Improved Differential Relay for Protection of Three Phase Delta-Wye Transformer

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Declaration

We solemnly declare that this report is written by us and is not copied from any online or printed material.

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ABBREVIATIONS

MI: Magnetizing Inrush

CT: Current Transformer

LL: Line to Line

TL: Triple Line

TLG: Triple Line to Ground

LCD: Liquid Crystal Display

PDR: Percentage Differential Relay

$N_{p:}$ turns on primary side of power transformer

$N_{s:}$ turns on secondary side of power transformer

$n_{p:}$ turns on primary side of current transformer

$n_{s:}$ turns on secondary side of current transformer

SOFTWARES USED

MATLAB/SIMULINK

CORAL DRAW

ARDUINO IDE

ABSTRACT

The proposed differential relay is a reliable, relatively low cost lab equipment, composed of power transformer whose primary and secondary currents are measured through electrical transducers connected in series with power transformer. Percentage differential scheme is applied to protect transformer in case of internal fault. This relay has significant advantages as compared to conventional differential relay. A Trainer is designed for performing the lab of power system protection. Proposed algorithm will compute the primary and secondary currents and will calculate their difference. This difference will be compared by fraction of input current. Designed relay will be able to trip on occurrence of internal fault and will have ability to restrain while introducing external fault. Relay will restrain mal-operation in case of starting inrush current. The proposed system will be simulated in MATLAB-SIMULINK environment and will be designed on microcontroller arduino MGA328.

CHAPTER 1: INTRODUCTION

- **Problem Statement**
- **Literature Overview**
- **Differential Protection**
- **Proposed Differential Relay**

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1.1 Problem Statement

Power transformer is the most important equipment to transfer power in power system. If power transformer experiences a fault then, it is necessary to have transformer out of service until fault is removed. The unplanned outage can cause a big damage. The cost to repair a damaged transformer is very high (millions of dollars). That's why protective relays are used to protect power transformer from being damaged. It ease to fix a relay rather than to a transformer. So, Differential relay is used to protect transformer from internal fault. In some cases it fails to operate or mal-operationdue to MI currents, stationary over excitation of core, external faults in the presence of CT saturation, power transformer ratio mismatch, operation due to high second harmonic component. In this scenario percentage differential protection, harmonic-restrained differential protection is used, respectively. Percentage differential protection is a developed idea of ordinary differential protection which had made quite satisfactory solutions to the above mentioned problems. The requirements include dependability (no missing operations), security (no mal-operation), and speed operation (short fault clearing time).

1.2 Literature Overview

Power transformers are important and widely used equipment in power system. Due to their large size and price, it is much difficult to replace them in case of any damage. Power system demands high protection and reliability against abnormal conditions to avoid instability and disturbance. So protection of this equipment has primary importance in protection system, transformer is protected through different techniques.

1.2.1 Background Study

Power transformer is the most important equipment to transfer power in power system which may subjected to internal fault, Magnetizing Inrush (MI), Current Transformer (CT) saturation and internal fault, through fault current due to transient disturbances in the system [1]. Saturation of CT may yield to mal-operation of relay. That's why CT is the most accurate equipment in power system protection and its ratio error must be lesser. Normally MI is evaluated through second harmonic component variation more than 10% [2]. Such as harmonic restraint differential relay based on that due to MI current second harmonic component is large, but second frequency component is decreased due to advancement in core.

Turn-to-turn fault may leads to some serious damage in transformer windings and cause explosion because of overheating of insulating liquid. Consequently, windings must be protected to avoid major damages. Diagnosis of incipient faults at an early stage is the key of ensuring reliable electrical power supply to consumers [3]. To detect incipient fault various methods are suggested as dissolved gas analysis, due to variability in gas data, it is ineffective method. A study of breakdown of power transformers, 70% of transformers are damaged permanently due to undetected short circuited faults earlier [4-5]. Thus it is necessary at very early stages to identify the fault so one can make progressive arrangements for counteractive measures and executed quickly [6]. Most of the times internal faults are catastrophic and thus results in permanent internal damage. It is there for very essential to carefully monitor their online behavior [7]. Losses in no load and increased load conditions have been studied as well to experimently show inter-turn faults if the windings get shorted. However the effect of core degradation can influence no-load losses [8]. Transformer protection method that use its terminal behavior based on differential protection and studies for enlargement of transformer protection have concentrated on discrimination between internal short circuit faults and inrush currents in transformers [9].

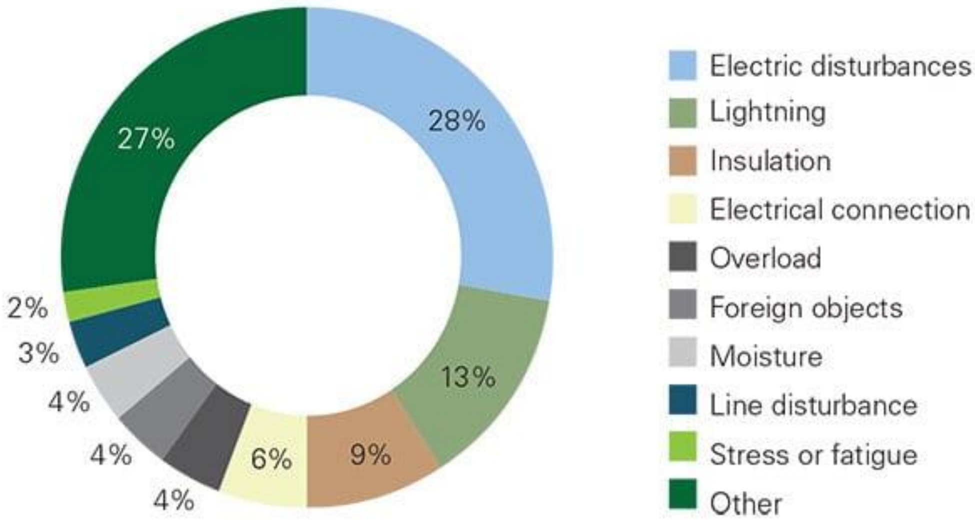

Fig. 1.1 Transformer damaging ratio in last decade

If power transformer experiences a fault then, it is necessary to have transformer out of service until fault is removed. The unplanned outage can cause a big damage. Stats have shown that almost 14% of transformer were burn out because of internal fault. **Fig. 1.1**. The cost to repair a damaged transformer is very high (millions of dollars). That's why protective relays are used to protect power transformer from being damaged. It ease to fix a relay rather than to a transformer. The requirements include dependability (no missing operations), security (no mal-operation), and speed operation (short fault clearing time) [10].

1.2.2 Protection schemes

The purpose of any protection scheme is to retain the main power system balanced and only the components that are under fault should get isolated from the system, So that most of the machinery out of fault still remain in operation. Therefore, protection schemes should carry out a very practical and derisive methodology for tackling system faults. The devices that are utilized for the protection of power systems are usually known as protection devices.

Relays are designed for identifying power system's irregular behaviors and inducts corrective action for stabilizing the power system in its actual state as soon as possible. The speediness of response is a crucial component of relays protection systems – response times of at least few milliseconds are usually required. Therefore, protection of the system is not possible through human involvement in this situatuons. The relay response time needed to be swift, automatic and must cause a minimum amount of disturbance to the power system. Various Protection Schemes are:

- Transmission Lines Protection
- Rotating Machinery Protection
- Bus Bar, Reactor Protection
- Transformer Protection
- Feeder Protection

The intrinsic characteristics of power transformers is a reason for introducing some exceptional complications that are not existing in the protection of transmission lines, generators and motors. [11]

1.2.3 Transformer protection

Transformer faults – i.e short circuits – are a reason of internal electric faults, and the most frequent one is phase-to-ground fault. And a bit less frequent one is turn-to-turn fault. The physical extent of a transformer is different from a transmission line as it is bounded within a substation, and hence differential relay scheme which is a quite appropriate method of protection present, can be utilized for protection of transformers. Generally fuses, overcurrent relays, differential relays, and pressure relays, are used for the protection of transformer and can be observed for incipient fault by winding temperature measurements, and chemical exploration of the gas above the insulating oil. Out of these the one to be used depends uon the following factors:

- **Transformer Size:** Transformers rated 2500 kVA or less are commonly protected through fuses. Transformers ranging from 2500 to 5000 kVA can also be protected by fuses, but prefered to be protected through instantaneous and time-delay overcurrent relays. And for ratings between 5000 and 10,000 kVA, an induction disc overcurrent relay is attached with system in a differential configuration. Above 10 MVA, a harmonic restraint, percentage differential relay is implemented. Some other realys utlilized with such ratings of transformers are Pressure and temperature relays.
- **Location and Function:** Only the size of transformer doesn't decide which relay is to be suitably utilized for the protection of system, One must consider the importance of the transformer within the power network., A more sophisticated relays is to be utlilized in terms of design and redundancy if transformer is an integral part of the power system. But if it is a simple step-down transformer of a distribution station, a single differential relay and overcurrent backup would be enough.

- **Voltage:** In general, more advanced and costly protective devices are reuired to deal with higher voltages, due to the irreversible destructive effect of a delayed fault clearing on the system operation and as the transformer repairing is quite costly.
- **Connection and Design:** When you shift from an autotransformer to two- or three-winding transformers the protection schemes would be varied accordingly. Even the winding connection of a three-phase transformer – whether delta or wye – will make the protection scheme chosen differently. The presence of tertiary windings, type of grounding used, tap changers, or phase-shifting windings must also be taken into account.

1.3 Differential Protection

Differential protection is a unit-type protection for a specified zone or piece of equipment. It can be applied considering the difference of currents between the internal fault zone and to the zone with high differential current (difference between input and output currents). However, even if there is no internal fault the differential current can sometimes be seen significantly due to some certain characteristics of current transformers (different saturation levels, nonlinearities) measuring the input and output currents.

Differential protection is based on the fact that power at input side to the transformer under normal condition is equal to power at output side [12].

The following are the classification of the differential protection relay:

- Current Differential Relay
- Voltage Differential Relay
- Biased or Percentage Differential Relay
- Voltage Balance Differential Relay

1.3.1 Ordinary differential protection

Conventional differential technique is based on difference of currents measured by primary and secondary side CT. Matching of CT ratios is important parameter in this technique. Ratios of current transformers used on primary and secondary side of power transformer are selected in such a way that secondary side of both current transformers show same current. Difference of these currents flows through differential relay.

In practical cases, exact CT ratios are not available commercially in order to fulfill our requirements. So, a certain value of current always passes through relay due to unbalance CT ratios. Another major problem in this technique is CT error. Current transformers does not measure actual value but have some error in measurement which causes flow of current in differential relay. This error is minimum at low current but increases as line current increases because this error is some percentage of primary side current of CT. An ordinary differential relay is shown in **Fig 1.2**.

