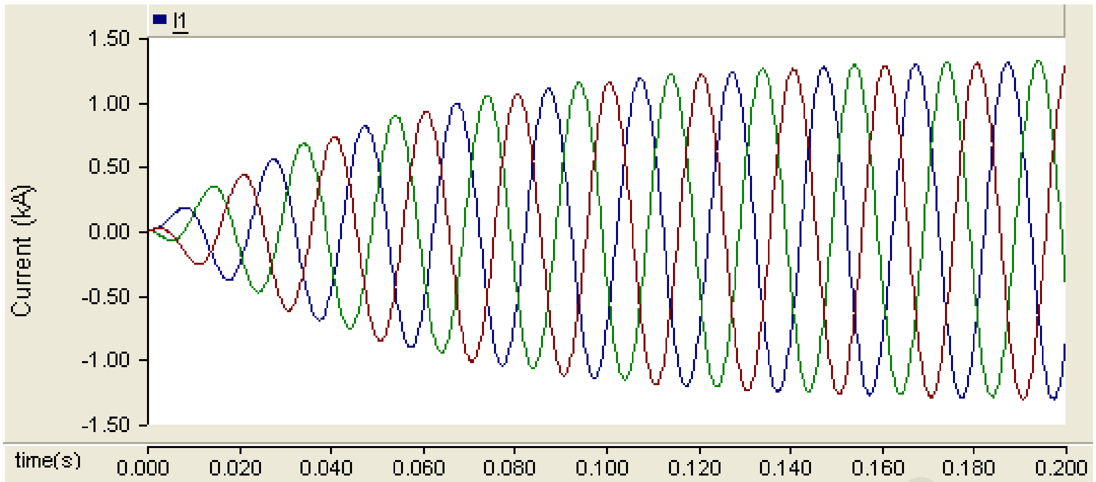

Figure 4.40: Case Study-2 Current at HV Side During Normal Condition

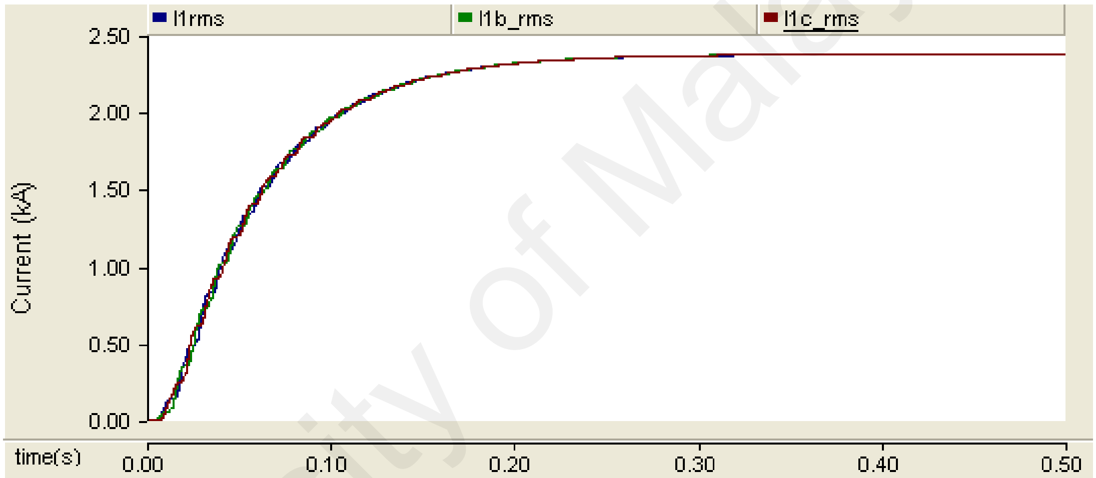

Figure 4.41: Case Study-2 RMS Current at HV Side During Normal Condition

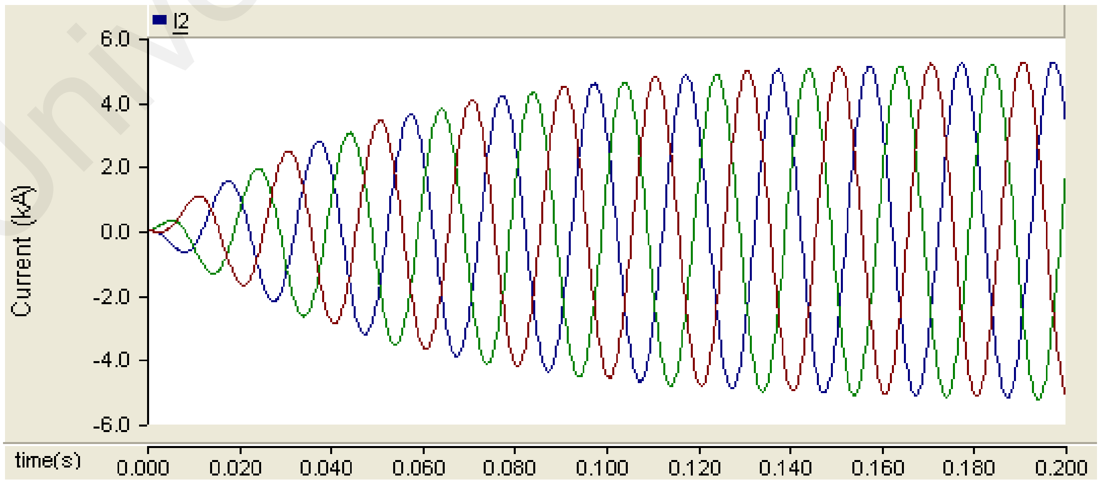

Figure 4.42: Case Study-2 Current at LV Side During Normal Condition

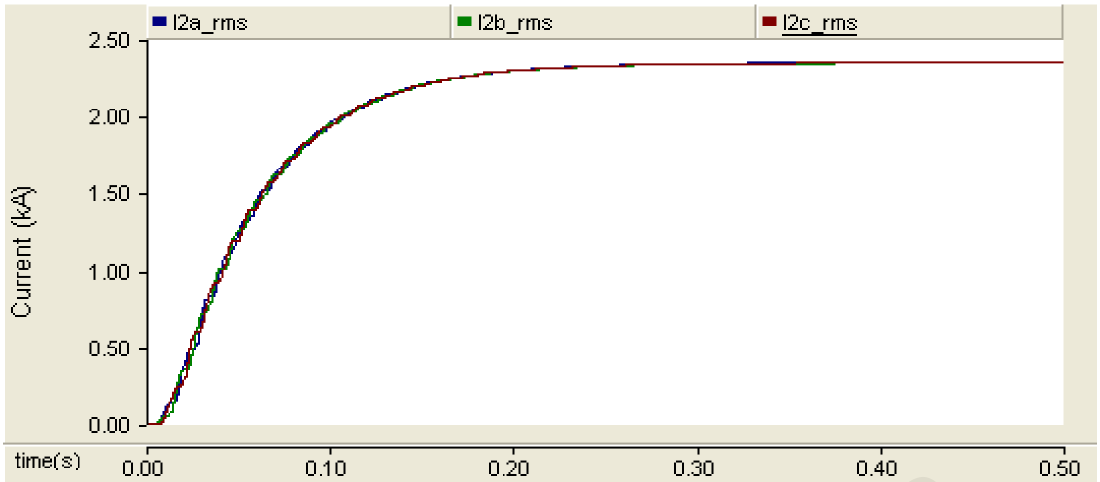

Figure 4.43: Case Study-2 RMS Current at LV Side During Normal Condition

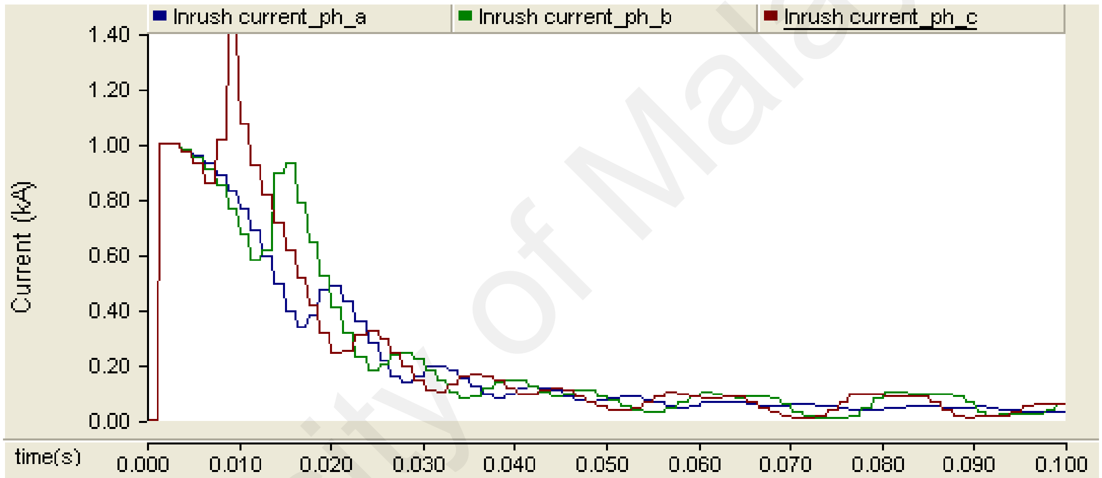

Figure 4.44: Case Study-2 Differential Current of Fundamental & Second Harmonic Content During Normal Condition

