DEVELOPMENT OF
PROTECTION RELAYS TESTING EQUIPMENT

LEE CHEE HIUN

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Electrical Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

April 2019

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : ______________________

Name : Lee Chee Hiun

ID No. : 1502623

Date : ______________________

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF PROTECTION RELAYS TESTING EQUIPMENT"** was prepared by **LEE CHEE HIUN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electrical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _________________________

Supervisor : Dr. Chua Kein Huat

Date : _________________________

Signature : _________________________

Co-Supervisor : Dr. Wong Jianhui

Date : _________________________

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to all those who had contributed and provided me the possibility to the successful completion of this project. A special gratitude I give to my research supervisor, Dr. Chua Kein Huat and co-supervisor Wong Jianhui, whose contribution in stimulating suggestions, guidance, invaluable advice, encouragement, and their enormous patience throughout the development of the research, helped me to coordinate my project especially in writing this report.

Nobody has been more important to me in the pursuit of this project than the members of my family. I would like to thank my loving parents, whose love and guidance are with me in whatever I pursue. They are the ultimate role models.

In addition, I wish to thank friends who had helped and given me encouragement and provided unending inspiration.

ABSTRACT

Protection relay plays an important role in protecting power system during faults or abnormal operations. Protection relays are designed to detect fault and make decision locally to isolate the fault section from the rest of the system. As such, a proper operation of the protection relays is crucial for the reliability and safety of power systems, which protecting other devices from damage and reducing impact of disturbances on power system security. Therefore, the testing of protection relays is vital during the installation and commissioning process, as well as routine maintenance programs throughout its service life. A reliable protection relay testing device plays a vital role in both providing a stimulus and monitoring the relay's response. Relays testing may range from a simple check of some parameters of the relay's characteristics to a complete verification of the protection scheme logic, including the response to transient waveforms and harmonics. This study aims to develop a protection relays testing device, which is capable of verifying the relay's response time with various fault current. The results obtained are then compared with the respective standards and guidelines. The protection relay testing device has been successfully developed to validate the performance of protection relays.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electrical power system which generates and supplies electrical energy to customers should be designed to deliver electricity safely, reliably and economically.The key to achieving the aforementioned mission is through the use of protective relays, which use to monitor the condition of the electrical power system. Power plants, switchyards, and associated facilities are important to the electrical power systems relied on by us daily.

Prolonged or frequent failure of these facilities may result in severe disruption to routine operations. These facilities contain complex electrical and mechanical devices that must be kept operational without severe interruption. Protective relays and associated components play an important role in protecting this devices as well as protecting the entire of the electrical power system. Therefore, to minimize prolonged power outage and maximize stable power delivery with a complete yet complicated system is the main concern of electrical engineers and one of the greatest challenges faced by utility providers today.

1.2 Background of the Study

As faults introduced on the power system, it is required decision-making times much too fast for professional intervention in order to protect crucial components of the electrical power system such as generators, transformers, and transmission lines. Protection relays testing equipment plays a vital role in providing a stimulus and monitoring the relay’s response in this very important area. Here, the challenge comes in how skills and knowledge are being apply to develop an equipment that could directly monitor the variation of voltage and current which ultimately make control decisions to stabilize the continuity supply of the electrical power.

1.3 Problem Statement

The main issues associated with existing single-phase testing equipment in the market is the lack of functions such as phase sequence measurement will lose its ability to judge the testing results. Besides, existing test equipment is not an ideal tool for electrical troubleshooting due to their low current carrying capability. For instance, available test equipment are not designed to be multi-functional, users would need to acquire test sets with different types of functions to fulfill their testing requirements.

As a result, prior to the commencement of this project, the study of the whole power system, protection system, and testing methodologies was conducted. Besides, discussion of input and output variables used is provided to develop a protection testing equipment which fulfills the requirement of the regulatory bodies. With this information readers are able to justify the quality of the study and should also provide a useful reference to whom might have interest in conducting a similar project in this area.

1.4 Aims and Objectives

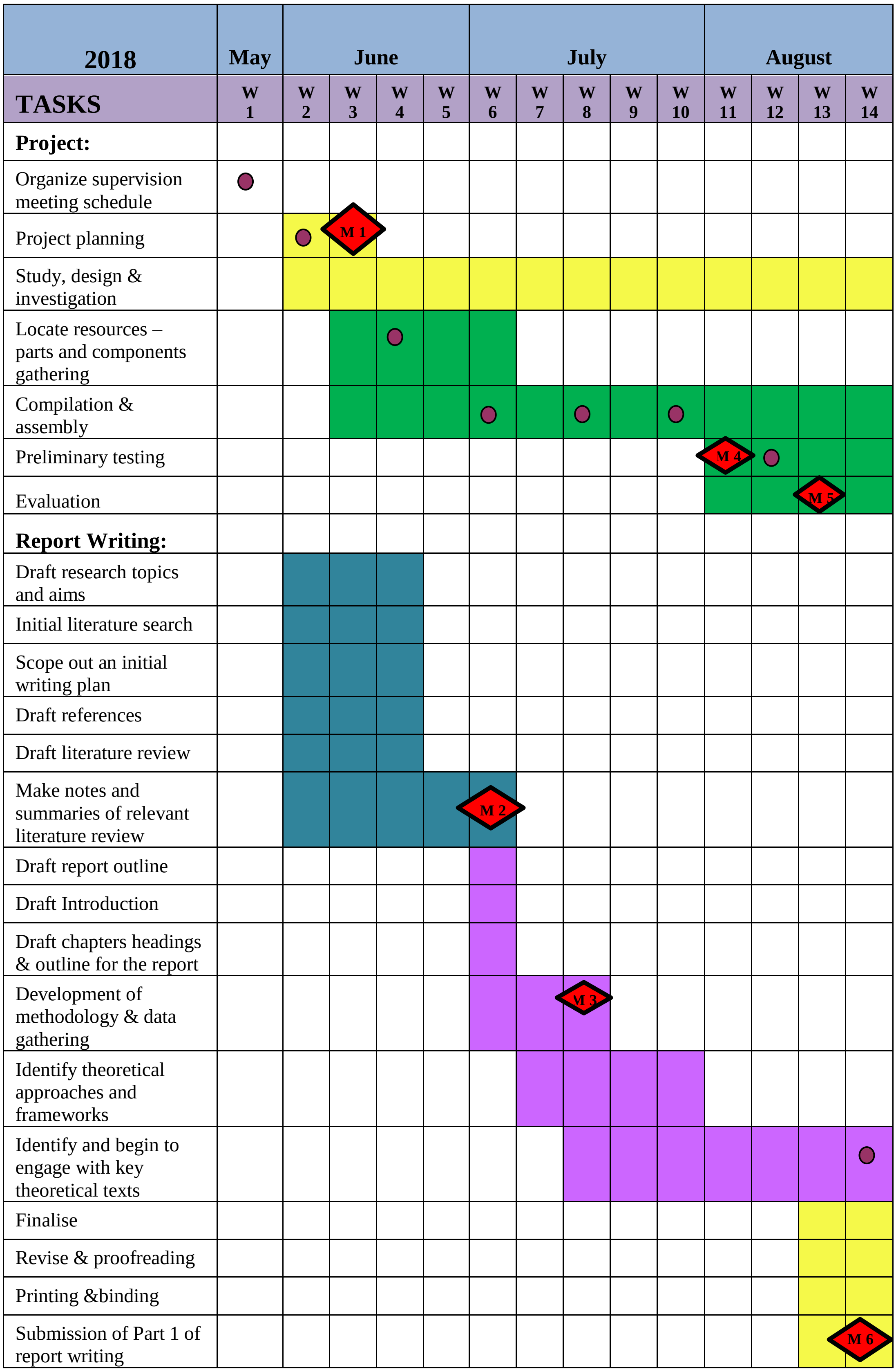
The aim of this study is to investigate the operational principles of protective relaysto build the groundworks of developing a protective relay test equipment with diversified features which make the protection relays testing equipment powerful, easy-to-use and multi-functional. Also, evaluation on the performance of the testing equipment will be carried out.

1.5 Scope of the Study

This study focuses on the developing of a single-phase protection relays testing equipment under time and budget constraints, also the availability of required tools and materials. The focus is made on the operation and testing methodology of protection devices as well as the use of the device as tools for creating the test equipment.

In the electrical industry, the majority of the single-phase and three-phase protection devices or relays can be tested by using a single-phase source. Fulfilling the industrial requirements, this portable universal single-phase relay testing equipment is based on offering diversified features which make it powerful, easy-to-use and multi-functional. Hence, this test equipment can speed up the protection relays testing process and ultimately reduce costs.

1.6 Gantt Chart 1



1.7 Gantt Chart 2

2019	Jan	Feb				Mar					Apr			
TASKS	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14
Project:														
Organize supervision meeting schedule	●													
Project improvement and planning		●	M 1											
Study, design & investigation														
Locate resources – parts and components replacement				●		●								
Compilation & assembly						M 2		●		●				
Product testing											M 4			
Evaluation on final product												●	M 5	●
Report Writing:														
Further study on literature study														
Review on references														
Review on report outline														
Review on chapters headings for report														
Review on methodology & data gathering								M 3						
Review on theoretical approaches and frameworks														
Finalise on report writing														
Revise & proofreading and														
Printing & binding														
Submission of Part 2 of report writing														M 6

Key:

- Reading/ Planning & Analysis
- Practical work
- Job applictions
- Report write-up
- ● Meeting with supervisor
- ◆ Milestone – report submission

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Electrical power system is one of the largest and complicated system human has ever developed. The purpose of electrical power systems is to provide electrical power to be used in a secure, reliable and economic manner. However, no matter how well the system is designed, faults will still occur, which is the main issue of power failure. Therefore, a complete arrangement of protection devices are used in the power system in order to minimize the occurrence of faults and to maximize continuity of power supply. Thus, the power system is protected throughout. Such equipment and devices formed a protection system to achieve a specific function base on the protection principle (Duncan, Mulukutla, and Thomas, 2012). Figure 2.1 shows a power transformer which was damaged due to inappropriate electrical protection.

Figure 2.1: Transformer Flashover Due to Inappropriate Protection Scheme

2.2 Literature Review

In the electrical industry, more than hundreds of types of protective relays that serve for different purposes. In order to design and build adequate test equipment for different kinds of relay testing, this chapter examines and comments critically on the literature review of relays operation, functions, testing methods, as well as, some of the common protection relays especially earth fault and overcurrent relay, also, it is necessary to understand the principle of time and current grading of relays.

2.2.1 Protection Relay and Instruments

In electrical protection system, the used of protection equipment and auxiliary devices comprises Relays, Current Transformer (CT), Potential Transformer (PT), Batteries, Circuit Breaker (CB) and etc., each of them has their functions and purposes. The relay is an essential device which receives information from measurement devices and used to clear the fault from the system in a very short time to protect equipment, circuit, and personality. Due to the different configurations and operating conditions of the power system, relays are designed in a different manner and high usability in order to fulfill the requirements. In general, it can be classified into four types:

- Electromechanical
- Digital
- Static
- Numerical

Each type poses their characteristics according to the limitation of technology used. CT and PT are measurement devices. CT is used to measure the current capacity flowing in a conductor of a system while PT is used to measure the system voltage magnitude. Batteries serve as an auxiliary power source to the whole protection system. Instead of the system power source, the battery bank is used because it can sustain a power supply to the whole protection system while power interruption occurred. As stated in the study of Wright and Christopoulos, (2012), Circuit Breaker (CB) is the one which is used to isolate the entire or part of the power circuit. Figure 2.2 shows a fundamental configuration of a protection scheme in a power system. The protective relay issues a trip signal to the circuit breaker to open the circuit once the fault is detected at downstream.

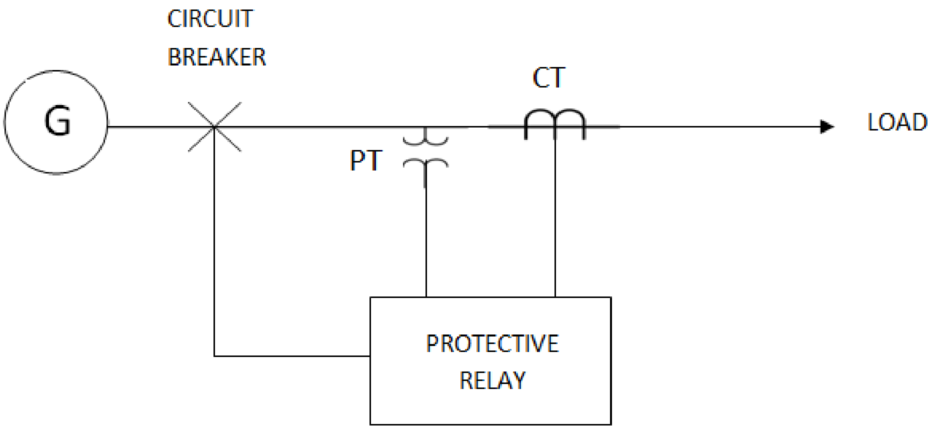


Figure 2.2: Basic Construction of Protection System in a Radial Circuit

In a complex power system where different kinds of the fault may occur everywhere, protection has become a challenge scheme. Most of the cases, a single relay can only provide one or two protective quantities. It is necessary to protect the system by using several or different types of relays in a single circuit in order to facilitate the system to be operated safely and effectively. For example, a combined Earth Fault and Over Current relay may be used in a single circuit. John (2006) stated that Directional relay and Distance relay may be used simultaneously in a ring connection transmission line. Also, to prevent the extent of power interruption in a whole system when the fault occurred, the protection scheme is arranged in the zone which shown in Figure 2.3. Therefore, a complete and adequate design of protection scheme shall be made by skilled electrical power engineers.

