DIGITAL DIFFERENTIAL RELAY FOR ELECTRICAL POWER TRANSFORMER

Adel Hamad Rafa

Faculty of Engineering, Tobruk University, Libya
E-Mail:- adel_rafa@yahoo.com

الملخص

تم في هذه الورقة تصميم مرحل وقاية تفاضلية رقمي لوقاية محولات القدرة الكهربائية. هذا المرحل يُحسن ويُعزز حساسية عمل المرحل التفاضلي الرقمي لوقاية المحول من الأعطال الداخلية باستخدام طريقة تمييز جديده تعتمد على ميل موجة تيار المغنطة والتيار الابتدائي للمحول للتمييز بين تيار المغنطة وتيار العطل الداخلي بدون تعطيل عمل المرحل اثناء شحن المحول ومنع فصل المحول اثناء الاعطال الخارجية للمحول هذا المرحل تم تصميمه واختباره باستخدام برنامج المحاكاة (PSCAD) وتم اختبار عمل المرحل باجراء اختبارات مختلفة من عمليات التشغيل العادية وحالات الاعطال الداخلية والخارجية لمحول القدرة.

ABSTRACT

A digital differential relay to protect power transformers has been designed in this work to improve and enhance the sensitivity of operation of the digital differential relay used to protects power transformers from the internal faults by using a new discrimination method based on the slop of the primary current and inrush current waves to discriminate between transformer inrush current and transformer internal fault current without blocking the relay during the power transformer energization, as well as to avoid tripping during the transformer external faults. The digital differential relay is designed using the simulation technique Power Systems Computer Aided Design (PSCAD) software. Different cases are selected to test the operation of the relay during normal operation and internal and external faults of power transformer.

KEYWORDS: Digital Differential Relay; Power Transformer; Inrush Current.

INTRODUCTION

The most important equipment's in the power system are transformer and generator but transformer has more use in power system promise [1, 2, 3]. The transformer expose to many types of faults which are external and internal faults [4,5]. However, there are different protective relays can protect the transformer from these faults. However, the internal faults are dangerous for the integrity of the power transformer [6]. The most important protection scheme is used to protect the transformer from the internal fault is the differential protection that has been chosen in this work [7]. Although electromechanically and solid state relays were and still used for protecting power transformer for the past several years, researchers have been studying the feasibility of designing relays using microprocessors. The digital relays have many features such as ,Reliability: due to self-checking., Flexibility: various protection functions can freely selected and level of current and voltage measurement, Display of information: the relay can digitally display values of the current, voltage etc. High speed: high speed relays for minimum tripping time, User friendly: digital relays are easy to apply, operate and use. Saving space: digital relay occupies a small area compared to other species in the power system [8-9]. However, the main problem facing the operation of the differential relay is the discrimination between the internal fault and inrush current. However the harmonic method is used to discriminate between internal fault and internal fault because the inrush current contain on higher second harmonic than that in fault current or normal current, the most of the loads today are power electronics also introduce of renewable energy such as wind energy and the solar energy which connected to the electrical network through power electronic converters lead to false operation of differential relay.

Therefore, in this paper the digital differential relay with discrimination method based on the slope of the current wave instead of harmonic method has been designed and implemented in PSCAD software.

PROBLEM FACING DIFFERENTIAL PROTECTION

Differential protection compare currents entering and leaving the protected zone and operates when the differential current between these currents exceed a pre-determined level [8]. Nevertheless, in power transformer there is magnetizing current results from any abrupt change of the magnetizing voltage. Although usually considered a result of energizing a transformer. This magnetizing current upsets the balance between the currents at the transformer terminals, and is therefore experienced by the differential relay as a “false” differential current [10]. The method used to discriminate inrush currents from internal faults is the harmonics restrain method [11]. Because of The magnetizing inrush currents have high component of even and odd harmonics. Harmonic-based methods allow the differential relay to remain sensitive to fault currents while keeping the relay from operating due to magnetizing currents [12-13]. But due to a wide availability of the power electronic devises that contain switches that are the sources of harmonics in power system thus the harmonic based method is a useless method to discriminate between the inrush current and fault current, so the method of the slop of the current waveform with respect of time has been suggested to solve this problem in this paper.

Generalized Digital Relay Structure

Digital relay protection system consists of hardware and software. This made the difference from conventional relay, which has no software control [14].

A. The hardware system

As shown in Figure (1) the system hardware consists of the following three functional blocks:

- Isolation and analog signal scaling block
- The data acquisition block
- The digital processor block

The isolation and analog scaling block 1. In this block, the measuring current and voltages are developed into a set of quantities required for measurement processing and operation of the relay. Also include the surge suppression circuits protect the system hard ware from voltage surges. The Data acquisition block 2 consists of hardware that samples and quantizes signal at a specified rate, to interface analog signals to the microprocessor. This analog signal must first be converted to a digital value before it can be processed by microprocessor. The data acquisition system (DAS) sampling analog signals and converting them to equivalent numbers the equivalent digital signals from block 2 are fed digital processor block 3. It consists of phase comparators, logic gates or microprocessor, for information processed and trip signal output [11,14].