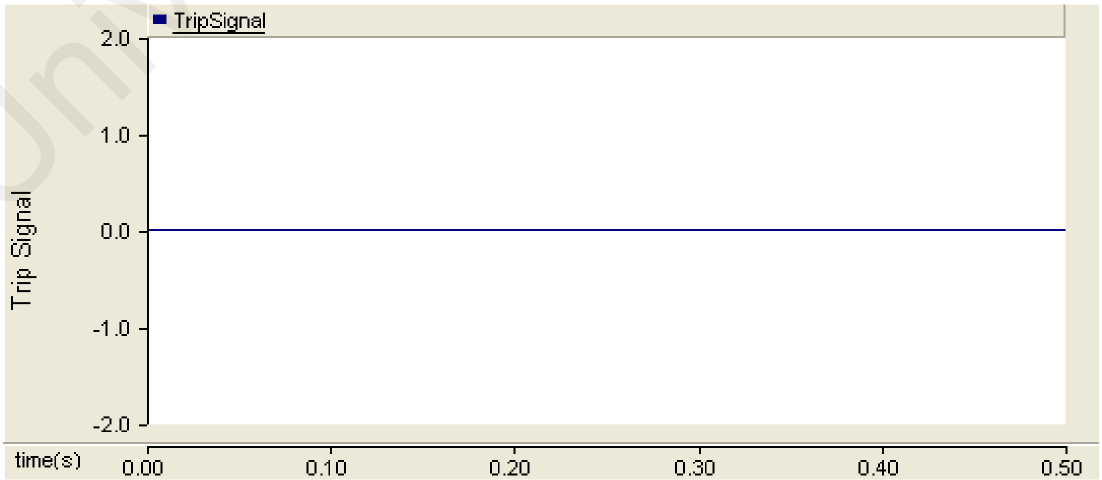

Figure 4.45: Case Study-2 Trip Signal During Normal Condition

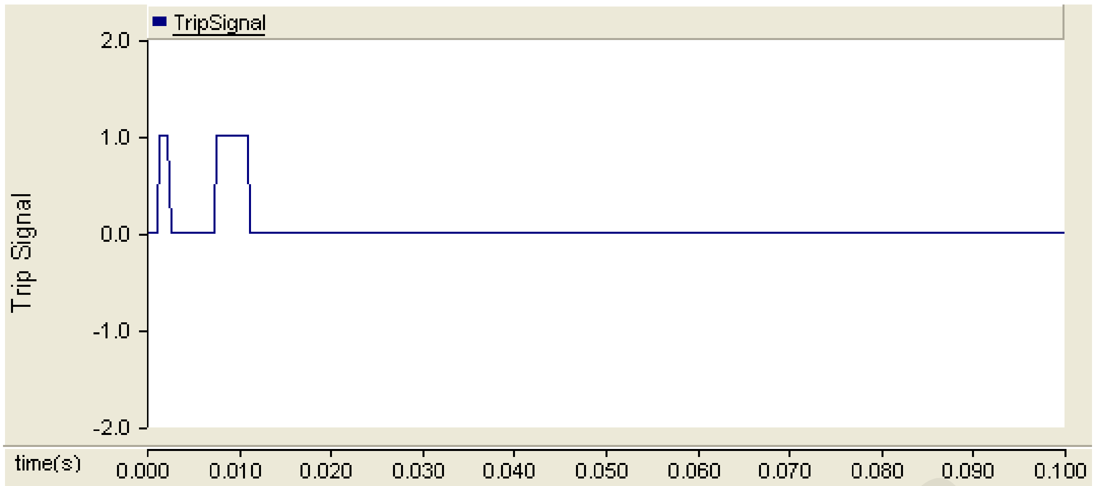

Figure 4.46: Case Study-2 Mal-Operation of Trip Signal

(b) ***Energize transformer during no load condition***

Figure 4.47 and Figure 4.48 show the instantaneous voltage and RMS voltage during no load condition. While the instantaneous current and RMS current at HV side of transformer and LV side of transformer during normal condition illustrated in Figure 4.49 to Figure 4.52 respectively. When the transformer energized with circuit breakers of loads is opened, the inrush current as shown in Figure 4.53 is higher than the inrush current during normal condition, but less than the peak up value setting. Figure 4.54 shows the trip signal of the differential relay. The relay operation does not issue any trip signal and it is the correct operation of the relay.