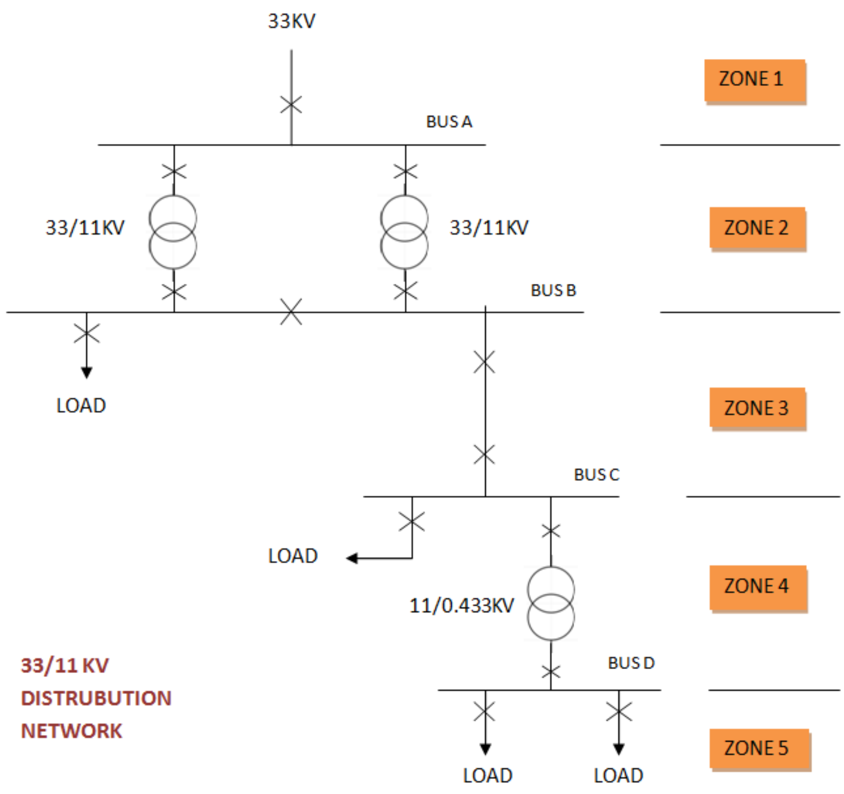


Figure 2.3: Zone of Protection

In order to ensure optimum and reliable operation of protection, protection equipment has been necessary to be well designed, set, tested and calibrated. Commissioning and periodic maintenance tests are usually conducted on site. On-site testing of protection scheme has become a problem since all the equipment are designed to operate under abnormal or fault conditions. Among the protective equipment that stated above, protection relay is one of the vital devices that need to be monitored or tested periodically, because it only operates during fault occurs in the system, normally, defects may not be revealed until system fault occurs. Practically, special designed protection relay test equipment is used to test the protection relays as well as other peripheral devices where a simulation of system fault is generated by the test equipment by means of injecting appropriate current to the system in order to force the protective equipment to operate especially protection relays.

The main function of the protection relay test equipment (test set) is to test the functionality and time grading of protection relays. Besides, the test equipment also provides additional functions such as auxiliary sinusoidal AC power supply, DC power supply, variable AC and DC power supply etc. These functions enable the protection scheme test to be carried out completely. There are two typical fault simulation methodologies namely Primary Injection and Secondary Injection. The detail of these two tests will be discussed in sections 3.2.2 and 3.2.5. In order to conduct current injection into the system and relays, the test equipment should be able to generate appropriate current rating without any hazard. Figure 2.4 shows an overcurrent relay being tested by using secondary injection. Red and Black colour clips are current injection circuit; Yellow and White colour clips are trip feedback circuit.

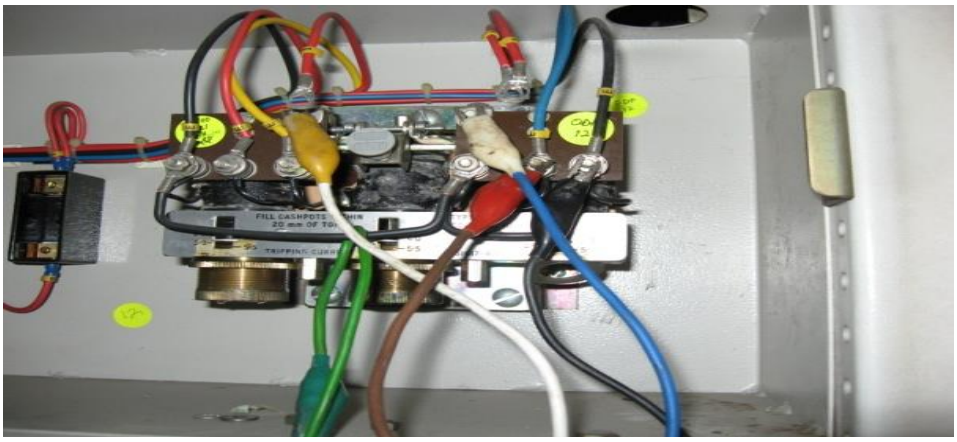


Figure 2.4: Secondary Injection Test on Oil Dashpots (Overcurrent Relay)

In the electrical industry, most of the installation must be tested before it can be safely operated. Therefore, test equipment has become an important tool for electrical power engineers.

2.3 Time and Current Grading

When a fault occurs on a line, the protection relay will trip the circuit breaker in order to clear or isolate the fault from the system. But if the line is divided into several sections and protected by numbers of relays and circuit breakers, it is desired to trip the only circuit breaker which is closest or within to the faulty section and leaving the rest of the system undisturbed. Recent literature by Bhuvanesh, (2010) has also suggested that this testing methodology required the knowledge of time and current grading.

2.3.1 Discrimination by Time

Time setting is available on earth fault and overcurrent relay. Bhuvanesh, (2010) found that this is to ensure when the fault happening at downstream cannot disturb the whole system especially for upstream. An appropriate time setting is set to the relay that controlling the particular circuit breaker to ensure that the circuit breaker nearest to the fault operates first. In a radial circuit which coordinates by several relays, the lowest time setting (fastest) always set to the relay which is farthest away from the source.

2.3.2 Discrimination by Current

When the fault occurred, the fault current varies with the location of the fault. This is because the impedance value is proportional to the length of the line between the source and the faulty point. Bhuvanesh (2010) stresses on the importance of an appropriate current setting which enables the desired relay to operate and trip the corresponding circuit breaker without affecting the rest of the system.

2.3.3 Discrimination by Both Time and Current

For the two schemes described so far, there are some fundamental disadvantages if each scheme is used independently to coordinate a system. Consider a radial circuit shown in Figure 2.5, if a fault F1 happened at line A is very huge and need an emergency trip, but the relay’s time setting at line A is not the lowest, it may lead to a severe damage to the installations and may interrupt the whole system. Again, if the fault F2 happens at line C, since the distance between bus B and bus C is close to each other and the difference of impedance value between them is not so significant, the relays at line B and C can trip their corresponding circuit breaker simultaneously (Bhuvanesh, 2010).

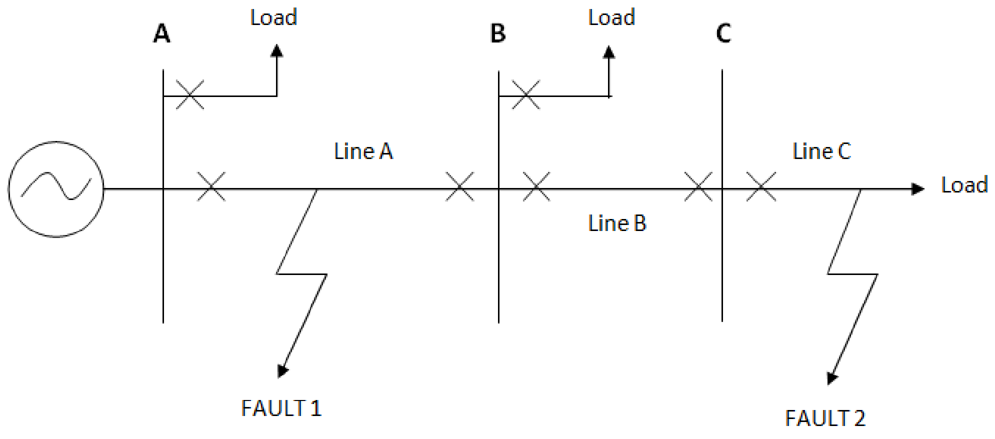


Figure 2.5: Radial Circuit with Bus A, B, and C

These drawbacks can be overcome by using both time and current discrimination. Most of the earth fault and overcurrent relays consist of time and current setting in order to provide better protective coordination to the system. Some of them provide a time multiplier setting (TMS). TMS is a time constant set to the relay which enables the relay to calculate itself and operates for the actual tripping time in accordance with the magnitude of fault current. This type of scheme is known as inverse definite minimum time (IDMT). As the name suggests, when the fault current is higher, the operating time becomes shorter. The characteristics of IDMT can be seen in Figure 2.6, which is also demonstrated in Sleva (2009).

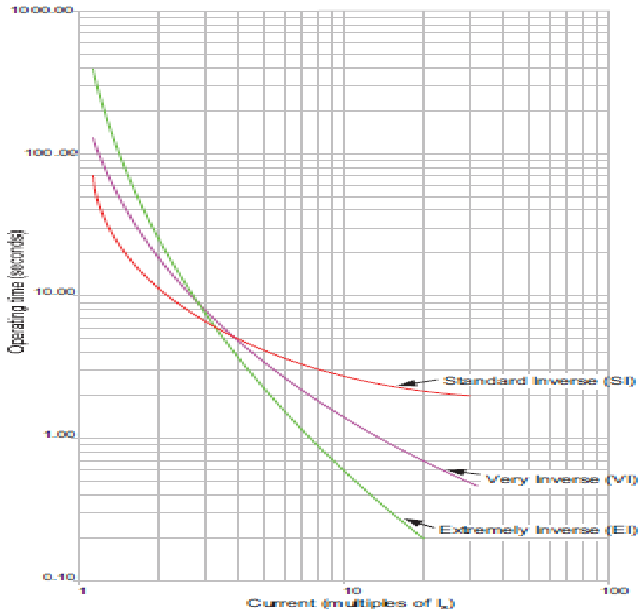


Figure 2.6: IDMT Relay Characteristics. TMS = 1.0 (Blackburn and Domin, 2006)

2.4 Protection Relay Operating Mode

According to the information discussed in section 2.2, protection relays using in the industry are developed to fulfill the requirement of discrimination. There are several types of relay operation mode which can be categorized as Instantaneous, Definite Time (DT), Inverse Time (IT) and Inverse Definite Minimum Time (IDMT).

2.4.1 Instantaneous

Instantaneous overcurrent relay operates when input current from the current transformer is higher than the setting current of the relay. Jignesh (2013) found that there is no intentional time delay applied. Application: Normally being applied in the radial circuit where the magnitude of line impedance is very small at the time of the fault.

2.4.2 Definite Time (DT)

The relay can be adjusted to issue a trip signal at the definite amount of time. Therefore time and current setting are available. Jignesh (2013), also proved that since the operating time is set, once the relay is triggered, the time delay depends on the time setting but not the magnitude of the input current. Application: Normally being applied in the backup protection of distance and differential relays.

2.4.3 Inverse Time (IT)

For an electromechanical relay, it starts operate when the input current is higher than the pickup setting of the no voltage coil of the relay. The higher the input current, the higher the magnetic field induced and hence the faster the disc to rotate in order to trigger the trip contact. This phenomenon inhered the operating time inversely proportional to the fault current. However in the reality, as revealed by Jignesh (2013), inverse time cannot be achieved ideally.

2.4.4 Inverse Definite Minimum Time (IDMT)

It is obvious that for inverse time, the time to issue the trip signal is reduced when the system fault current increased. If the current transformer gets saturated at a certain level, its secondary current would not be proportional to the fault current and hence the relay's delay time will stay at the point at just it gets saturated. This is known as the minimum time delay.

The tripping characteristics of IDMT relays may need to be varied in according to the required tripping time in a particular situation which compromises with the characteristics of other protection devices. This relates to the time and current grading as discuss earlier which is proved to be true (Jignesh, 2013). Application: Normally being applied in any circuit where time and current grading is needed.

2.5 Protection Devices Studies

Since protection relays test equipment is used to measure the parameters possessed by the protective devices itself, it is necessary to study their functions and operation behaviours.