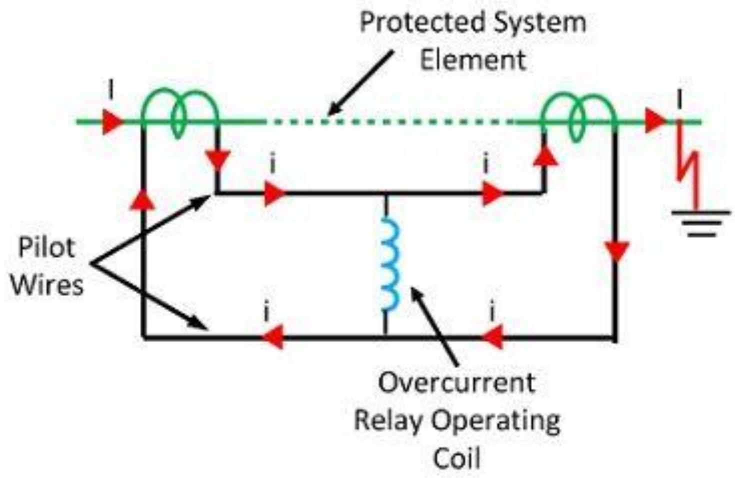

Fig. 1.2: Ordinary differential relay

At very large current this difference is significant and consequently results in mal operation of relay. Starting inrush current is another problem in conventional differential technique. Power transformer draws heavy starting current for magnetizing of core. This current is seen by only primary side current transformer which creates major difference in measurement of both currents causes ultimate false tripping of relay.

1.3.2 Percentage differential protection

Differential protection is used to protect transformer from internal fault. In some cases it fails to operate or mal-operationdue to MI currents, stationary over excitation of core, external faults in the presence of CT saturation, power transformer ratio mismatch, operation due to high second harmonic component. In this scenario percentage differential protection, harmonic-restrained differential protection is used, respectively. Percentage differential protection is a developed idea of ordinary differential protection which had made quite satisfactory solutions to the above mentioned problems.

A restraining coil is used in a percentage differential relay for overcoming the fault occuring due to external short circuit which causes the difference of currents. The percentage differential system consists of a restraining coil attached in the pilot wire as shown in the **Fig 1.3.** and the current induced in both the CTs flows through it. There is a operating coil attached between the midpoint of the restraining coil.

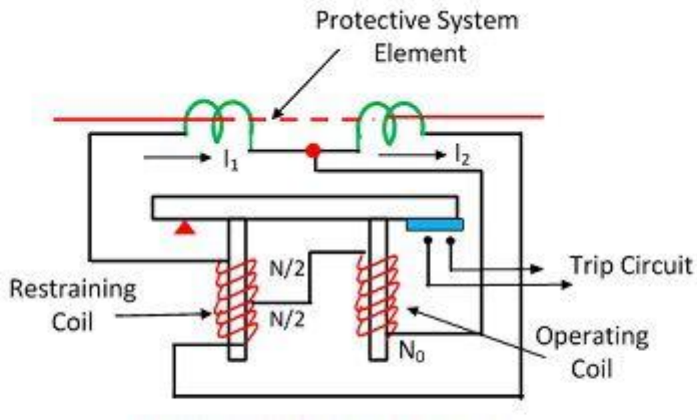

Fig. 1.3: Percentage differential relay

The problems (MI currents, stationary over excitation of core, external faults in the presence of CT saturation, power transformer ratio mismatch, operation due to high second harmonic component) are considered in percentage differential technique to provide stability to power system. In this protection scheme spill current is not compared to constant value but it varies as input current varies. Spill current is compared with fraction of line current. As current increases, fractional value of current also increases.

Starting inrush magnetizing current is although very high but it is controlled by percentage differential relay. Because when input current increases specific percentage of line current also increases and relay withstands input transient response of transformer. Similarly, Margin of CT error as well as CT mismatch is also considered in this scheme.

1.4 Proposed Differential Relay

A restraining coil is used in a percentage differential relay for overcoming the fault occuring due to external short circuit which causes the difference of currents. Our relay also based on current difference principle. It measures the current on both sides of transformer with CT and take difference. Designed differential relay will retain on external fault and will trip on occurrence of internal fault. High inrush current results in mal-operation of conventional differential relays. Percentage differential relay is used to solve this problem. Our relay compares percentage of line current with spill current. If spill current is greater than 40% of line current, it will cause trip of relay. High inrush current will be allowed by relay as spill current is less than percent in case of starting of transformer.

CHAPTER 2: EXPERIMENTAL SETUP

- **Power Transformer**
- **Arduino**
- **Display**
- **Current Sensors**
- **Buttons**
- **Wires**
- **Load**
- **Connectors**
- **Relays**
- **Indicators**
- **Acrylic Sheet**
- **Wooden Sheet**
- **Power Supply**

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2.1 Power Transformers

We have used 3 single phase transformers and have configured them in three phase wye-delta connections. The basic purpose of a Power Transformer is to transfer electrical energy through circuits to either electrical or electronics components like generators or the distribution primary circuits. Such transformers are basically used for stepping up and down the voltages in distribution systems. Power transformer is the major equipment to transfer power in power system which may subjected to internal fault, Magnetizing Inrush (MI), Current Transformer (CT) saturation and internal fault, through fault current due to transient disturbances in the system.

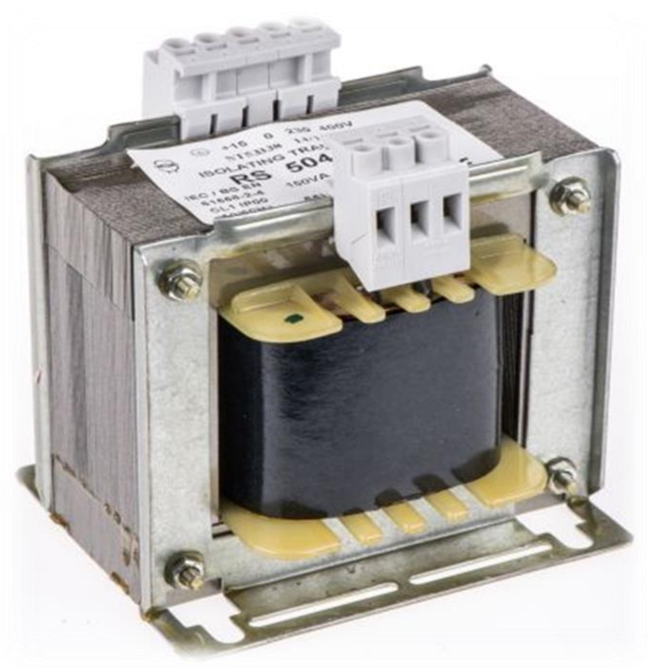

Fig. 2.1: Ordinary small transformer

Trasformer parameters	
Paramater	**Value**
Power Rating	440VA
Operating Voltage	220V
Output Voltage	75V, 110V, 220V
Operating Frequency	50Hz
Maximum Current	2.02A

Table 2.1: Trasformer parameters

2.2 Arduino

We have used arduino in our project for interfacing the relays, current sensors and LCD with the transformer and the main system. Arduino Uno is comprised of an ATmega328P processor chip built in on a microcontroller board. It consist of 14 digital I/O pins (out of these 6 can be used as PWM outputs) and 6 analog input pins. Moreover it has a 16 MHz quartz crystal, USB connection, power jack, an ICSP header and reset button. It consists of most of the major components to support the microcontroller.

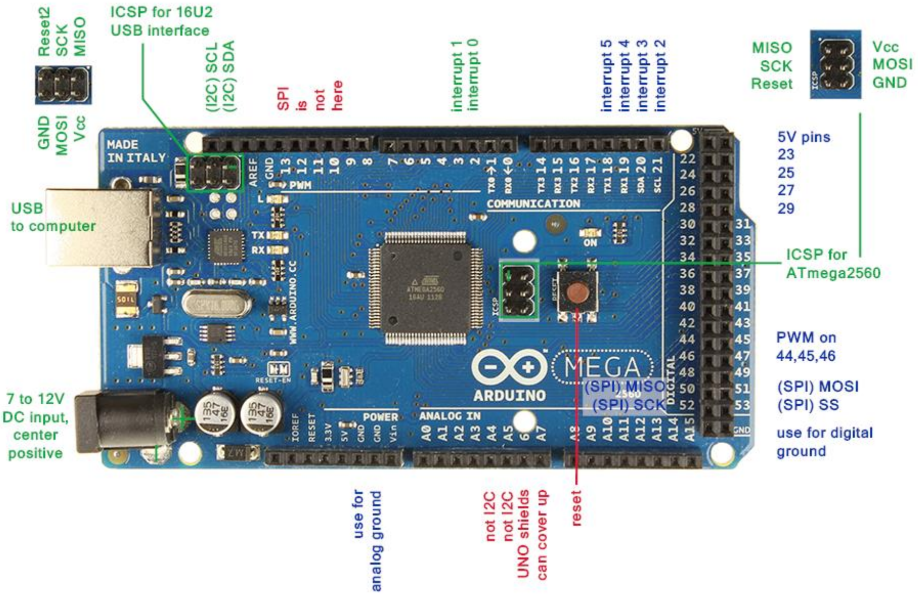

Fig. 2.2: Arduino MEGA328

Arduino Datasheet	
Paramater	**Value**
DC Current per I/O Pin	20 mA
Operating Voltage	5 V
Flash Memory	32 KB
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

Table 2.2: Arduino Datasheet

2.3 Display

We have attached an 16x4 LCD (Liquid Crystal Display) to Display the required outputs and results of the working system. LCD is an electronic module used as display screen and and have many applications. LCD display with dimensions 16x4 is usually used in several electronic devices. Consisting of seven and multi segments LEDs they display the required output on screen. They are usually prefered beacause are easy to program, low cost, can dsilay animations and have no unnecessary limitation of displaying different characters. A 16x4 LCD can display 16 characters per line and there are 4 such lines.

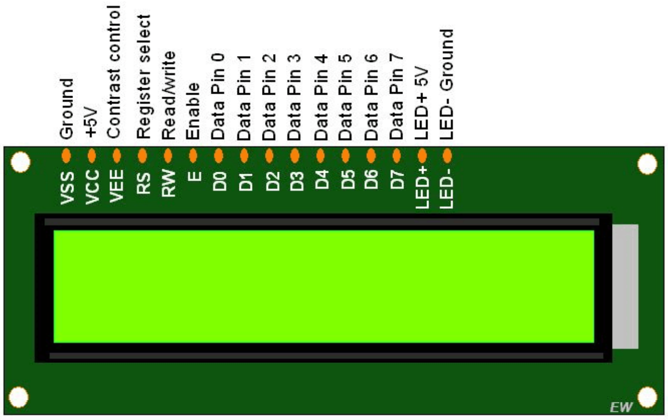

Fig. 2.3: 16*4 LCD

2.4 Current Sensors

We have used six ACS712 current sensors for measuring the current using Hall Effect. Three sensors on the primary side and three on the secondary followed by relays. The ACS712 Module consist of a ACS712 IC to measure the current and uses Hall Effect principle for it. The name of this module is due to the IC (ACS712) implanted in it, as it is basically using the IC for the work.. This module can comute AC or DC current having range from +5A to -5A, +20A to -20A and +30A to -30A. The one we have used in our project is of range +30A to -30A for the accurate operation of the system. Depending upon the current flowing through the wire this modules outputs Analog voltage (0-5V); making it quite easy for interfacing this module with any microcontroller.