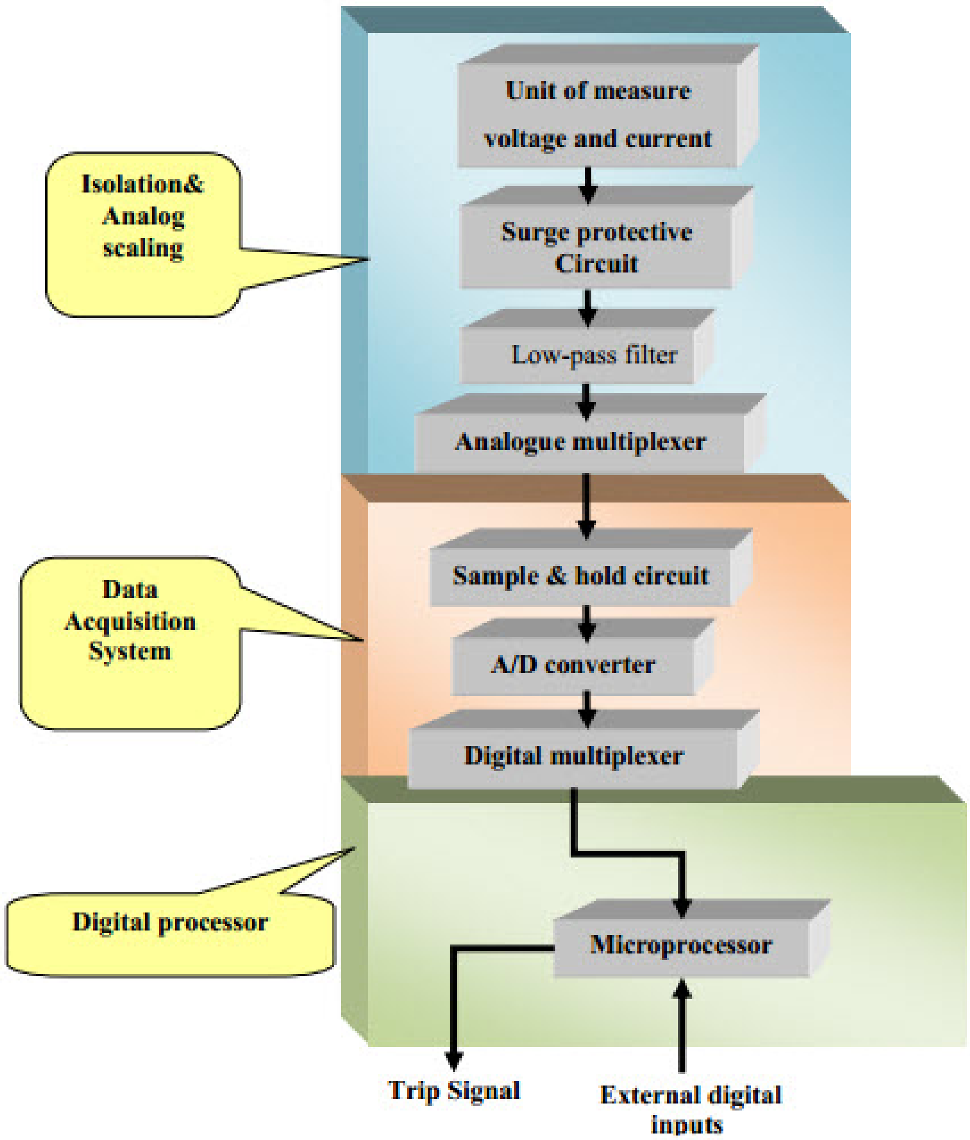

Figure 1: Generalized digital relay structure

B. The System Software

The system software is algorithm, which is a set of equations whose evaluation and comparison with certain predetermined levels determines the operation of the relay and are implemented through computational code at the interior of the relay microprocessor. This software is divided into two parts; inrush current and internal fault discrimination software and differential protection software

Inrush Current and Internal Fault Discrimination Part

This part implements the discrimination method that is suggested in this paper to discriminate between the internal fault and inrush current. This method based on slope of the current wave that mathematically is the derivative of the current with respect to time (di/dt). The slop of the current wave during the inrush current is difference than that during the fault current. This difference of di/dt is used as threshold value (TF).

Differential Protection Software

In the work the percentage differential relay method has been used for stability during external faults and load conditions with ratio mismatch and/or saturation of the CTs, a differential relay uses a restraining quantity as a reference for the differential signal. Figure (2) shows the percentage differential protection-operating characteristic which consists of a straight line having a slope equal to K and a horizontal straight line defining the relay minimum pickup current, $I_{PU.}$ The protection-operating region is located above the slope characteristic and the restraining region is below the slope characteristic and minimum restrain current, I_r.

To explanation differential protection software supposing that the I_1 and I_2 are the currents in the primary and secondary of the transformer respectively. The differential current, $I_d = |I_1 - I_2|$. A restrain differential current is fixed, I_R, this current is given by the ratio between the primary and secondary transformer current, $I_R = |I_1 + I_2|/2$. The restraint establishes an upper limit for the differential current in the relay without disconnecting the system. The differential protection generates a tripping signal if the following conditions are satisfied:

CASE 1:

$\mathbf{I_R < Ir}$

If $\mathbf{I_d > I_{PU}}$ then trip

CASE 2:

$\mathbf{I_R \geq Ir}$

IF $I_D \geq K I_R + I_R$ then trip

The differential current, is greater than a percentage of the restraining current. Moreover the relay generates instantaneous tripping signal if the differential current, is greater than two times rated current (I_{dmax}).

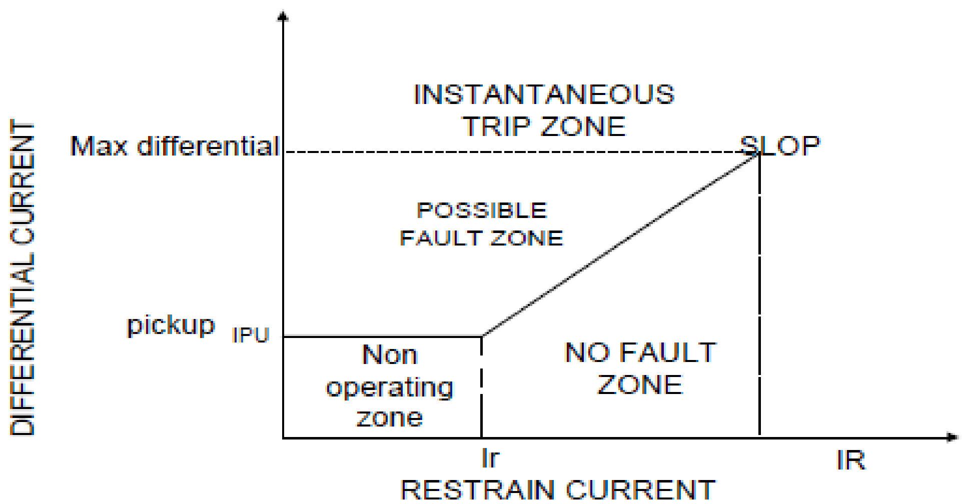

Figure 2: The characteristic of a percentage differential protection

Network used in the Study

The network used in this paper is 66kV Network in Tobruk power station as shown in Figure (3).The transformer that used to test the relay is three-phase, 50 MVA, 220kV/66kV,50Hz, Δ /Y three-phase power transformer connected between the 66kV network to 220 kV network.

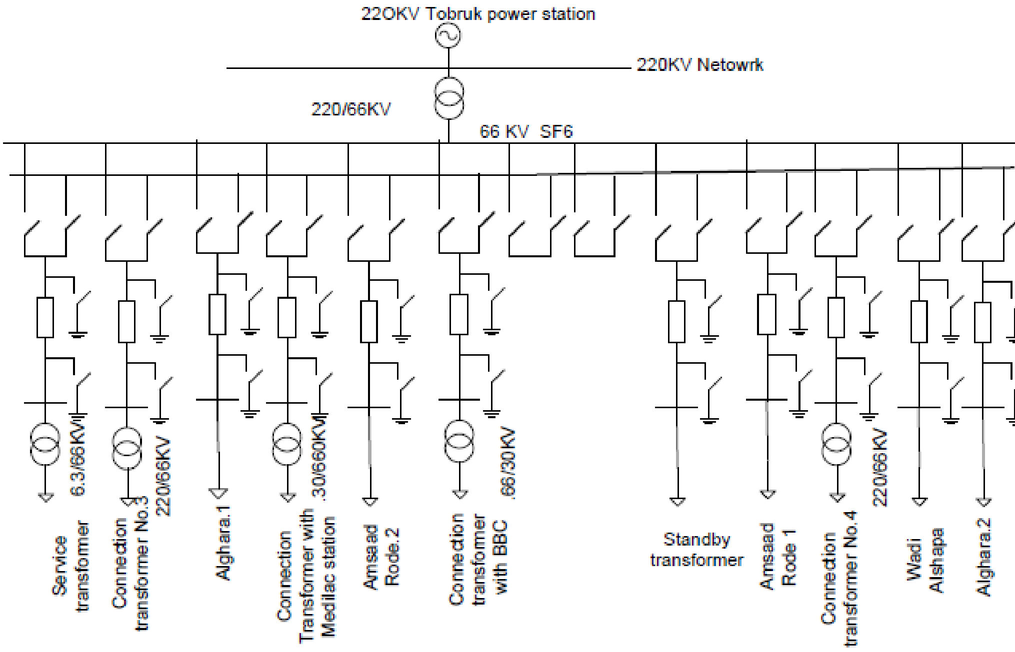

Figure 3: Tobruk 66kV Network (bus bars, transformers and feeders).