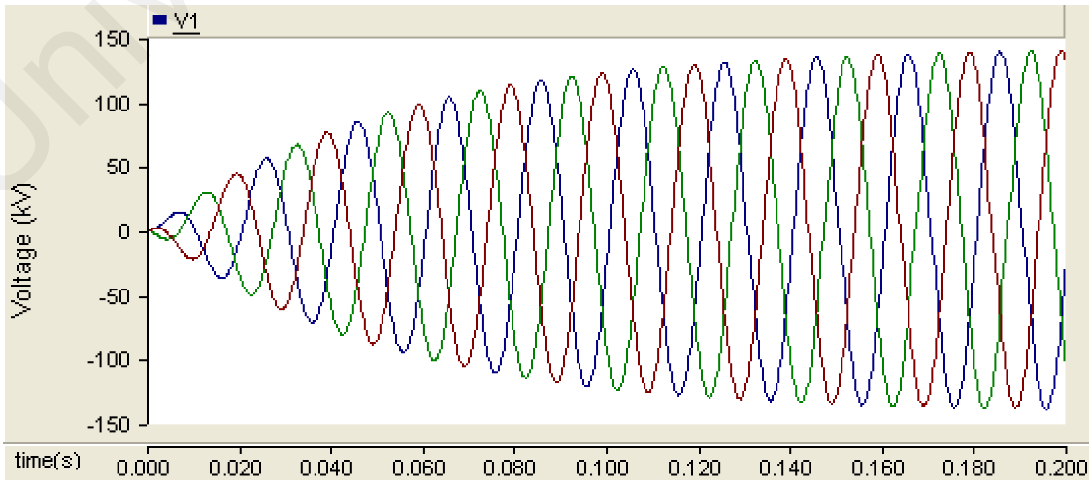

Figure 4.47: Case Study-2 Voltage at HV Side During No Load Condition

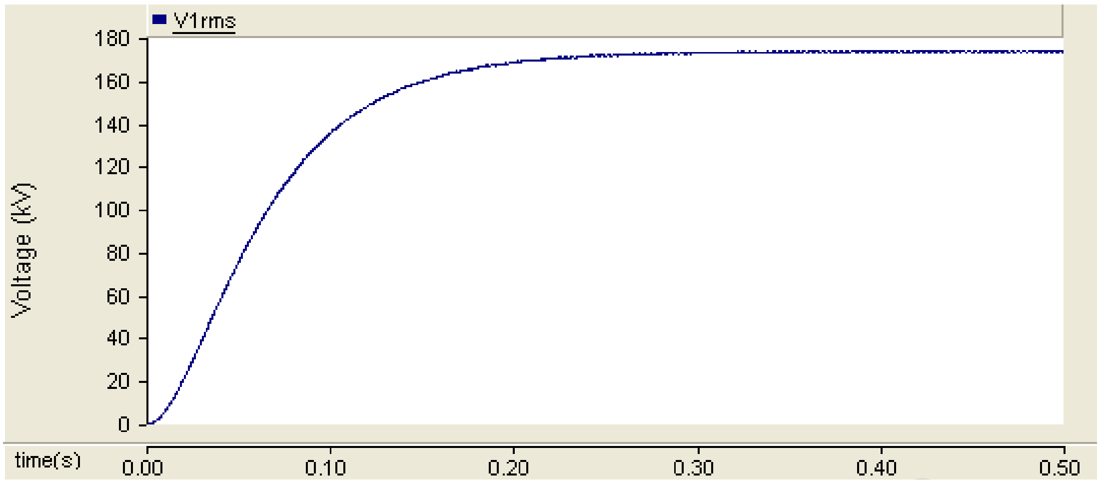

Figure 4.48: Case Study-2 RMS Voltage at HV Side During No Load Condition

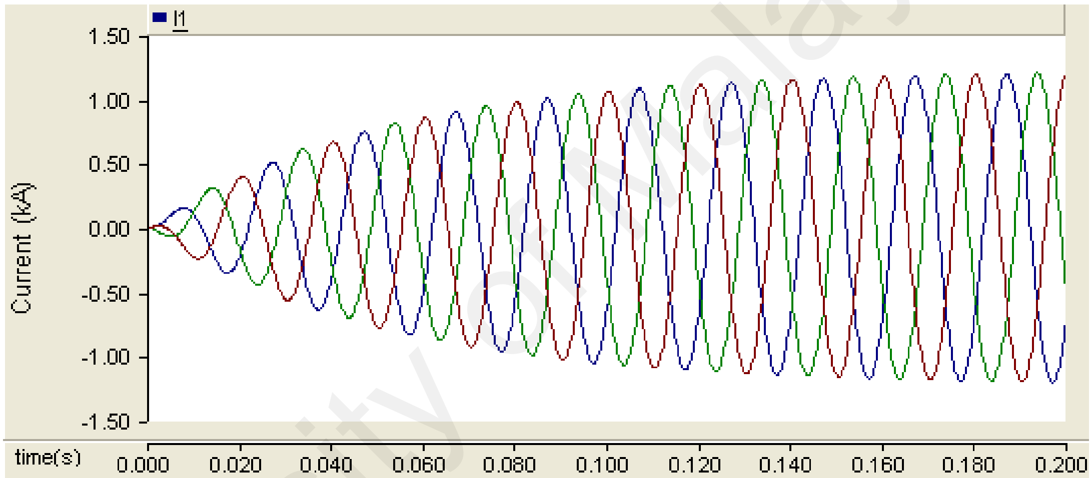

Figure 4.49: Case Study-2 Current at HV Side During No Load Condition

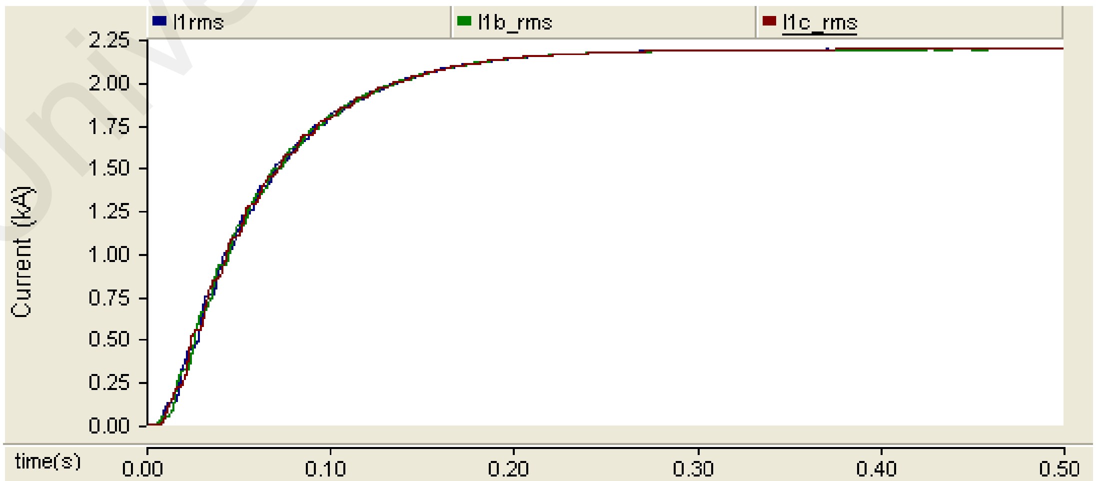

Figure 4.50: Case Study-2 RMS Current at HV Side During No Load Condition

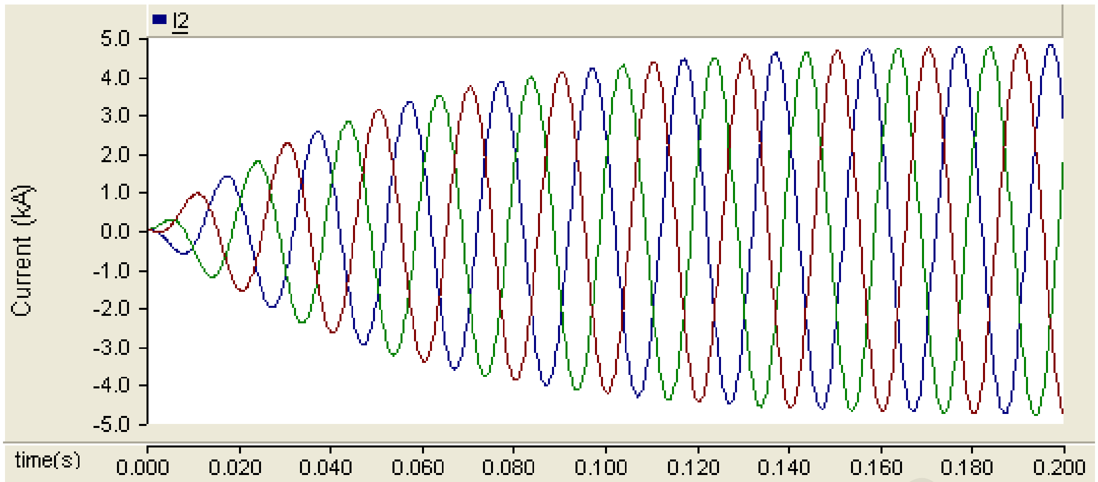

Figure 4.51: Case Study-2 Current at LV Side During No Load Condition

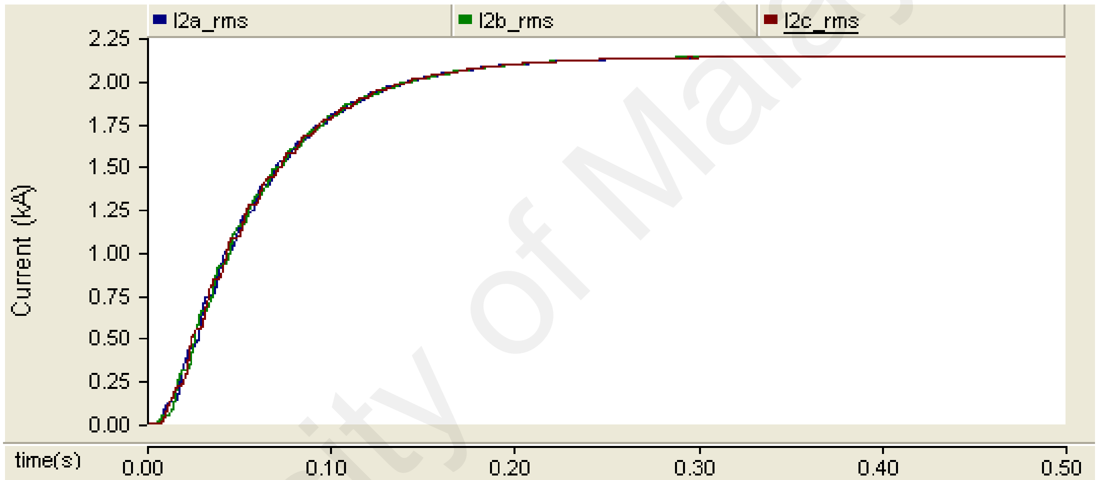

Figure 4.52: Case Study-2 RMS Current at LV Side During No Load Condition

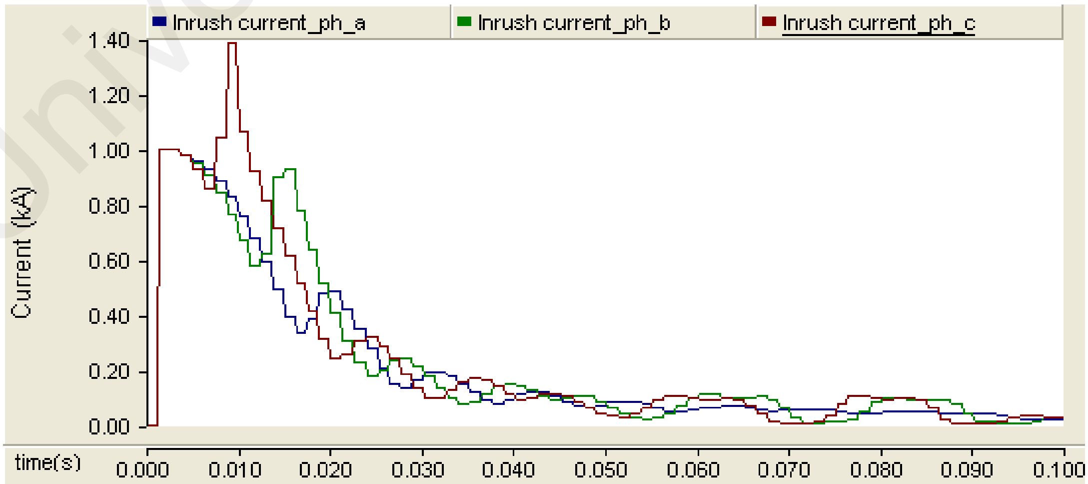