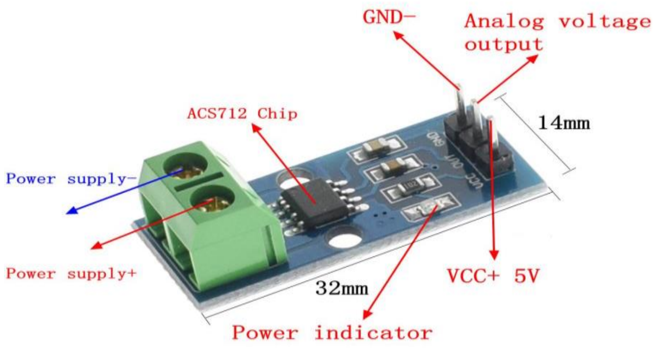

Fig. 2.4: ACS712 current sensor

ACS 712 Datasheet	
Paramater	**Value**
Supply Voltage (VCC)	5V dc
Measurement Range	-5 to +5 Amps
Voltage at 0A	VCC/2 (nominally 2.5Vdc)
Scale Factor	185 mV per Amp
Chip	ACS712ELC-05A

Table: 2.3: ACS 712 Datasheet

2.5 Buttons

Different buttons are used in project according to our requirement such as push buttons, On-Off buttons as well as small push buttons. Detail of these buttons and area of use is given below.

2.5.1 Fault Buttons

To generate the faults we have placed three push buttons (Red, Green, Yellow) on our trainer through which we test the functionality of our relays. Red button is for the incipient fault, Blue for line to line and Yellow for triple line. These buttons are normally open in normal state and their contacts become short circuited on pushing buttons.

Fig. 2.5: Small push button

2.5.2 Load Buttons

We have used a switch board with six buttons on it and have connected the load with it. Through these buttons we control the load on the system and examine system operation.

2.5.3 Reset Buttons

A reset button is attached as well to bring our system back to normal after testing it on different faults. This button is also open in normal state and gives high value to reset pin of arduino. When we push this button it becomes short circuited and make a contact between arduino ground and arduino reset pin. This gives low value to arduino reset pins and it resets microcontroller from its working state to initial state. Simple digram of this push button is given in next page in Fig. 2.7

2.6 Wires

Different types of wires are used in this project according to scenario of project and requirement. This wires are used to connect arduino to transducers and relays, connection betweens source and transformers as well as transformers to load side. Transformers are connected to designed trainer through these wires. Area of wire depends upon current passing through area in which we using these wires.

2.6.1 Jumper Wires

For making connection of Arduino with the current sensors, relays, LCD display and reset button, we have used jumper wires to make connections feasible, reliable, easy to understands and replaceable if required. These wires are male-male, male-female, female-female according to requirement.

2.6.2 3/29 Wires

For making connections of load, switch board and fault buttons we have used 3/29 wire that is commonly used in house wiring. This wire is selected due to its normal current carrying capability feasible for our load attached and bearing of potential that is applied on this load. It has 3 conductors and each conductor has diameter of 29mm that leads to its name. this wire connects source voltages to transformers through primary current sensors and relays on source side. Connection of load with secondary side of transformer are also made with this wire through secondary current sensors.

2.6.3 7/29 Wires

This wire is used on source side to connect three phase voltage source to three single phase transformers snf to make equivelant three phase transformer. It has 7 conductors and each conductor has diameter of 29mm that is clealy visualized by it name. This wire has high current carrying capability as compared to 3/29 wire and relatively high potential bearing capacity.

2.7 Load

Incadescent bulbs are attached as load on secondary side of transfomers. Load in connected in wye configuration. This load can be varied in steps and burdon can be applied in any configuration to make unbalance situation. This load will be used to create external fault and testing behavior of our proposed relay. Load variation graphs will also be drawn by varying external load. These bulbs are connected with holders. Details of load equipments in given below.

Load Parameters	
Paramater	**Value**
Power Rating	160Watt
Resistance	300 Ohm
Nominal Current	0.75 A
Operating Frequency	50Hz
Load configuration	Wye

Table 2.4: Load Parameters

2.7.1 Holders

There are six holders through which we connect the load (Incandescent bulb) with the system. These hodlers are responsible for fix connections of bulb with transformers. In case of any damage of load, these bulbs are easy to replace because of use of these holders.

2.7.2 Incandescent Bulb

We have used Incandescent bulbs as load to the system rated 60 Watts each as normal operating load and 100 Watts each for over current scenerio. This bulb is preffered in load due to in resistive nature. This will help us to reduce complexity of system and will avoid leading and lagging of currents with voltages as currents and voltages are inphase with each other in resistive load.

2.8 Connectors

Diffent type of connectors are used in our project such as three phase connector, probes for transformer connections and their female and male connectors. Here is details discussion of all connectors used in designed trainer.

2.8.1 Three Phase Connectors

We have used a three phase connector to connect our transformers with the main line followed by a circuit breaker. These connectors are used to build a connection to the electrical mains with high voltages and currents rating than household plugs and sockets. They are normally utilized in polyphase systems, consisting of high currents, or when protection from environmental hazards is needed.

Fig. 2.6: Three phase connector

2.8.2 Connecting Probes

To connect transformers in delta wye configuration on the trainer, we have used connecting probes. In this way it would be much easier to make the connections. These probes are easy to remove and can be used to connect transformer in any configuration rather than delta wye.

2.8.3 Female Connectors

We have attached total of sixteen female connectors on the trainer to connect the system in three phase wye to delta. These connectors are fixed on trainer and can't be removed easily but accessible in case of any damage. Different color schemes are used to make connections understandable and reduces chances of error in designed trainer. Two on the primary side and two on the secondary of each transformer and rest of four for input voltage source phases and ground.

2.9 Relays

We have used three single channel relay modules for each phase and configured them as differential relays through Arduino. The operation of Differential relay is that it takes the phase difference of two or more same electrical quantities when they exceeds a predetermined figure and functions accordingly. These relays works on the principle of comparison between the phase angle and magnitude of two or more similar electrical quantities. These relays are normally in closed state and turned ot open state when signal is given to relay. Red leds are used to represent functionality of relays. LEDs turns on when relay is in operating mode. A commonly used relay is shown in Fig. 2.7.

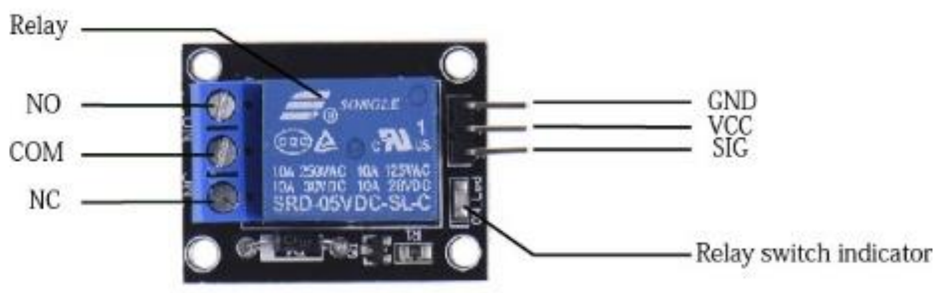

Fig. 2.7: Relay

2.10 Indicators

There are three indicators Red, Green and Yellow which get brighten when the system is connected with the main supply. These indicators are connected as individual single phase with one phase and ground connected to each indicator. These indicators turns on when voltage supply turns on and voltage appears across input terminal of designed trainer. These trainers are connected parallel with phases. Current drawn by these connectors is ignored in source code as they draw current in milli amperes.

2.11 Acrylic Sheet

We have used a 6mm thick Acrylic Sheet having dimensions 18x12 cm to design the fornt side of board for our trainer. Through laser cutting and engraving we have designed the required model for the components placement on the sheet.

2.12 Wooden Sheet

For making a support at the backside of our trainer on which we have placed our transformers, bulbs and holders we have used a wooden sheet. All remaining three faces and bottom of our trainer is designed by 4mm thick wooden sheet. This sheet is used to insulate transformers and isolation of our trainer with work station as well as other equipments.

2.13 Power Supply

A power supply is used to provide the power to Arduino mega. Power supply is rated 2A, 5V output. This power is consumed in providing power to relays, current sensors, and LEDs that are used for indication of relay tripping and restraining.

CHAPTER 3: METHODOLOGY

- **Working Principle**
- **Internal Fault Behavior**
- **External Fault Behavior**
- **Simulations**
- **Results**

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3.1 Working Principle

"Differential protection based on the principle of that power input to the transformer under normal condition is equal to power out"

Differential protection is used to protect transformer from internal fault. In some cases it fails to operate or mal-operation due to MI currents, stationary over excitation of core, external faults in the presence of CT saturation, power transformer ratio mismatch, operation due to high second harmonic component. In this scenario percentage differential protection, harmonic-restrained differential protection is used, respectively. Percentage differential protection is a developed idea of ordinary differential protection which had made quite satisfactory solutions to the above mentioned problems. Conventional differential technique is based on difference of currents measured by primary and secondary side CT. Matching of CT ratios is important parameter in this technique. Ratios of current transformers used on primary and secondary side of power transformer are selected in such a way that secondary side of both current transformers show same current. Difference of these currents flows through differential relay. In practical cases, exact CT ratios are not available commercially in order to fulfill our requirements.

So, a certain value of current always passes through relay due to unbalance CT ratios. Another major problem in this technique is CT error. Current transformers does not measure actual value but have some error in measurement which causes flow of current in differential relay.

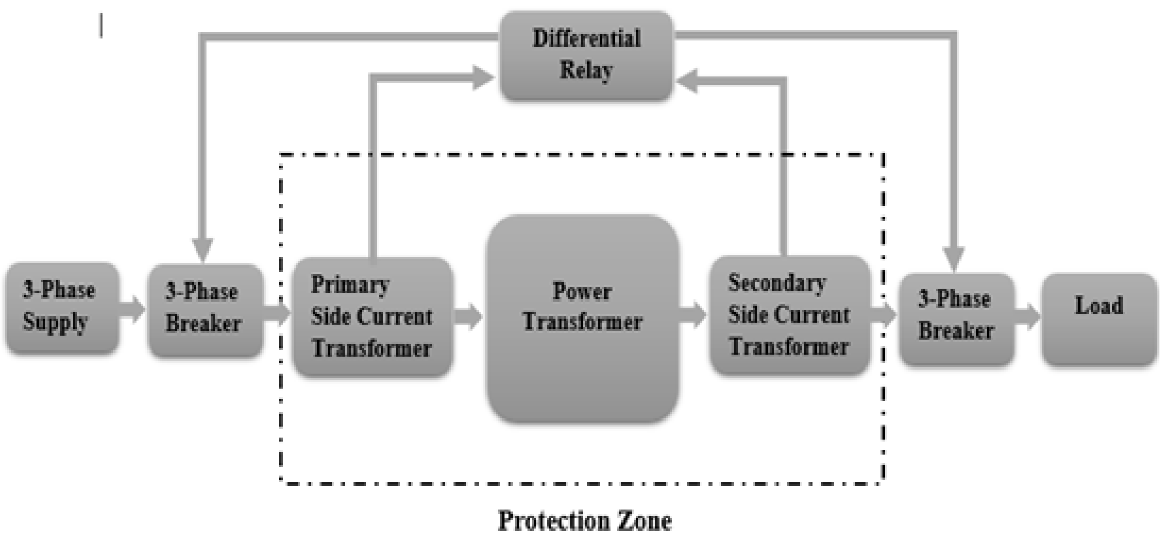

Fig. 3.1: Block Diagram

This error is minimum at low current but increases as line current increases because this error is some percentage of primary side current of CT. At very large current this difference is significant and consequently results in mal operation of relay. Starting inrush current is another problem in conventional differential technique. Power transformer draws heavy starting current for magnetizing of core. This current is seen by only primary side current transformer which creates major difference in measurement of both currents causes ultimate false tripping of relay.