Implementation of the Network in PSCAD

The simulation model by PSCAD single line diagram is shown in Figure (4). The power transformer is connected to power system consisting of a three phase power generator , represent 220kV network, feeds two active and reactive loads represent 66kV network, through the power transformer between two circuit breakers CB1 and CB2. The primary and secondary currents must be reduced to values suitable for the relay; this is achieved by using current transformers. Moreover, due to the connection of a two winding of the three phase, power transformer is delta-wye (**Δ /Y**), the primary and secondary line currents are not in phase, and they are displaced by 30 electrical degrees. To eliminate the phase shift, the primary CTs are connected in wye. And secondary CTs are connected in delta.

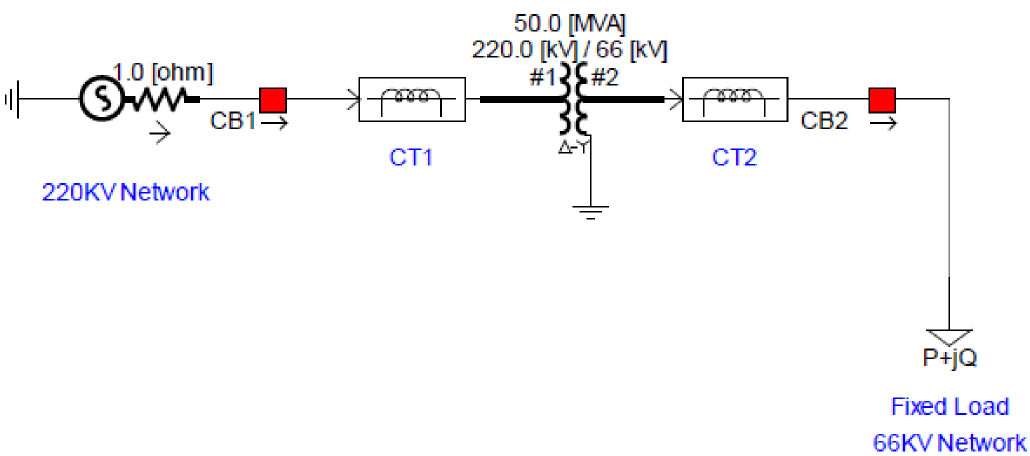

Figure 4: Single line Diagram of the Simulation Model

Implementing of Digital Relay N PSCAD

The proposed digital differential relay is designed using a simulation technique in PSCAD environment. This software has been chosen in this study because of ,it is a multi-purpose tool. It is equally capable in the areas of power electronic design and simulation, power quality analysis, protection and electrical utility system planning studies [15].The design of the proposed relay is implemented to protect the power transformer against internal faults and prevent interruption due to inrush currents. Flowchart of digital relay can be represented with five blocks as shown in Figure (5). Figure (6) shows the digital relay implementation in PSCAD, which is consist of two parts the first part is a differential relay part and the second part is the inrush current and internal fault discrimination part. In the differential relay part the primary and secondary currents are measured by current transformers (CT1,2), the output of CTs are the input to the an online Fast Fourier Transform (FFT), the input is processed to provide the magnitudes and phase angle of the fundamental frequency and its harmonics. The magnitudes of the currents are the input of differential relay, the output signal of the differential relay connected to one the terminal inputs of AND Logic Gate. The other terminal of the AND Gate is connected to the inrush current and internal fault discrimination part. The function of this part is to differentiate the primary current with respect to time (di/dt) and then compare this value with threshold value (TF), to prevent the differential relay from trip in case of inrush current, otherwise send trip signal to the AND gate incase of internal fault. Therefore if the two signals from the differential relay and discrimination part are true the AND gate outputs logical true. This output is the trip signal for CB1. Moreover another AND gate has been added to the system to trip the CB2 in case of fault, that is to more security for the transformer.

