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MASTER

In **Power Engineering**

Option: **Power Engineering**

Title:

Study and Testing of the Directional Phase Overcurrent Protection Relay And The RCA’s Impact On Its Performance and Directional Decision Making.

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Abstract:

This thesis presents a background on power system protection devices, relay principles, modern relay technology and relay testing.

It focuses on the study of the directional phase overcurrent relaying concept that can be briefly explained by the relay tripping whenever the faulted current exceeds a pre-determined pick up value in a specific predefined direction, in order to isolate only the faulted part of the network. This reliable and selective protection is generally used in multisource networks, parallel transmission lines and mesh distribution networks. It is mainly characterized by its Maximum Torque Angle and Relay Characteristic Angle (RCA) also known as the directional angle as it decides the direction of the tripping zone. The variation of the RCA setting has a direct impact on the sensitivity operation of the relay (45 degrees' maximum sensitivity operation for any type of fault).

Tests have been performed on The Four Step Directional Phase Overcurrent Protection Function of the Line Distance Protection REL670 ABB IED numerical relay. In one hand, the 51/67 ANSI protection has been tested and results were discussed in order to make a simplified testing guide for this protection.

In the other hand, different cases of RCA settings were evaluated under symmetrical and asymmetrical fault types to showcase that the 45 degrees' angle is the best applicable value for a maximum sensitivity.

Acknowledgement

We would like to express our sincere gratitude to our dear supervisor ***Dr. Mohammed Bouchahane*** *for his advice, guidance, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways. we would also like to thank all teachers of our institute who taught and educated us in this master's program.*

Our sincere thanks also goes to Tennessee University of Chattanooga, for offering us all the information about the power system protection and for giving us the access to their laboratory for the realization of tests on the protective relay. And that could not be possible without the support of our supervisor.

Dedication

“I would like to dedicate this humble work to my beloved parents specially my mother for her endless support
Special thanks go also to my dear twin Ryma who stands with me all the times and to my brothers
To all my dear friends and family
Thank you so much for believing in me “

BOUHADDA Wafa Imene

“I have a great pleasure to dedicate this work to my parents for their continuous support.
To my sister Sarah and Brother Omar.

To all my best friends CHELIHI Nehad, OUSSAD Linda and ABDI Lina Amel.

A special thank you to my hard working, patient and my best friend, thesis pair BOUHADDA Wafa Imene.

To family, my aunt LADJADJ Nacira and her husband, my cousins MISBAH Sonia and MISBAH Brahim.

A special thank you for my precious late grandmother MALOUM Fatima for raising and taking care of me.

To my grandmother ZIBANI Wardia and aunt CHIKHI Zahia, and all my uncles, To my baby cousins Razan and her mother Zahia, Youba, Elissa and Eline.

Thank you!”

CHIKHI Belynda

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List of Abbreviations:

ANSI	American National Standard Institute
IEEE	Institute of Electrical and Electronics Engineers
CT	Current Transformer
VT	Voltage Transformer
CC	Current Coil
VC	Voltage Coil
ANSI 67G	Ground Directional Overcurrent
ANSI 67N	Neutral Directional Overcurrent
ANSI 67P	Phase Directional Overcurrent
ANSI 67SG	Sensitive Ground Directional Overcurrent
67Ns	Earth fault directional
67Q	Negative Sequence Directional Overcurrent
ANSI 51DT	Definite-Time Overcurrent Relay
OIP	Oil-Impregnated Paper
IOC	Instantaneous Overcurrent
DTOC	Definite Time overcurrent
PMU	Phasor Measurement Units
RCA	Relay Characteristic Angle
MTA	Maximum Torque Angle
ROA	Relay Operating Angle
I/O	Input / Output
IED	Intelligent Electronic Device

In	Nominal Current
IB	Base Current
IMin1	Minimum Current Zone1
Ubase	Voltage Base
IEC Norm.Inv	Normal Curve in International Electrotechnical Commission standards
DirMode	Directional Mode
tnom	Time Nominal
tmin	Time Minimum
tmax	Time Maximum
tact	Time Actual

INTRODUCTION:

With the fast growth of worldwide population comes the constant increase of electrical power demand from both society and the industry. In order to allow more power to be continuously conveyed to any given location, electrical networks are becoming more and more complex, from multiple power sources, parallel transmission lines to different distribution configurations such as mesh configuration designed for this purpose.

Protection engineers are challenged to design a reliable protection system to fulfil the continuous power flow criteria and minimize interruptions. This is accomplished by using essential protection devices such as protective relays that must be carefully parametred and periodically tested to assure its correct functioning. Unfortunately, it is reported from past experiences that numerous large scale Black-outs have been caused by incorrect setting of relays, and this makes the study and testing of relays is the main focus in the protection field.

Directional phase overcurrent relay protection is the widely used protection device in parallel transmission lines as well as for mesh distribution networks, because it achieves a proper fault discrimination. The relay typically consists of two elements: “Directional Protection” and “Overcurrent Protection”. The parameters of this last must be set carefully as faults need to be cleared in a very short time, to avoid feeding the fault and to damage the electrical equipments.

Contrary to the popular beliefs, there are few engineers who are well informed and well experienced in the study and testing of the directional phase overcurrent relay despite being widely used. The lack of technical testing guides, makes it difficult for engineers and engineering students to learn the basic testing steps as well fundamental knowledge concerning the directional phase overcurrent relay.

The objective of our thesis is to study the working principle of the directional phase overcurrent numerical relay and its characteristics. We will focus on studying and testing the impact of Relay Characteristic Angle (RCA) setting on the its directional decision making as well as its performance overall. A series of tests will be performed using the Four Step Directional Phase Overcurrent Protection Function of the Line Distance Protection Relay ABB REL670 IED (Intelligent Electronic Device) relay, in order to showcase its relaying concept. Finally, after collecting and analysing the data obtained, a simplified guide will be proposed at the end, that will present and explain the steps followed in order to accomplish the test and a full analysis on the result obtained. The aim of this report is to contribute in providing the basic knowledge needed to test the directional function of the ABB REL670 Intelligent Electronic Device (IED) numerical relay. This will contribute to solve the problem of lacking resources concerning the directional phase overcurrent protection relay. The thesis is presented as the following:

- **Chapter one:** This chapter focuses on providing an overview about power system at its different levels and some abnormalities that may disturb of the network and all levels. Basics power protection devices has been reviewed providing the needed background knowledge needed for the second chapter.
- **Chapter two:** In this chapter, the directional phase overcurrent protection was studied by explaining its principle of working, its different characteristics and the standard settings for a correct directional decision making and its application.
- **Chapter three:** In this chapter, different fundamental routine testing types will be introduced and explained. The testing procedure followed for the ABB REL670 directional phase overcurrent numerical protection relay has been shown with a detailed results and discussion considering different RCA settings.

CHAPTER 1:

POWER SYSTEM PROTECTION

1.1. Introduction:

With the fast growth of worldwide population comes a fast growth in the industry, thus the higher demand of electrical power. New generation and transmission facilities are being constructed to satisfy the needs of the society. As a result, power system networks are becoming more complex, it may face many disturbances and abnormalities which may cause interruption of the electricity flow towards consumers, material loss and in the worst cases human losses. These abnormalities can be caused by environmental conditions, human error or by equipment’s failure such as transformers and rotating machines. In order to prevent or minimize the loss of supply to customers and the damages caused by these abnormalities, protection engineers are challenged to design a protection system with high security at all aspects of the power system starting from generation, transmission to distribution, with a better modelling and testing tools. The objective of a protection system is to sense, detect the direction and isolate any type of fault that can occur in any section of the power system in a fast manner. Unfortunately, protection systems are not unfillable at accomplishing their main goal of isolating electrical faults. Actually, it reported from [1] and [2] that from past experiences; numerous large scale Black-outs have been caused by incorrect setting of relays and bad coordination between different protection elements.

This chapter will focus on providing an overview about power system at its different levels, the causes and consequences of faults that may disturb the power flow of the network and the faults at all levels and their associated basic equipment that constitute a protective system, such as fuses, circuit breakers, instrument transformers and relays.

Since protection system has evolved from primitive devices with limited capability to complex intelligent electronic devices, the emphasis will be on the brain of protective systems, which are numerical relays. The back ground knowledge seen in the previous academic years is provided such as symmetrical components, that are necessary for the development of the thesis in the next chapters.

1.2. Power System Network:

The power system is a network which consists of generation, transmission and distribution system. Electric power systems are real-time energy delivery and not storage systems like water systems and gas systems, which means that the power is generated, transported, and supplied as the demands calls for it. The Figure I.1 shows the basic building blocks of a traditional electric power system structure [3].

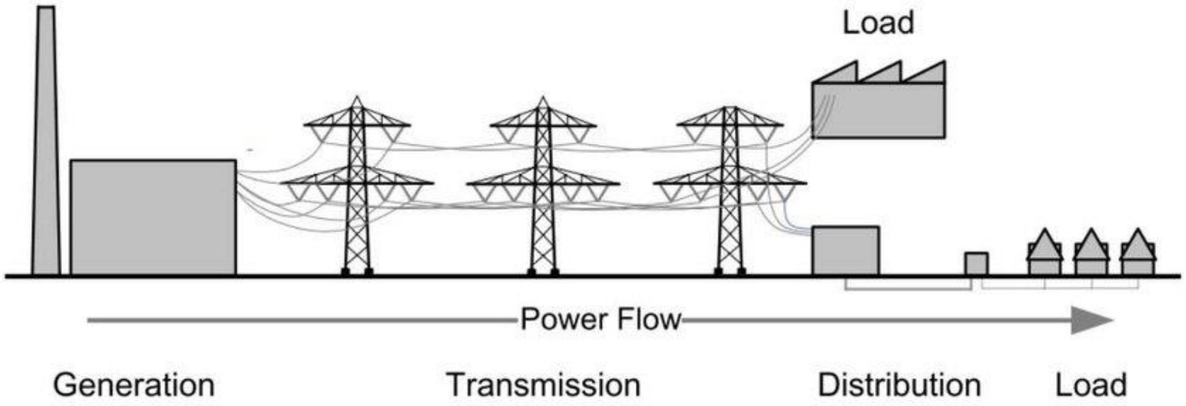


Figure 1.1: Traditional power system structure [4].