Figure 4.53: Case Study-2 Differential Current of Fundamental & Second Harmonic Content During No Load Condition

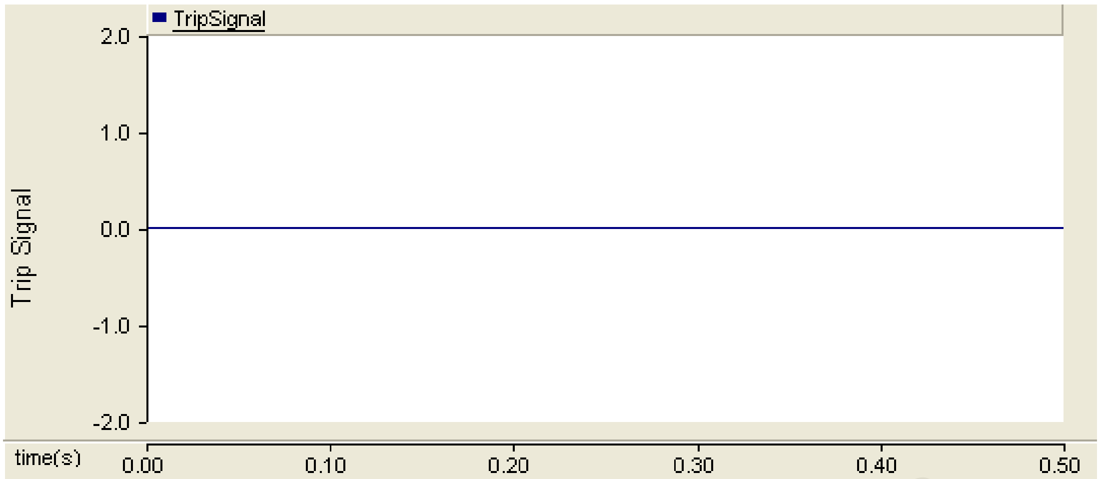

Figure 4.54: Case Study-2 Trip Signal During No Load Condition

(c) Energize transformer during internal fault condition (A-G fault)

Waveforms in Figure 4.55 and Figure 4.56 show the current at HV side of transformer during single-phase-to-ground A-G fault is applied to the power system between 0.05s to 0.1s. The instantaneous and RMS current at LV side illustrated in Figure 4.57 and Figure 4.58 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.59 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.60, where the relay only trips during fault duration.