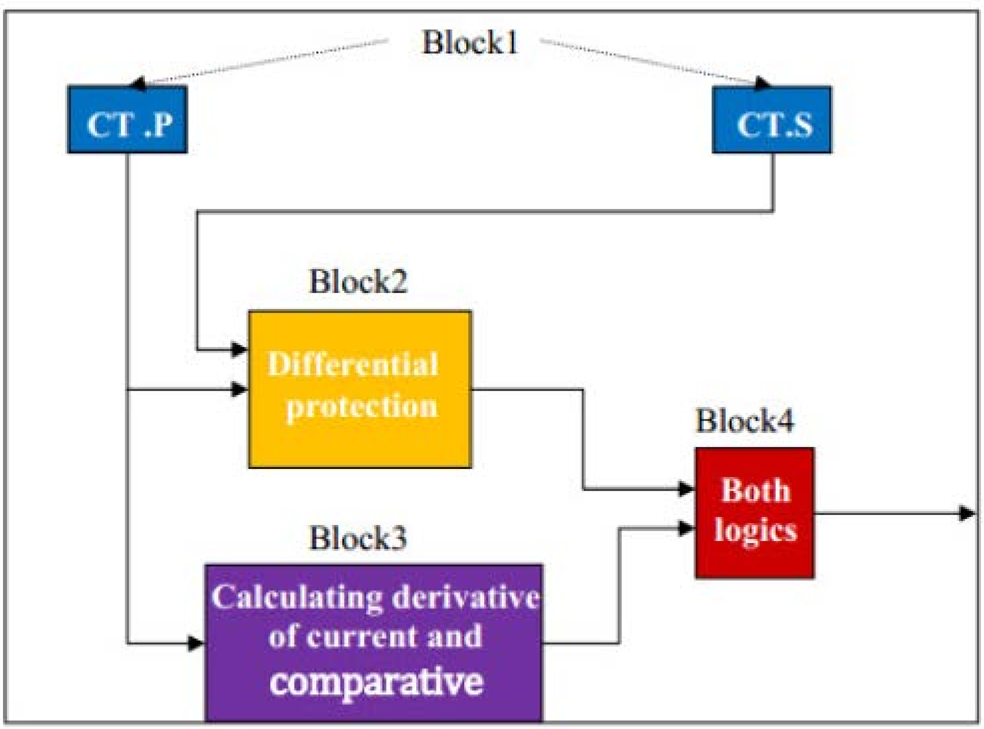

Figure 5: Digital relay

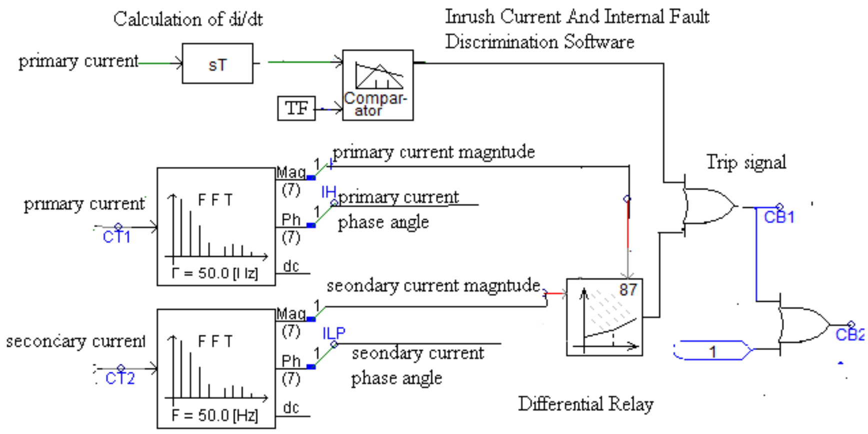

Figure.6: The digital relay in PSCAD

Simulation and Calculation Results

The results are given for different cases:

In these cases, the four types of simulation and calculation procedures have been done for setting and testing the performance of the proposed relay.

Case 1: Relay setting

Case 2: Testing inrush current discrimination software

Case 3: Testing the performance of the relay during three phases to ground fault between two current transformers as an internal fault.

Case 4: Testing the performance of the relay during three phases to ground fault outside two current transformers as an external fault.

Figure (7) shows the location of the external and the internal faults.

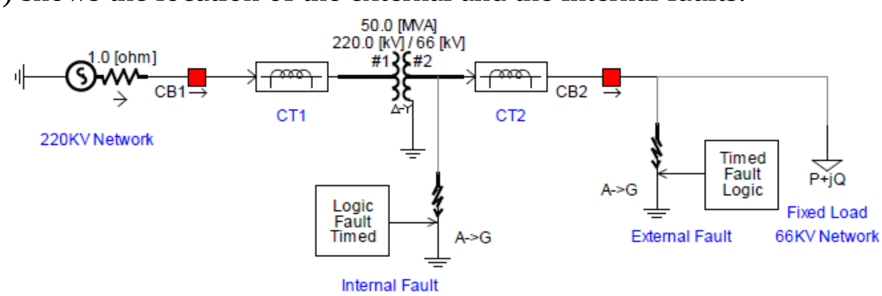

Figure 7: Internal Fault and External Fault Location

Case 1: Relay Setting

After the implementation of the proposed relay in PSCAD, the setting of the relay is necessary for the relay operation. The setting of the relay needs to determine some parameters that will be calculated in the following subsections.

Calculation and Measuring of the Differential Relay Input Parameters

For setting of the differential relay, the input parameters are calculated and compared with the measured values.

- **Differential relay calculation**

The operation process of the protection system needs to measure the primary and secondary currents and determine some parameters. For a 50 MVA, 220kV/66kV star - delta transformer, the design of the percentage differential scheme is shown in the worksheet of Table (1).

Table.1: Worksheet for differential relay calculations

<table>
<tr><th>Step</th><th>220 KV star side</th><th>66 kV delta stde</th></tr>
<tr><td>1-Full-load line Current IF</td><td>$\frac{50x10^6}{\sqrt{3}x220x10^3} = 131.2A(0.131KA)$</td><td>$\frac{50x10^6}{\sqrt{3}x66x10^3} = 437.4A$ (0.437KA}</td></tr>
<tr><td>2-To allow for 25% overload, choosing (IFx 1.25) as primary current</td><td>131.2X1.25=164 A</td><td>437.4X1.25=546.7 A</td></tr>
<tr><td>3- CT ratios (5A relay)</td><td>Choosing a CT of 200 : 5
i.e. CT ratio = 40</td><td>Choosing a CT of 600 : 5
i.e. CT ratio = 120</td></tr>
<tr><td>4-CT secondary currents</td><td>CT secondary current
$\frac{131.2}{40} = 3.28A$</td><td>CT secondary current
$\frac{437.4}{120} = 3.645A$</td></tr>
<tr><td>5 Pilot wire currents</td><td>(CT secondaries are in Δ)
Current in the pilot wires
$\sqrt{3}x3.28 = 5.6811A$</td><td>(CT secondaries are in Y) Current in the pilot wires
3.645 A</td></tr>
<tr><td>6 Turns ratio of the interposing CT
$\frac{5.6811}{3.28}:1$
1.731:1
For this digital relay there is no need to connect interposing CTs jus dived the CTs secondary current by this value
$\frac{5.6811}{3.645} = 1.558$ A</td><td>Current after the interposing CT
$\frac{5.6811}{1.731} = 3.282$ A
$\frac{5.6811}{1.55} = 3.645$ A</td><td>Current in the pilot wires
3.645 A</td></tr>
<tr><td colspan="3">The restrain current is $I_R = \left(\frac{3.648+3.646}{2}\right) = 3.647A$ Assuming a slope of (K) 40%,differential current required for tripping is $K.I_R = 0.4\left(\frac{3.648+3.646}{2}\right) = 1.4588A$
Actual differential current Id= 3.648 - 3.646 = 0.002 A. Therefore, the scheme remains stable on full load or external fault.
The tripping criteria can be formulated as:
CASE 1: When $I_R < 3.647A$: If $I_d > 0.002A$ then trip
CASE 2: When $I_R \geq 3.647A$: If $I_d \geq 0.4\ (I_R) + 3.647$ then trip
The relay output will be '1' only if the trip condition is satisfied.</td></tr>
</table>

The primary and secondary currents are compared after being reduced by their corresponding current transformers (CTs) from the calculation the pilot wire currents are

5.6811A from the star side CTs while they are 3.645 A from the delta side CTs. Thus, intermediate CTs are needed to correct this mismatch as shown in Figure (8) Such CTs are known as interposing CTs and are usually autotransformer types. The turn's ratio of the interposing CTs is, therefore, found out to be 5.6811:3.28 = 1.731: 1. The ratio of current transformers on the primary side (CT1) equal to 200:5 and the ratio of current transformers on the secondary side (CT2) equal to 600:5. As shown in step.6 For turns ratio of the interposing CT, instead of using interposing CT in this digital relay the ratio between the secondary sides of CT1 and CT2 has been used to modify the difference which only this value included in the software so there is no need to added hardware (CTs).

- **Differential Relay Simulation Results**

Figure (9) and Figure (10) show the simulation results that are similar to calculation results for the primary and secondary currents during normal operation. Figure (11) shows the CTs secondary currents that similar to the calculation results with primary, secondary and differential currents at normal operation.