In generating station, the fuel (coal, water, nuclear energy, etc.) is converted into electrical energy. The generated electrical energy range depends on the production capacity of the power plant. Power plants are mainly classified into three types, i.e., thermal power plant, hydropower plant and nuclear power plant. The main components of the generating station are: generator and the transformer. The role of generators is to convert the mechanical energy that comes from the burning of coal, gas and nuclear fuel, gas turbines, into electrical energy, while the transformers step-up the generated energy to a high voltage which is suitable for long distance transmission, mainly to avoid the loss of energy. In other hand, another power transformer is used to transform electrical power to lower voltage levels near the load centers [5].

The high voltage transmission line is terminated in substations which are called high voltage substations or primary substations, where the voltage is stepped-down to a suitable value for domestic, commercial and relatively small consumers. The consumers require large blocks of power which are usually supplied at sub-transmission or even transmission system [5].

1.2.1. Distribution network configurations:

There are two main topologies for the configuration of a distribution network, the radial and the mesh network topology. The radial system is a tree shaped topology where only open loops exist, this means that the power start at one original bus that receives power from transmission system at a single substation and gradually steps the voltage down to be delivered to the next bus until reaching consumers without possibility of reflow. This type of topology is the simplest and the cheapest for an electrical network, but not reliable. It is utilized only when generated power is at low voltage and the substation is close to the load [6].

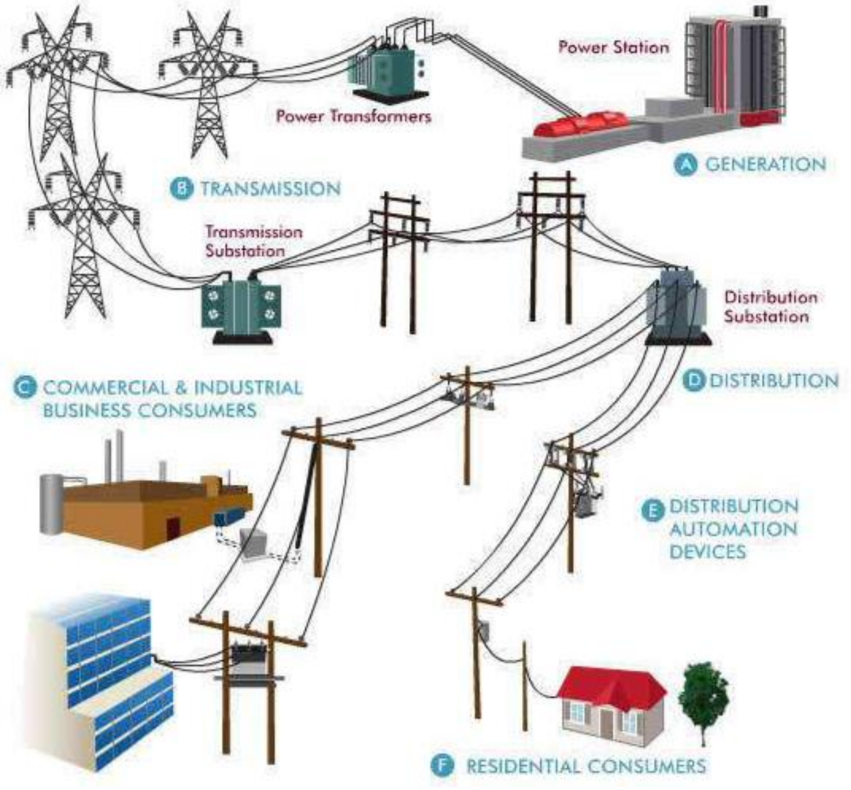


Figure 1.2: Classical Radial Network [5].

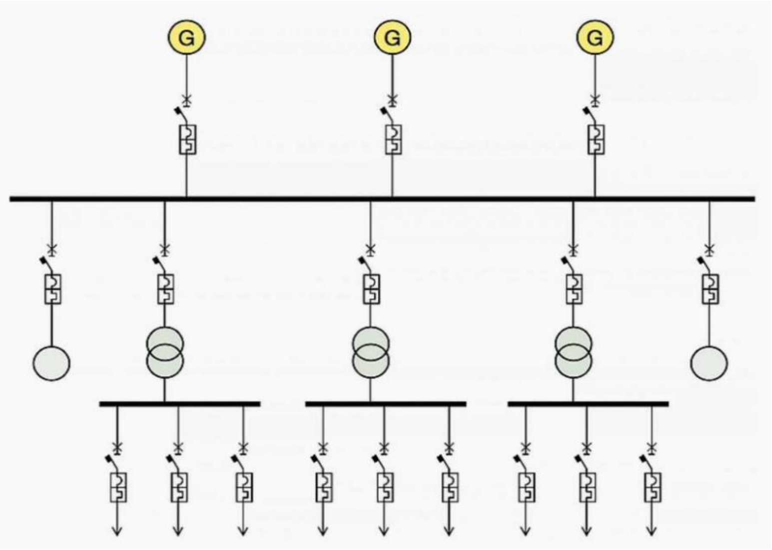


Figure 1.3: Simplified diagram of Radial Network [6].

In mesh (loop or ring) system topology, open loops are inexistent. Contrary to the radial topology, the power is delivered through multiple lines connected to each other forming a loop shape. The ring structure is usually used with higher or medium voltage in a high density population area. In general, most substations are connected to a mesh network of the medium voltage distribution system. This topology is more expensive and more reliable than the radial structure [7].

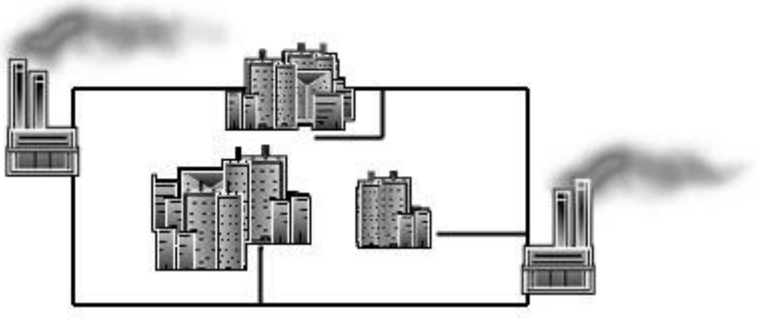


Figure 1.4: Classical Mesh Network [8].

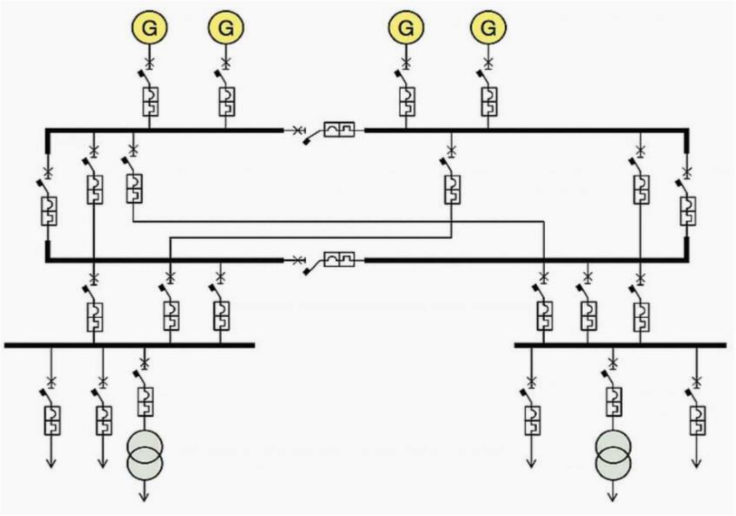


Figure 1.5: Simplified diagram of Mesh Network [6].

The table below summaries main difference between radial and mesh distribution system.

Topology	**Advantages**	**Disadvantages**
Radial	-Simplicity -Operation -Installation coasts	-Quality of service -Less reliable -Maintenance require feeder interrupting
Mesh	-Simplicity -Quality of service -More reliable -Maintenance does not require feeder interrupting	-Installation coasts

Table 1.1: Comparison between radial and mesh network [6].

1.3. Electrical Faults in transmission lines:

An electrical fault is an abnormal condition defined as the defect in the power system due to which the current is distracted from the intended path. It can be caused by equipment failures such as transformers and rotating machines, insulation failures and conducting path failures, human errors, and environmental conditions. Theses faults cause interruption to electric flows, equipment damages, and in the worst cases the death of humans, birds, and animals [9]. Under normal operating conditions, the electric equipment in a power system network operate at normal voltage and current ratings, but once the fault occurs in a circuit or device, voltage and current values deviates from their nominal ranges, causing over current, under voltage, unbalance of the phases, reversed power and high voltage surges. This results in the interruption of the normal operation of the network, failure of equipment, electrical fires [10]. Usually power system networks are protected with switchgear protection equipment such as circuit breakers and relays in order to limit the loss of service.

1.4. Types of Faults:

The fault in the power system is mainly categorized into two types they are: Open Circuit Fault and Short Circuit Fault. The scheme below shows the different types of power system faults.

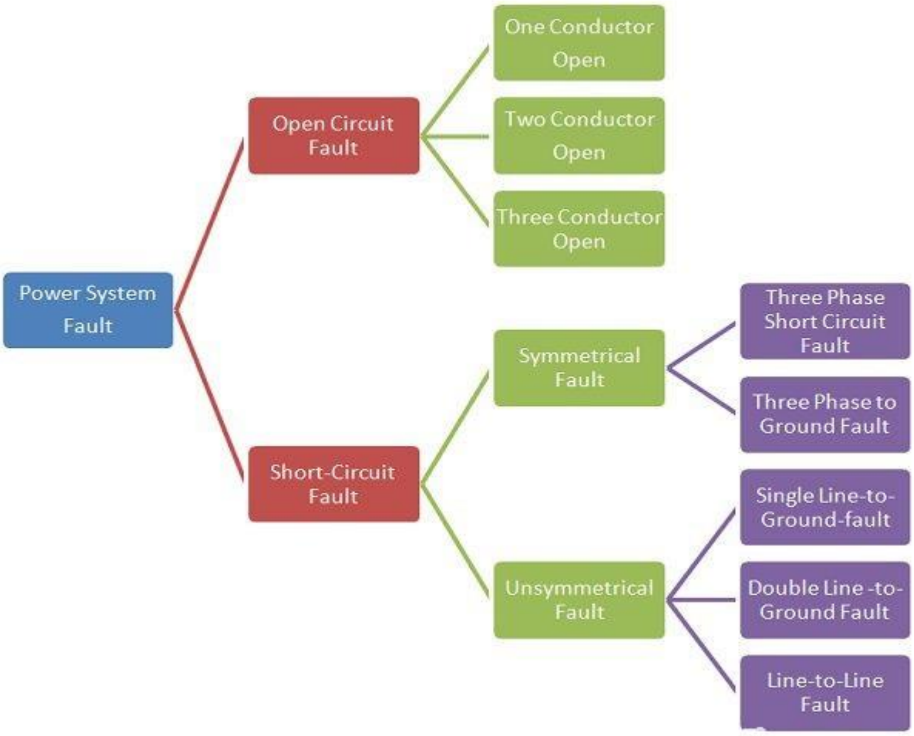


Figure 1.6: The different types of power system faults [9].