These problems are considered in proposed differential technique to provide stability to power system. In this protection scheme spill current is not compared to constant value but it varies as input current varies. Spill current is compared with fraction of line current. As current increases, fractional value of current also increases. Starting inrush magnetizing current is although very high but it is controlled by percentage differential relay. Because when input current increases specific percentage of line current also increases and relay withstands input transient response of transformer. Similarly, Margin of CT error as well as CT mismatch is also considered in this scheme.

3.2 Internal Fault Behavior

The faults which can be occurred inside the Transformer is known as Internal faults. There are some types of internal fault mentioned below

- Incipient Fault
- Line to line Fault
- Triple line Fault
- Overheating
- Contamination of oil

Differential protection based on current, voltage or impedance difference is termed as current differential relay, voltage differential relay and impedance difference relay respectively. Proposed paper describes design of current differential relay based on difference principle i.e. primary and secondary current difference (is always zero at normal or no fault condition) and no current passes through the relay.

$$I_d = I_p - I_s \qquad (1)$$

In Eq. (1), I_d is current difference, I_p is primary side current, I_s is secondary side current.

$$I_r = k\,(I_d) \qquad (2)$$

I_r is relay current and k is fraction factor used for input feedback in Eq. (2). In case of internal fault current of one CT (say primary) exceeds (almost 100%) to normal current value, that current passes through ground and no current passes through secondary side. Therefore, heavy current passes through the relay, which results in relay tripping. During the normal conditions, the sum of ampere-turns of primary and secondary of a power transformer is equal to Magneto Motive Force (MMF) required for transformer core. Because of small air gap MMF's negligible (almost less than 0.5% of MMF of load current) and hence for a normal power transformer:

$$N_1 i_{1p} = N_2 i_{2p} \qquad (3)$$

N_1 are primary turns and N_2 are secondary side turns, i_{1p} is CT's primary current at primary side and i_{2p} is CT's primary current at secondary side of a power transformer in Eq. (3). If CT's having turn ratio of $1:n_1$ and $1:n_2$ at primary and secondary side, respectively, then currents in secondary windings of CT's can be related as:

$$N_1 n_1 i_{1s} = N_2 n_2 i_{2s} \qquad (4)$$

i_{1s} and i_{2s} CT's secondary currents at transformer primary and secondary side, respectively in Eq. (4). If we select CT's such that $N_1 n_1 = N_2 n_2$, then for a normal transformer $i_{1s} = i_{2s}$. But in case of internal fault, difference between i_{1s} and i_{2s} become larger which is proportional to fault current, that differential current (I_d) is :

$$I_d = i_{1s} - i_{2s} \qquad (5)$$

The magnetizing currents upset the current balance, as the unbalance condition relay experiences a fault current. The relay must not be activated at inrush condition as it is quite an undesirable situation for the system.

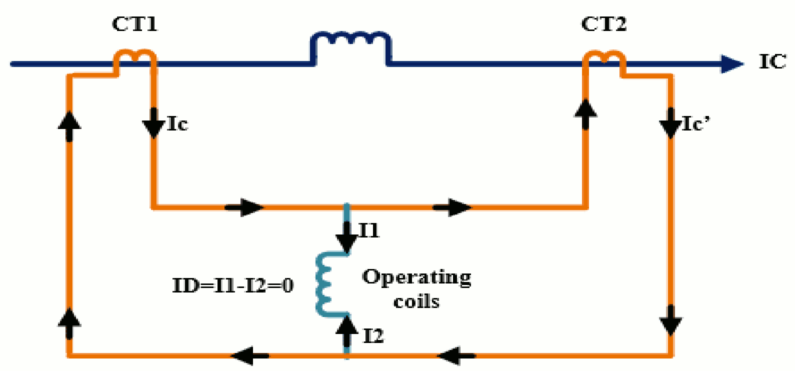

Fig. 3.2: Internal fault behavior of proposed relay

Over excitation can also cause an unwanted tripping of the differential relays. Even in generating plants such condition can arise when a unit connected generator is isolated while exporting V_{AR}. More power flows through primary than that of secondary when primary winding of a transformer is overexcited. In case of external faults, the differential current is of very high magnitude which can lead to relay mal-operation.

Harmonic restraint follows the fact that inrush current has a large second harmonic component and over-excitation has also large fifth harmonic component . These harmonics may cause false operation of differential relay.

3.3 External Fault Behavior

The Faults which are occurred outside of the Transformer is known as External Faults. Some of the External faults in listed below

- Lighting Strike
- Unbalancing of the System
- Over loading of system

In our case, relay will restrain on External Fault. In external faults high current passes through both CT's and no current passes through the relay due to zero current difference and the relay doesn't operate, as shown in Fig.1. However due to certain phenomena our relays can be tripped even in no fault conditions as it let some substantial differential current to flow like: MI currents, over excitation conditions and CT saturation.

Transformers required a large starting current to magnetize its core which usually result in MI current. The other reasons are [13]:

- Occurrence of an external fault.
- Voltage recovery after clearing an external fault.
- Change of the character of a fault (for example when a phase-to-ground fault evolves into a two-phase-to-ground fault).
- Out-of-phase synchronizing of a connected generator.

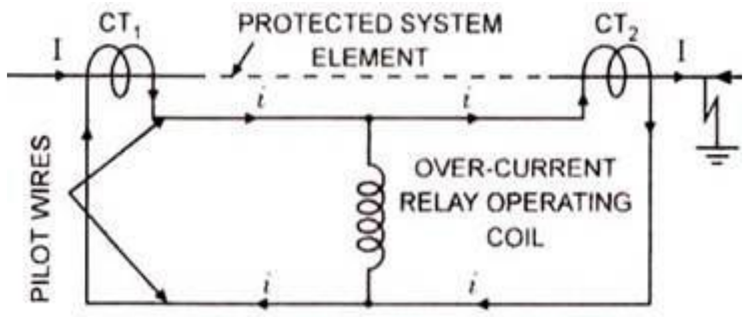

Fig. 3.3: External fault behavior of proposed relay.

We are preferring Percentage Differential Relay because the main advantage of using percentage differential protection over ordinary is that relay compares percentage of line current with spill current. If spill current is greater than predetermined value, it will cause trip of relay. High inrush current will be allowed by relay as spill current is only 40 percent in case of starting of transformer. It can also compensate the false current due to MI inrush and over-excitation.

3.4 Simulation

Simulation is done on software MATLB Simulink Fig.3.4 Shows simulation diagram of system in which transformer is protected by percentage differential relay. Transformer is configured in wye-delta connections for simulation model. System model consist of three phase source, current measurements on both sides of power transformer, three phase circuit breaker on primary side for isolation of transformer from source in case of internal fault. RL load on secondary side is used to indicate three phase inductive load on secondary side

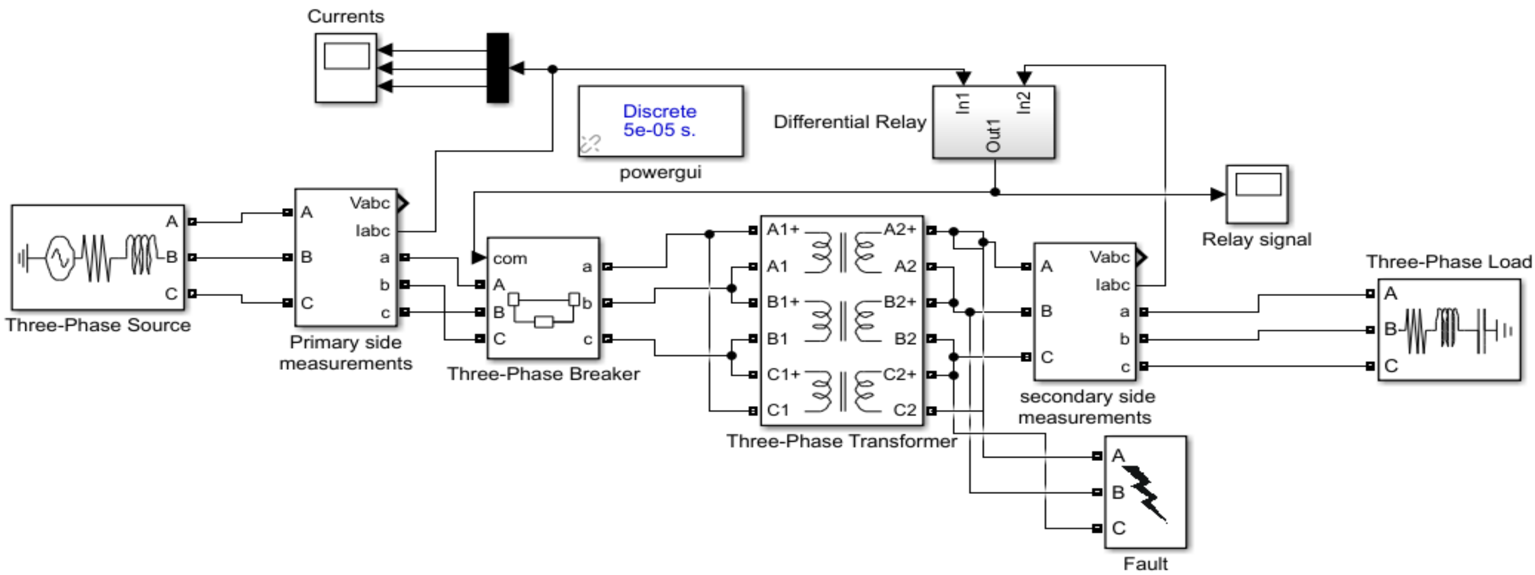

Fig. 3.4: Simulation Diagram

Differential relay is provided to system for protection of specified zone. This relay is responsible for detection of fault within its operating zone and will trip the circuit breaker. Fig.3.5 shows simulation model of designed differential relay. This relay takes primary and secondary currents of power transformer as input parameter and give logical output in form of Boolean variable. Designed differential relay consists of two input ports and one output port. Input port In1 takes primary current of all three phases of transformer while input port passes secondary side current of power transformer. Three phase Power transformer is 2:1 step down transformer, its primary side current is 2 times less than secondary side. Amplitude gain with gain factor 2 to balance both side currents to nullify the difference of currents. Currents are converted into RMS values to have smooth output to make difference operator easier and reliable.