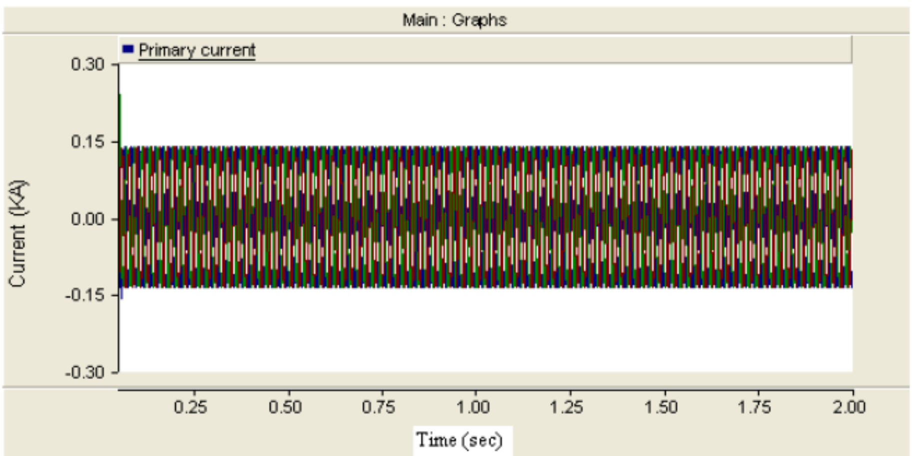

Figure 9: Primary current during normal operation

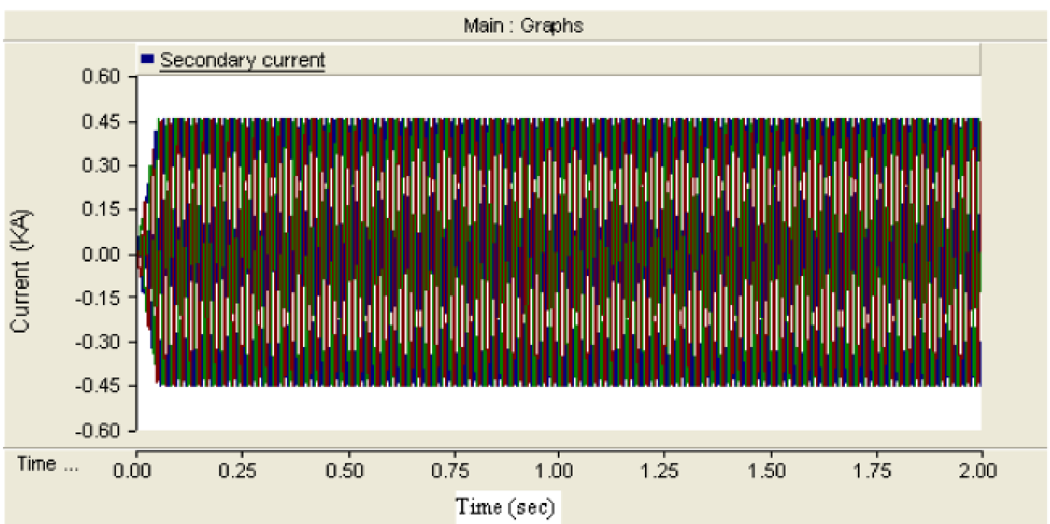

Figure 10: Secondary current during normal operation

- **Differential relay parameters**

According to the calculation and simulation results, the percentage differential protection operating characteristic shown in Figure (2) is determined. As shown in the Figure (11) and Table (1) at the normal operation, the differential current is not zero (0.002A) due to mismatch between the CT ratios and the power transformer ratio and angular displacement between the primary and secondary currents. To avoid mal-operation of differential protection due to last reasons the following values were choose. The minimum value of differential current is pickup value, I_{PU}= 0.002, the minimum value of restrain current, I_r=3.647 A maximum differential current I_{dmax} = 200 % from rated current. The slop of the percentage differential characteristic K is equal to 40%. Moreover the simulation result showed in Figure (12) the restrain current same as the calculated value. The relay operates when the differential current, I_d, overcome the restraining current I_R.

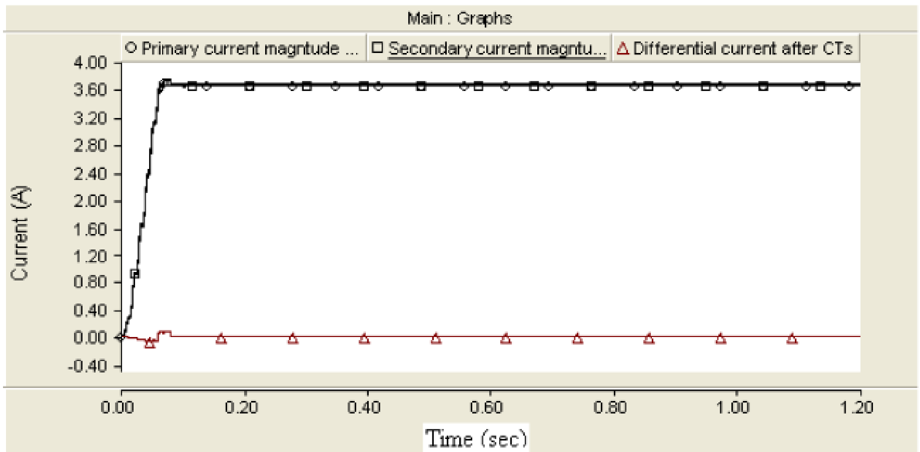

Figure 11: Primary, secondary and differential currents at normal operation.

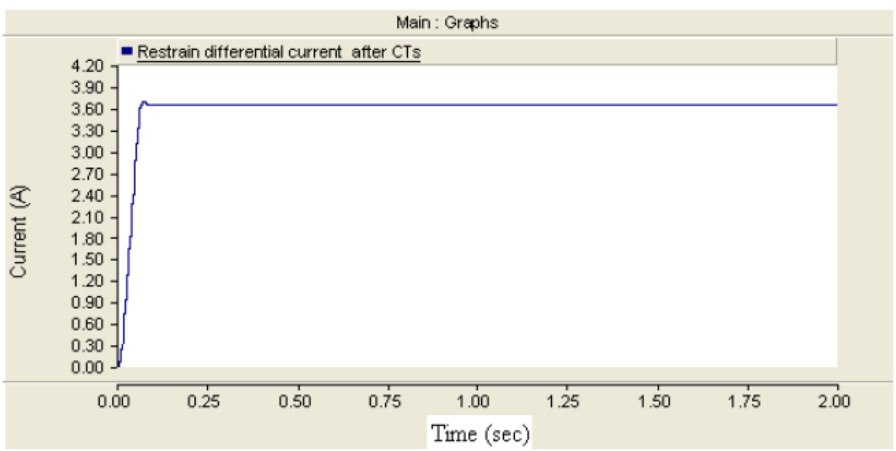

Figure 12: Restrain current from CT secondary currents

Magnetizing Inrush Current Wave Shape

The objectives of this test are to show the different between the inrush current waveform and the primary current wave form. The other objective is to calculate the threshold value (TF) of the di/dt of inrush current.