2.5.1 Overcurrent Relay

Overcurrent relay is one of the most commonly used relays that can be seen in most of the electrical circuit. For example, the main incomer, transmission and distribution line, transformer and load protection. This relay is designed to protect the circuit from further damage while over current is occurred. There are several situations which can cause overcurrent such as short circuit (line to line or line to neutral), the internal fault of the load and overload situation which against the original load design. Under normal situation, Walter (1994) found that overcurrent relay will not operate until the load current is exceeded the current setting of the relay. Figure 2.7 shows a typical overcurrent and earth fault relay.

Figure 2.7: IDMT Overcurrent and Earth Fault Relay (Electromechanical)

2.5.2 Earth Fault Relay

In the section 2.51, we described phase fault overcurrent protection, a more sensitive protection against earth fault can also be acquired by using an earth fault relay. Earth fault relay responds only residual current of the system and unaffected by the load current whether it is unbalanced or not. However, since the setting of Earth Fault relay is always a few percents of the system rating, the setting is limited to the design of the device and unbalance leakage or capacitance current to earth. This is an important consideration if the relay setting is too small since leakage current may contribute a residual quantity of this order.

In the study of Walter (1994) revealed that the operation of Earth Fault relay is same as overcurrent relay and Instantaneous, DT and IDMT are also available. Figure 2.8 shows three different configurations of Earth Fault protection which commonly used in industry, (a) shows basic earth fault protection, (b) and (c) shows earth fault and overcurrent protection. Where $I_o >$ is earth fault low set, $I >$ is overcurrent low set.

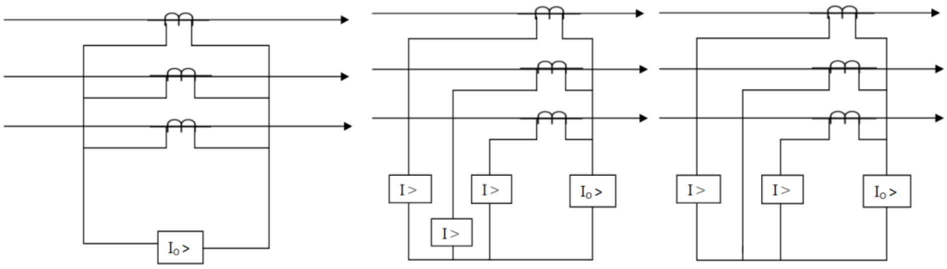


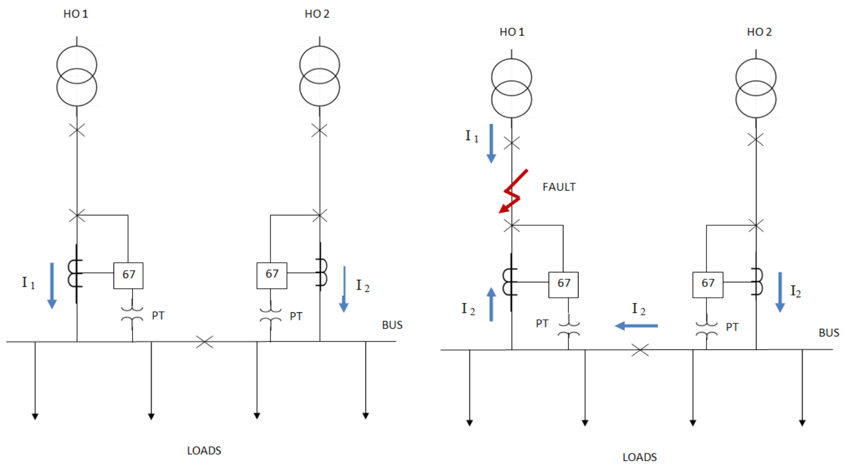
Figure 2.8: Different Configurations of Earth Fault and Overcurrent Protection

2.5.3 Directional Overcurrent Relay

Correct application of over it. In the radial connection circuit, fault current I_F that flow toward the faulty point is always from upstream. In order to obtain optimal protective coordination, the protection system is designed to minimize the zone of interruption. In other words, the relay which is closest to the fault must operate first and clear the fault before the upstream relays can trip the corresponding circuit breaker (Robertsand Guzman, 1994).

In aring main circuit, as illustrates in Figure 2.9, the fault current I_F that flow toward the faulty point can come from two directions simultaneously. Under normal condition, bothI_1 and I_2 flowing to the bus and supplies to the loads as shown in Figure 2.9 (a).

Now consider a fault happened at line 1which illustrated in (b), both I_1 and I_2 will flow to the faulty point. At this moment, I_1 is still flowing in the normal direction while I_2 can flow in the opposite direction at line 1. If normalovercurrent relays are used at line 1 and line 2, both of them will trip their corresponding breakers and resulted in a power outage to the consumers. To prevent this to happen, a directional relays 67 (Directional relay) are used. Directional overcurrent relay can detect the direction of the fault current where it is not supposed to flow. As fault happened, the directional relay may able to differentiate the phase angle of the symmetrical components and operate when it exceeds the desired limit.

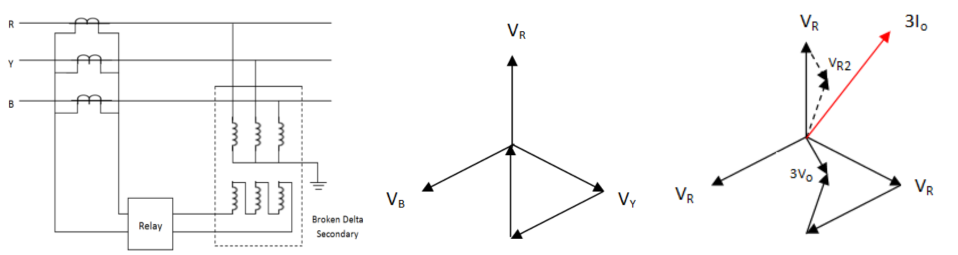


(a) (b)

Figure 2.9: Working Principle of Directional Overcurrent Relay

2.5.4 Directional Earth Fault Relay

In some of the MV system, earth fault may be protected by using an insulated network where the star point of the secondary of the transformer is not grounded. Therefore, a small earth fault current may not be detected easily. Hence, a sensitive earth fault protection is designed. As suggested in Lensner, and Schwanenflugel, (1966) study, this scheme relies on the detection of the imbalance of the per-phase charging current as shown in Figures 2.10 and 2.11. Figure (a) shows directional relay connection by using broken delta to polarize the directional relay, (b) and (c) are vector diagrams of a balanced, and unbalanced system.



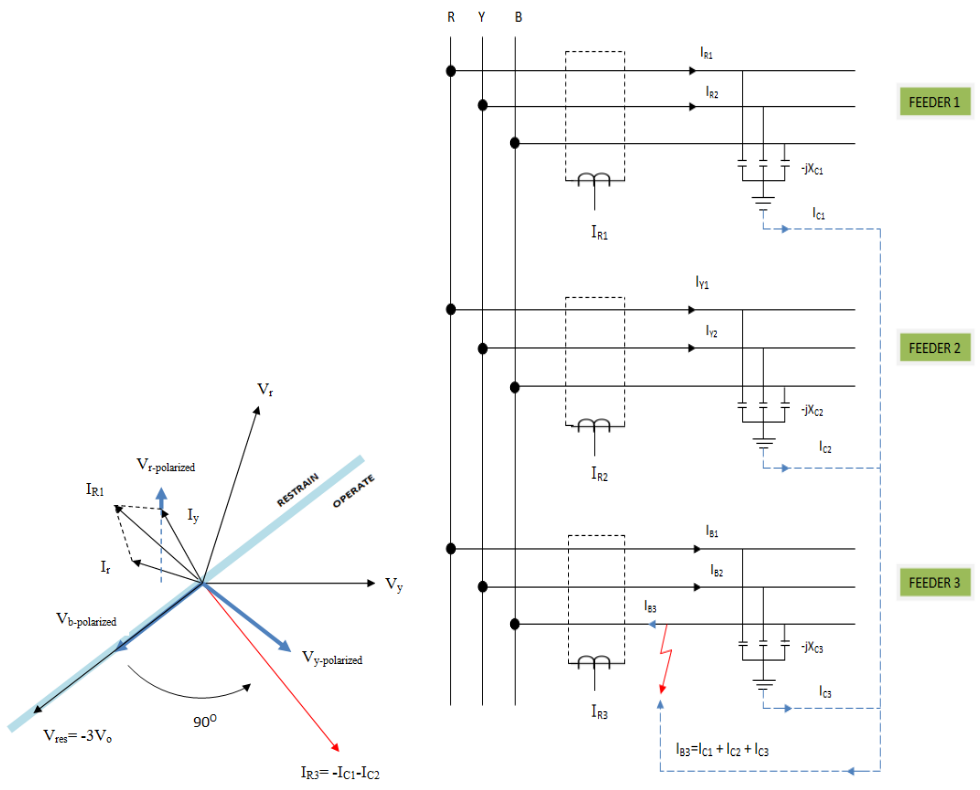
(a) (b) (c)

Figure 2.10: (a) Broken Delta Connection (b) Balanced System and (c) Unbalanced System

In a balance system, the residual voltage will be zero. If phase R fault to ground, its phase voltage will collapse below its normal value and the vector sum of the three voltages produce three times the zero sequence of voltage drop on the source impedance. Hence, the characteristic angle of the source impedance is displaced from the residual current. Typically, the current will lag the voltage and the product of current and voltage may mostly be VAR flow. These quantities are applied to the directional earth fault relay (Robertsand Guzman, 1994).

Figure 2.11(b) shows the charging current and residual current distribution in an insulated network with phase B fault to ground. The relays on the healthy feeder see only the unbalance charging current of its own feeder while the faulted feeder see the charging current of the rest of the feeder. The charging current of the healthy feeder is $\sqrt{3}$ times of their normal value and the residual current (faulted feeder) in this case is three times of the normal charging current. From the phasor diagram shown in figure 2.11 (a), the residual current I_{R1} is opposite in direction with I_{R3}. This property can provide the discrimination required for directional earth fault relay.

The polarizing quantity in this situation is residual voltage where shifted by 90^o and the residual current of the healthy feeder will lie on the restrain region while the residual current of the faulted feeder lies on the operating region. Therefore, the relay characteristic angle required is 90^o (Blackburn and Domin, 2006).



(a) (b)

Figure 2.11: (a) Phasor Diagram and (b) Insulated Network

2.5.5 Instrument Transformer

Unlike a transformer using in the power line, the purpose of the instrument transformer is used for electrical isolation and transformation of voltage or current to the desired level. It is mainly used for electrical measurement, metering and protection purposes. Instrument transformer can be classified into two types, namely current transformer, and potential transformer as shown in Figure 2.12.

Current transformer (CT) is used to transform high current level to an appropriately low level which is affordable by the measurement devices or protection relays. In order to ensure the metering and protection system to work accurately, the parameters test of CT is necessary before it can be used. Some typical CT tests are:

1. Ratio test (To ensure the transformation ratio is consistent with the label)
2. Polarity test (To ensure the secondary output is in phase with the primary)
3. Continuity test (To ensure the winding is continuous between terminals)
4. Insulation test (To ensure leakage current is minimized under the rated voltage level)

5. Magnetism test (To check the knee-point voltage level)
6. Tangent delta test (To ensure the quality of insulator)

Potential transformer (PT) or voltage transformer is used as a step-down transformer for the purpose of metering and protection. Some of the protection relays may rely on both CT and PT, for example, Directional or Reverse Power Relays. Kappenman, Albertson, and Mohan (1981) revealed that it is similar to a current transformer, the abovementioned tests are needed to be done on PT except for polarity test.

(a) (b)

Figure 2.12: (a) Wound Primary Current Transformer (b) Potential Transformer

2.6 Test Equipment

Test Equipment (test set) is an important tool in the Electrical industry. Almost every part of the electrical installation and circuits must be tested before they can be operated safely. There are many types of power protection test equipment which are designed for different purposes. For instances, insulation tester, high-potential tester, low resistance tester etc. All these test equipment provide variable voltage or current output which directly inject to the device or circuit under test.

Secondary injection tester is the most popular test equipment using in the industry. It is the most convenient way of fault simulation in order to force the protection relay to operate under normal situation. Without the presence of a real fault on the power line, a desired amount of current is injected to the protection relay independently and meanwhile, the operating time is counted. This current is injected tantamount to the current which generated by the current transformer at the time of the fault. As the relay received the current, the condition of operating characteristics can be seen. In Klancher's study (1998), he proved that the main purpose of this test is to determine the sensitivity and operating time of the relay.

Although secondary injection test is the most common way for protective relay testing, there are some drawbacks that bring the results obtained from the test cannot provide a full reference of the condition of the whole protection system. This is because the test current is injected only to the relay and it has nothing to do in other parts of the system. Therefore, the results can only indicate the condition of the relay instead of the whole protection system.

However, if the test current can be injected into the system, the results that obtained can be represented as a full reference of the whole protection system. This can be done by injecting the test current to the busbar, which is also the primary side of the current transformer. The test which fulfills the requirements is known as primary injection test.