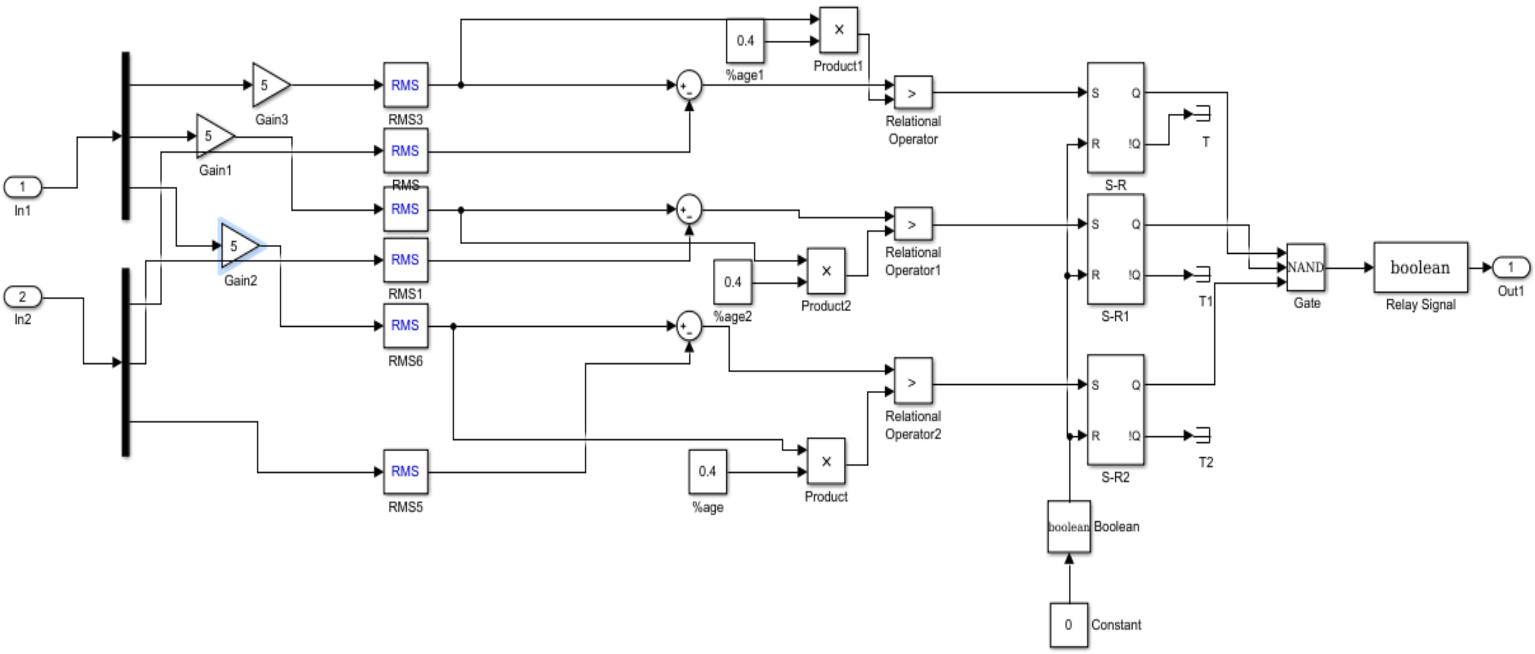

Fig. 3.5: Designed Relay Diagram

S-R latches are used as memory device to retain last logic state of comparator. Another logic is designed such that in case of any internal fault. Relay output is logical 1 in normal conditions and 0 in case of occurrence of fault in its operating zone. Relay output is used as input parameter for circuit breaker on source side. Circuit breaker is normally and opens when it receives logical 0 input. Simulation paratmeters are designed according to actual lab trainer to show exactly same results in case of software and hardware. Table 3.1 shows parameters of simulation that are selected in this simulataion.

Simulation Parameters	
Paramater	**Value**
Primary voltage phase to phase rms	400V
Secondary voltage phase to phase rms	220V
Source voltge	400V
Source Frequency	50Hz
Transformer Rating	1.5KVA
Transformer Configuration	Δ/Y
Resistance	300 Ohm

Table 3.1: Simulation Parameters

3.5 Results

Results are plotted on scope to analyze behavior of system as well as relay in case of external and internal faults. Current waveforms and relay signal is observed and results are extracted on variation of these parameters. Results are matched with real time hardware trainer and according to calculations.

3.5.1 Internal Fault Analysis

For internal fault, three phase fault is introduced between secondary side CT and power transformer. Output line current waveform and relay trip signal is given in Fig.3.6 and Fig.3.7 respectively. Fault is produced at time t=0.5s to 1s. Relay gives logical 1 before fault and logical 0 after fault. Circuit breaker which is closed in normal condition opens and no further current passes through circuit. It is clearly seen in Fig.4 that no current passes through system model after t=0.5s.

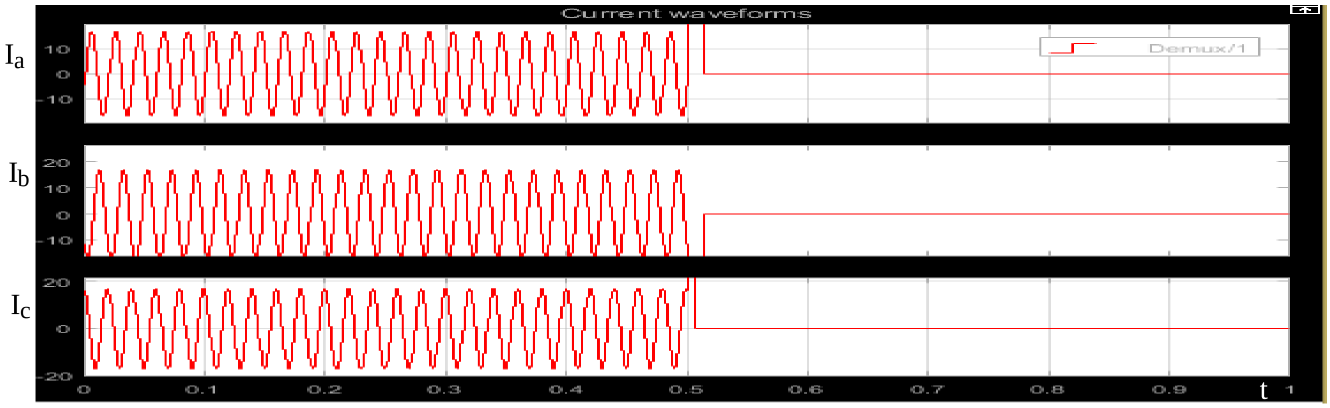

Fig. 3.6: Current Waveform during internal fault

relay tripping time is minimized and clear from both figures that relay tripping time is exactly same as time of introducing fault.

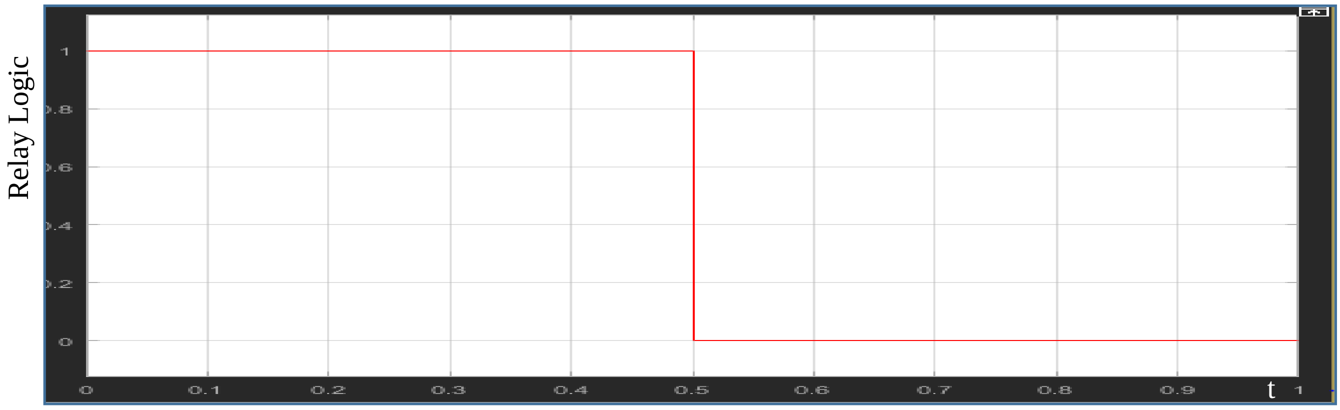

Fig. 3.7: Relay signal during internal fault

3.5.2 External Fault Analysis

External fault is introduced between load and secondary side current transformer. Fault is introduced at t=0.5s. Heavy current is drawn by fault during fault time. Current waveforms and relay restrain signal are shown in Fig.3.8 and Fig.3.9 respectively. When heavy current is drawn by fault than no significant difference on both side of currents is seen by relay. Relay is restrained and avoid mal-operation that conventional relays often do.

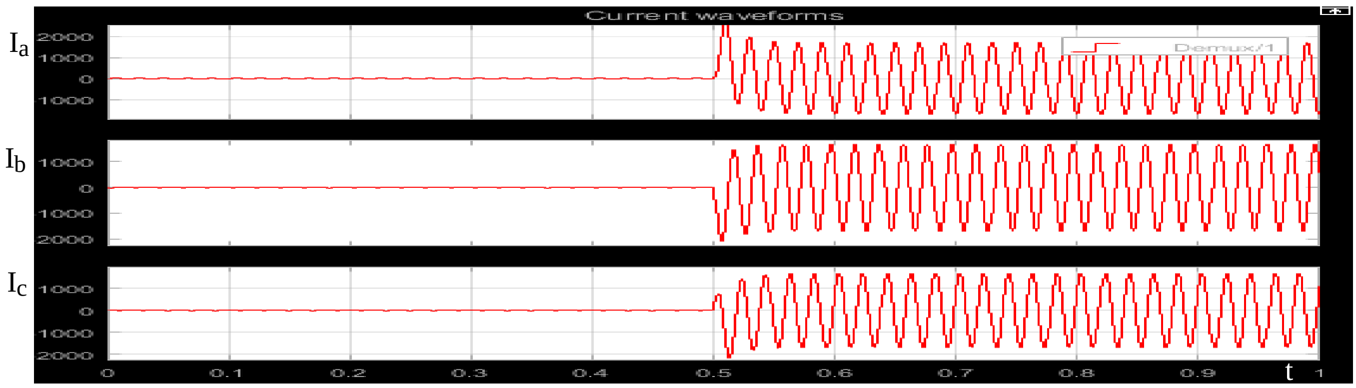

Fig. 3.8: Current Waveform during external fault

Figure 3.9 shows the relay signal before and after fault analysis. Relay gives constant logical 1 output before and after fault and keep the circuit breaker closed just like in normal condition. No tripping is seen by relay on heavy current drawn by load. So, relay has no mal-operation on external fault and restrains on all type of faults except internal faults.