As shown in Figure (13) the inrush current waveform and the primary current waveform when the transformer is energized, the rate of change in the current with respect to time (di/dt) is high in case of inrush current, furthermore the time of first half cycle around 5msec, that mean the frequency of the wave around 100Hz which prove that the second harmonic exist in inrush current wave.

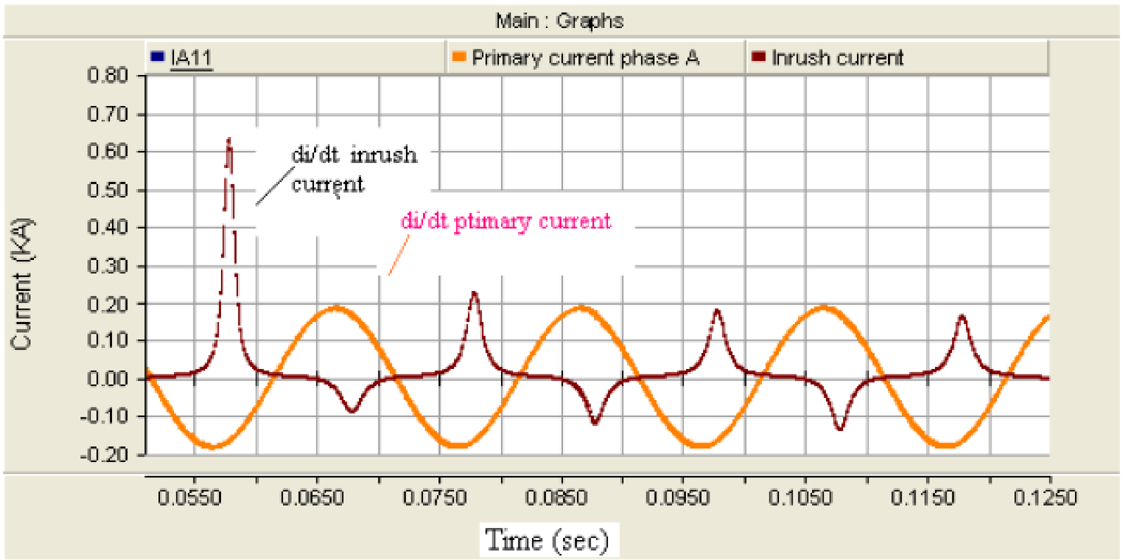

Figure 13: Inrush current and primary current waveform

- **Calculation of the Derivative of the Current Wave**

The function of this part of simulation is to calculate the di/dt of inrush current and internal fault current to determine the threshold value (TF). As shown in Figure (14), the maximum value of di/dt of the internal fault 34.5 and- 34.5 respectively. On other hand as shown in the Figure (15), the value of di/dt of the inrush current is higher than that for the di/dt of the internal fault. Thus the threshold value (TF) is the absolute value of TF =34.5.

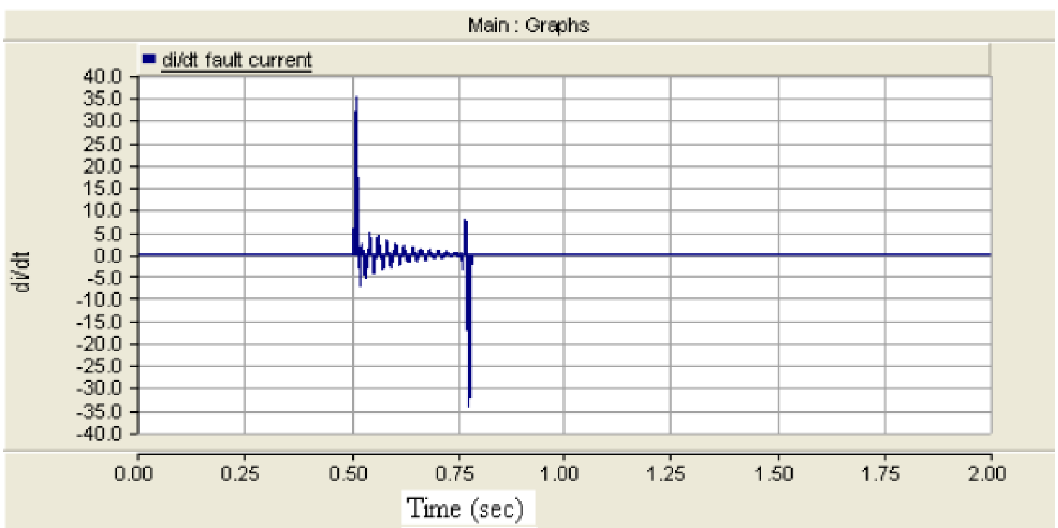

Figure 14: Derivative of internal fault current

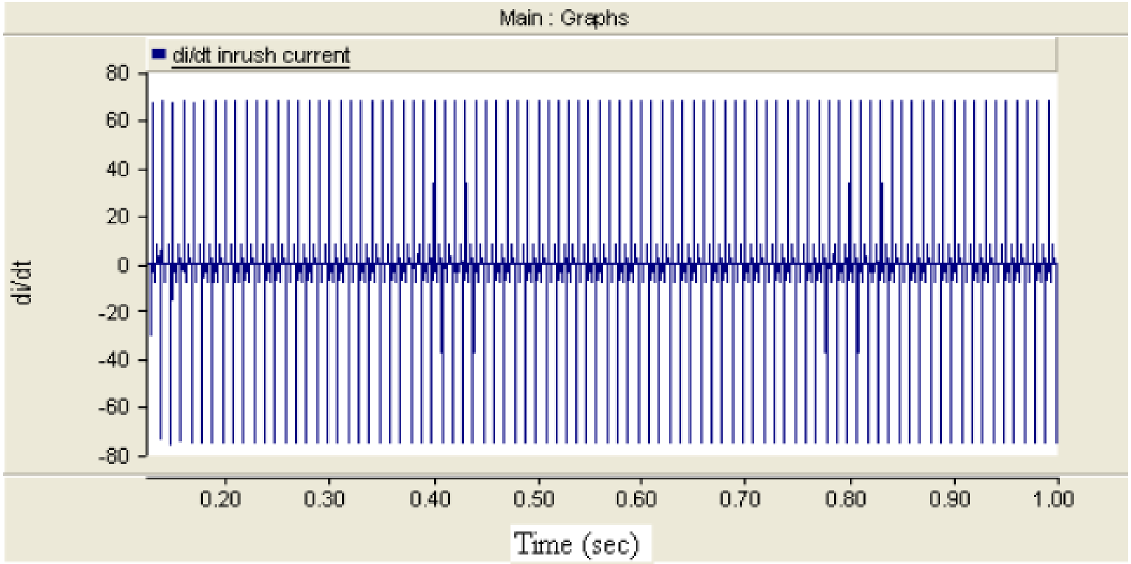

Figure 15: Derivative of inrush current

Case 2: Testing Inrush Current Discrimination Software

To avoid mal-operation of differential relay due to inrush current during the transformer energization time, the relay must discriminate between inrush current and internal fault. The function of this software, if the di/dt of the primary current wave when the transformer is switch on exceeds the threshold value (TF), this means that the transformer is in magnetizing inrush current phenomena. If the transformer is in magnetizing inrush current phenomena, the relay gives time delay before starting differential protection software.