1.4.1. Open Circuit Fault:

The open circuit fault occurs when conductors fail (break) or malfunctioning of protection devices like circuit breaker in one or more phases which affects the reliability of the system. The open circuit fault is categorized as:

- Open Conductor Fault.
- Two conductors Open Fault.
- Three conductors Open Fault.

The figure below can visualize the open circuit fault is shown in the figure below.

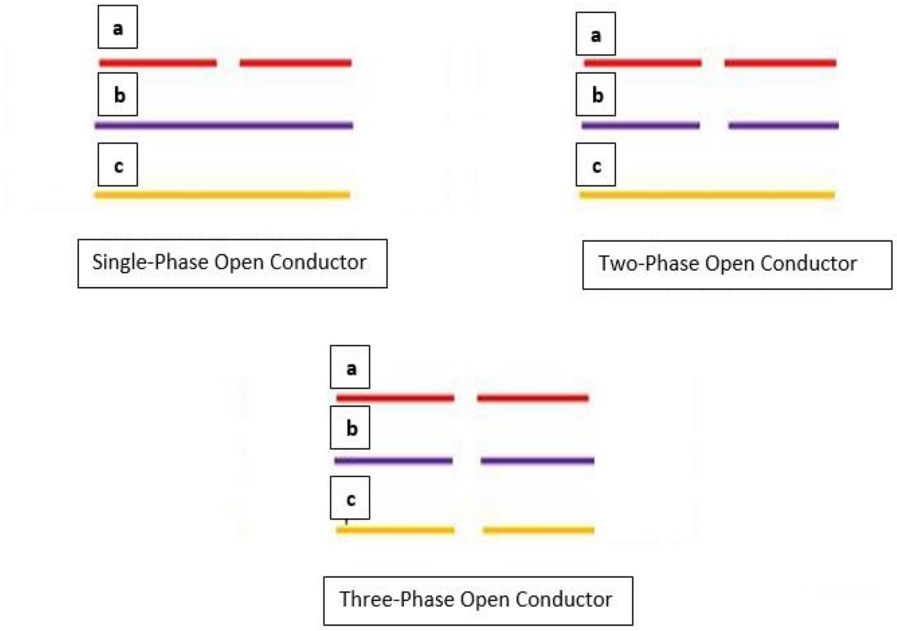


Figure 1.7: The open circuit fault [9].

Effects of the open circuit faults [11]:

- Abnormal operation of the system.
- Danger to the personnel as well as animals.
- Exceeding the voltages beyond normal values in certain parts of the network, which further leads to insulation failures and developing of short circuit faults.

Although open circuit faults can be tolerated for longer periods than short circuit faults, these must be removed as early as possible to reduce the discontinuity time of the service.

1.4.2. Short-Circuit Fault:

The conductors of the different phases come into contact with each other with a power line, power transformer or any other circuit element, thus causing a large current flow through one or two phases of the system. It may occur due to internal or external effects. Internal effects may include breakdown of transmission lines or equipment, deterioration of insulation in generator, transformer and other electrical equipments and improper installations [12]. External effects may include overloading of equipments, insulation failure due to weather conditions and mechanical damage caused by the public [12]. Short-circuit faults are divided into the symmetrical and unsymmetrical faults.

The effects that short circuit faults are more damaging than the open circuit effects, this is why it must be cleared in the shortest time possible. The effects caused may include [13]:

The large current flow due to short-circuit causes excessive heating which may result in fire and causes considerable damage to the system.

The low voltage created by the fault has a very harmful effect on the service rendered by the power system. If the voltage remains low for even a few seconds, the consumers' rotating machines may be shut down or may become unstable.

Figure 1.8: An oil-impregnated paper (OIP) bushing failure on the 400-kV, 100-MVAR reactor caused this reactor fire an oil-impregnated paper (OIP) bushing failure on the 400-kV, 100-MVAR reactor caused this reactor fire [14].

The different types of short circuit fault can be divided into four groups with the following approximate percentage distribution: [15]

- Three-Phase (-to-Ground) Faults: <5 %
- Phase-to-Ground Faults: 80%
- Phase-to-Phase Faults (to-Ground Faults): 15 %

1.5. Symmetrical and Asymmetrical faults:

Short-circuits are also classified into symmetrical and asymmetrical faults. Three-phase fault is a symmetrical fault because all phases are affected and the system remains balanced. The other three fault types (line-to-ground, line-to-line, and two-line-to-ground) are called unsymmetrical or asymmetrical faults.

To explain symmetrical and asymmetrical short circuit faults, an example from [16] will be taken into consideration:

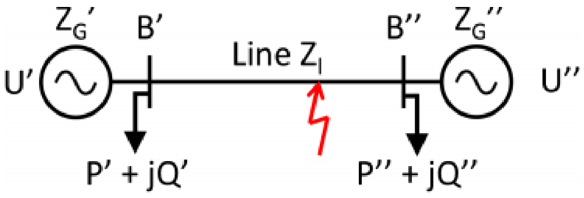


Figure 1.9: Simple Two Bus Network with Fault on Line [16].

- Z'_g , $Z"_g$ - Respective Generator Impedances.
- $U', U"$ - Respective Generator Voltages.
- $P' + jQ'$, $P" + jQ"$ - Respective Active and Reactive Power Consumption .
- Z_l- Line Impedance.

1.5.1. Three-Phase(-to-Ground) Faults (symmetrical):

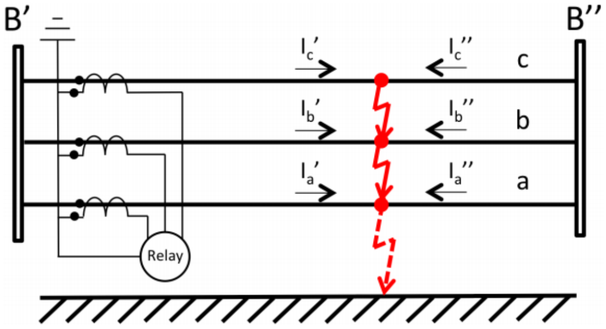


Figure 1.10: Three-Phase(-to-Ground) Fault [16].

The Figure 1.10 represent a three phase (to ground) fault. Background for symmetrical components needed for the analysis can be found in Appendix A. The Sequence Networks Interconnection in Figure 1.11 shows that there are no negative or zero sequence currents for this type of fault, therefore, the original three-phase system can be represented with just the positive sequence components of the symmetrical components:

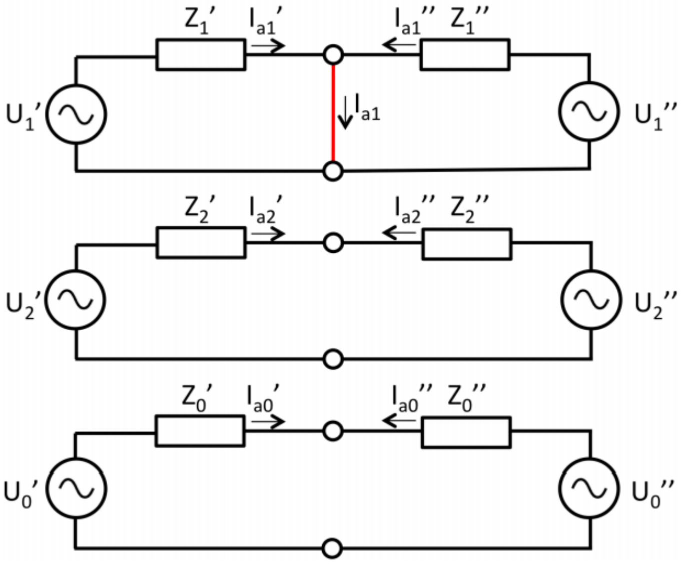


Figure 1.11: Reduced Sequence Networks Interconnection for Three-Phase Fault. No Negative or Zero Sequence Network Component [16].

- Z'_1 , Z'_2 ,Z'_0 Positive, Negative and Zero sequence Impedance of generator at bus B’ and the line from Bus B’ to fault location.

- $Z"_1$, $Z"_2$,$Z"_0$ Positive, Negative and Zero Sequence Impedance of Generator at bus B” and the line from Fault Location to Bus B”.

The positive sequence current I_{a1} is equal to the fault current I_F which can be calculated as the following:

$$I_F = I_{a1} = I'_{a1} + I"_{a1} \qquad (1.1)$$

Where :

$$\begin{cases} I'_{a1} = I'_a = \frac{U'_1}{Z'_1} \\ I"_{a1} = I"_a = \frac{U"_1}{Z"_1} \end{cases} \qquad (1.2)$$

I'_{a1} , $I"_{a1}$: the currents contribution flowing from bus B’ and bus B” respectively.

1.5.2. Phase-to-Ground Faults (asymmetrical):

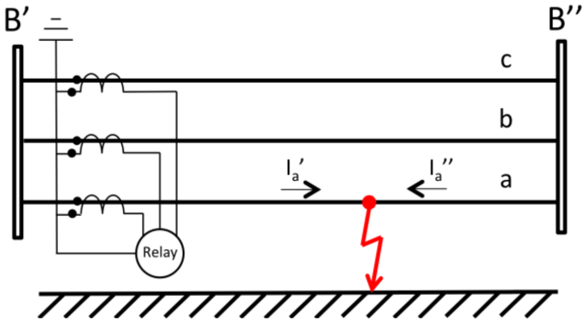


Figure 1.12: Phase-to-Ground Fault [16].

The analysis of this fault is done using symmetrical components. we considered a case where the faulted phase is phase (a), then the equivalent sequence networks will be as in Figure 1.13.