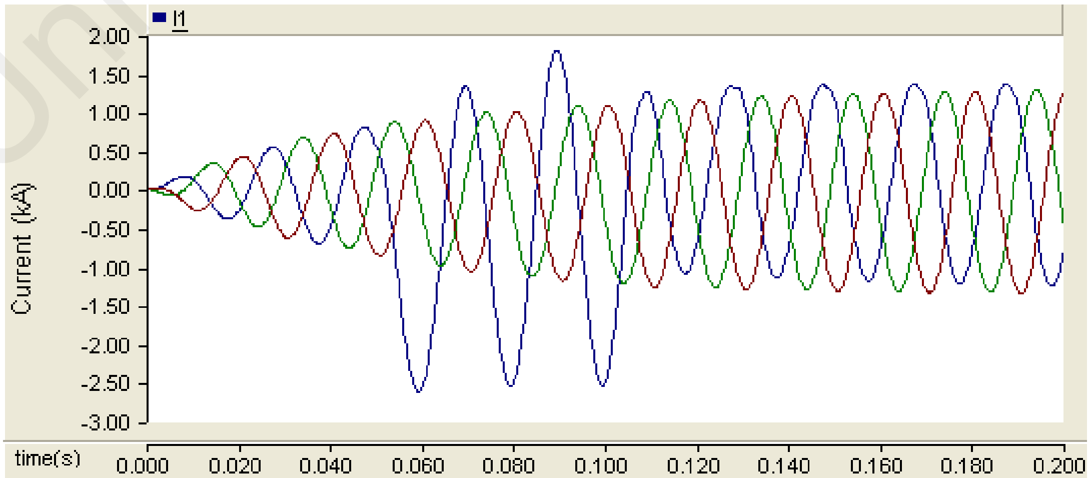

Figure 4.55: Case Study-2 Current at HV Side During A-G Fault

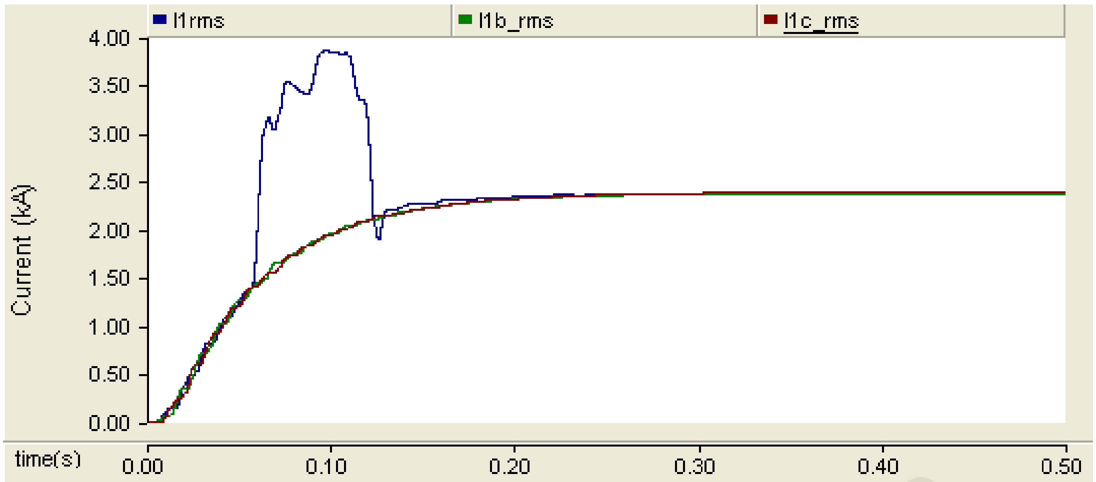

Figure 4.56: Case Study-2 RMS Current at HV Side During A-G Fault

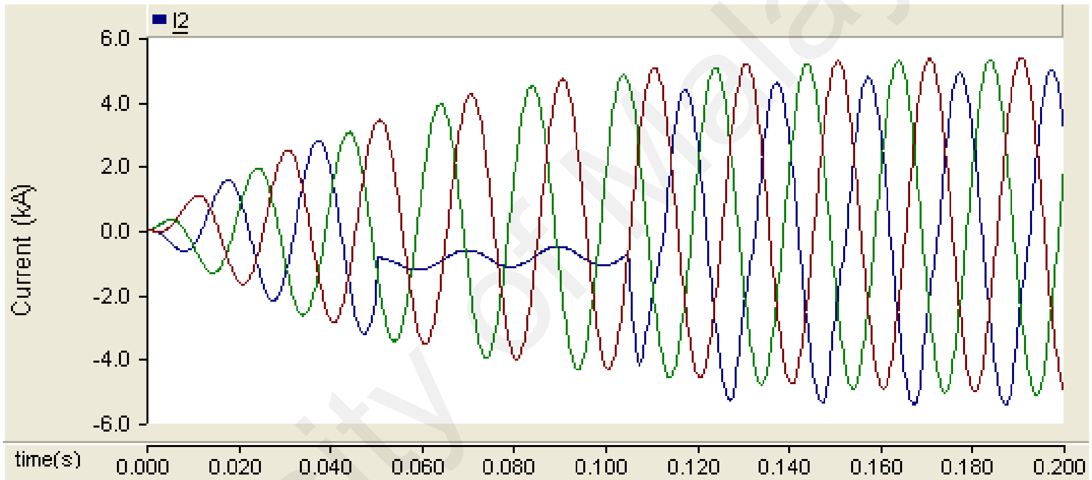

Figure 4.57: Case Study-2 Current at LV Side During A-G Fault

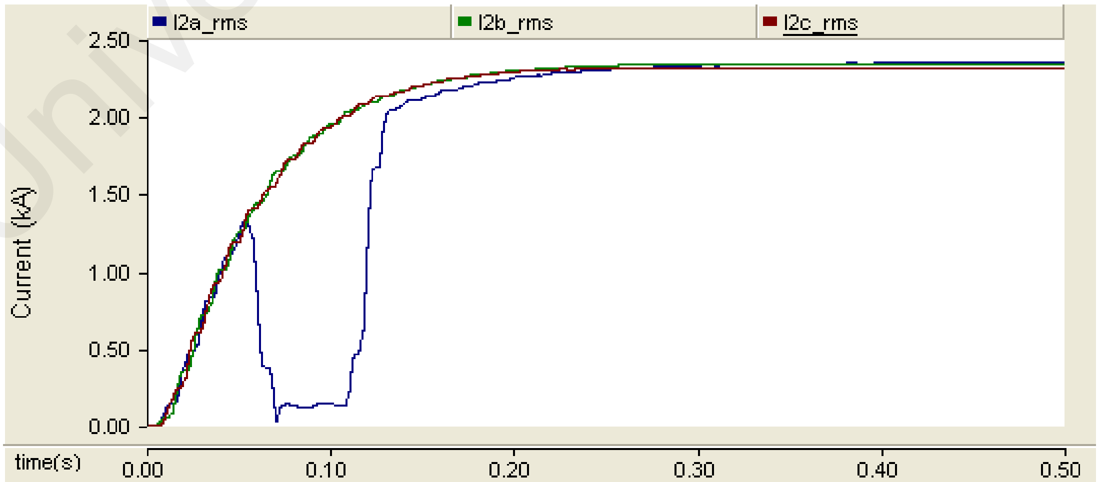

Figure 4.58: Case Study-2 RMS Current at LV Side During A-G Fault

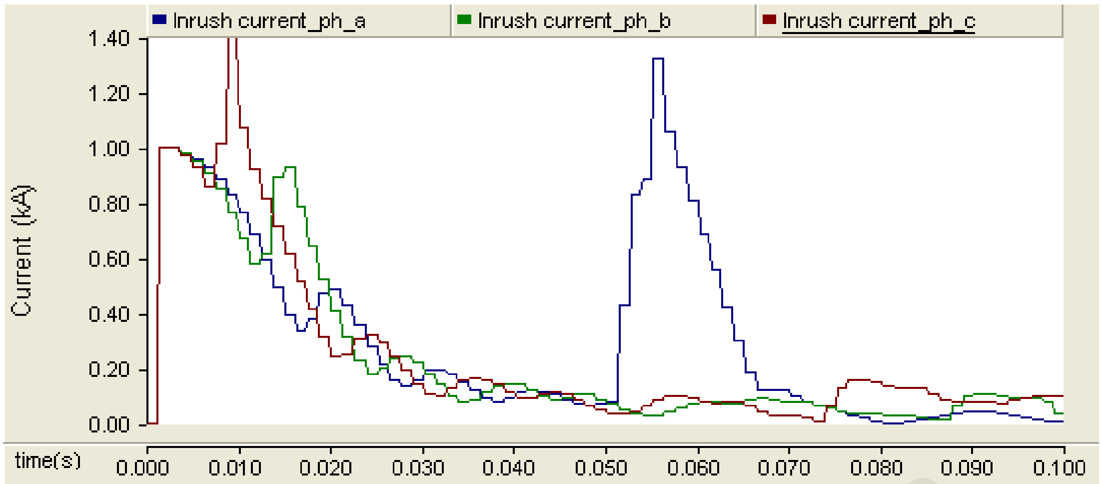

Figure 4.59: Case Study-2 Differential Current of Fundamental & Second Harmonic Content During A-G Fault Condition

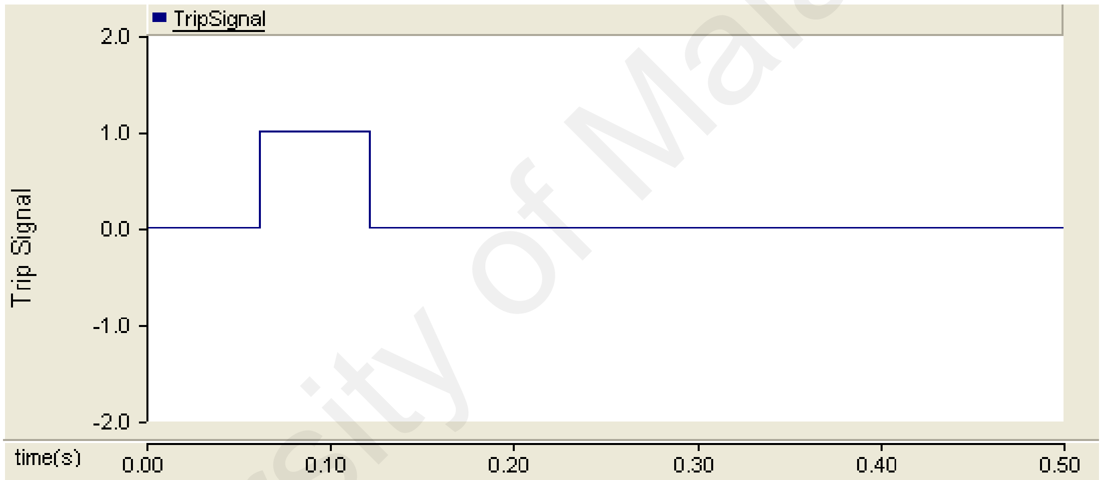

Figure 4.60: Case Study-2 Trip Signal During A-G Fault

(d) ***Energize transformer during internal fault condition (A-B-G fault)***

Waveforms in Figure 4.61 and Figure 4.62 show the current at HV side of transformer during phase-to-phase-to-ground A-B-G fault is applied to the power system between 0.05s to 0.1s. The instantaneous and RMS current at LV side illustrated in Figure 4.63 and Figure 4.64 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.65 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.66, where the relay only trips during fault duration.