Fig. 3.9: Relay signal during external fault

CHAPTER 4: HARDWARE IMPLEMENTATION

- **Hardware Design**
- **Fault Introduction**

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4.1 Hardware Design

Hardware of project is designed to make it reliable and feasible for lab performance. Input and output port are adjustable removable and replacable according to requirement of lab task.

4.1.1 Designing on Coral Draw

Project trainer is made of wooden and acrylic sheet and designed on Coral Draw software for accuracy and neat look. Project front side is made of designed 6mm acrylic sheet which is transparent in original form. Cutting and drilling on acrylic sheet can be shown in Fig. 4.1. Dimensions of holes and rectangles are taken according to size of buttons, LEDs, LCD and load buttons.

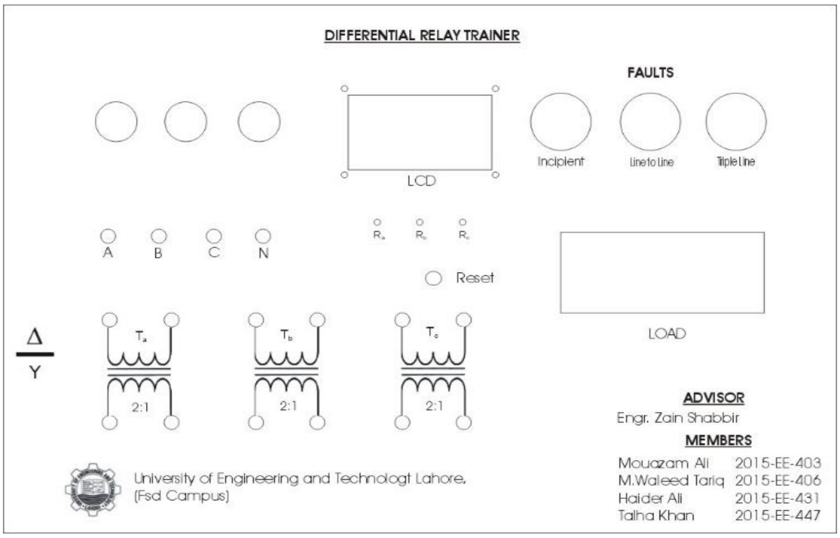

Fig. 4.1: Coral Draw Design

4.1.2 Laser Engraving

Trainer connections start from left to right in order to perform lab tasks. After making coral draw design and verifying its dimensions on actual hardware, this design is brought to engrave on acrylic sheet by means of Laser Engraving Technique. Holes and rectangles were verified after engraving of sheet by fitting all components in trainer.

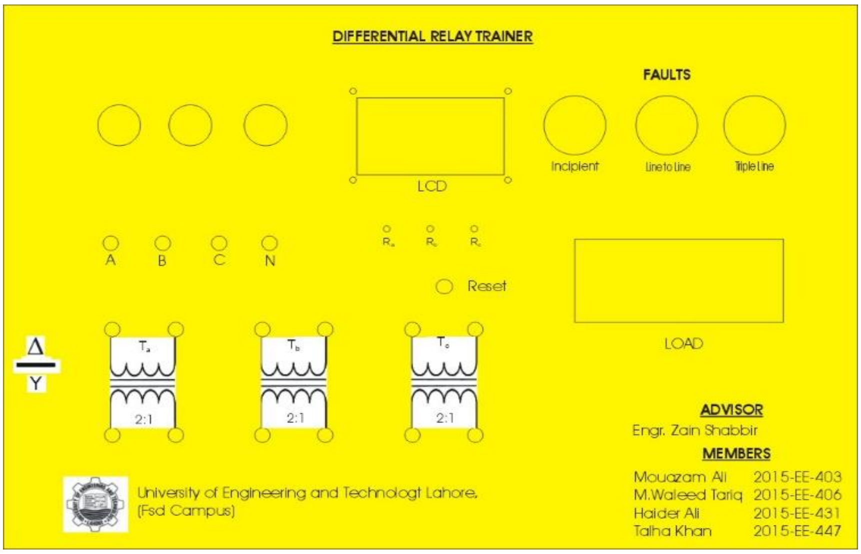

Fig. 4.2: Laser Printed Colored Design

4.1.3 Assembling of components

After engraving, this sheet is sparyed black color on front side and paper is removed from sheet. By this technique, only engraved place remained colored and all other place remained transparent because of paper on sheet.

Then this sheet is sprayed orange yellow color on back side. This color is chosen to make it similer to other lab equipments. Look of trainer after coloring it on front and back side in shown in Fig. 4.2. After coloring, this project is placed in sunshine to make it dry and shining purpose. After completing this step, components are fitted in trainer. Components fitted trainer diagram is shown in Fig. 4.3. This project is now quite similer to other trainers available in lab. Then all remaining sides of transformer are fixed with front side and complete model is designed.

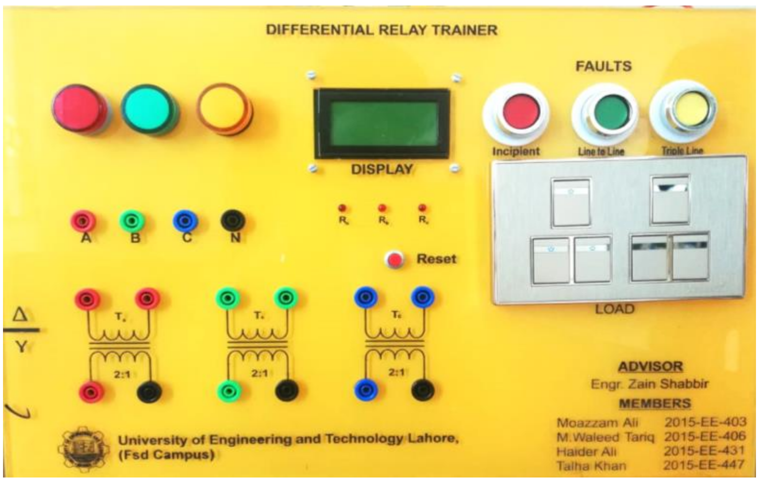

Fig. 4.3: Real time trainer.

4.1.4 Making final connections

Input output connections are made to perform a lab. This task was completed by verifying all connections by checking continuity on digital multimeter. All connections were perfect and were able to perform lab.

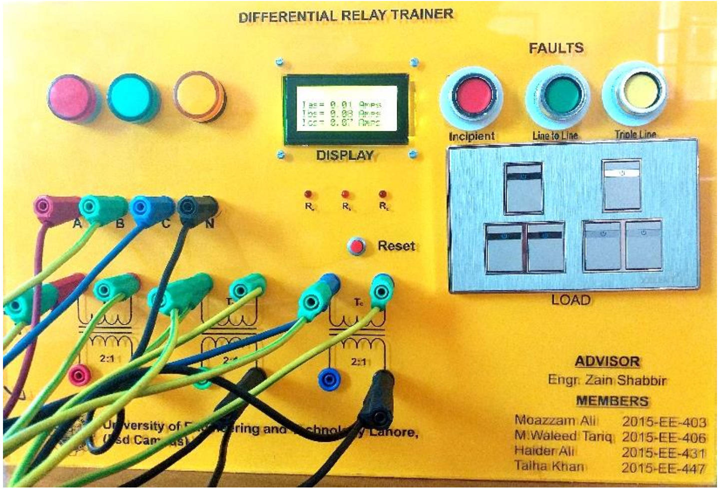

Fig. 4.4: Trainer With Input Output Connections.

In this way, an effective, reliable, low cost lab equipment for Power System Protection lab is designed to perform differential protection scheme lab on hardware.

4.2 Fault Introduction

Faults are indroduced via push buttons in order to check it transient as well as fault behavior. Three types of fautls are indroduced in system. Details of these faults are given below:

4.2.1 Incipient fault

Incipient transformer faults usually develop slowly, often in the form of a gradual deterioration of insulation due to some cause. When the condition of system equipment degrades because of some electrical, thermal or chemical effects, intermittent incipient faults begin to persist in the system.

4.2.2 Line to line fault

A line to line fault or unsymmetrical fault occurs when two conductors are short circuited. When fault occurs, the 3-phase system is no longer balanced i.e. angles and magnitudes change dramatically.

4.2.3 Tripple line fault

A three phase or symmetrical fault occurs when all of three conductors are short circuited. Only 2-5 percent of system faults are symmetrical faults. If these faults occur, system remains balanced but results in severe damage to the electrical power system equipments.

CHAPTER 5: CONCLUSION AND FUTURE WORK

- **Conclusions**
- **Features**
- **Applications**
- **Future Work**

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5.1 Conclusion

This project analyse improved form of conventional differential relay with feedback input current for power system protection. Algorithm is based upon current difference principle and feedback of input current as comparator. Main objective of project is to operate the relay against internal fault and restrains in case of external fault. Idea is implemented successfully implemented on hardware trainer that is lab trainer of power system protection lab. Applied technique compares fraction of input current with spill current to prevent mal-operation due to magnetizing inrush current. This relay has advantage over ordinary relay that it does not operate on starting magnetizing inrush current. Results conclude that proposed relay model was able to distinguish between internal fault and external fault. Operating time was reduced in this scheme. Relay is capable of discriminating fault conditions from transient response of transformer.

5.2.1 Features

User Friendly

This project is user friendly for students providing them learnig environment in order to make students acknowledged about differential protection basics, working principle and practical hardware implementation. Students can also perform experiments to see behavior on changing transformer configuration in either side. Connections are open and easy to understand with color description.

Trainer for Lab.

This trainer will be helpful for students to analyze transformer configuration waveforms of current and voltages in either configuration. They will be able to distinguish between external and internal fault and matching of actual values with simulated values.

Connection Reliability

Input output ports are reliable to configure in any configuration according to requirement of experiment. Ports are used according to color of input wire to increase level of understanding and avoiding of any inconvenience.

Protection Zone limited

Protection zone is limited to transformers only to avoid mal-operation. It will help students to calculate currents in case of fault by simple power system analysis techniques.

5.2.2 Applications

This project has wide range of application due to its novelity of designing. This project has some application as by product that makes this project feasible and reliable for future purposes. Some of its main applications are described as follow.

Application in Power System Protection

As this project is concerned to power system protection basics, obviously it has main area of application in power system protection. Designed relay will used in npower system protection lab as hardware trainer for students. Microcontroller based relay has wide range of reliability to change its source code and easy to make any relay as it used basic electrical transducers as input to relay. By using these results and some mathematical computations. We are able to find diversity in this project in future.

Application in Power System Analysis

As it is discussed in above sections that trainer has open ports for input connection, this feature makes it useable in analyzing of power flow in tranformers. Students will be able to understand parameter that varies according to variation in transformer configuration. i.e phase angle lagging in delta wye transformer and factor of 1.731 that is included in delta wye or wye delta configuration.

5.2.3 Future Work

This project has wide scope of future work in both hardware as well as in software. The source code is open to make it harmonic restraint relay using frequency spectrum analyzer and filtering third harmonic current on starting inrush current and differentiation between fault condition and transient response of transformer on basis of harmonics. Hardware can be improved to make it GSM based and IOT based to send an alert to user in case of any fault so that user may be able to troubleshoot it.