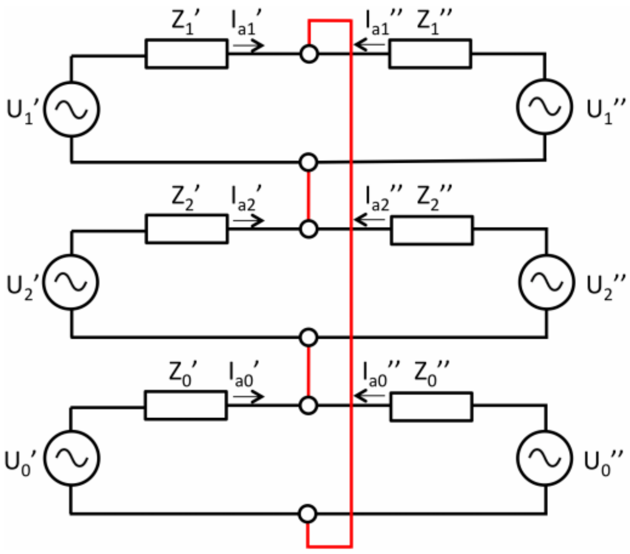


Figure 1.13: Reduced Sequence Network for Phase-to-Ground Fault [16].

The current in Phase (b) and (c) becomes zero, while phase a will carry the entire fault current:

$$\begin{cases} I_a = I_F \\ I_b = 0 \\ I_c = 0 \end{cases} \tag{1.3}$$

Sequence currents for this type of fault flow in all the three sequence networks and are equal. Inserting (1.3) into Equation A.1 leads to the following relationship:

$$I_{a1} = I_{a2} = I_{a0} = \frac{I_a}{3} = \frac{U'_1}{Z'_1+Z'_2+Z'_0} + \frac{U''_1}{Z''_1+Z''_2+Z''_0} \tag{1.4}$$

From Sequence Network in Figure 1.13 the following currents can be derived:

$$\begin{cases} I_a = I'_a + I''_a \\ I_{a1} = I'_{a1} + I''_{a1} \\ I_{a2} = I'_{a2} + I''_{a2} \\ I_{a0} = I'_{a0} + I''_{a0} \end{cases} \tag{1.5}$$

Where:

$$\begin{cases} I'_a = \frac{3U'_1}{Z'_1+Z'_2+Z'_0} \\ I''_a = \frac{3U''_1}{Z''_1+Z''_2+Z''_0} \end{cases} \tag{1.6}$$

The fault current may then be expressed as follows:

$$I_F = I_a = 3I_{a1} = 3I_{a2} = 3I_{a0}$$

$$I_F = \frac{3U'_1}{Z'_1+Z'_2+Z'_0} + \frac{3U''_1}{Z''_1+Z''_2+Z''_0} \tag{1.7}$$

1.5.3. Phase-to-Phase Faults (asymmetrical):

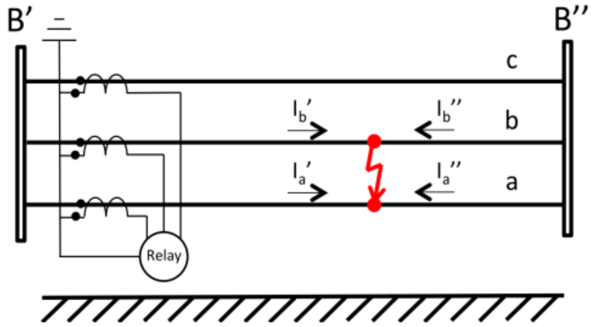


Figure 1.14: Phase-to-Phase Fault [16].

Consider a case where Phase (a) and (b) are the faulted phases which is represented in Figure 1.14. The currents in the faulted two phases would have equal amplitude, with reverse polarity, and the current in phase (c) will be zero. The sequence networks interconnection for the double phase fault is represented in Figure 1.15.

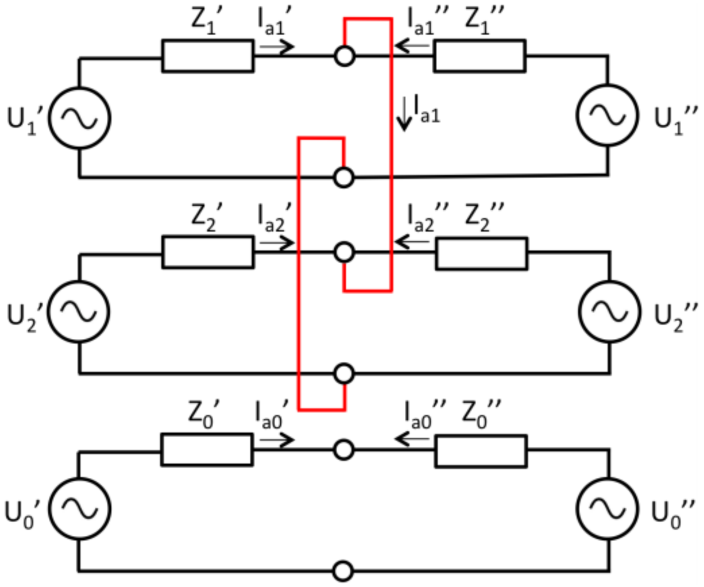


Figure 1.15: Reduced Sequence Networks Interconnection for Phase-to-Phase Fault. No Zero Sequence Network Component [16].

Usually, the positive and negative sequence impedances are taken to be equal impedances and No zero sequence current flows for the line-to-line fault since there is no path to ground. The phase currents may then be expressed as follows:

$$\begin{cases} I_a = I'_a + I"_a = \quad I_F \\ I_b = I'_b + I"_b = -I_F \\ \qquad I_c = 0 \end{cases} \tag{1.8}$$

as follows:

$$I_F = I_a = \sqrt{3}\frac{U'_1}{2Z'_1} + \sqrt{3}\frac{U"_1}{2Z"_1} \tag{1.9}$$

1.5.4. Double-Phase-to-Ground Faults (asymmetrical):

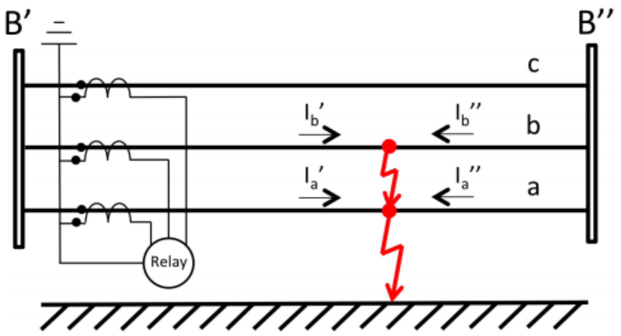


Figure 1.16: Double-Phase-to-Ground Fault [16].

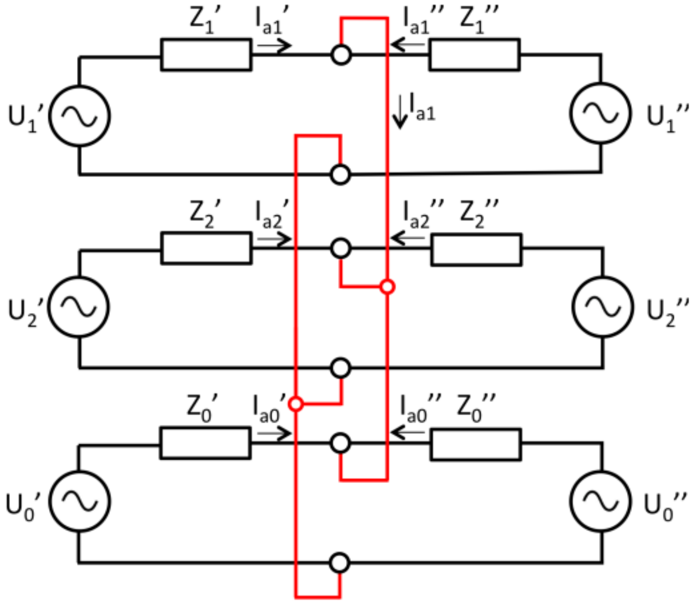


Figure I.17: Reduced Sequence Networks Interconnection for Double-Phase-to Phase Fault [16].

Consider a case where Phase (a) and (b) are faulted. The current in Phase (c) becomes zero. The symmetrical component representation in Figure 1.17 includes the positive, negative and zero sequence. This gives the following current equations:

$$I_{a1} = I'_{a1} + I"_{a1} = \frac{U'_1}{Z'_1+\frac{Z'_2Z'_0}{Z'_2+Z'_0}} + \frac{U"_1}{Z"_1+\frac{Z"_2Z"_0}{Z"_2+Z"_0}} \quad (1.10.a)$$

$$I_{a2} = I'_{a2} + I"_{a2} = -I_{a1}\left(\frac{Z'_0}{Z'_2+Z'_0} + \frac{Z"_0}{Z"_2+Z"_0}\right) \quad (1.10.b)$$

$$I_{a0} = I'_{a0} + I"_{a0} = -I_{a1}\left(\frac{Z'_2}{Z'_2+Z'_0} + \frac{Z"_2}{Z"_2+Z"_0}\right) \quad (1.10.c)$$

1.6. Power System Protection Attributes:

The fundamental objective of a protection system is to detect and isolate the faults section of the system, or the equipment, that generates fault currents as quickly as possible in order to maintain the integrity and stability of the power system and to minimize the damages and to protect other equipment from getting damaged or from failing permanently. Every protective system must satisfy four basic requirements: Reliability, Selectivity, Sensitivity, Speed and Economic.

- **Reliability**: The reliability of a protective system is by definition the probability that the system will function correctly when required to act it indicates the correctness of its operation. Dependability and security are two aspects of the reliability. This reliability has two aspects: first, the system must operate in the presence of a fault that is within its zone of protection and, second, it must refrain from operating unnecessarily for faults outside its protective zone or in the absence of a fault [17], [18].