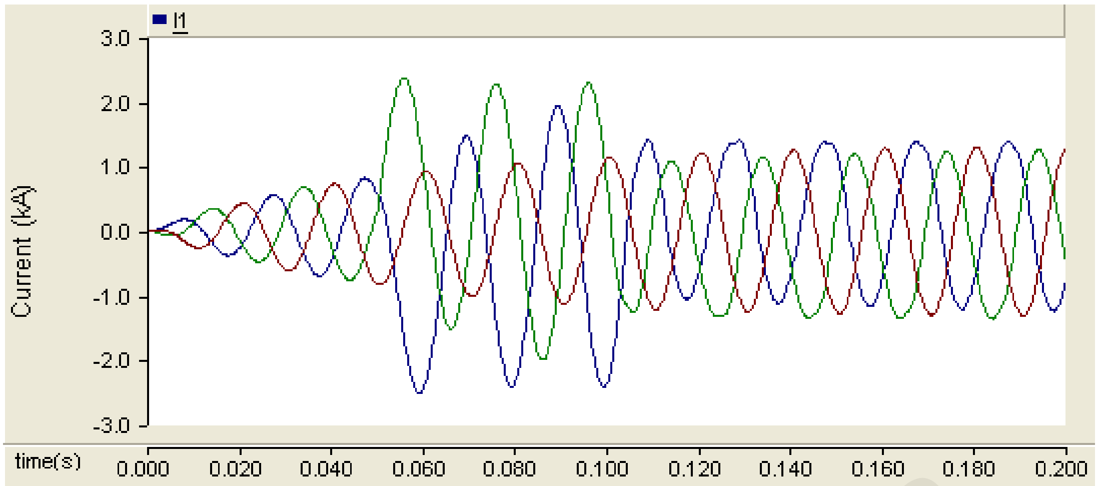

Figure 4.61: Case Study-2 Current at HV Side During A-B-G Fault

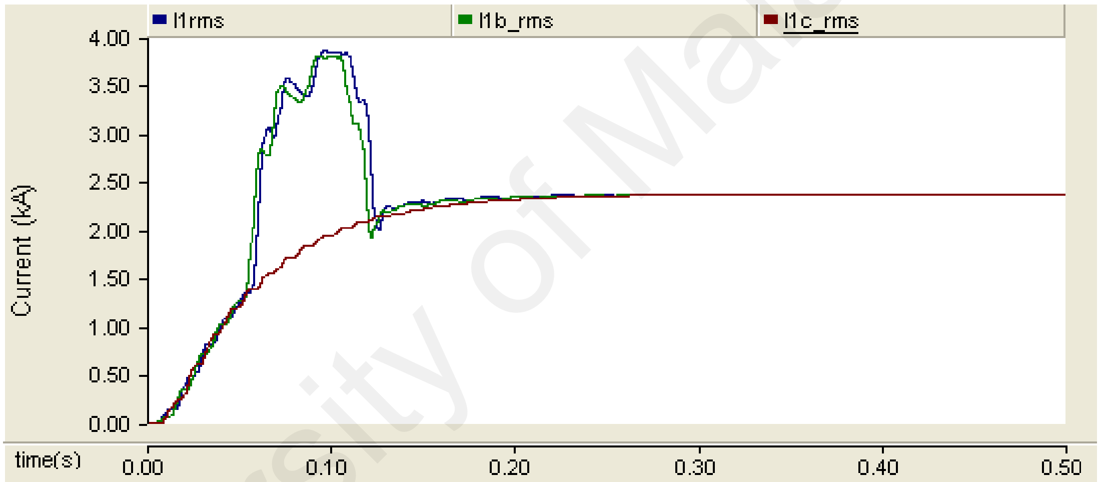

Figure 4.62: Case Study-2 RMS Current at HV Side During A-B-G Fault

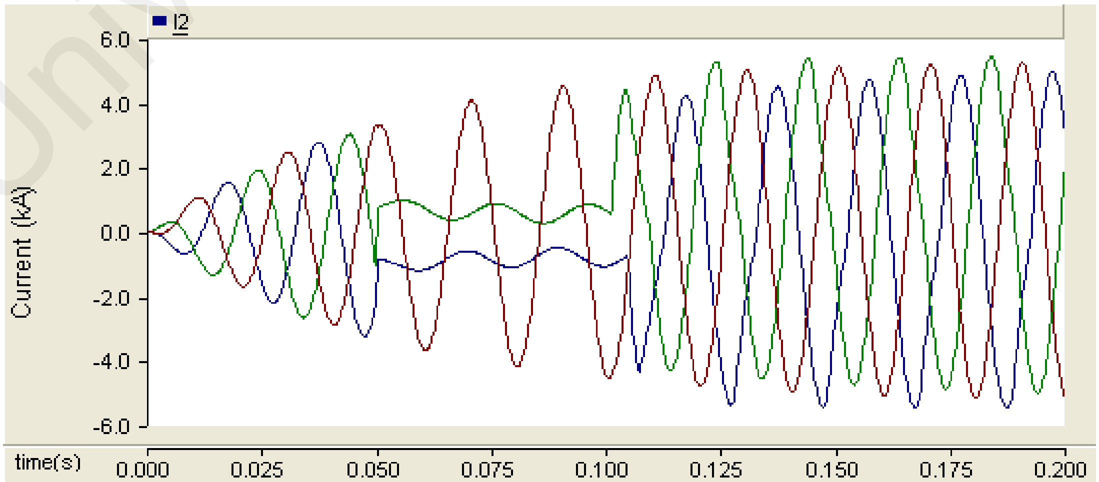

Figure 4.63: Case Study-2 Current at LV Side During A-B-G Fault

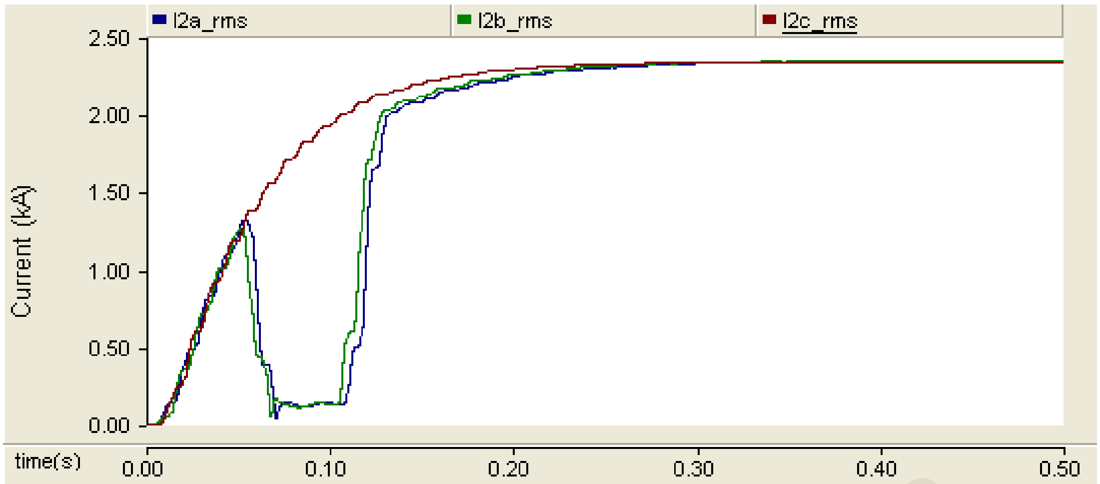

Figure 4.64: Case Study-2 RMS Current at LV Side During A-B-G Fault

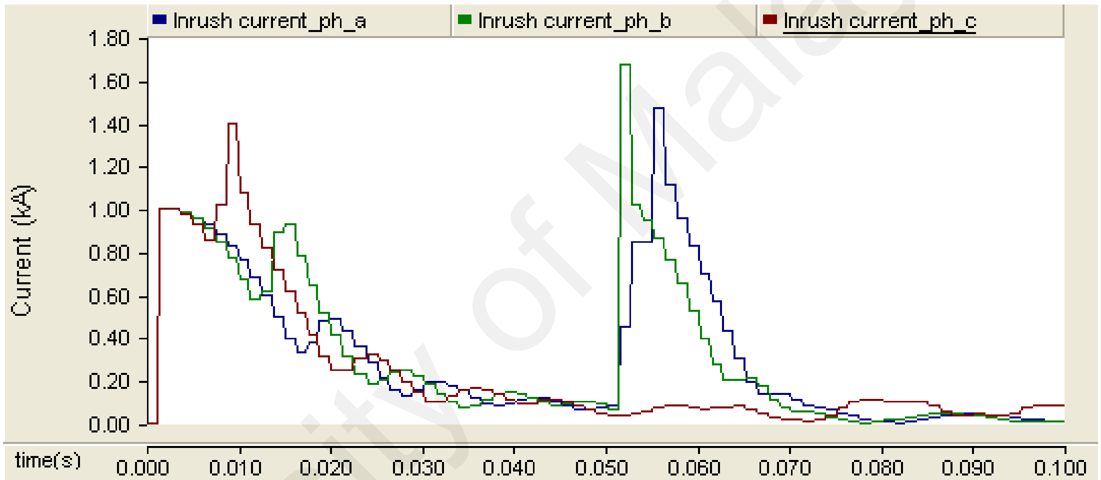

Figure 4.65: Case Study-2 Differential Current of Fundamental & Second Harmonic Content During A-B-G Fault Condition