As the test current is injected to the busbar, the current transformer will read the amount of test current that flowing in the busbar and send a signal to operate the corresponding relay. The relay will subsequently trip the circuit breaker if the amount of test current that flows is larger than the pre-set value of the relay. This kind of test is similar to the fault that happens on the power circuit. Therefore, the amount of test current that applied to the busbar must be sufficiently high and powerful current source is hence required.

Unfortunately, the test equipment using in the industry did not provide a combination of the two functions that mentioned above simultaneously. One of the reasons is the transformer used for primary injection test is too large in size which will increase the size and weight of the equipment if the two functions are combined together. Another reason is the output terminal of the secondary injection test equipment required a higher potential level while it is not necessary for primary injection test equipment. Therefore, if one transformer is designed for different output potential levels together with a wide range of output current level, the selection of transformer core material and the winding technology can be the greatest challenge (Schneider Electric, 2001).

2.7 Transformer

In the field of electricity, most of the tests implement injection of current or voltage directly to the device under test. Therefore, the test current or voltage must have a superior condition in order to ensure the accuracy of test results. In the alternating current system, the most convenient way to generate the source is by using an isolation transformer.

As we know that isolation transformer can be used to isolate the electrical appliance from the original power source. Stephen (2014) suggested that this becomes one of the advantages if any unusual event such as a fault or electrical leakage happens on the appliance, the original power source will not be affected. In the industry, some of the electrical testing methods are designed with the possibility of electrical leakage, for instance, high potential pressure test and secondary injection test. With the advantage of the isolation transformer, these kinds of test can be carried out favourably without the constraint of power interruption. Another advantage of using an isolation transformer is some electrical disturbances created during the injection of the test current or voltage to the device under test will not affect the power quality of the original power source. Figure 2.13 shows the configuration of test current injection by using an isolation transformer to isolate the original source from entering to the device under test. Leakage current at the device under test will have no return path back to the source and the protective device at the primary side of the isolation transformer will not detect any fault.

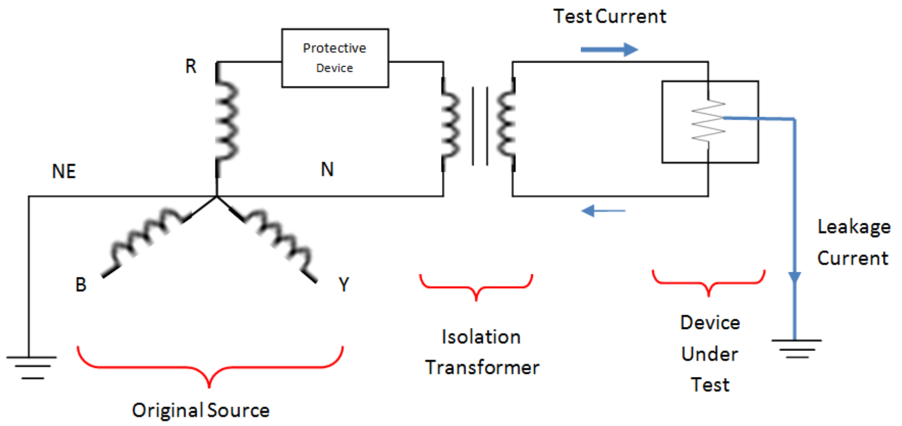


Figure 2.13: Test Current Supplied by Isolation Transformer

One of the important issues that need to be considered is the transformer condition. When current or voltage is supplied to the device under test, it is normally a wide range of level adjustment is required. A wide range can be interpreted in terms of current or voltage level adjustment and resolution adjustment etc. For example in secondary test, the test current level may be required ranging from 0 to 15A with appropriate fine resolution; in primary injection test, it is ranging from 0 to hundreds of amperes or sometimes 0 to 10A with a minimum resolution of 10 mA. All these conditions must be taken into account in order to avoid any inconvenient or unavailable.

Since test current is always forcibly injected to circuit or device under test, the output voltage must be sufficiently high in any situation. If the test current is injected into a live circuit, because the potential level of the test current is low, the opposite potential level may force the power reverse to the test equipment. On the other hand, the inappropriate increment of voltage level may cause the transformer to saturate. Therefore, proper sizing of the transformer is essential.

2.8 Test Equipment Functions

Power protection system consists of a set of components. Each of them unleashes its function to comply with others to achieve the desired protection scheme. Every single component or device may have its own specification that determines the accuracy and requirement of performance during communication among components.

In the electrical testing industry, test equipment always designed to fit the operation method of components or device under test. For example, open and close contact operation of protection relay; current transformer required 80% and above of primary rated current to achieve its specified accuracy etc. Due to this reason, test equipment shall be designed to perform these requirements (Gruenert, 2002).

For security reasons, electrical installation tests are usually carried out in the case of no electricity supply. In other words, all the switchgear shall be in off position to ensure the live circuits are dead. In this situation, there will be the power supply to the protective relays and other peripheral devices and therefore obstructs the testing event. If we look at the conventional test equipment such as OMICRON and MERLIN GERIN, they provide several auxiliary power outputs which enable to power the relays and devices under test.

Some typical functions that should have provided in the test equipment are listed below:

1. Open and Close contact feedback input.
2. Dry and wet feedback input.
3. Timer.
4. Variable current source.

5. Output current resolution selection.
6. Output current ranging selection.
7. Variable voltage source.
8. Fixed voltage source (240VAC, 110VAC, 110VDC, 30VDC).
9. Voltage divider.

With the combination of these functions, most of the test of protection system can be carried out easily and favourably (Omicron, 2018).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

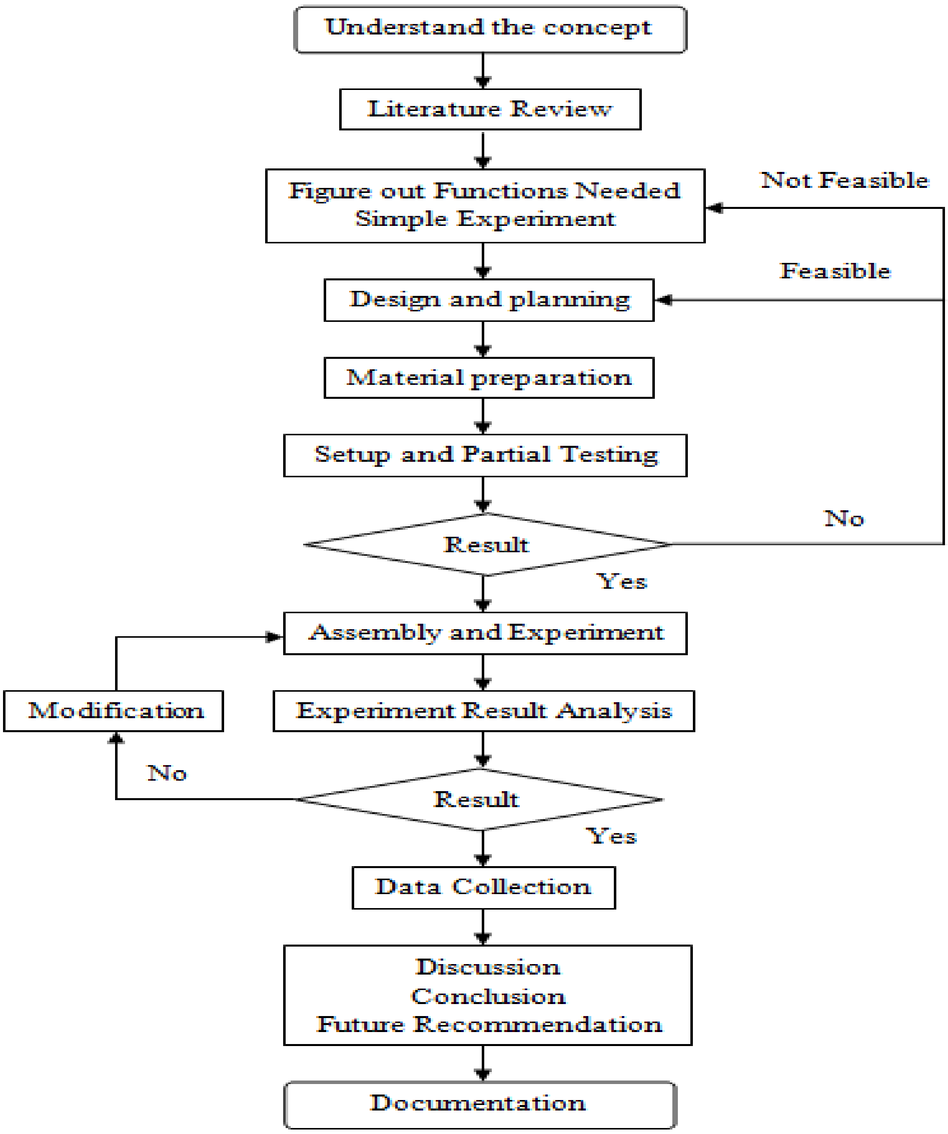


Figure 3.1: Workflow Diagram

3.2 Test Equipment Functions Design and Build

According to the above studies, protection relay test equipment should be well designed and be able to test the abovementioned protective devices. Therefore, the equipment or simply test set must provide adequate functions which enable the user to perform their work easily, accurately and safely.

As we know that, in a basic but complete protection scheme as illustrated in Figure 3.2, the fault current is measured by a current transformer (CT) and the system voltage is measured by a potential transformer (PT) at the time of the fault. The secondary of the CT and PT then send their proportional signals to the protection relay that controlling the circuit breaker.

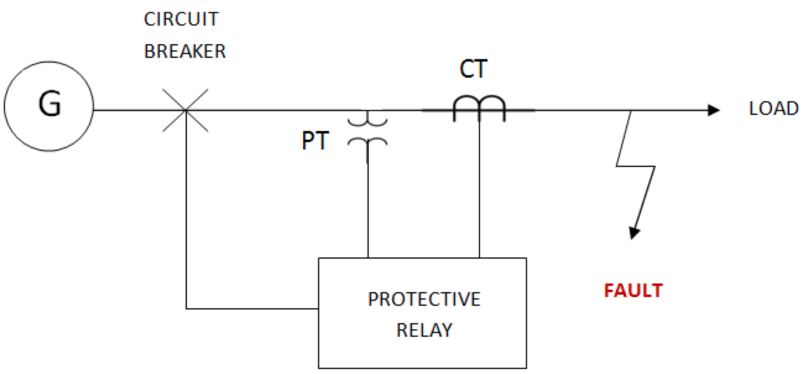


Figure 3.2: Basic Protection Scheme

Once these signals matched the relay's operating condition, the relay will operate and issue a trip signal to trip the corresponding circuit breaker. Therefore, if we wish to test the system whether it can perform properly and accurately, there are several portions that we have to concern about, that is the accuracy of the instrument transformer and the relay. The following tests are specially designed to test these elements,

1. Instrument transformer ratio and magnetism test.
2. Protection relay primary and secondary injection test.

These are the fundamental tests for most of the protection schemes. A complete test equipment should be able to perform these tests in any protection system. In other words, the product is necessary to be designed to perform the abovementioned task.

3.2.1 Auxiliary Power Sources

Most of the time when the protection relay is being tested, it is recommended to shut off the main power supply of the whole system. This may result in the relays to shut off due to a power outage. Therefore, it is convenient if the test equipment can supply an appropriate power source to the relay under test. Some useful voltage sources are 30VDC, 110VDC, 110VAC, 240VAC and a variable AC/DC voltage source which can be used to perform a ratio test for the potential transformer.

3.2.2 Primary Injection

We know that the current transformer is used to sense the line current, In order to simulate this situation, the test equipment has to supply the actual amount of current to the line which enables the current transformer to read the actual current value and operate the relay. Such an amount of current normally can reach from tens up to hundreds of amperes. Therefore, a powerful current source is needed. Since the current is injected to the primary side of the current transformer, that is known as a primary injection. A typical configuration of primary injection is shown in Figure 3.3 below.