- **Selectivity**: Selectivity in a protective system refers to the overall design of protective strategy wherein only those protective devices closest to a fault will operate to remove the faulted component. Different protection relays are installed and configured to protect different parts of the power system. If the relay settings are coordinated properly, the primary relay will operate as quickly as possible when there is a fault within its protection zone and it also provides backup protection with a delay time for faults outside its protection zone. This implies a grading of protective device threshold, timing, or operating characteristics to obtain the desired selective operation. This restricts interruptions to only those components that are faulted [17], [18].
- **Sensitivity:** sensitivity in protective systems is by definition the ability of the system to identify an abnormal condition that exceeds a nominal "pickup" or exceeds a pre-determined threshold values which initiates protective action. The margin between trip and restraint regions determines the sensitivity of the protection system. The smaller the margin between its trip and restraint regions, the higher sensitivity the system will have and vice versa [17], [18].
- **Speed:** A protection system is required to remove a fault after it has been detected as fast as possible. The time that the protective system takes to detect and isolate the damaged section of the power system determines the severity of the equipment damage and can also influence the stability of the power system [19].
- **Economic:** It is fundamental to obtain the maximum protection possible for the minimum cost possible.

1.7. Power Protection Devices:

1.7.1. Instrument Transformer:

A general classification applied to current and voltage devices used to change currents and voltages from one magnitude to another or to perform an isolating function, that is, to isolate the utilization current or voltage from the supply voltage for safety to both the operator and the end device in use. Instrument transformers are designed specifically for use with electrical equipment falling into the broad category of devices commonly called instruments such as voltmeters, ammeters, wattmeters, watt-hour meters, protection relays, etc. Figure 1.18 shows some of the most basic uses for instrument transformers.

Voltage transformers are most commonly used to lower the high line voltages down to typically 120 volts on the secondary to be connected to a voltmeter, watthour meter, or protection relay. Similarly, current transformers take a high current and reduce it to typically 5 amps on the secondary winding so that it can be used with a watthour meter, ammeter, or protection relay [20].

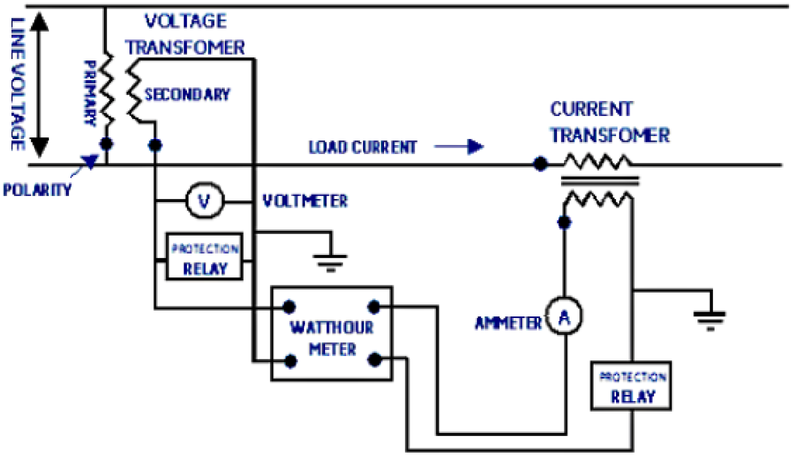


Figure 1.18: Common connection of instrument transformers [20].

1.7.2. Circuit Breaker:

A circuit breaker is one kind of electrical switch used to guard an electrical circuit against short circuit. The basic function of a circuit breaker is to stop the flow of current once a fault has occurred. Not like a fuse, a circuit breaker can be operated either automatically or manually to restart regular operation [21].

1.7.3. Fuse:

The first type of protection for electrical networks were fuses. It is an electrical device used to protect the circuit from overcurrent. It consists of a metal strip that liquefies when the flow of current through it is high. Fuses are essential electrical devices, and there are different types of fuses available in the market today based on specific voltage and current ratings, application, response time, and breaking capacity. A melted fuse will need to be manually replaced, and this is one of the drawbacks of using fuses for protection [22]. The characteristics of fuses like time and current are selected to give sufficient protection without unnecessary disruption. The Figure 1.19 represent the time-current characteristic for a fuse [16].

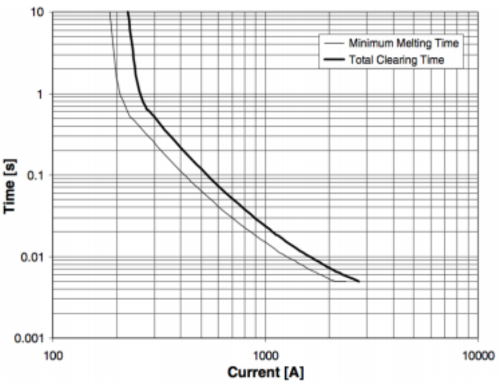


Figure 1.19: Time-Current Characteristics for a Fuse [23].

1.7.4. Auto Recloser:

It is a dielectric automatic circuit recloser (as circuit breaker) but it also can make to remote for cutting off power, it is easy to monitor and control. it is fixed each station along the network to protect the power network by circuit breakers or fused which will turn off power in the event of a short circuit, a tree branch blows off during a windstorm and lands on the line may cause a short circuit, it uses over load of power might cause to trip or earth fault that cause to power off. it can fix the adjustable time delays if the fault is appearing [24].

1.7.5. Sectionalizer:

A Sectionalizer is a device that automatically isolates faulted sections of a distribution circuit once an upstream breaker or Recloser has interrupted the fault current and is usually installed downstream of a Recloser. Since sectionalizes have no capacity to break fault current, they must be used with a backup device that has fault current breaking capacity.

Sectionalizer count the number of operations of the recloser during fault conditions. After a preselected number of recloser openings, and while the recloser is open, the Sectionalizer opens and isolates the faulty section of line. This permits the recloser to close and re-establish supplies to those areas free of faults. If the fault is temporary, the operating mechanism of the Sectionalizer is reset [25].

1.7.6. Relays:

Relays are the primary protection as well as switching devices in most of the control processes or equipments. All the relays respond to one or more electrical quantities like voltage or current such that they open or close the contacts or circuits. A relay is a switching device as it works to isolate or change the state of an electric circuit from one state to another. Classification or the types of relays depend on the function for which they are used. Some of the categories include protective, reclosing, regulating, auxiliary and monitoring relays [26].

1.8. Protection relay types:

Different relays have different characteristics that are used for different applications. In order to provide a complete and efficient protection for the power system from various types of fault and for various locations of faults, different type of relays with different characteristics are required. The available relay options are listed below.

1.8.1. Differential protection:

Differential relay protection is considered to be one of the most versatile protection techniques available today. The ANSI device number is 87. Differential relays operate when the phasor difference of two or more similar electrical quantities exceeds a predetermined value. A current differential relay operates when there exists a result of comparison between the magnitude and phase difference of the currents entering in and leaving out of the system to be protected. Under normal operating condition, the currents entering and leaving are equal in magnitude and phase so the relay is inoperative. But if a fault takes place in the system, these currents are no longer equal in magnitude a phase.

This type of relay is connected in such that the difference between the current entering and current leaving flows through the operating coil of the relay. Hence the relay coil is energized under fault condition due to the difference quantity of the current. Thus the relay operates and opens the circuit breaker so as to trip the circuit [16].

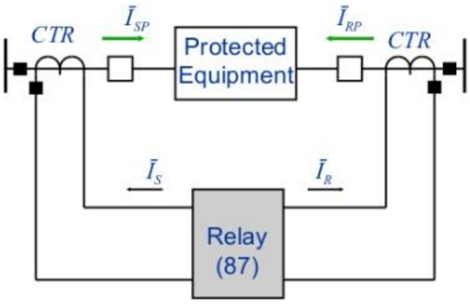


Figure 1.20: Differential protection operating principle [27].

1.8.2. Distance protection:

There is one type of relay which functions depending upon the distance of fault in the line. The ANSI device number is 21. More specifically, the relay operates depending upon the impedance between the point of fault and the point where relay is installed. The operation of such relay depends upon the predetermined value of voltage to current ratio. As the ratio of voltage to current is nothing but impedance so a distance relay is also known as impedance .The relay will only operate when this voltage to current ratio becomes less than its predetermined impedance (voltage/current) value .

Basically, the distance relay receives the measured voltage and current of the transmission lines from the Voltage Transformer (VT) and Current Transformer (CT) then calculates an impedance that can be represented in Equation (1.11) bellow, that is the result of secondary values [28].

$$Zsec = \frac{Iprim/Isec}{Vprim/Vsec} * Zprim \tag{1.11}$$

$Iprim/Isec$: CT transformation ratio

$Vprim/Vse$c: VT transformation ratio

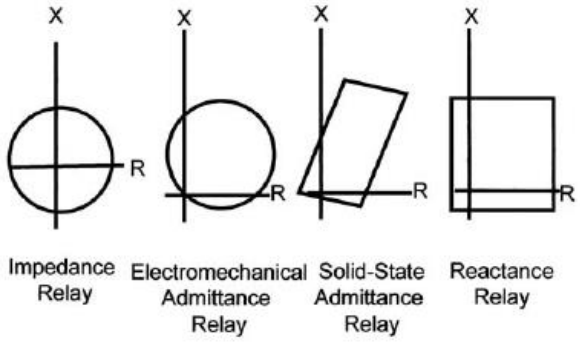


Figure 1.21: distance relay characteristics [29].

Distance relays may be set based in percentages of the line impedances, for example a typical setting for zone 1 is 80% of the impedance of the total line, the zone 2 is set at 120% of the impedance of the total line and Zone 3 sometimes is disabled or set to cover an adjacent line.

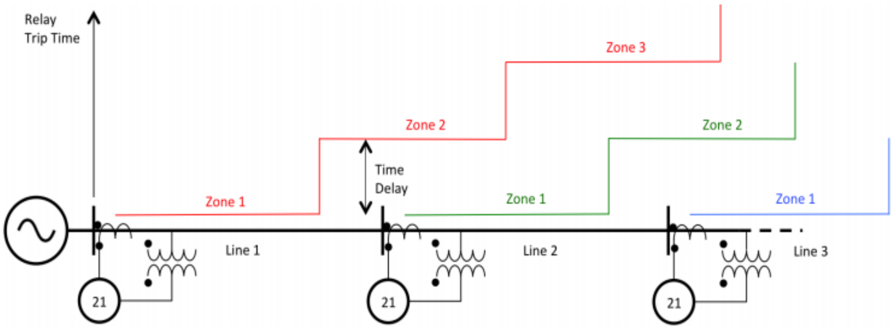


Figure 1.22: Distance Relay zones [16].