GSM Technology

This project can be extended to GSM techniques to send a text or message to concerned authorties in case of induction of any type of internal fault, In case of any serious condition, system gerenrated phone call can be offered to concerned person and after clearance of fault. It can be auto reset to avoid complexity.

IOT bassed data collection

This poject can be based on IOT to collect date on online data server from electrical transducers. With this improvement, authorties will be known with relay performance and data can be used for it maintenance in future. This data can predict its future performance on basis of artificial intelligence.

Harmonic Restrainted Relay.

This relay can be harmonic restrained by using MATLAB coding and allow to pass specific range of frequencies to pass through circuit. This will discriminate fault from transient response.

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APPENDIX A:

Source Code:

```
#include <LiquidCrystal.h>
#include <Filters.h>
 // ==================== System Parameters=======================
float testFrequency = 50;                    // test signal frequency (Hz)
float windowLength = 20.0/testFrequency;
float intercept = -0.1310; // to be adjusted based on calibration testing
float slope = 0.04099;
 // ============================================================

 // ===================== Variable Declaration==================
int sensorValue1 = 0;int sensorValue2 = 0;int sensorValue3 = 0;
int sensorValue4 = 0;int sensorValue5 = 0;int sensorValue6 = 0;
float current_amps1,current_amps2,current_amps3;
float current_amps4,current_amps5,current_amps6; // actual measure current

 // ============================================================

unsigned long printPeriod = 1000; // in milliseconds

unsigned long previousMillis = 0;
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

 // ========= Input Output pins Declaration===============

 pinMode(relayPin1,OUTPUT);
 pinMode(relayPin2,OUTPUT);
 pinMode(relayPin3,OUTPUT);
int relayPin1=8;
```

```
int relayPin2=9;
int relayPin3=11;
void setup() {
   Serial.begin( 9600 );    // start the serial port
  // ===============================================================


 lcd.begin(16, 4);
  // ==============Advisor and Group Members information================

  lcd.print(" Differential");
  lcd.setCursor(0, 1);
  lcd.print("Relay Trainer");
  lcd.setCursor(0, 2);
  lcd.print("Advisor:");
  lcd.setCursor(0, 3);
  lcd.print("Engr. Zain Shabir");
  delay(3000);
  lcd.setCursor(0, 0);
   lcd.print("Moazzam Ali EE15");
  lcd.setCursor(0, 1);
  lcd.print("Walid Tariq EE15");
  lcd.setCursor(0, 2);
  lcd.print("Haider Ali  EE15");
  lcd.setCursor(0, 3);
  lcd.print("Talha Khan  EE15");
  delay(3000);

 // ===============================================================
```

```
}

void loop() {
lcd.clear();
delay(500);
// ============ Calculating variable for current===================

  RunningStatistics inputStats1,inputStats2,inputStats3;                // create statistics to look at the raw
test signal
  RunningStatistics inputStats4,inputStats5,inputStats6;
  inputStats1.setWindowSecs( windowLength );
  inputStats2.setWindowSecs( windowLength );
  inputStats3.setWindowSecs( windowLength );
  inputStats4.setWindowSecs( windowLength );
  inputStats5.setWindowSecs( windowLength );
  inputStats6.setWindowSecs( windowLength );

   // ==================================================================

  while( true ) {

    // ============== Reading Sensors=================
    sensorValue1 = analogRead(A6);
    sensorValue2= analogRead(A1);
    sensorValue3= analogRead(A2);
    sensorValue4= analogRead(A3);
    sensorValue5= analogRead(A4);
    sensorValue6= analogRead(A5);

     // ==================================================================
```

```
// ================ calculating slope variables===================
inputStats1.input(sensorValue1);
inputStats2.input(sensorValue2);
inputStats3.input(sensorValue3);
inputStats4.input(sensorValue4);
inputStats5.input(sensorValue5);
inputStats6.input(sensorValue6);// log to Stats function

 // ============================================================

if((unsigned long)(millis() - previousMillis) >= printPeriod) {
  previousMillis = millis();

  //===========Calculating currents using function y=m*x+c===================
current_amps1 = intercept + slope * inputStats1.sigma();
current_amps2 = intercept + slope * inputStats2.sigma();
current_amps3 = intercept + slope * inputStats3.sigma();
current_amps4 = intercept + slope * inputStats4.sigma();
current_amps5 = intercept + slope * inputStats5.sigma();
current_amps6 = intercept + slope * inputStats6.sigma();

 // ============================================================

Serial.print("   Iap   ");Serial.print(current_amps1   );
Serial.print("   Ibp    ");Serial.print(current_amps3  );
Serial.print("   Icp   ");Serial.println(current_amps5   );
```

```
// ============  Displaying primary currents=============

lcd.setCursor(0,0);
lcd.print("Primary Currents");
lcd.setCursor(0,1);
lcd.print("Iap= ");
 lcd.setCursor(6,1);
lcd.print(current_amps1   );
lcd.setCursor(11,1);
lcd.print("Amps");
lcd.setCursor(0,2);
lcd.print("Ibp= ");
 lcd.setCursor(6,2);
lcd.print(current_amps3   );
lcd.setCursor(11,2);
lcd.print("Amps");
lcd.setCursor(0,3);
lcd.print("Icp= ");
lcd.setCursor(6,3);
lcd.print(current_amps5   );
lcd.setCursor(11,3);
lcd.print("Amps");
delay(3000);

 // =======================================================

Serial.print("   Ias    ");Serial.print(current_amps2   );
Serial.print("   Ibs   ");Serial.print(current_amps4   );
Serial.print("   Ics   ");Serial.println(current_amps6   );
```

```
// ============== calculating secondary currents=================

lcd.clear();
delay(500);
lcd.setCursor(0,0);
lcd.print("Secondary Current");
lcd.setCursor(0,1);
lcd.print("Ias= ");
 lcd.setCursor(6,1);
lcd.print(current_amps2   );
lcd.setCursor(11,1);
lcd.print("Amps");
lcd.setCursor(0,2);
lcd.print("Ibs= ");
 lcd.setCursor(6,2);
lcd.print(current_amps4   );
lcd.setCursor(11,2);
lcd.print("Amps");
lcd.setCursor(0,3);
lcd.print("Ics= ");
 lcd.setCursor(6,3);
lcd.print(current_amps6   );
lcd.setCursor(11,3);
lcd.print("Amps");
delay(3000);

 // ===========================================================
```

```
// ================= Differential Relay Design===================

int id1=abs(current_amps1-2*current_amps2)*1000;
int id2=abs(current_amps3-2*current_amps4)*1000;
int id3=abs(current_amps5-2*current_amps6)*1000;
if(id1>500 || id2>500 || id3>500)
{
   digitalWrite(relayPin1, HIGH);
   digitalWrite(relayPin2, HIGH);
   digitalWrite(relayPin3, HIGH);

// ============================================================
  }
}}    }
```

APPENDIX B:

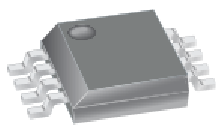
Datasheet of ACS712:

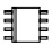
Features and Benefits

- Low-noise analog signal path
- Device bandwidth is set via the new FILTER pin
- 5 µs output rise time in response to step input current
- 80 kHz bandwidth
- Total output error 1.5% at T_A= 25°C
- Small footprint, low-profile SOIC8 package
- 1.2 mΩ internal conductor resistance
- 2.1 kV_{RMS} minimum isolation voltage from pins 1-4 to pins 5-8
- 5.0 V, single supply operation
- 66 to 185 mV/A output sensitivity
- Output voltage proportional to AC or DC currents
- Factory-trimmed for accuracy
- Extremely stable output offset voltage
- Nearly zero magnetic hysteresis
- Ratiometric output from supply voltage

TÜV America
Certificate Number:
U8V 06 05 54214 010

Package: 8 Lead SOIC (suffix LC)



Approximate Scale 1:1 

Description

The Allegro® ACS712 provides economical and precise solutions for AC or DC current sensing in industrial, commercial, and communications systems. The device package allows for easy implementation by the customer. Typical applications include motor control, load detection and management, switched-mode power supplies, and overcurrent fault protection.

The device consists of a precise, low-offset, linear Hall sensor circuit with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is programmed for accuracy after packaging.

The output of the device has a positive slope (>$V_{IOUT(Q)}$) when an increasing current flows through the primary copper conduction path (from pins 1 and 2, to pins 3 and 4), which is the path used for current sensing. The internal resistance of this conductive path is 1.2 mΩ typical, providing low power

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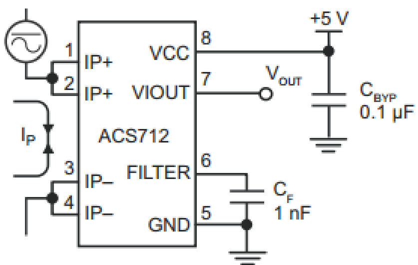
Typical Application



Application 1. The ACS712 outputs an analog signal, V_{OUT}, that varies linearly with the uni- or bi-directional AC or DC primary sensed current, I_P, within the range specified. C_F is recommended for noise management, with values that depend on the application.

Description (continued)

loss. The thickness of the copper conductor allows survival of the device at up to 5× overcurrent conditions. The terminals of the conductive path are electrically isolated from the sensor leads (pins 5 through 8). This allows the ACS712 current sensor to be used in applications requiring electrical isolation without the use of opto-isolators or other costly isolation techniques.

The ACS712 is provided in a small, surface mount SOIC8 package. The leadframe is plated with 100% matte tin, which is compatible with standard lead (Pb) free printed circuit board assembly processes. Internally, the device is Pb-free, except for flip-chip high-temperature Pb-based solder balls, currently exempt from RoHS. The device is fully calibrated prior to shipment from the factory.

Selection Guide

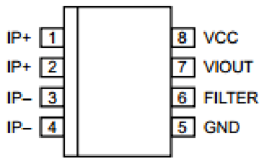
Part Number	Packing*	T_A (°C)	Optimized Range, I_P (A)	Sensitivity, Sens (Typ) (mV/A)
ACS712ELCTR-05B-T	Tape and reel, 3000 pieces/reel	–40 to 85	±5	185
ACS712ELCTR-20A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±20	100
ACS712ELCTR-30A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±30	66

*Contact Allegro for additional packing options.