However this test has been done in case of no fault, normal operation, as shown in Figure (16) when the transformer is energized the value of di/dt is high and the relay does not trip because of there is no internal fault, and gives time delay before starting differential relay program.

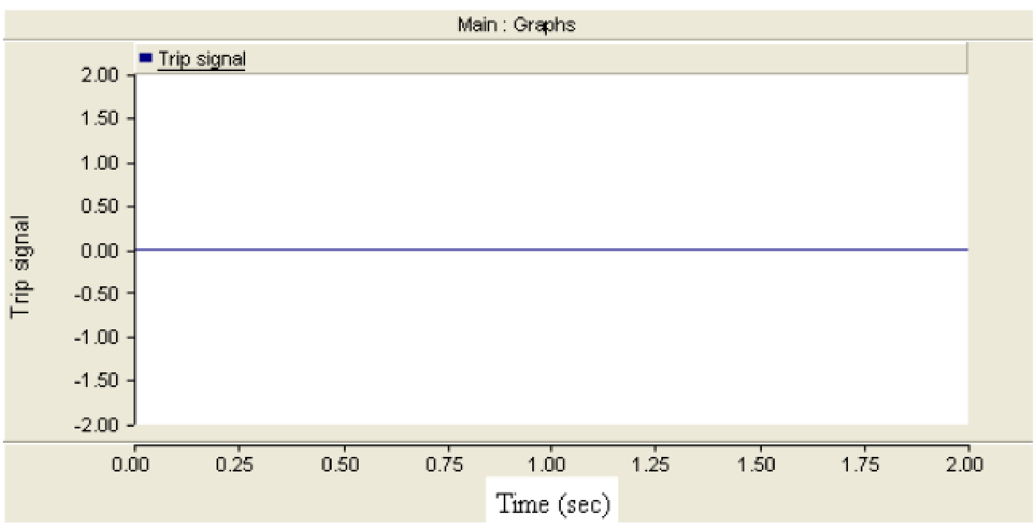

Figure 16: Relay output signal

Case 3: Simulation Results during Internal Fault

In this case, a three phase to ground fault is created to test the security of the algorithm. After the switching of CB1 at 0.05sec, an internal fault, between CT1 and CT2, is created at 0.5 sec by connecting the three phases A, B and C to the ground. As shown in Figure (17) the primary and secondary currents (The CTs on phase A) are in phase and are equal in magnitude during normal operating conditions before 0.5 sec. when the fault occurs at time 0.5 sec a significant increase of the primary current takes place compared by secondary current due to the fault occurrence inside the protected zone of differential relay. On other side, there is no current on secondary side of power transformer. In addition, Figure (18) shows primary, secondary and differential currents magnitudes during normal operation and internal fault. During the normal operation (before 0.5 sec) the differential current is less than pickup current (0.002 A), after fault occurred the differential current is higher than pickup current. The first step of the relay operation the relay detected this difference between two currents and the second step investigate this difference due to inrush current or internal fault current using the slope of the current wave comparators and realized it as an internal fault. Consequently, the transformer is isolated from the grid. In addition, it is obvious from Figure (19) that the relay has released a trip signal after 2.5 msec after the occurrence of the fault, which can be considered as a very good speed to isolate the transformer from the system.

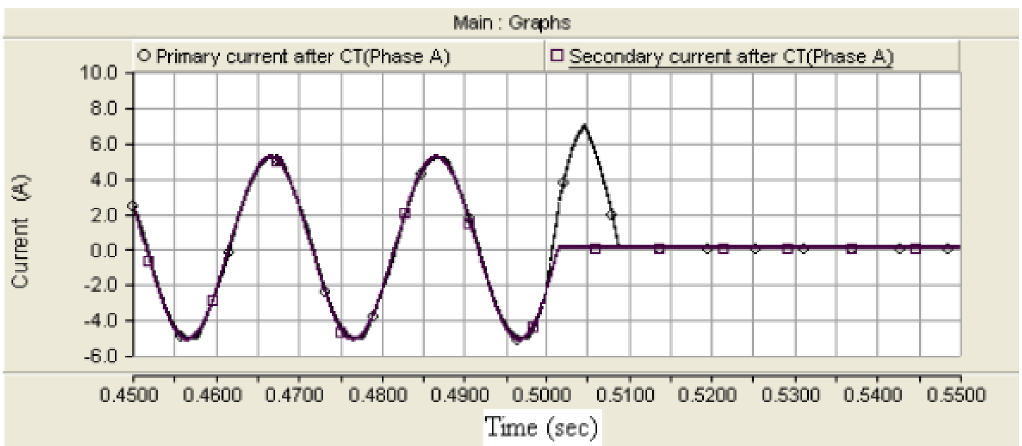

Figure 17: The output CTs of the primary and secondary current waves of phase A

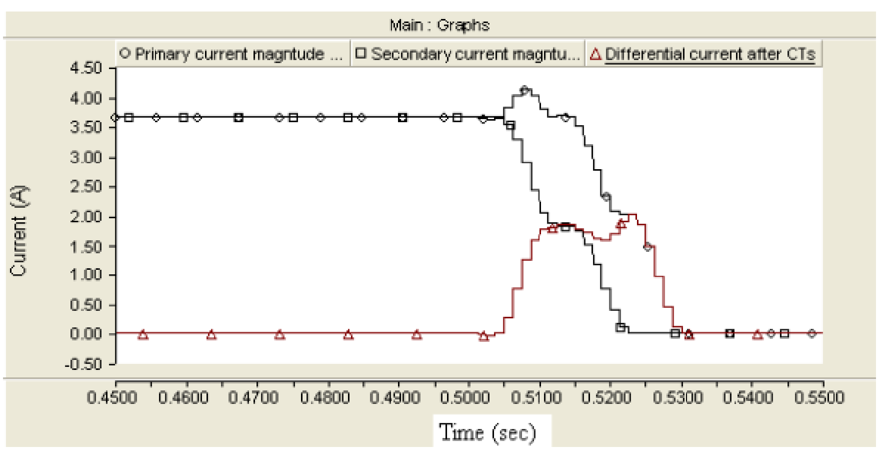

Figure 18: Primary, secondary and differential currents during internal fault.