As the impedance of a transmission line is directly proportional to its length, it can easily be concluded that a distance relay can only operate if fault is occurred within a predetermined length of line [16]. There are mainly two types of distance relays: Definite distance relay and Time distance relay.

1.8.3. Overcurrent Protection:

The basic overcurrent protection device is an overcurrent relay, it gives protection against: Phase faults Earth faults and Winding faults that can be caused by overload or short-circuit faults. The aim of using an overcurrent relay is to isolate and protect equipments when the operating current exceeds a pre-set threshold current value. The ANSI device number for an instantaneous overcurrent (IOC) or a Definite Time overcurrent (DTOC) is 50 and for the Inverse Definite Minimum Time is 51.

The overcurrent relay operates by continuously measuring currents flowing in the power system using CTs. Normally, in a three-phase system, there are three CTs per location, one per phase. This supplies the relay with information about current in each phase, as well as the current flowing in the neutral (ground) [16].

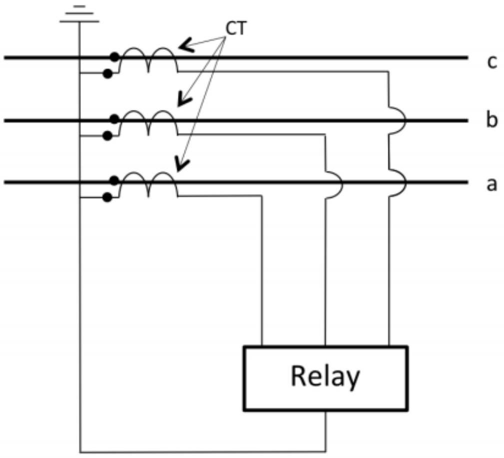


Figure 1.23: Connection of Current Transformers for Overcurrent Relay [16].

Overcurrent relays operate with inverse/definite time and instantaneous characteristics. The relays have a set pick-up current, Is, and when the current reaches and/or surpasses this value a timer starts. There are three types of operating characteristics of overcurrent relays:
Standard inverse, Very inverse and Extremely inverse.

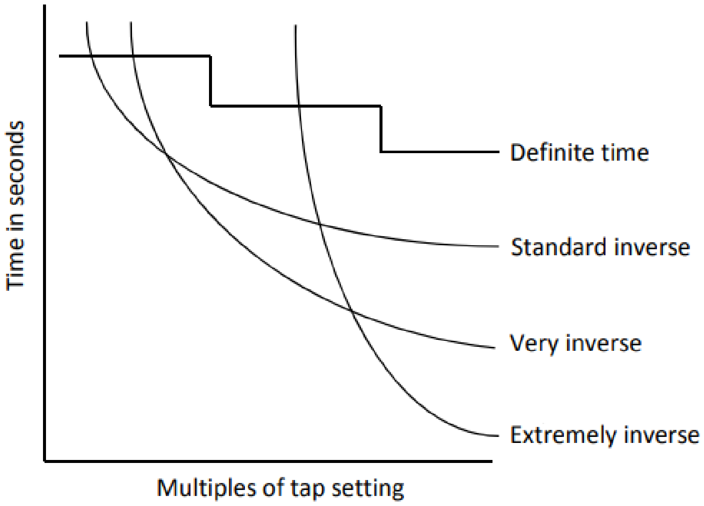


Figure 1.24: Definite time and inverse time characteristics of the overcurrent relay.

The characteristic equations for the aforementioned types of inverse-time overcurrent relays are defined as follows.

Standard inverse overcurrent relays:

$$t_{op} = \frac{0.14}{M^{0.02}-1} \times TM \tag{1.11}$$

Very inverse overcurrent relays:

$$t_{op} = \frac{13.5}{M-1} \times TM \tag{1.12}$$

Extremely inverse overcurrent relays:

$$t_{op} = \frac{80}{M^{2}-1} \times TM \tag{1.13}$$

Where: t_{OP} = operating time.

M = ratio of the input current to the pickup current.

TM = time multiplier or time dial setting.

1.8.4. Directional Overcurrent Protection:

Directional overcurrent relays with ANSI number code 67, respond to an excessive current flow in a particular direction in the power system. The relay typically consists of two elements, one is a directional element, which determines the direction of current flow with respect to a voltage reference and the second element is a standard over current relay [31].

The relay first determines whether the fault is located in front of or behind the relay. If the fault is located behind the relay, then no operation will take place. But if the fault is located in front of the relay, a comparison of fault magnitude and reference current will take place in order to make the decision whether to operate or not. Directional relays require two inputs, the operating current and a reference, or polarizing quantity (either voltage or current) that does not change with fault location.

Directional overcurrent relays are said to be used on incoming line circuit breakers on buses that have two or more sources. The aim of that is to trip an incoming line breaker for fault current flow back into the source, so that any fault on one source is not fed by the other sources [31].

1.9. Directional Overcurrent Protection Relays Types:

There are different types of directional overcurrent relays depending on their functions, according to reference [32], the main types can be named and described as the following:

1.9.1. Directional Phase Overcurrent ANSI 67P:

It is by definition a phase-to-phase short-circuit protection, with selective tripping according to fault current direction. It comprises a phase overcurrent function associated with direction detection, and picks up if the phase overcurrent function in the chosen direction (line or busbar) is activated for at least one of the 3 phases [32]. It is the type of directional overcurrent relay that this thesis will focus on studying and testing.

1.9.2. Neutral Directional Overcurrent ANSI 67N:

The Neutral Directional protection relay is used for diverse applications like main protection of aerial lines and cables, of transformers of distribution, motors among many others. It can be used either individually for control or alarm by energizing the auxiliary output relays. Usually it used as backup protection for power transformers and large generators and as emergency protection for distance protections and line differentials.

1.9.3. Ground Directional Overcurrent ANSI 67G:

A ground relay is a phase-to-ground faults protection device. It detects all phase-to-ground faults within its defined zone of protection that can be defined as a current threshold or measured impedance. The classical method for detecting ground faults on a looped system has been the measurement of the zero-sequence current but microprocessor-based relays now offer negative-sequence current elements as a means of detecting ground faults and determining fault direction. The measured earth fault current can be obtained following one of the two ways: Direct Ground Current Measuring or Residual Ground Current Measuring. Selection of Polarizing voltage is different for these two types of earth faults.

All the types of directional over current relay are mentioned in the Table 1.2 shown below with their corresponding ANSI number code:

ANSI code	Description
67	Ac Directional Overcurrent Relay
67G	Ground Directional Overcurrent
67N	Neutral Directional Overcurrent
67P	Phase Directional Overcurrent
67SG	Sensitive Ground Directional Overcurrent
67Ns	Earth fault directional
67Q	Negative Sequence Directional Overcurrent

Table 1.2: ANSI Standard Device Numbers & Common Acronyms [33].

1.10. conclusion:

In this chapter, essential background knowledge was treated and presented in order to illustrate the role and the importance of an efficient power system protection for electrical networks.

The chapter further treated different types of faults, mostly short circuited ones which are classified into symmetrical faults (three phase short circuit) and asymmetrical faults (phase-to-phase and phase-to-ground short circuit). To assure the continuity of the power flow towards the load under any circumstances, a reliable, selective and sensitive protection system with a fast response is required. Reviews on essential protective devices in the protection system have been presented starting from basic elements like fuses and ending with relays. There are different types of relays depending on its main function like distance relay, overcurrent relay and directional overcurrent relay which will be the main focus of this thesis. Directional over current relay are widely used in distribution side of the electrical network protection, thus, making the study of its relaying concept as well as the testing and setting parameters for this protection device is so important to avoid its malfunctioning.

CHAPTER 2

STUDY OF DIRECTIONAL PHASE OVERCURRENT PROTRCTION RELAY

2.1. Introduction:

Directional overcurrent protection is used as a backup protection when it is necessary to protect the system against fault currents that could circulate in both directions through a system element, and when bidirectional overcurrent protection could produce unnecessary disconnection of circuits. This can happen in ring or mesh type distribution network and in systems with a multiple of infeed points. Three conditions must be satisfied for its operation: current magnitude, time delay and directionality. The directionality of current flow can be identified using voltage as a reference of direction. Directional Phase overcurrent relaying (67P) refers to relay that can use the phase relationship of voltage and current to determine the direction to a fault, and this is done by following a variety of concepts. Electromechanical and early microprocessor-based relays were less sensitive and could not easily respond to system changes. Newer numerical relays are more sensitive and flexible. This chapter will focus on studying the mainstream method followed by numerical directional phase overcurrent relay that uses the phase relationship to sense fault direction.

2.2. Directional Phase Overcurrent Working Principle:

2.2.1. Directional Relaying Concept:

The directional relay is a two input quantities protection device that receives line current from the line (CT) secondary current and bus voltage from the bus potential transformer (PT). The relay first determines whether the fault is located in front of or behind the relay. If the fault is located behind the relay, then no operation will take place. But if the fault is located in front of the relay, a comparison of fault magnitude and reference current will take place in order to make the decision whether to operate or not [34]. Directional phase overcurrent protection is activated if the following two conditions are satisfied:

- The fault current is higher than the setting threshold.
- The current phase in relation to the polarizing voltage lies within the tripping zone.

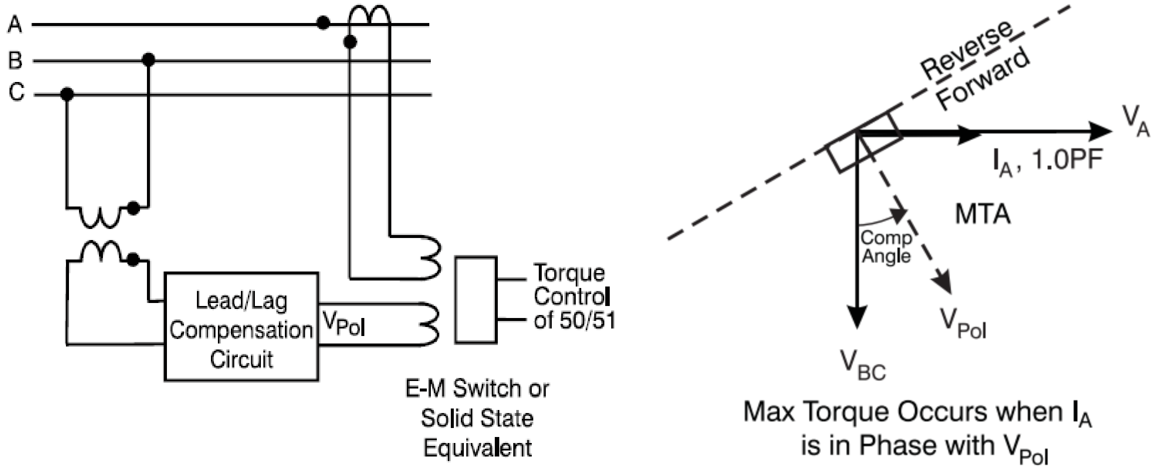


Figure 2.1: Quadrature Directional Element [35].