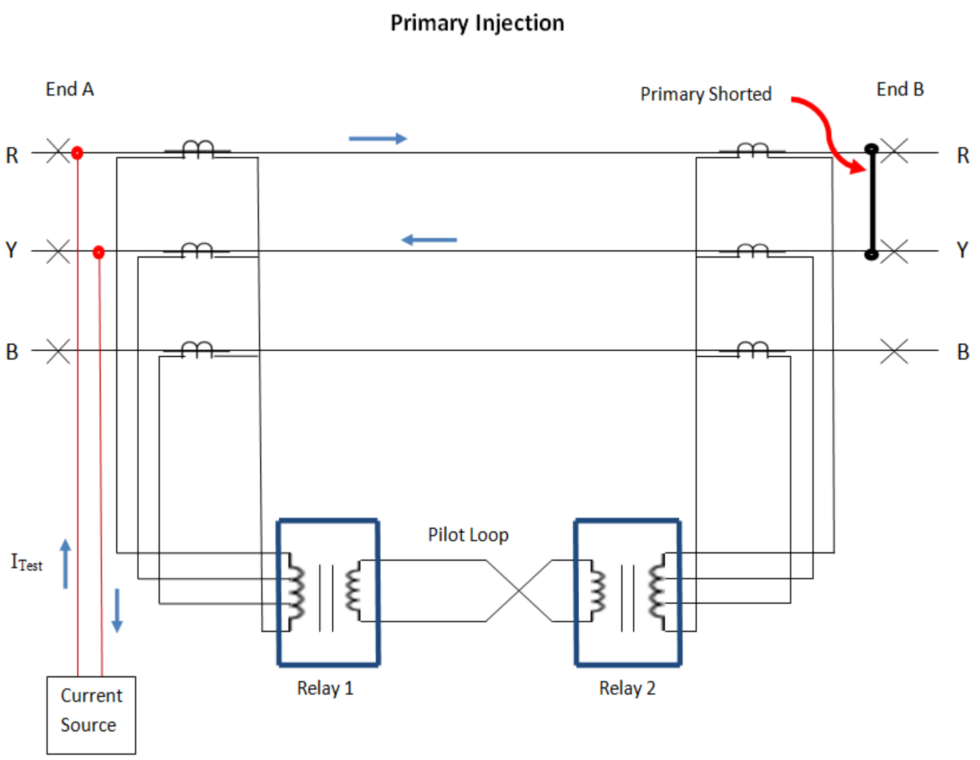


Figure 3.3: Differential Relay Stability Test by Using a Primary Injection Method

3.2.3 Current Transformer Test

As discussed in section 3.4.5, the current transformer (CT) test is necessary before it can be used. One of the typical CT tests is known as the ratio test is shown in Figure

3.4. It is normally difficult to conduct due to the specially designed equipment is needed. Most of the CT can only produce its secondary current precisely proportion to the primary when it is loaded 80% and above of its rated primary value. Therefore, a high power current source must be used.

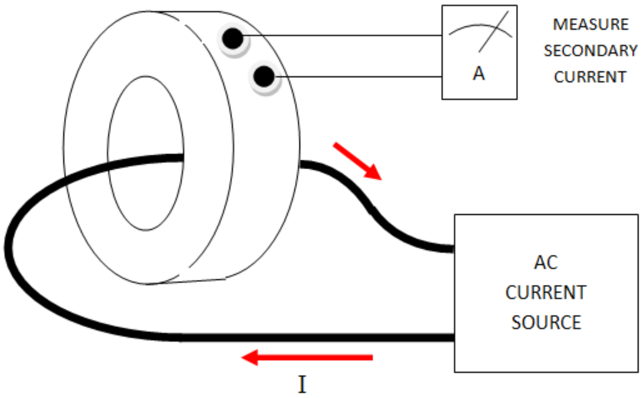


Figure 3.4: Current Transformer Ratio Test

3.2.4 Low Resistance Measurement

For low resistance measurement especially ranging from mΩ to µΩ, the conventional ohmmeter may not be able to measure unless a special but costlier low resistance meter. Low resistances normally exist at the contacts of the circuit breaker when it is closed. This is known as “contact resistance”. One of the methods to measure this resistance is to inject high current into the path and measure the voltage drop across the closed contact point. This can be seen in Figure 3.5. By using Ohm's law, we can calculate the contact resistance easily. For convenience in measurement, the current injected into the path is normally 100A and able to sustain for a certain period of time. If the injected current is too low, the voltage drop across the contact may be far too low which may hamper or difficult to be measured.

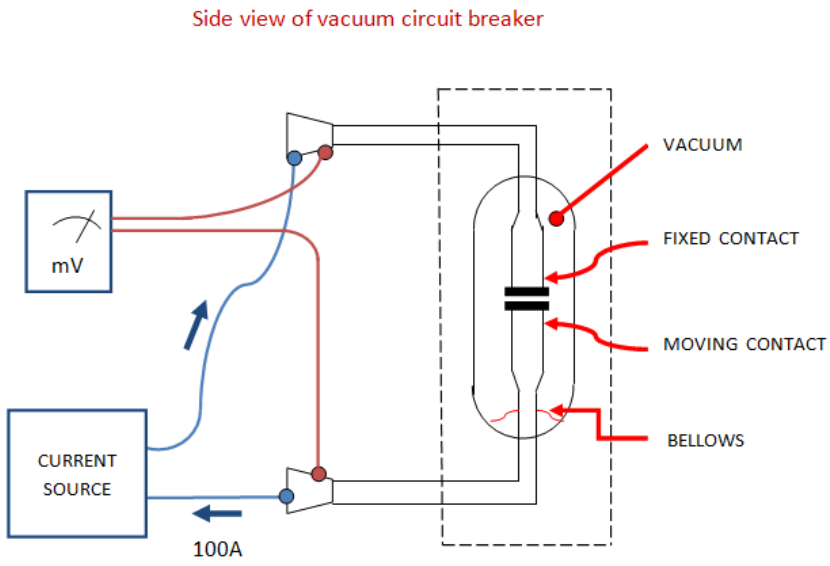


Figure 3.5: Contact Resistance Test

3.2.5 Secondary Injection

The input current of the relay actually comes from the secondary side of the current transformer as shown in Figure 3.6. If we wish to test the relay tripping accuracy, a similar amount of current is injected to the relay's input. Such an amount of current normally ranging from tens milli-amperes to tens amperes.

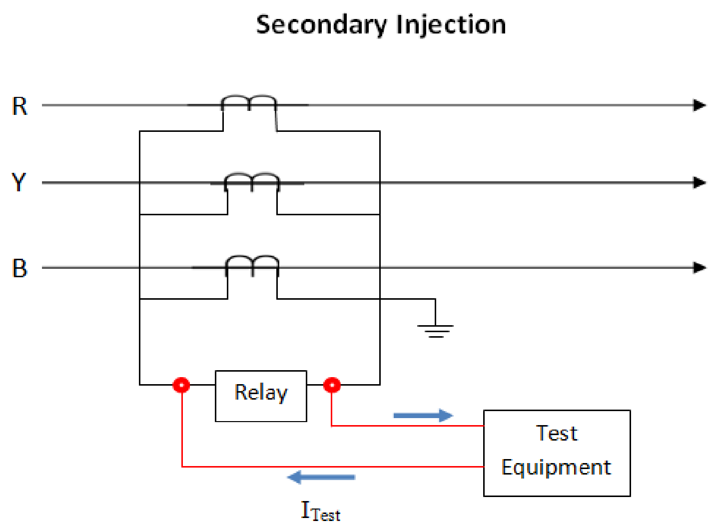


Figure 3.6: Earth Fault Relay Stability Test by Using Secondary Injection Method

Since the measured parameter of the relay is a time in second, it is necessary to ensure that the relay receives a maximum desired amount of current at a time equal to zero. Therefore, the test equipment must be able to provide a step change of current from zero and reach its desired level immediately at a time equal to zero. This can be seen from the Figure 3.7.

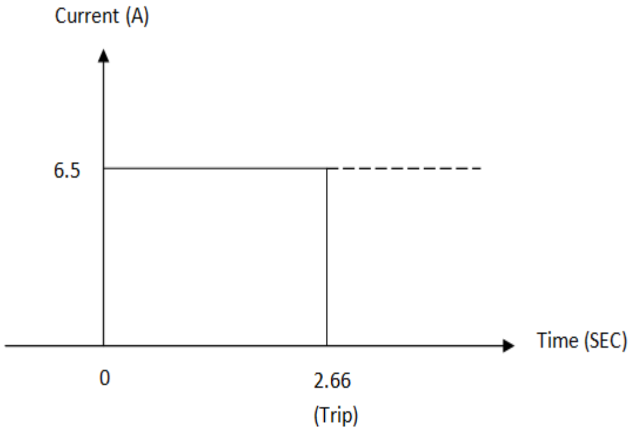


Figure 3.7: Step Change of Current Start at t= 0, the Relay Trips at 2.66 Seconds

3.2.6 Resistor Bank and the Auxiliary Capacitor

A set of power resistor is used to limit the current which generated by the test equipment's current source in order to provide fine tuning resolution of the output current level. It can also be used as a voltage divider when an appropriate voltage source is needed. An auxiliary capacitor, when connected in series to the current source, can provide a phase shift of 90^{o} which can be used to test directional relays.

3.2.7 Phase Rotational Detector

It is sometimes necessary to check the phase sequence in a three-phase system to ensure that the control wiring of the protection system is connected correctly.

3.3 Current Source Design

For protection devices testing, a variable sinusoidal current source is always used and it needs to be designed for short circuit application. This can be obtained by a well-designed transformer. In this project, a toroidal transformer is used because the toroidal transformer can achieve a low level of stray field (leakage flux) due to its closed-loop core. Therefore, the efficiency and electrical performance are higher compared with the E-I core transformer. Also, due to its toroid shape that results in the lower stray field, the transformer radiates less electromagnetic interference which may affect sensitive electronics.

Toroid core loss is normally 10% to 20% of its total power loss while conventional E-I core loss is 50% of its total power loss. Hence, a toroidal transformer contributes cooler operating temperature. As seen in Theodore's research study (2002), another advantage is low noise (Humming).

3.3.1 Transformer Primary Winding Design

First of all, we need to calculate an appropriate number of turns for the windings. By using the following equation,

$$N = \frac{V}{4.44 \times f \times B \times A} \tag{3.1}$$

where

N = number of turns

f = frequency (Hz)

V = voltage

B = magnetic flux density (teslas)

A = cross section area of the core (cm^2)

As suggested in Theodore's study (2002), as we obtained the appropriate number of turns. In order to make sure that the transformer is fully utilized, the magnetism test should be carried out. By connecting the primary side of the transformer to a voltage source and leave the secondary open, slowly increase the voltage from 0V and record the primary current every time the voltage increased. If the primary current increased by 50% with 10% increased in voltage, that is the "knee point" voltage. Knee point voltage indicates the transformer core is going to saturate at that voltage level. If the knee point voltage is slightly larger than the designed voltage level, which means that the transformer is fully utilized. Conversely, if the knee point voltage is too far away from the designed voltage level, it is oversized or undersized. Chapman (2002) also suggested that this is true. The magnetism test results will be demonstrated in section 4.2.

3.3.2 Transformer Secondary Winding Design

The secondary winding of the transformer is to supply output current to the load. Since we need to provide primary (high current low voltage) and secondary (low current high voltage) injection test, therefore a double secondary is needed.

For high current output, the winding conductor should be large enough in terms of diameter in order to sustain high current level up to 120A. For low current output, the voltage level should not be too low because sometimes it needs to inject to a high impedance circuit which may resist the desired amount of current to flow. The optimal voltage level is 21V for 20A output.

3.3.3 Reactor Design

With a potential difference of 21V, it is high enough to generate a huge current to flow when the output terminal is shorted. To overcome this, the source impedance has to be increased. A suitable component which is known as "Reactor" is introduced to the circuit as shown in Figure 3.8.

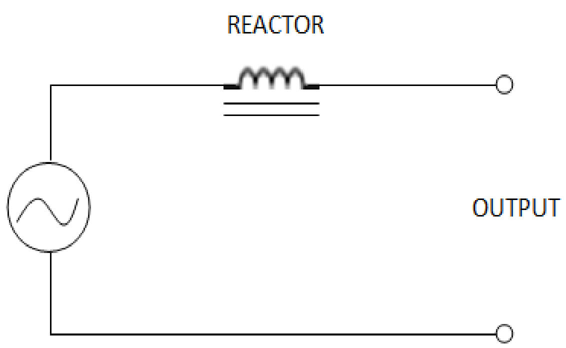


Figure 3.8: Reactor is Used to Increase Source Impedance

According to Stephen (2014), the reactor which connected in series in the circuit may act as a current limiter when the output terminal is shorted. Since the source is variable, the reactor also provides fine tuning when a desired amount of current is needed. The reactor cannot operate under core saturation condition, careful design is needed otherwise overheat and electrical hazards may occur. Reactor design is similar to the transformer design as describes in section 3.3.1. The only different is reactor must consider the magnetic field produced by the coils which may induce a current in the nearby metal objects. Another consideration is the reactor must be designed to operate below the Knee Point voltage during a short circuit and the maximum desired current level (For the purpose of this project, it is 20A).

3.3.4 Voltage Source Design

The voltage source is an important power source for testing purposes. As we know that some protection relays not only receive the input from the current transformer but also potential transformer, for example, directional relay. This can be obtained by using an auto -transformer. Besides, several fixed voltage source also required for relay powering purposes such as 240Vac, 110Vac, 110Vdc, and 30Vdc. These are the typical voltage level that most of the relays are using. These can be obtained by using a conventionalstep-down transformer and rectification.

3.3.5 Metering System Design

For testing purposes, metering is one of the vital elements that enable the user to interpret the results which are measured. In this test equipment, a current meter and a stopwatch are needed. Current meter enables the user to realize the amount of current that injected to the device under test while stopwatch can be used to record the relay actual operating time as fault simulation test is carried out. The stopwatch must be designed precisely and provide optimal resolution to achieve better accuracy. Besides, it needs to be synchronized with the output current source of the equipment. That means, the stopwatch can start itself immediately at the time the output is high and stop when a trip signal is sent back from the relay under test. Figure 3.9 shows the stopwatch being tested during the development process.