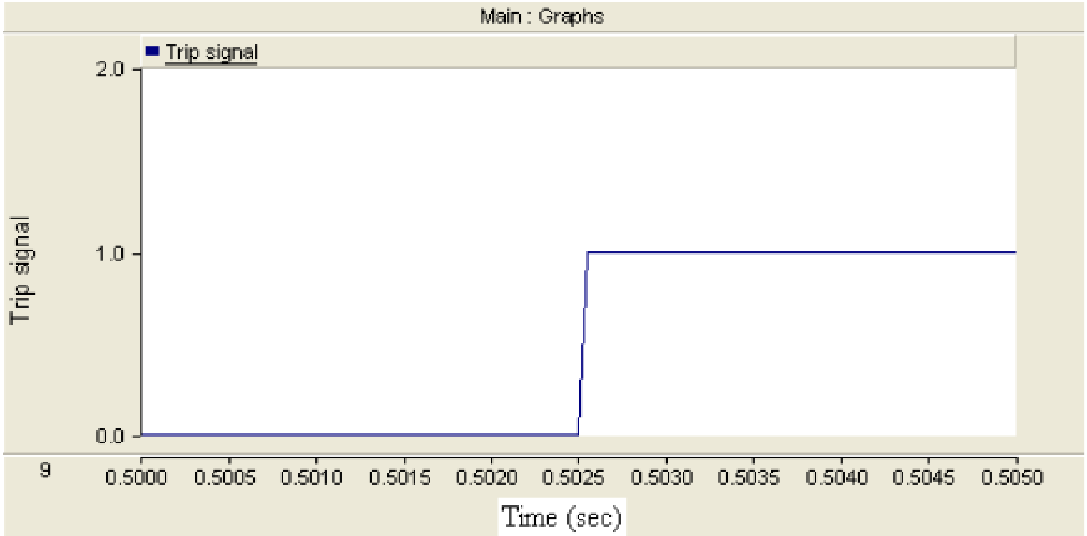

Figure 19: Trip signal go to circuit breaker

Case 4: Simulation Results during External Fault

In this case, a three phase to ground fault is created to test the security of the algorithm during external fault. After the switching of CB1 at0.05sec, an external fault is created at 0.5 sec at the load side (after the CT2) by connecting the three phases (A, B and C) to the ground of the cable between the secondary side of the power transformer and the load. As shown in Figure (20) a significant increase of the primary and secondary currents takes place due to the fault occurrence outside the protected zone. The primary and secondary currents are equal during normal operating conditions and external faults. In addition, the result shows there is no change in differential current. Therefore, in this case there is no trip signal issued by the relay as shown in Figure (21) because there is no difference in the secondary and primary currents detected by the relay this due to the fault occurred outside operating zone of differential relay.

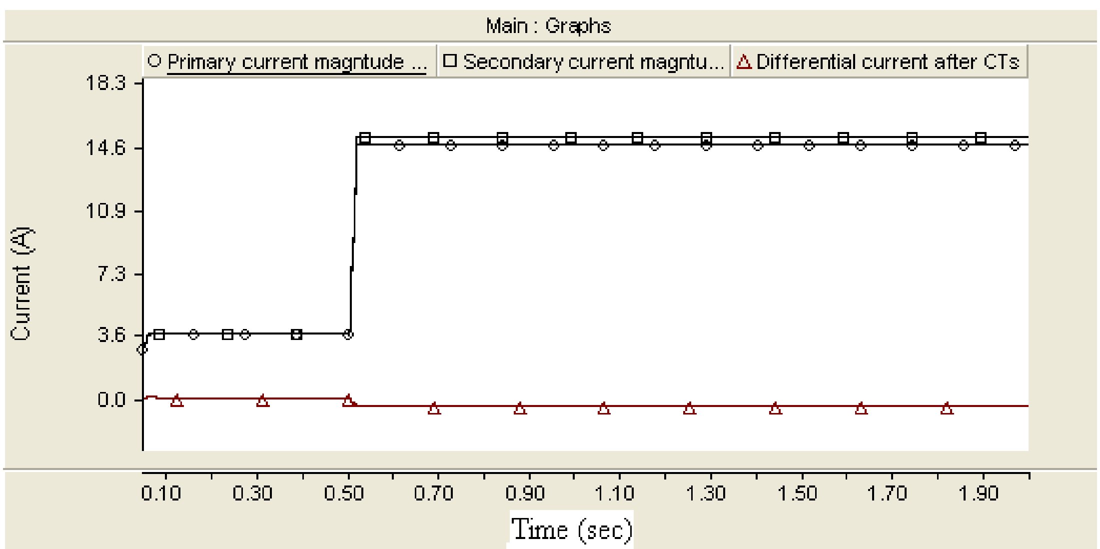

Figure 20: Primary, secondary and differential currents during external fault

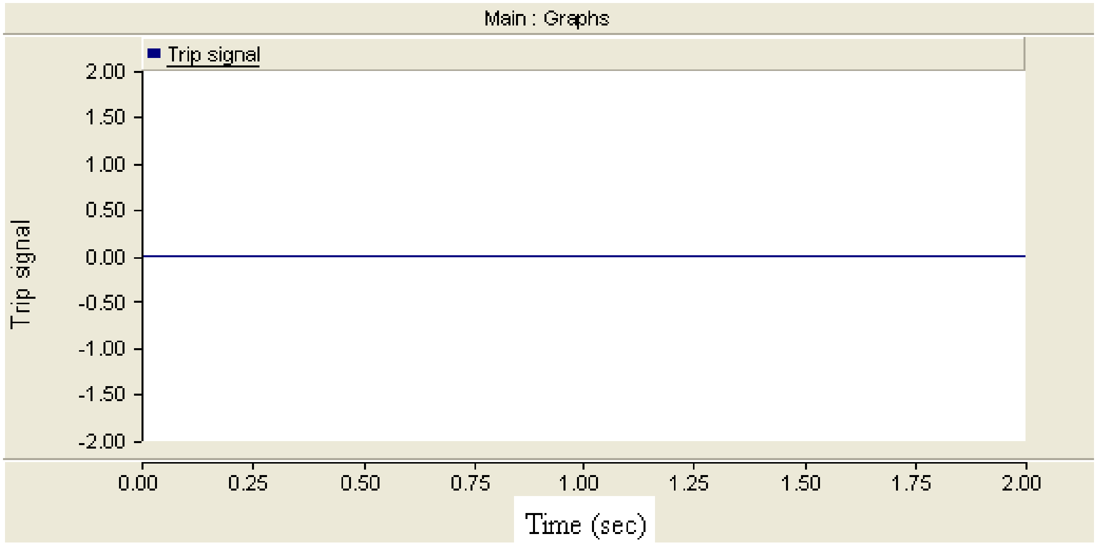

Figure 21: Relay output signal

CONCLUSIONS

The design of digital relay in PSCAD for power transformer has been described. The major emphasis of this paper has been the detailed description of hardware and software development of the relay. The method of rate of change of the primary current with respect to time (di/dt) in the first quarter of primary current wave method has been used to discriminate the internal fault current from inrush current. The magnetizing inrush current wave has high di/dt compared with di/dt of internal fault current wave.

The results demonstrated that the operating time of the relay is 2.5 msec, which means that the relay is fast. In addition, the differential protection does not issue a trip command during normal operation; magnetizing inrush and external fault conditions, this means that the system is reliable. Moreover using this relay reduces the cost of protection system for example there is no need to use interposing current transformers.

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