The directional elements of classic electromechanical relays, solid state relays and numeric relays which we will focus on, respond to the phase shift between a polarizing quantity (current or voltage) and an operating quantity. The basic directional element principle can be explained in Figure 2.2**.** The faulted phase voltage, V, is the polarizing quantity also known as the reference quantity (abbreviated as V_{pol}), and the faulted phase current, I, is the operating quantity. Because lines are highly inductive, I lags V by the fault loop impedance angle, φ_F, for forward line fault. If the fault is in the reverse direction, the faulted phase current I, will be leading V, by approximately 180 degrees minus the fault loop impedance angle, φ_R [36].

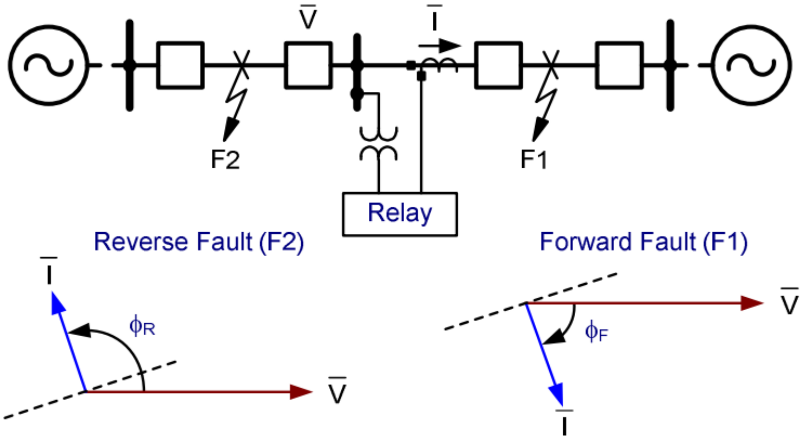


Figure 2.2: Basic directional element principle [36].

The polarizing quantity which can be a voltage or a current signal needs to be stable and reliable, no matter where the fault is located. The relay uses a phase-to-phase voltage as the polarisation variable [37]. The phase-to-neutral voltage is not used because it varies greatly when a fault occurs to earth, due to the displacement effect of the neutral point. Thus for a phase-to-ground fault, the voltage of the faulted phase can collapse to 0, and the current I of this last will be highly lagging, this prevent the relay from making a correct directional decision. To resolve the low voltage issue, quadrature parameters (i.e., V_{BC} vs. I_A) are commonly used. In this case, the protection equipment's angle of connection is said to be 90° [35].

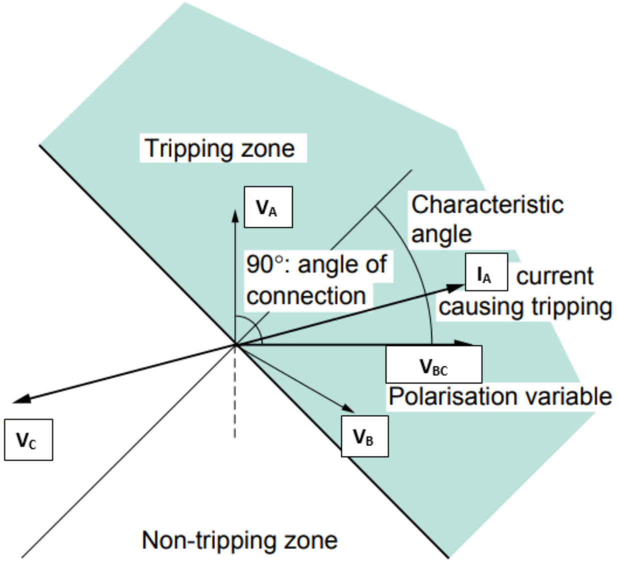


Figure 2.3: A relay measuring the current I_A and the voltage V_{BC} has a 90° relay connection [38].

2.2.2. Angle of Connection:

By definition Angle of connection is the angle by which the current applied to the relay (at unity power factor) is displaced from the voltage applied to the relay (the polarising voltage) [39]. It describes the phase relation (30°, 60°, 90°) of the current-coil (CC) and the polarizing voltage under balanced unity power factor as shown in Figure 2.3. Relay connections must be made so that the relay achieves a positive and sufficiently a maximum operating torque under all types of faults [34]. In a digital or numerical protection relay, the phase displacements are determined by software, while electromechanical and static protection relays typically get the needed phase displacements by connecting the input signals to the protection relay. The history of the topic ends in the protection relay connections being specified as if they were received by appropriate connection of the input signals, irrespective of the actual process used [40]. The three most commonly used connections are illustrated in Table 2.1 and Table 2.2.

Types of connections	Fault involving phase A		Fault involving phase B		Fault involving phase C	
	Current	Voltage	Current	Voltage	Current	Voltage
30°	I_A	V_{AC}	I_B	V_{BA}	I_C	V_{CB}
60°	$I_A - I_C$	V_{AC}	$I_B - I_C$	V_{BA}	$I_C - I_A$	V_{CB}
90°	I_A	V_{BC}	I_B	V_{CA}	I_C	V_{AC}

Table 2.1: Quantities fed to phase element of directional relay [34].

The connection angle can be set to 30°, 60°, and 90° by suitable connection of CTs and PTs in the relaying circuit. Connections of 30° offer a negative torque and maloperation of the directional relaying scheme for certain types of faults. Connections of 60° produce low torque for certain types of faults. Hence, 30° and 60° connections are not widely used for directional relaying scheme. In 90° connections, the polarizing voltage is fed to phase element in such way that it produces maximum torque [34] .

If we just consider the directional overcurrent element of phase A, with:

- The phasor reference V_{an} at zero degrees in the 12 o'clock position.
- Unity Power Factor.

We get the following three connections shown in the table 2.2:

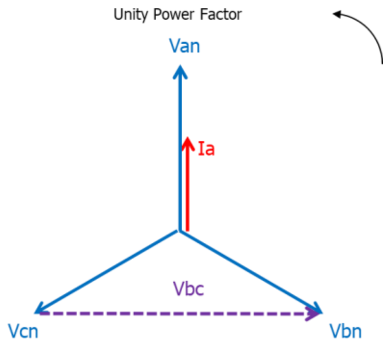
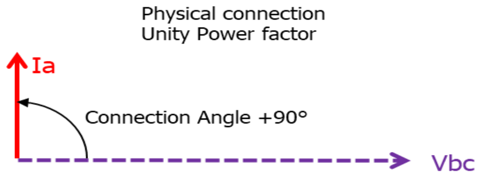
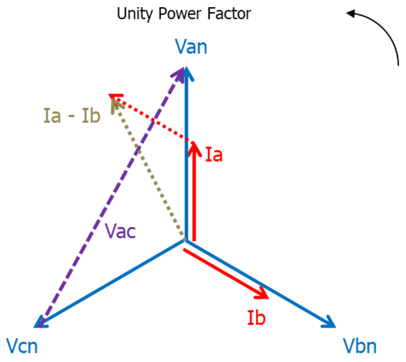
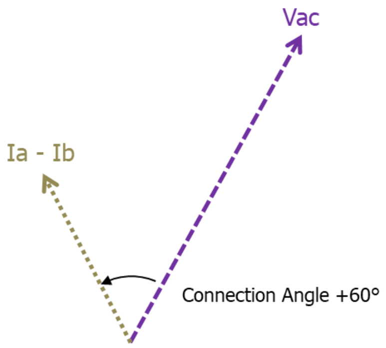
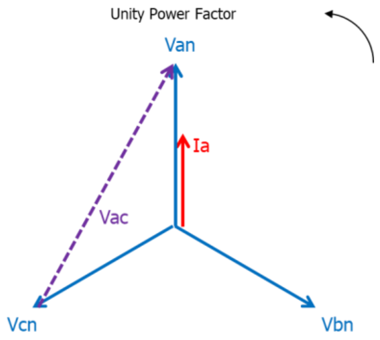
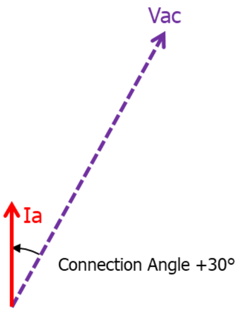
Type	System Phasors	Connected Phasors
90° or Quadrature		
60°		
30°		

Table 2.2: Different phase connections of phase directional relay for phase A [40].

2.2.3. Maximum Torque Angle (MTA):

When the current and voltage supplied to the Current Coil (CC) and the Voltage Coil (VC) of the directional phase overcurrent relay from the line and the bus respectively, a maximum positive torque is produced [34]. Hence the angle made by fault current with respect to its phase voltage is defined as the Maximum Torque Angle (MTA) as shown in Figure 2.4.

The MTA is used to calculate Characteristic angle and identify center of the tripping zone. However, there is no setting for maximum torque angle in numerical relays, instead we deal with Relay Characteristic Angle (RCA) [41].

$$\textit{MTA} = \textit{RCA} - 90^{o}\ [\textit{Angle of Quadrature}] \tag{2.1}$$

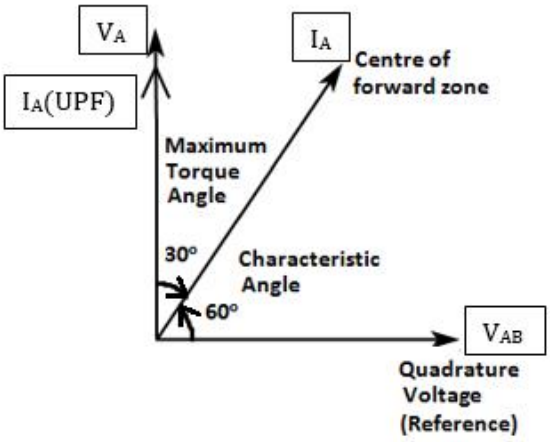


Figure 2.4: Characteristic Angle Setting for Fault at Phase A.