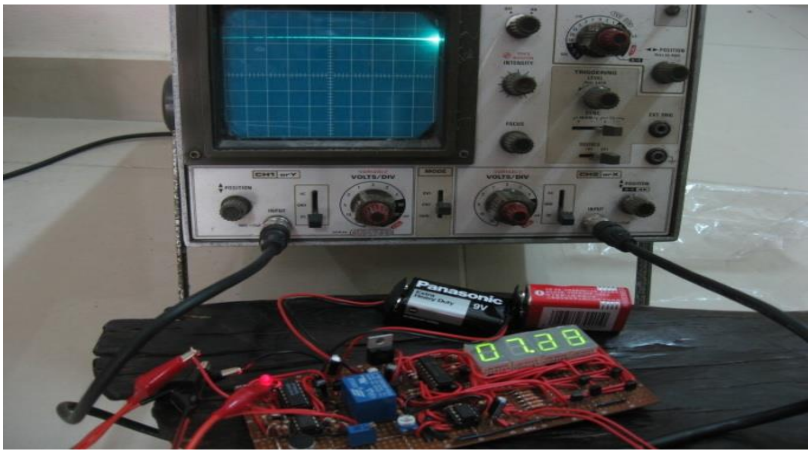


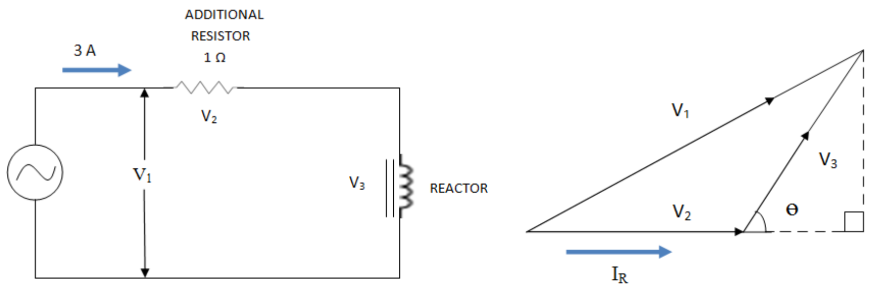
Figure 3.9: Testing of Stopwatch in the Development Process

3.3.6 Control Circuit Design

When we compose all the functions together in a single set of equipment, each individual feature is necessary to compromise with the characteristics of the others. A good control system enables the equipment to provide well performance which convenient to the user. Therefore, a complete control circuit must be well designed.

3.3.7 Output Power Factor Measurement and Correction

Since the 20A output terminal consists a built-in reactor connected in series, the current will lag the voltage by 90^o and leads to a poor power factor if the two output terminals are shorted, as seen in James and Richard study (2014). In order to correct the phase shift between voltage and current, the power factor needed to be measured. In Figure 3.10 (a), an additional resistor of 1 Ω is connected in series and I = 3A is injected into the circuit. Where the values of V_1, V_2, and V_3 can be measured and (b) shows vector diagram representation. Note that I_R and V_2 are in phase.



(a) (b)

Figure 3.10: (a) Output Equivalent Circuit (b) Vector Diagram Representation

Figure 3.10 (b), the current flows through the resistor is in phase with the voltage drop across it. On the other hand, current and voltage are out of phase at the reactor. V_3 is the reactor voltage while θ is the angle between voltage and current of the reactor. As we know that, if it is a right angle triangle, then

$$V_1^2 = V_2^2 + V_3^2 \quad (3.2)$$

therefore, apply Pythagorean Theorem,

$$V_1^2 = (V_2 + V_3\cos\theta)^2 + (V_3\sin\theta)^2 \quad (3.3)$$

Rearrange Eq. (3.3), we obtained

$$\cos\theta = \frac{V_1^2 - V_2^2 - V_3^2}{2V_2V_3} \quad (3.4)$$

By measuring V_1, V_2 and V_3, the angle θ and power factor ($\cos\theta$) can be calculated by using Eq. (3.4). By knowing the power factor, real power and the required reactive power for compensation can be found. That is,

$$P = V_1 I \cos\theta \quad (3.5)$$

then

$$Q = P(\tan\theta_1 - \tan\theta_2) \quad (3.6)$$

where

θ_1 = original angle θ

θ_2 = angle of the desired power factor which is $\cos^{-1}0.99$

The calculated Q indicates the reactive power which required for power factor correction. In order to obtain the required capacitor value (*Farad*), the following equation is used:

$$Farad = \frac{Var}{2\pi f V^2} \tag{3.7}$$

where

Var	=	calculated reactive power (Q)
f	=	frequency (50 Hz)
V	=	applied voltage (V)

Charles and Mattew (2013) proved that with the right value of capacitor connected in parallel with the reactor, the opposite phase angles enable one to cancel the effect of the other and the line current is an absolute value of the difference of I_C and I_L as shown in Figure 3.11.

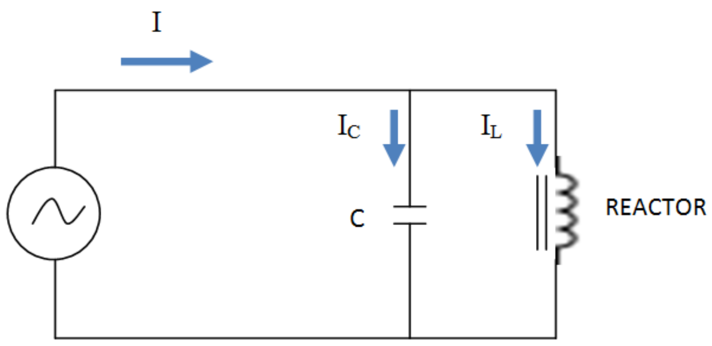


Figure 3.11: Power Factor Correction by Using Parallel Capacitor

3.3.8 Accuracy and Safety Control

Any measuring devices should provide good accuracy and quality assurance. As a test equipment, each component must be tested before being assembly in order to ensure their accuracy and reliability. This process must be carried out for a few numbers of time or by different ways of method. However, accuracy not only limited to numerical results, but also related to controlled precision.

For the main output of this test equipment, it is possible to suffer from over current destruction if the current is kept increasing by unprofessional user. In order to limit the output current to the desired level, over current protection must be applied. In this project, Hall Effect sensor is used as current sensing transducer. With a combination of monitoring electronic control circuit, we can precisely control and limit the output current to the maximum allowable level. Figure 3.12 shows the configuration of Hall sensing transducer which used as over current detector. When the output current level is higher than the set point, the monitoring circuit will send a trip signal to the main control circuit in order to cut off the current source. The working principle of the device is shown in Figure 3.13.

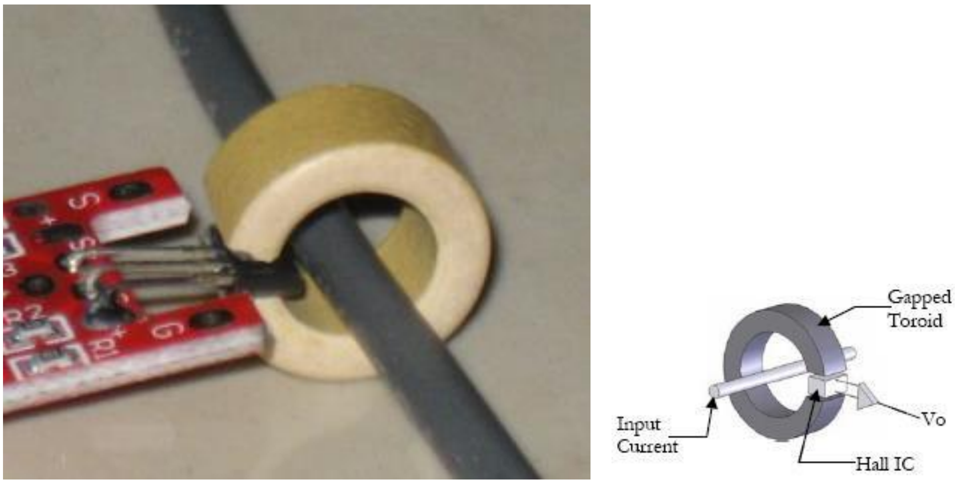


Figure 3.12: Hall Effect Sensing Transducer. A Hall Sensor is Placed in a Gapped Toroid

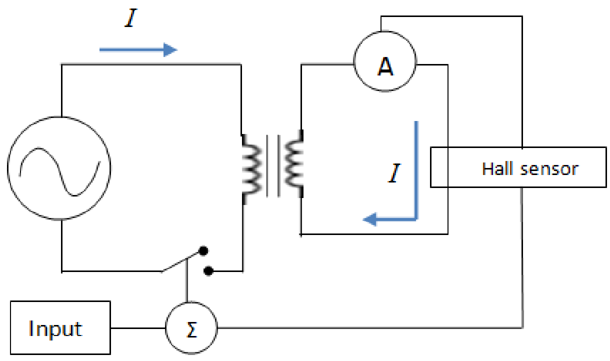


Figure 3.13: Working Principle of Overcurrent Protection

The main concern of an electrical product is much related to safety issues. As such, this protection relays testing unit is designed and be used in a safe manner to minimize danger to testing technicians and other personnel.

The protection relays test unit shall have been tested, calibrated and certified to be in fully functional condition; in accordance with the recommended calibration intervals, prior to performing any testing. Test technicians or users of the test unit must be familiar with the use of this unit and have a thorough understanding of the devices that are being tested.

All precautions necessary to ensure that owner personnel or users are not exposed to safety hazards that may exist is provided in Appendix A – Product User Manual.

CHAPTER 4

PRELIMINARY RESULTS

4.1 Introduction

Testing is a vital process for each element or function that built. This process ensures that the elements or functions which are built can achieve the desired performance as well as fulfilled safety requirements.

4.2 Transformer Magnetism Test

Design engineer always designs their product which can be fully utilized in order to manage the cost. To ensure that the transformer is designed with appropriate sizing, magnetism test is the one that can provide the information. Voltage level from 0V is injected to the primary winding of the transformer and the corresponding current is measured. If 10% of voltage increased in the winding results 50% of current increased, that is the "Knee Point" which indicates that the transformer core is getting saturation from that point onwards. If the designed voltage is slightly less than the Knee Point, the transformer is fully utilized. Otherwise, it is oversized or undersized. The testing configuration is shown in Figure 4.1. Table 4.1 and Figure 4.2 shows the testing result of transformer magnetism test.

Desired maximum primary voltage = 272V
Primary current = less than 2 amperes

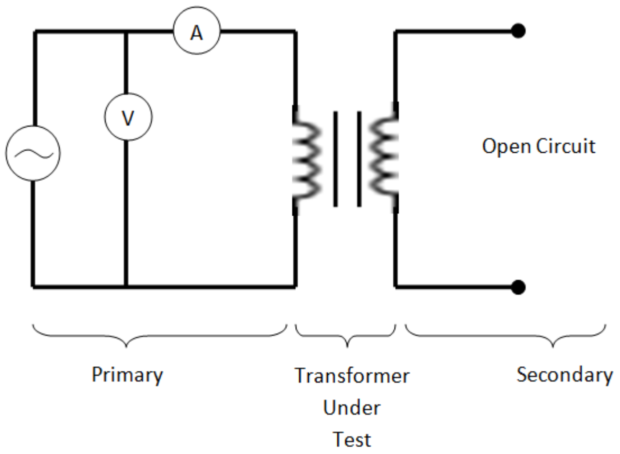


Figure 4.1: Transformer Magnetism Test

Table 4.1: Testing Result of the Transformer

Primary Voltage (V)	Primary Current (A)
0	0
50	0.05
100	0.07
125	0.08
150	0.10
175	0.12
200	0.13
225	0.15
250	0.17
275	0.19
302.5	0.25
332.75	0.81

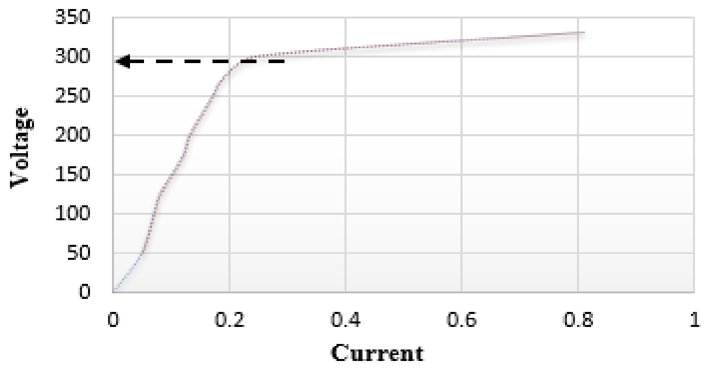


Figure 4.2: Knee Point Voltage Test

As we can see from the graph above, the knee point voltage of the transformer is around 300V. Therefore, the transformer can be operated with a maximum input voltage of 272V without core saturation.