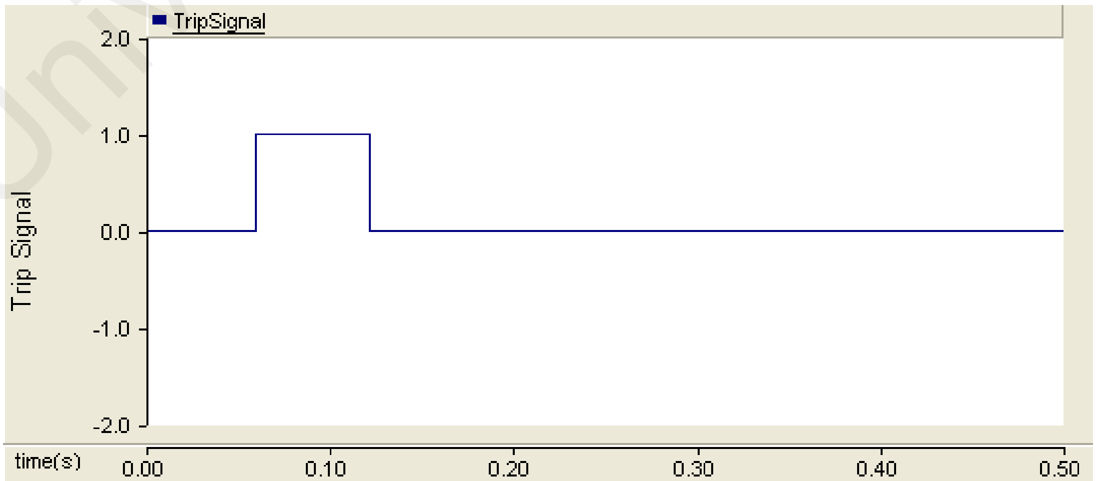

Figure 4.66: Case Study-2 Trip Signal During A-B-G Fault

(e) ***Energize transformer during internal fault condition (A-B-C-G fault)***

Waveforms in Figure 4.67 and Figure 4.68 show the current at HV side of transformer during three-phase-to-ground A-B-C-G fault is applied to the power system between 0.05s to 0.1s. The instantaneous and RMS current at LV side illustrated in Figure 4.69 and Figure 4.70 respectively. When the transformer is energized during this internal fault condition, the differential current of fundamental and second harmonic content that show in Figure 4.71 is below the setting peak up value. The trip signal of transformer differential protection operated as shown in Figure 4.72, where the relay only trips during fault duration.