Absolute Maximum Ratings

Characteristic	Symbol	Notes	Rating	Units
Supply Voltage	V_{CC}		8	V
Reverse Supply Voltage	V_{RCC}		–0.1	V
Output Voltage	V_{IOUT}		8	V
Reverse Output Voltage	V_{RIOUT}		–0.1	V
Reinforced Isolation Voltage	V_{ISO}	Pins 1-4 and 5-8; 60 Hz, 1 minute, T_A=25°C	2100	V
		Voltage applied to leadframe (Ip+ pins), based on IEC 60950	184	V_{peak}
Basic Isolation Voltage	$V_{ISO(bsc)}$	Pins 1-4 and 5-8; 60 Hz, 1 minute, T_A=25°C	1500	V
		Voltage applied to leadframe (Ip+ pins), based on IEC 60950	354	V_{peak}
Output Current Source	$I_{IOUT(Source)}$		3	mA
Output Current Sink	$I_{IOUT(Sink)}$		10	mA
Overcurrent Transient Tolerance	I_P	1 pulse, 100 ms	100	A
Nominal Operating Ambient Temperature	T_A	Range E	–40 to 85	ºC
Maximum Junction Temperature	T_J(max)		165	ºC
Storage Temperature	T_{stg}		–65 to 170	ºC

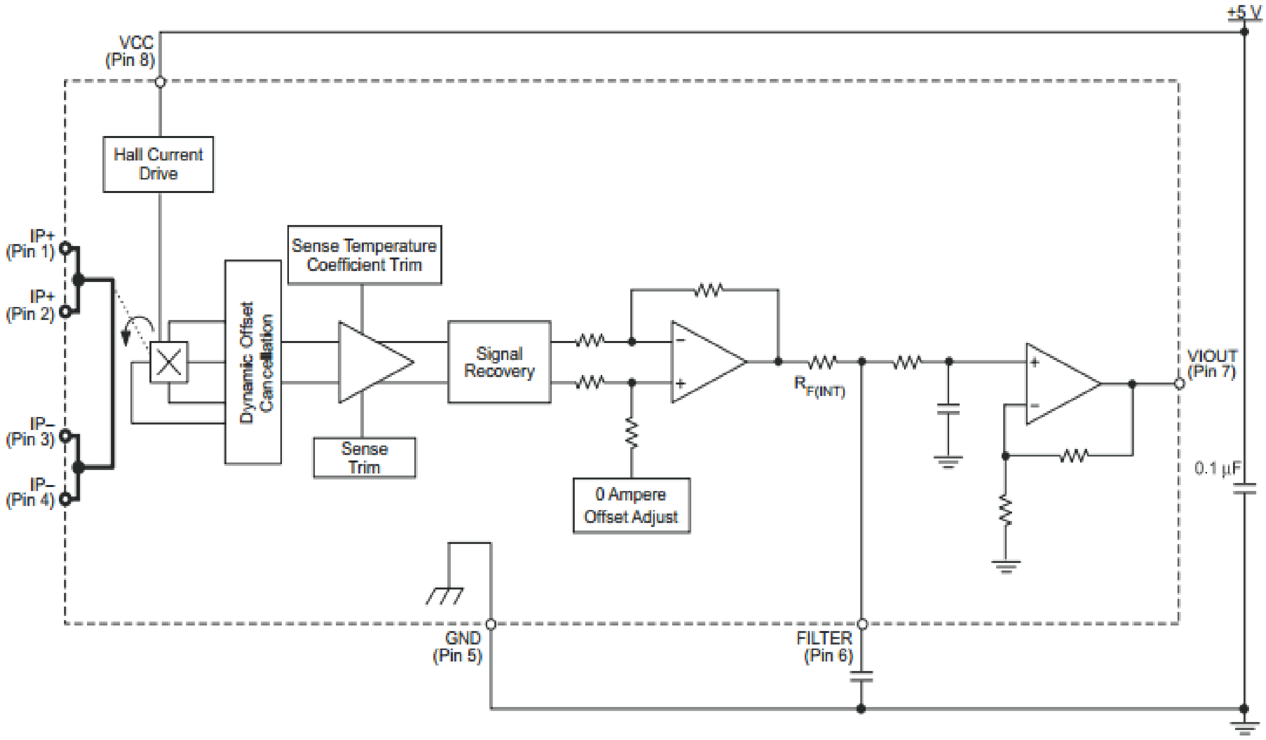
Pin-out Diagram



Terminal List Table

Number	Name	Description
1 and 2	IP+	Terminals for current being sensed; fused internally
3 and 4	IP–	Terminals for current being sensed; fused internally
5	GND	Signal ground terminal
6	FILTER	Terminal for external capacitor that sets bandwidth
7	VIOUT	Analog output signal
8	VCC	Device power supply terminal

Functional Block Diagram



COMMON OPERATING CHARACTERISTICS[1] over full range of T_A, C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
ELECTRICAL CHARACTERISTICS						
Supply Voltage	V_{CC}		4.5	5.0	5.5	V
Supply Current	I_{CC}	V_{CC} = 5.0 V, output open	–	10	13	mA
Output Capacitance Load	C_{LOAD}	VIOUT to GND	–	–	10	nF
Output Resistive Load	R_{LOAD}	VIOUT to GND	4.7	–	–	kΩ
Primary Conductor Resistance	$R_{PRIMARY}$	T_A = 25°C	–	1.2	–	mΩ
Rise Time	t_r	$I_P = I_P$(max), T_A = 25°C, C_{OUT} = open	–	5	–	μs
Frequency Bandwidth	f	–3 dB, T_A = 25°C; I_P is 10 A peak-to-peak	–	80	–	kHz
Nonlinearity	E_{LIN}	Over full range of I_P	–	1.5	–	%
Symmetry	E_{SYM}	Over full range of I_P	98	100	102	%
Zero Current Output Voltage	$V_{IOUT(Q)}$	Bidirectional; I_P = 0 A, T_A = 25°C	–	V_{CC} × 0.5	–	V
Power-On Time	t_{PO}	Output reaches 90% of steady-state level, T_J = 25°C, 20 A present on leadframe	–	35	–	μs
Magnetic Coupling[2]			–	12	–	G/A
Internal Filter Resistance[3]	$R_{F(INT)}$			1.7		kΩ

[1]Device may be operated at higher primary current levels, I_P, and ambient, T_A, and internal leadframe temperatures, T_A, provided that the Maximum Junction Temperature, T_J(max), is not exceeded.

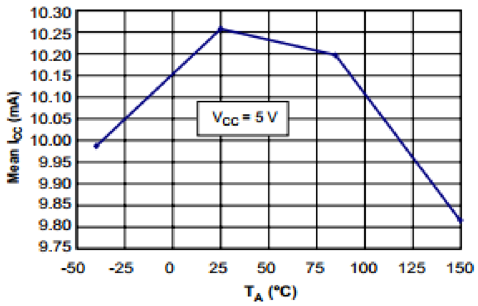
[2]1G = 0.1 mT.

[3]$R_{F(INT)}$ forms an RC circuit via the FILTER pin.

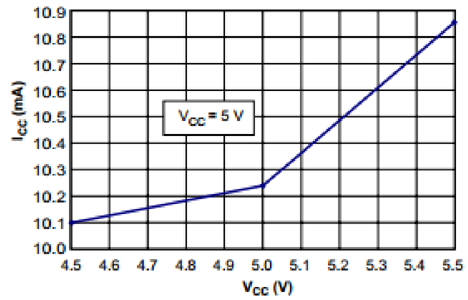
Characteristic Performance

I_P = 5 A, unless otherwise specified

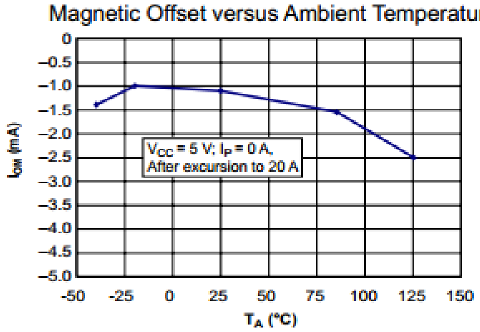
Mean Supply Current versus Ambient Temperature



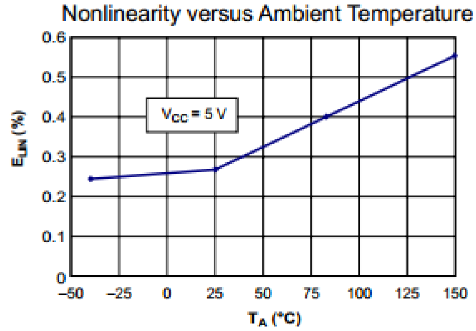
Supply Current versus Supply Voltage



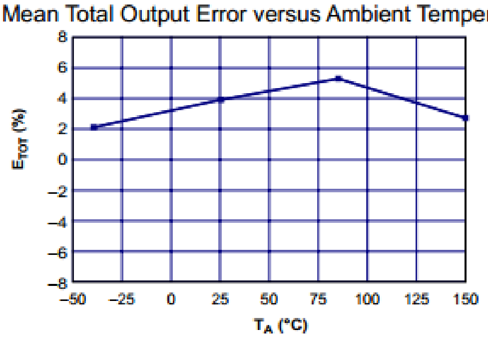
Magnetic Offset versus Ambient Temperature



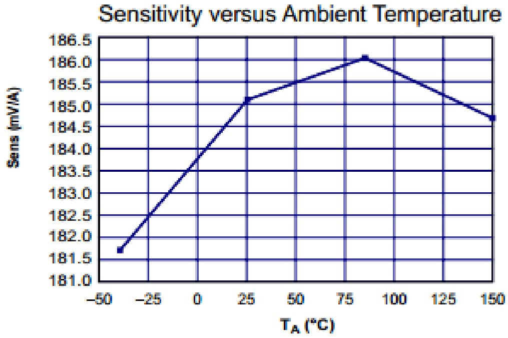
Nonlinearity versus Ambient Temperature



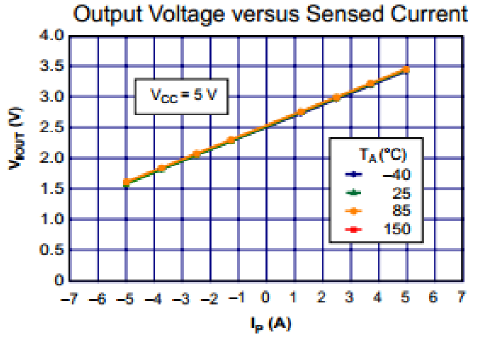
Mean Total Output Error versus Ambient Temperature



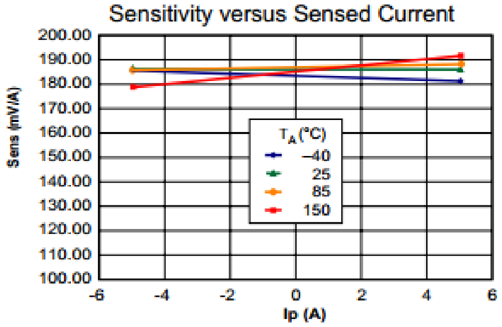
Sensitivity versus Ambient Temperature



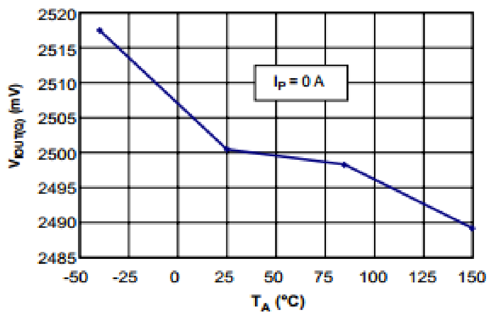
Output Voltage versus Sensed Current



Sensitivity versus Sensed Current



0 A Output Voltage versus Ambient Temperature



0 A Output Voltage Current versus Ambient Temperature