4.3 Output Waveform Test

Since a rector is connected to the transformer, it is necessary to check the output waveform to ensure that the harmonic distortion is minimized. The wave shape displayed on the oscilloscope in Figure 4.3 shows a triangular waveform is obtained. It indicates a severe harmonic distortion in the waveform and needs to be corrected. After an adjustment on number of turns of the reactor is made and an appropriate value of the capacitor is added in parallel to the reactor, the waveform becomes close to the sinusoidal wave shape as shown in Figure 4.4.

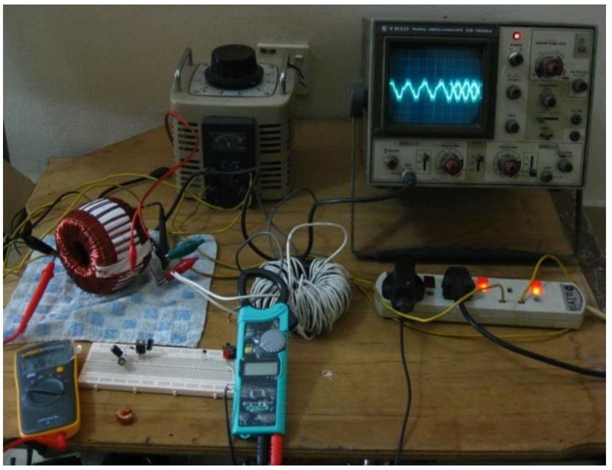


Figure 4.3: Distorted Transformer Output Waveform

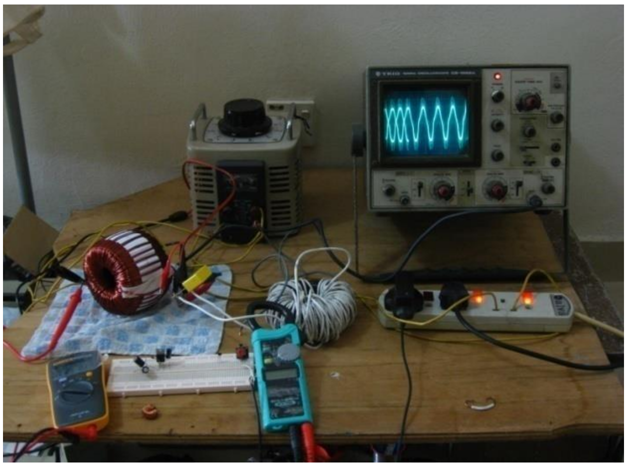


Figure 4.4: Adjusted Output Waveform

4.4 Reactor Magnetism Test

To ensure the reactor operating with no saturation when the terminals are shorted, it is necessary to test its knee point voltage. An additional winding is a temporary wound to the reactor which acts as the secondary winding. When a desired amount of current is injected into the reactor, the secondary winding will induce voltage which proportional to the injected voltage. The recorded secondary voltage in Table 4.2 can be used to plot an I-V curve and the knee point voltage can easily be obtained from the graph shown in Figure 4.5.

Table 4.2: Testing Result of the Reactor

Input Voltage (V)	Output Current (A)	Reactor Secondary Voltage (V)
20	2.1	0.8
40	5.0	1.62
60	9.1	2.38
80	14.9	3.0
100	19	3.87
120	24	4.72
140	28.2	5.05
160	32.6	5.1

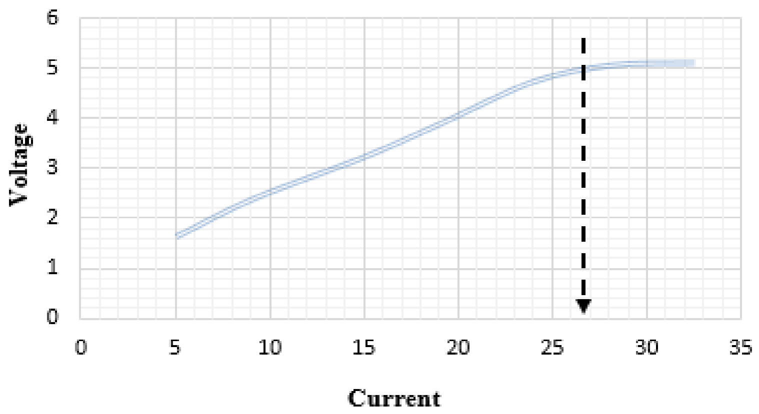


Figure 4.5: Reactor Saturated as Current Reaches 27A

From the above result, it can be seen that the knee point voltage of the reactor fall at the point where the current is approximately 27A. Since the maximum output current will be limited to 20A, the reactor is, therefore, safe to be used without saturation.

4.5 Final Product Test Results

After the assembly, it is necessary to conduct the final tests in order to evaluate the performance of the product. This including function test, output current level test, waveform test and internal protection test. All the tests are to be carried out based on ambient temperature of 25°C or 77°F. The testing results are summarized in the following sections. All the results are also stated in the user's manual-specification attached in appendix A.

4.5.1 Output Current Testing

There are two sets of output terminals which are 0 – 20A terminal and 0 – 120A terminal. The results are shown in Table 4.3.

Table 4.3: Output Current Test

Terminal	No load voltage	Load time (max)	Unload time
1: 0 – 20A	21V	60 sec	30 min
2: 0 – 120A	3V	5 min	30 min

4.5.2 AC Current Protection Characteristics

The output current level is protected by thermal relay with appropriate time delay. Thermal relay is reset automatically once the temperature has decreased to a 38°C. Table 4.4 shows the tripping characteristics.

Table 4.4: AC Current Trip Time and Reset Time

Terminal	Trip Time	Reset Time
1: 0 – 20A	60 sec (20A)	10 sec
2: 0 – 120A	5 min (120A)	20 sec

4.5.3 Output Voltage Sources Testing

There are several output voltage source that can be controlled independently. Each voltage source is protected by fuse and miniature circuit breaker. The testing results are shown in Table 4.5.

Table 4.5: AC and DC Voltage

Range	Output Voltage (max)
0 – 250 VAC	256V (1A) – ---
0 – 350 DAC	357V (1A) – 5 sec
240 VAC	242V (3A) – 3 sec
110VAC	113V (3A) – 3 sec
110VDC	117V (3A) – 3 sec
30 VDC	30V (3A) – 3 sec

4.5.4 Resistor Bank Testing

There is a set of resistors with each carries different resistance. The resistance values and the current carrying capacity for each resistor are tested and the results are shown in Table 4.6.

Table 4.6: Resistor Values and Current

Resistance (Ω)	Max Current (A)
0.5	4
1	3
25	0.6
100	0.3
500	0.15

4.5.5 Overcurrent Cut-off Testing

The output current source is protected by overcurrent protective device to prevent the generator from over loading. Once the device has tripped the circuit, it can be reset by switching off the current source. The results of cut-off characteristics are shown in Table 4.7.

Table 4.7: Maximum AC Current Cut-off

Terminal	Trip current (max) /	Trip Time
1: 0 – 20A	21A	instantaneous
2: 0 – 120A	128A	instantaneous

4.5.6 Waveform Evaluation

It is essential for a test equipment to generate an appropriate waveform in order not to affect the test results of the device under test. Figure 4.6 shows the waveform has been tuned to pure sinusoidal.

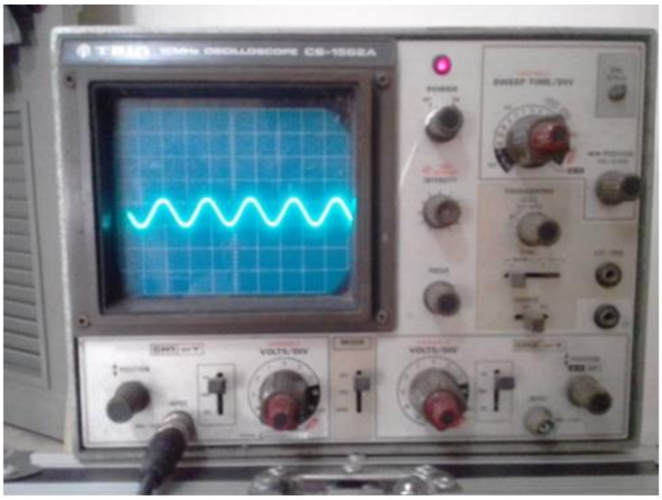


Figure 4.6: Output Sinusoidal Waveform

4.6 Evaluation of Performance of Final Product

In order to evaluate the performance of the test equipment, two protective relays with complete controlling circuit have been tested by the test equipment. This is shown in Figure 4.7. The protective relay’s setting parameters and test results are shown in Table 4.8. Note that the PSM values injected to the relay are 1.3, 2.0 and 3.0.

Figure 4.7: Final Product Test

Table 4.8: Relay's Setting and Testing Results

<table>
<tr><th colspan="3">O/C Relay Details</th><th colspan="3">E/F Relay Details</th><th colspan="3">CT Details</th></tr>
<tr><td colspan="2">Make</td><td>ABB</td><td colspan="2">Make</td><td>ABB</td><td colspan="2">Make</td><td>MECO</td></tr>
<tr><td colspan="2">Type</td><td>SPAJ 140C</td><td colspan="2">Type</td><td>SPAJ 140C</td><td colspan="2">Ratio</td><td>600/5A</td></tr>
<tr><td colspan="2">Rated Amp</td><td>5A</td><td colspan="2">Rated Amp</td><td>5A</td><td colspan="2">CL/Burden</td><td>CM/15VA</td></tr>
<tr><td colspan="2" rowspan="2">Relay Setting</td><td>O/C = 3.5A</td><td colspan="2" rowspan="2">Relay Setting</td><td>E/F = 0.5A</td><td colspan="3" rowspan="2">XXX</td></tr>
<tr><td>TMS = 0.1 sec</td><td>TMS = 0.1 sec</td></tr>
<tr><th colspan="9">Operating Current Test Results (relay's pickup)</th></tr>
<tr><td colspan="5">Overcurrent</td><td colspan="4">Earth Fault</td></tr>
<tr><td colspan="2">Red</td><td colspan="3">3.4A</td><td colspan="2" rowspan="3">N-E</td><td colspan="2" rowspan="3">0.46A</td></tr>
<tr><td colspan="2">Yellow</td><td colspan="3">3.6A</td></tr>
<tr><td colspan="2">Blue</td><td colspan="3">3.2A</td></tr>
<tr><th colspan="9">Operating Time Test Results</th></tr>
<tr><td colspan="6">Overcurrent</td><td colspan="3">Earth Fault</td></tr>
<tr><td colspan="3">Current injected</td><td colspan="3">Operating Time (Sec)</td><td colspan="2">PSM (A)</td><td rowspan="2">Operating Time (Sec)</td></tr>
<tr><td>PSM</td><td>Pri (A)</td><td>Sec(A)</td><td>Red</td><td>Yellow</td><td>Blue</td><td>Pri</td><td>Sec</td></tr>
<tr><td>1.3</td><td>546</td><td>4.55</td><td>2.67</td><td>2.54</td><td>2.60</td><td>78</td><td>0.65</td><td>2.52</td></tr>
<tr><td>2.0</td><td>840</td><td>7.0</td><td>1.00</td><td>1.00</td><td>1.03</td><td>120</td><td>1.0</td><td>1.03</td></tr>
<tr><td>3.0</td><td>1260</td><td>10.5</td><td>0.62</td><td>0.68</td><td>0.65</td><td>180</td><td>1.5</td><td>0.62</td></tr>
</table>

Operating current test indicates the relay's pickup with respect to the current setting. Operating time test is the actual tripping time of the relay with respect to the TMS setting.

The results shown in Table 4.8 can be verified by using the following equation,

$$Time\ (t) = \frac{3 \times TMS}{Log_{10} \times PSM} \tag{4.1}$$

Where,

TMS = time multiplier setting

PSM = plug setting multiplier = $\dfrac{\frac{fault\ current}{CT\ primary} \times CT\ secondary}{CT\ secondary\ setting}$

PSM is defined as multiplier of current that flowing in the busbar (fault current) compare with the nominal current setting. PSM 1 means 100% of the desired current flow (full load). Meanwhile, TMS can be defined as a time constant that provides to the relay in order to enable the processor or mechanism to determine the actual tripping time associate with the PSM value. Both PSM and TMS are the basic operational parameters of IDMT relays.

Table 4.9 shows the actual results that provided by IEC 60255 regarding to the same setting of IDMT relays and CT parameters.