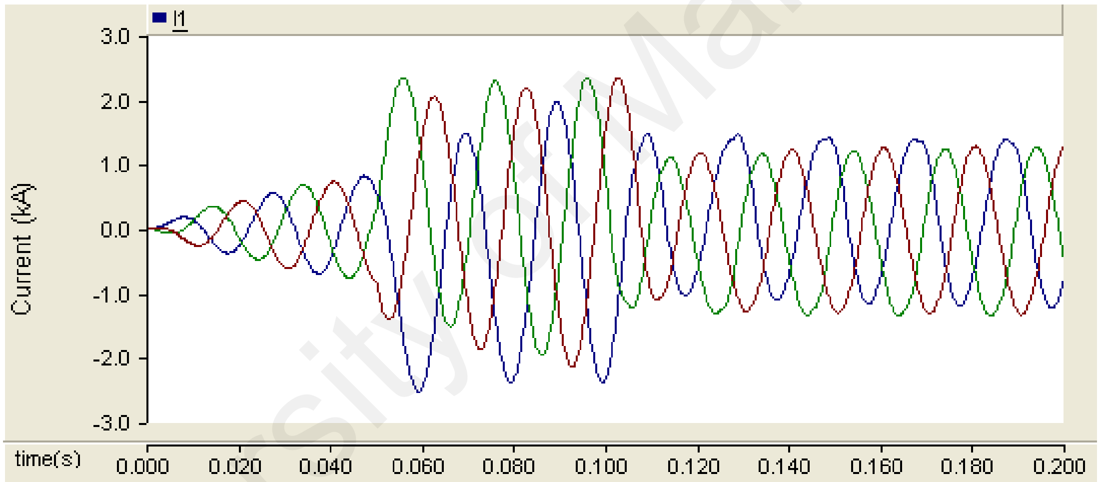

Figure 4.67: Case Study-2 Current at HV Side During A-B-C-G Fault

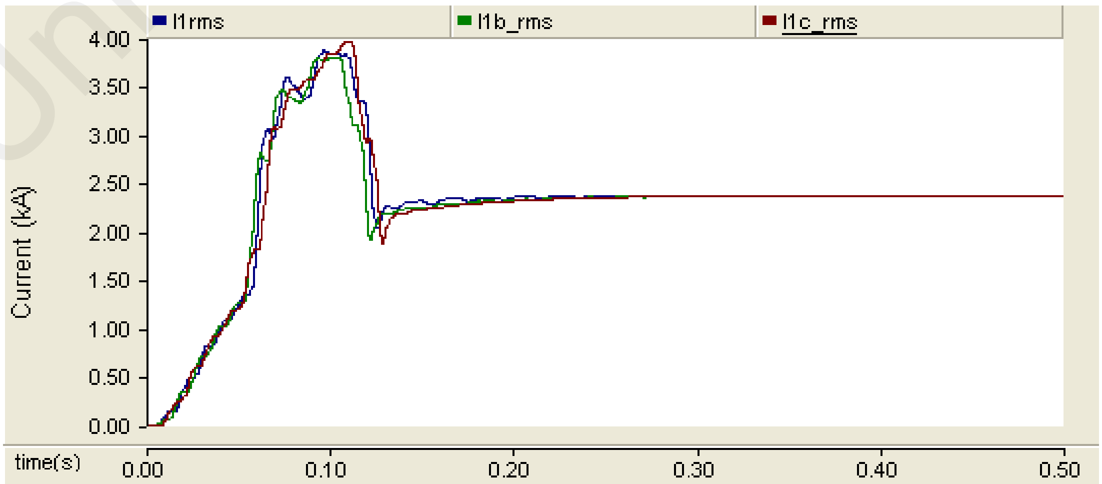

Figure 4.68: Case Study-2 RMS Current at HV Side During A-B-C-G Fault

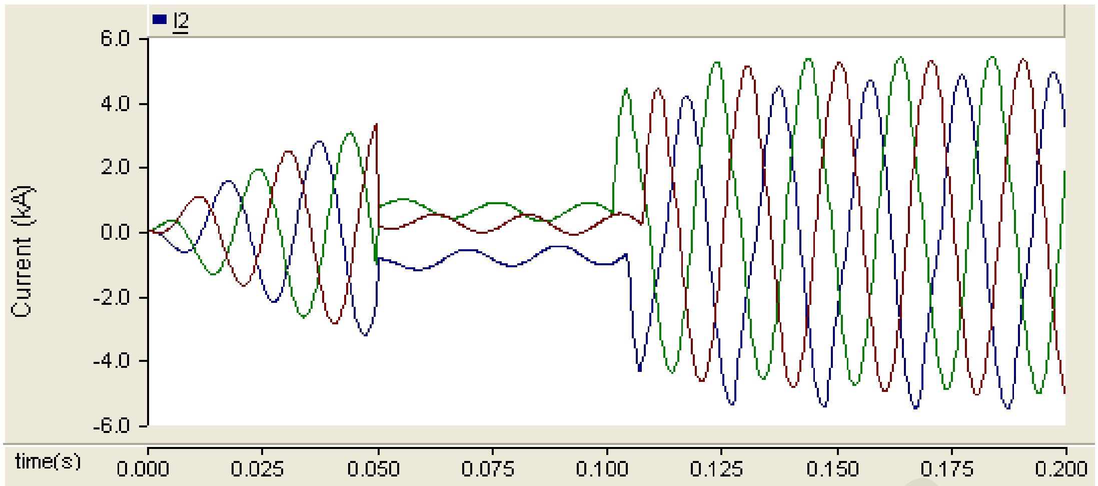

Figure 4.69: Case Study-2 Current at LV Side During A-B-C-G Fault

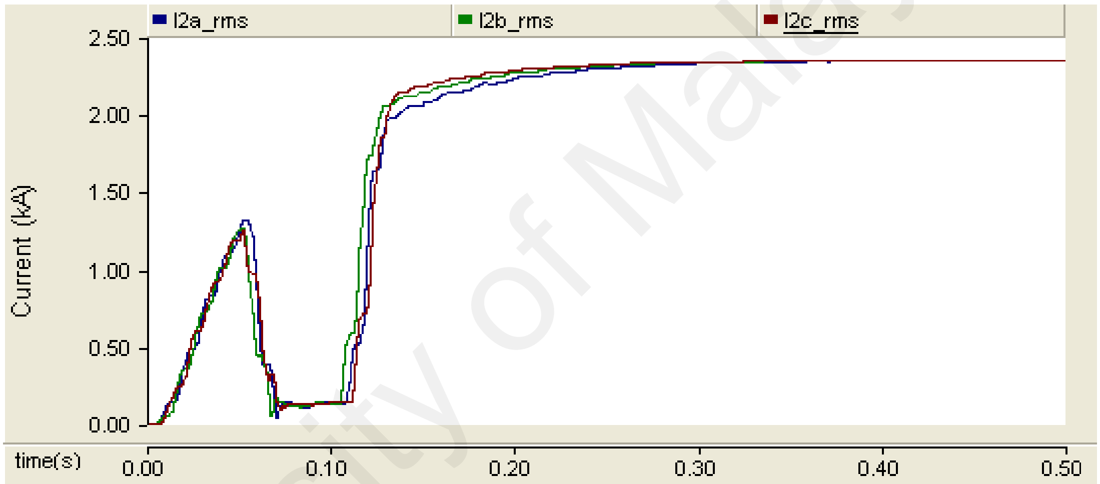

Figure 4.70: Case Study-2 RMS Current at LV Side During A-B-C-G Fault

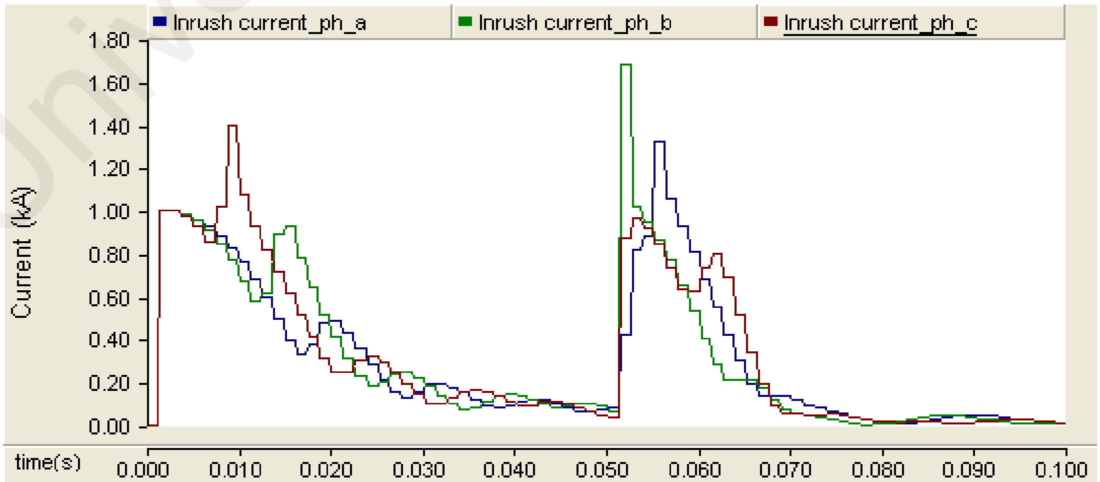

Figure 4.71: Case Study-2 Differential Current of Fundamental & Second Harmonic Content During A-B-C-G Fault Condition

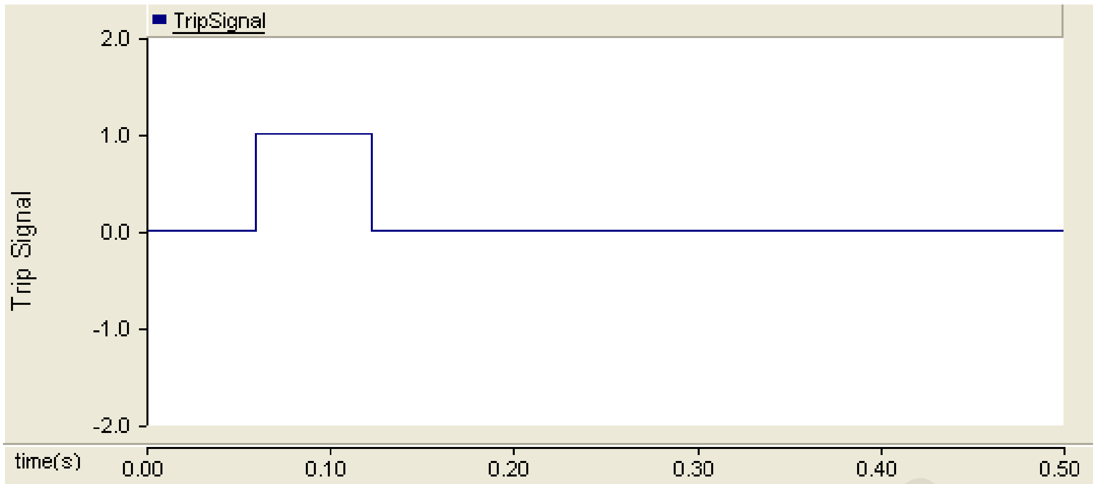

Figure 4.72: Case Study-2 Trip Signal During A-B-C-G Fault

The analysis results of trip signal for the differential transformer protection are summarize in Table 4.3 below:

Table 4.3: Comparison Between Case Study-1 and Case Study-2

No.	Condition of analysis	Trip Signal	
		Case Study-1	Case Study-2
1.	Energize transformer during normal condition (based on upper setting inrush current value)	Not trip	Not trip
2.	Energize transformer during normal condition (based on below setting peak up value)	Trip	Trip
3.	Energize transformer during no load condition	Not trip	Not trip
4.	Energize transformer during internal fault condition (A-G fault)	Trip	Trip
5.	Energize transformer during internal fault condition (A-B-G fault)	Trip	Trip
6.	Energize transformer during internal fault condition (A-B-C-G fault)	Trip	Trip

4.3 Discussion

By using PSCAD software, simulation results above indicated that inrush current can be detecting by second harmonic component. By properly set the detection of the second harmonic current in the transformer differential protection, false tripping towards power system can be avoided. The analysis showed that the modeling of the transformer differential protection successfully differentiates the fault current and inrush current during normal operation, no load condition, and during fault condition. The relay will mal-operate if the overcurrent limit value in OC detection block component of transformer differential protection is set less than the differential current of fundamental and second harmonic content.

4.4 Summary

This chapter presented the simulation results of inrush current that can be detecting by second harmonic component. There are two case studies analyze in this research which are case study-1 with 230/25kV YNyn0 50MVA frequency 60Hz power transformer and case study-2 with 132/33kV 90MVA frequency 50Hz power transformer. The analysis showed that trip signal in the relay is correctly operated. If not proper set of second harmonic detection, the inrush current will impact towards transformer differential protection.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

In practical, protection engineer usually faced problem with transformer inrush current event that impact towards transformer protection capability. This analysis can be used to prove that the transformer inrush current can be detected by second harmonic technique in transformer differential protection. As mentioned in previous chapter, magnetizing inrush current is not a fault. Thus, the proper setting and design of detection of inrush current is required to avoid mal-operation towards transformer differential protection and further towards power system. In this research, the modeling of transformer differential protection in PSCAD software successfully used to analyze inrush current and fault current during normal operation, no load condition, and internal fault current condition.

5.2 Future Work

In future, this work can be extended with following recommendations.

1. Magnetizing inrush current can occur under three conditions, which are energization or normal inrush, recovery inrush, and sympathetic inrush. This research focused on normal inrush, thus the study can be extended to other conditions in the future.
2. This research focused on analyzing the inrush current on transformer. In the future, discussion can be done on inrush current impacts towards other equipment in power system such as capacitor bank and reactor.
3. There are certain phenomena that can cause of false differential current other than inrush current, which are over-excitation conditions and current transformer saturation that can be discuss further.
4. Transformer differential protection modeling in this research concern on inrush current. There are other algorithm elements in the protection can be study.

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