Table 4.9: Reference Results which Comply with IEC 60255

<table>
<tr><th colspan="3">O/C Relay Details</th><th colspan="3">E/F Relay Details</th><th colspan="3">CT Details</th></tr>
<tr><td rowspan="2">Relay Setting</td><td colspan="2">O/C = 3.5A</td><td rowspan="2">Relay Setting</td><td colspan="2">E/F = 0.5A</td><td colspan="2">Ratio</td><td>600/5A</td></tr>
<tr><td colspan="2">TMS = 0.1 sec</td><td colspan="2">TMS = 0.1 sec</td><td colspan="2">CL/Burden</td><td>CM/15VA</td></tr>
<tr><th colspan="9">Operating Current Test Results (relay’s pickup)</th></tr>
<tr><td colspan="5">Overcurrent</td><td colspan="4">Earth Fault</td></tr>
<tr><td>Red</td><td colspan="4">2.8 – 4.55A (PSM 0.8 – 1.3)</td><td rowspan="3">N-E</td><td colspan="3" rowspan="3">0.4 - 0.65A (PSM 0.8-1.3)</td></tr>
<tr><td>Yellow</td><td colspan="4">2.8 – 4.55A (PSM 0.8 – 1.3)</td></tr>
<tr><td>Blue</td><td colspan="4">2.8 – 4.55A (PSM 0.8 – 1.3)</td></tr>
<tr><th colspan="9">Operating Time Test Results</th></tr>
<tr><td colspan="6">Overcurrent</td><td colspan="3">Earth Fault</td></tr>
<tr><td colspan="3">Current injected</td><td colspan="3">Operating Time (Sec)</td><td colspan="2">PSM (A)</td><td rowspan="2">Operating Time (Sec)</td></tr>
<tr><td>PSM</td><td>Pri (A)</td><td>Sec(A)</td><td>Red</td><td>Yellow</td><td>Blue</td><td>Pri</td><td>Sec</td></tr>
<tr><td>1.3</td><td>546</td><td>4.55</td><td>2.66</td><td>2.66</td><td>2.66</td><td>78</td><td>0.65</td><td>2.66</td></tr>
<tr><td>2.0</td><td>840</td><td>7.0</td><td>1.00</td><td>1.00</td><td>1.00</td><td>120</td><td>1.0</td><td>1.00</td></tr>
<tr><td>3.0</td><td>1260</td><td>10.5</td><td>0.63</td><td>0.63</td><td>0.63</td><td>180</td><td>1.5</td><td>0.63</td></tr>
</table>

4.7 Discussion

In the testing section, it was found that a lot of problem encountered. Some of the results are out of expectation. For example, the output waveform was distorted by the self-generated harmonics of the transformer; heat generated in conductors during high current generating; internal protective devices do no work properly or inaccurate etc. All those problems need to be solved by doing plenty of experiments.

Some problems that cannot be solved have to be redesigned. These include the transformer and the internal overload protection system. Transformer winding and core sized need to be coordinated or otherwise the output waveform may be distorted. As we look at equation 3.1 which described in section 3.3.1, the number of turns is highly depends on the cross section area of the core and the generated magnetic flux density (B-field). The important part is phase distortion of the waveform which is mainly caused by electrical reactance. Phase distortion can be minimized by adding an appropriate value of resistance in the circuit in order to reduce the magnitude of reactance and meanwhile raising the power factor.

In final evaluation of the product, it was found that the test results of the two protective relays which shown in Table 4.8 matched with the results calculated by using equation 4.1. This means that the performance of the test equipment meets all the requirements.

From Table 4.8, the minimum current that injected to the overcurrent relay is 4.55A or 1.3 times of the setting (3.5A). In the idealised operation of IDMT relay, relay's pickup can only occur as PSM exceed 1.0. This can be seen from equation 4.1. If PSM is equal to 1.00, the denominator will become zero and the result is infinity, which means that the relay should not operate. However, in practice, there may be some inaccuracies or mechanical delay which will make the pickup level higher than 1.0, says 1.1 or 1.2. In order to ensure that operation will always occur when fault is introduced, a minimum PSM of 1.3 is always chosen. According to IEC 60255, the suitable PSM values that testing IDMT relay are 1.3, 2.0 and 3.0. The same PSM values are also applied in earth fault relay testing.

Similarly, PSM value which is less than 1.0 is not always guarantee non-operate of the relay. Therefore, a value of 0.8 is generally used in normal operation to ensure non-operation of the relay. The PSM values of 0.8 and 1.3 are provided by IEC 60255. As we can see from Table 4.8, the results obtained from operating current pickup test are 3.4A, 3.6A and 3.2A for over current and 4.6A for earth fault. These are lie between PSM 0.8 to 1.3. Therefore, we can conclude that the relay's pickup is normal.

CHAPTER 5

CONCLUSIONS

5.1 Summary

The center piece of this project is to develop a protection relays test equipment. As a design engineer, a good study and understanding of related information are essential before a product can be designed to meet the requirement of consumers. To begin with, the basic of industrial power protection scheme was studied. This is the fundamental knowledge that the subsequent tasks of this project are related to the understanding of the whole protection scheme as well as testing requirements in the industry.

Some protective relays such as Earth Fault, over current and directional relays, are studied in terms of their operation theories and functions. These are the important relays as most of the other protective relays are operated based on the same theories. As a result, test equipment which designed to suit the above-mentioned fundamentals may be used to test some other relays.

As we know that instrument transformer is one of the important devices in the power protection system where it always been used in accompany with protective relays. Therefore, some details and testing methods of instrument transformer are also studied. It is a credit that the test equipment can be used to perform a test on the instrument transformer.

Since protection relays test equipment always used in the industry, many shortcomings of the convention test equipment have been reviewed. It was found that the lack of some particular functions in the conventional equipment brings inconvenience to workers and may tarry to the whole testing process. Upon designing new test equipment, the rise of these functional shortfalls becomes one of the objectives of this project.

The primary focus of this relay test unit is productivity, hence, this portable relay test unit is designed to be operated via its front-panel interface with no PC required for testing and cover just about the entire gamut of relay testing. This test unit has a lot of possibilities and is extremely powerful, it appeals to users of relay testers who understand the power system and like to be involved in the physical aspect of testing by pressing buttons and turning dials. Every function of this protection relay test unit is extremely useful and reliable. This unit ensures protection devices to detect faults promptly and without fail, as such interruptions to power supply can be minimized by selectively isolating at fault sections of the power system. In short, this is where this protection relays test unit shines.

5.2 Problems Encountered

As all the information is gathered, design work becomes much more convenient. However, there are some details that are still unpredictable during the process. For instance, some of the materials that are decided to be used in a particular design are not available in the market, such as stopwatch with feedback control input, conductors with desired size and current carrying capability and suitable capacity rating of variable voltage transformer etc. All these problems should be overcome by either change the original design or custom made. In this project, the output current rating and feedback control system have been modified from the original design as a result of a shortage of materials. On the other hand, stopwatch, main output transformer, and an auxiliary power supply are customs made in order to preserve the best design.

Another important issue that must be taken into account is safety measures. Since the product is designed for electrical works and users' profession may not be always justified, the insulation quality, input/output voltage, and current level, as well as the configuration of the product, must be considered. Also, sufficient protection and safety precaution of every single function on the panel of the product is mandatory.

During the design process, there are some difficulties that are worth to be discussed here. One of it is the design of the main transformer which acts as an output current source. Since the product is also designed to be used as Primary Injection Equipment, the ability to generate an output current must be strong enough. Based on the current carrying capacity and the appropriate output voltage level, the transformer can become very big in size or weight and this is not the optimal product. To overcome this problem, several designs such as E-I core, C-I core, and Toroid core were tried. It was found that Toroid core is the best choice where the size can be minimized as a result of lesser core loss compared with other types of cores. Also, the transformer is designed to operate just right below its knee point voltage. This is to minimize the number of turns that wound to the core in order to prevent it from oversized.

Based on the abovementioned process, some of the tiny errors were still existed and affected the desired result. For example, high reactance value of the transformer caused poor power factor and inappropriate magnetic flux density created a higher harmonic level of the output waveform. A suitable method for power factor measurement and improvement which discussed in section 3.3.7 was implemented. Harmonic distortion was improved by changing the applied voltage and number of turn of the winding. Since the transformer is designed to operate under maximum performance, the B-H characteristic was pushed to the maximum limit and no longer linear. The applied voltage was therefore chosen carefully. More than hundreds of iterations of the test have been conducted in order to improve the design.

The stopwatch is one of the difficult issues in the design process. Since the circuit was designed with reference to basic electronics, stability control becomes the most difficult part as a result that the selection of electronic components must be done and calculate carefully. The design has also involved the communication with the control circuit, digital resolution, and counting range. Some of the calculated results did not really infer precise performance. Therefore, to figure out the error, testing is the best solution.

Throughout the process of this project, I have learned a lot about protective relay operating theories, testing theories and design knowledge especially transformer design through experiments. Besides, I have gain valuable guidance through interaction with both of my supervisor and co supervisor to make this project possible.

5.3 Recommended Solutions to Safety Issues

Regarding safety issues, the selection of material is essential. All the material used in every single part of the product must be considered in terms of electrical and thermal characteristics. This is especially important for the output of the main current transformer. The conductor sizes and thermal insulation will be the first consideration. Also, the thermal protective relay will be added into the design.

There are some minor problems with the main current transformer and reactor, such as noise (hum) when the higher input voltage is applied to it. Some modifications are needed to be studied. The testing methodology will be improved in order to achieve a better solution for the design. However, all designs will be in accordance with the original plan.

5.4 Recommendations for Future Work

Since this product is special designed for protective relays testing, it is necessary to provide precise output and its high reliability. As we look beck the whole designs of the product, all the desired features and functions were achieved. However, there are some shortfalls that may be restrains the relay testing activity on site. For instance, the output current that injects to the relay under test is only a single phase. In other words, testing can only be conducted phase by phase. This may constrain its performance for some other relays such as distance relay and directional overcurrent relay as they need three phases of source to operate simultaneously in order to compare their polarized electrical angle as fault is introduced. Therefore, single phase injection becomes inappropriate for them.

The product with three-phase source is going to develop in the future in order to widen the usage and performance of the product as well as to satisfy the industrial requirements. Since the main power supply of the product is always single phase, the generation of three-phase from the single phase source associated with their internal and external communication systems may become the most challenging parts.

Again, higher current output of the product must be developed. Although the existing product can generate high current level up to 120 amperes for single wire and able to achieve higher for more turns of wire when inject the primary side of current transformer, these are only limited to ring-type current transformer testing. For higher rating bar-type or wound-primary type current transformer injection, only single wire is allowed. Therefore, higher rating of single wire output is necessary.

REFERENCES

Bhuvanesh, A., 2010. *Power system Protection and Switchgear*. Singapore: McGraw-Hill.

Blackburn, J.L. and Domin, T.J., 2006. *Protective relaying: principles and applications*. CRC press.

Chapman, S.J., 2002. *Electric machinery and power system fundamentals* (Vol. 3). New York: McGraw-Hill.

Charles, K. and Mattew, N., 2013. *Fundamental of Electric Circuit*. Singapore: McGraw-Hill.

Duncan, G., Mulukutla, S. and Thomas, J., 2012. *Power System Analysis and Design*. Stamford, USA: Cengage Learning.

EdvardCsanyi., 2010. *Distance Relays*. Retrieved from http://electrical-engineering-portal.com/distance-relays
Electricity Training Association ed., 1995. *Power System Protection: Application* (Vol. 3). IET.

Gruenert, H., Omicron Electronics GmbH, 2002. *Method and device for testing differential protection relays or differential protection relay systems*. U.S. Patent 6,396,279.

James, A. and Richard, C., 2014. *Introduction to Electric Circuit.* United State of America: Willey.

Jignesh. P 2013. *Electrical Notes and Articles*. Retrieved from https://electricalnotes.wordpress.com/2013/01/01/types-of-over-current-relay/

John, D., 2006. *Electric Power Substations Engineering*. New York, USA: Taylor and Francis Group.

Kappenman, J.G., Albertson, V.D. and Mohan, N., 1981. Current transformer and relay performance in the presence of geomagnetically-induced currents. *IEEE Power Engineering Review*, (3), pp.23-24.

Klancher, F., Eaton Corp, 1998. *Method and apparatus for remote testing of coordination of overcurrent protection devices in an electrical power system*. U.S. Patent 5,734,576.

Lensner, H.W. and Schwanenflugel, P.J., Westinghouse Electric Corp, 1966. *Directional overcurrent relays*. U.S. Patent 3,278,804.

Omicron., 2018. *Testing Solutions for Protection Measurement System*. Available through: Omicron website:

<https://www.omicronenergy.com/en/applications/protection-testing/#contact-menu-open> [Accessed 28 June 2018].

Roberts, J. and Guzman, A., 1994, October. Directional element design and evaluation. In *proceedings of the 21st Annual Western Protective Relay Conference, Spokane, WA*.

Schneider Electric., 2001.*Full Function Test Kit*. Available through: Schneider Electric website: <https://download.schneider-electric.com/files?p_enDocType=Instruction+sheet&p_File_Name=48049-183-06+Rev02.pdf&p_Doc_Ref=48049-183-06> [Accessed 28 June 2018].

Sleva, A.F., 2009. *Protective relay principles*. CRC Press.

Stephen, D., 2014. *Fitzgerald & Kingsley's Electric Machinery*. Singapore: McGraw-Hill.

Theodore, W., 2002. *Electrical Machines, Drives, and Power Systems.* Upper Saddle River: Prentice Hall.

Walter, A., 1994.*Protective Relaying Theory and Applications*. New York, USA: Marcel Dekker Inc.

Wright, A. and Christopoulos, C., 2012. *Electrical power system protection*. Springer Science & Business Media.

APPENDIX A

Product User's Manual