2.2.4. Relay Characteristic Angle (RCA):

The characteristic angle is the phase angle by which the reference or the polarization variable (generally the voltage) is displaced to ensures a maximum sensitivity operation wherever the faults are located. It is always adjusted in the middle of the operating zone [42]. Also known as Directional Angle as it decides the tripping zone direction of the relay. In order to be able to measure the fault direction, the polarization voltage must have a sufficiently high value. This RCA which varies within the range of (-95° to +95°) is generally set to 45° [38].

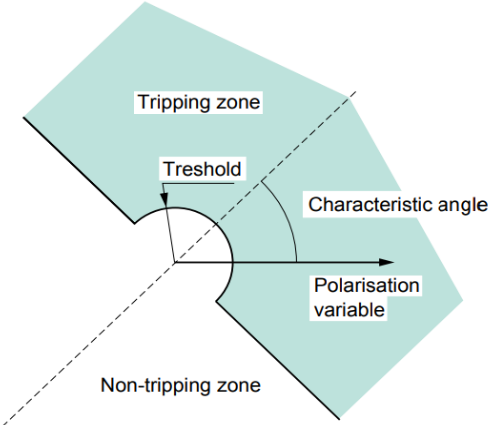


Figure 2.5: Operating characteristics of directional overcurrent protection equipment [38].

The tripping zone for faults on phase A includes the ranges of phase angle values for a phase-to-ground fault, phase-to-phase faults (between phases A-B and A-C). These three cases are treated separately below to ease understanding [37]. The circuit impedance considered is of resistive-inductive nature. We consider a three phase balanced electrical system of order (ABC).

When a phase-to-ground fault occurs on phase A, the range of phase angle values of the faulted current I_A that is expected is illustrated in Figure 2.6.

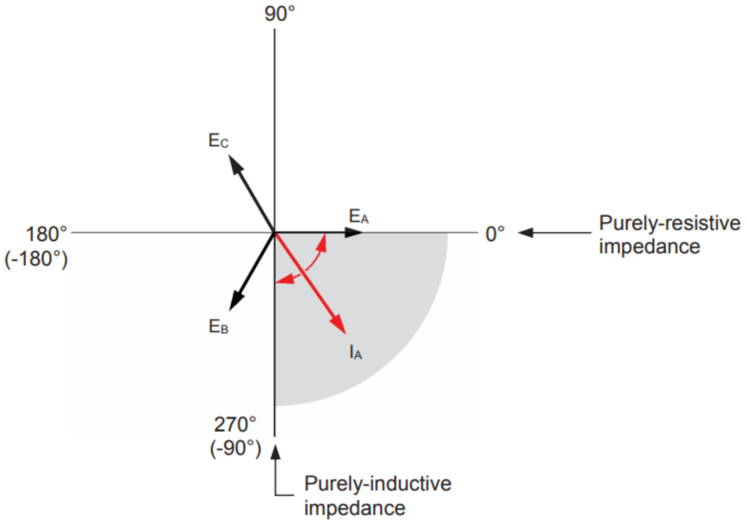


Figure 2.6: Range of phase angle values of faulted current I_A expected for a phase-to-ground fault on phase A [37].

When a phase-to-phase fault occurs between phases A-B and between phases A-C, the ranges of phase angle values of faulted current I_A are shown in Figure 2.7.

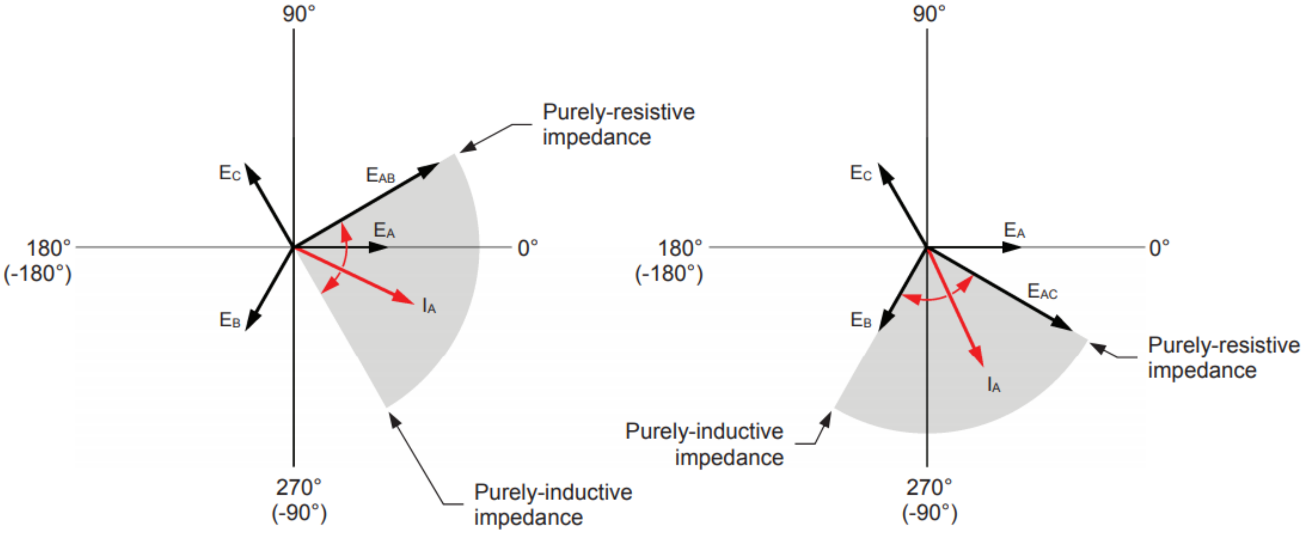


Figure 2.7: Ranges of phase angle values of faulted current I_A expected for phase-to-phase faults between phases A-B (left) and between phases A-C (right) [37].

The superposition of the ranges of phase angle values of the faulted current I_A involved in Figure 2.6 and Figure 2.7 is represented in Figure 2.8. The total range covers 150°. Similarly, the total range of phase angle values of the current is also 150° for faults on phase B or phase C.

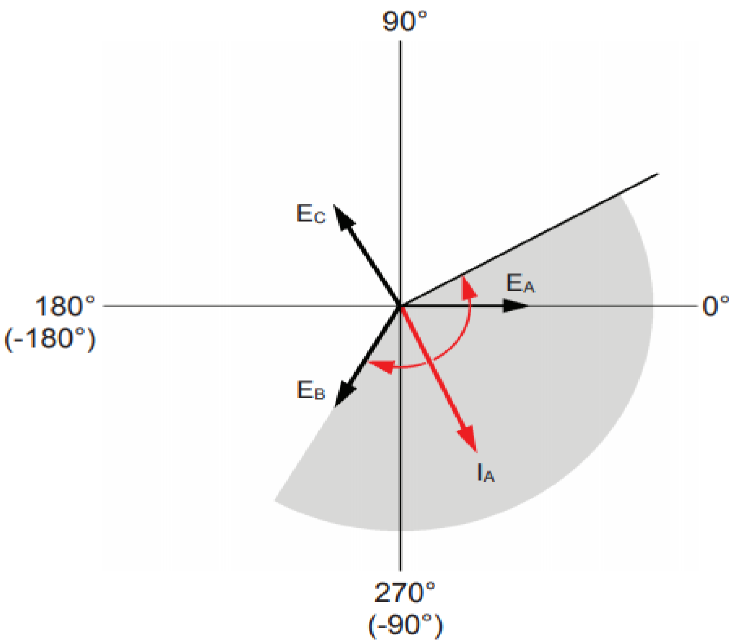


Figure 2.8: Range of phase angle values of current IA expected for faults on phase A [37].

Setting RCA to 45° properly aligns the forward and reverse direction zones of the directional overcurrent relay with the vectors of fault current expected for phase A, as illustrated in Figure 2.9. Notice that the forward direction zone must enclose every expected vector of fault current for phase A with a safety margin on each side of the expected range of phase angle values of current. The tripping zone set for the directional overcurrent relay must be equal or greater than 150°, with a safety margin equal or less than 15° depending on the relay's manufacturer. These settings ensure an optimal operation of the directional overcurrent relay.

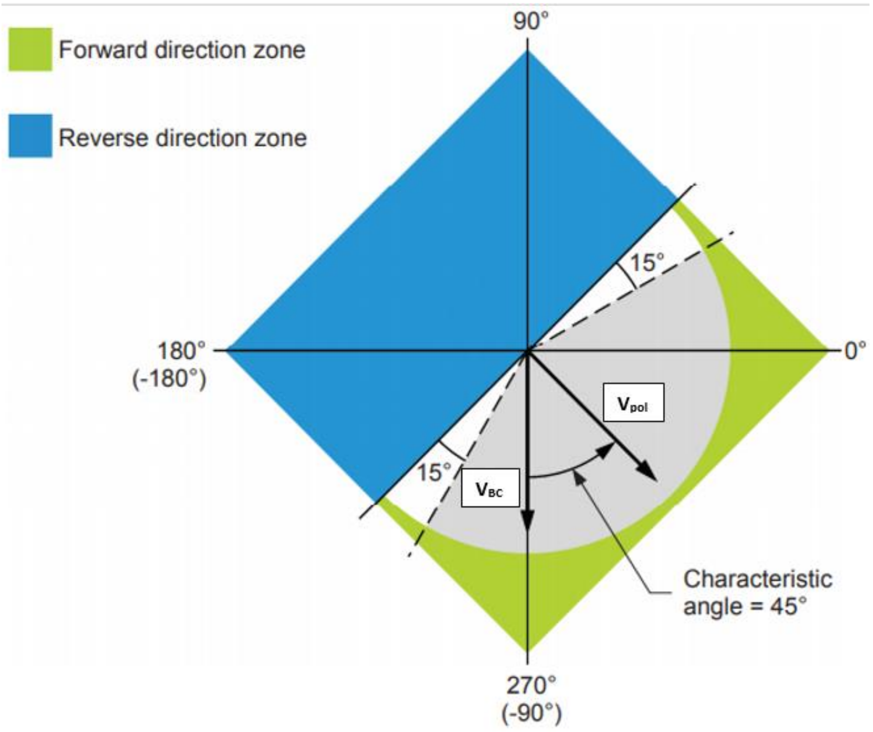


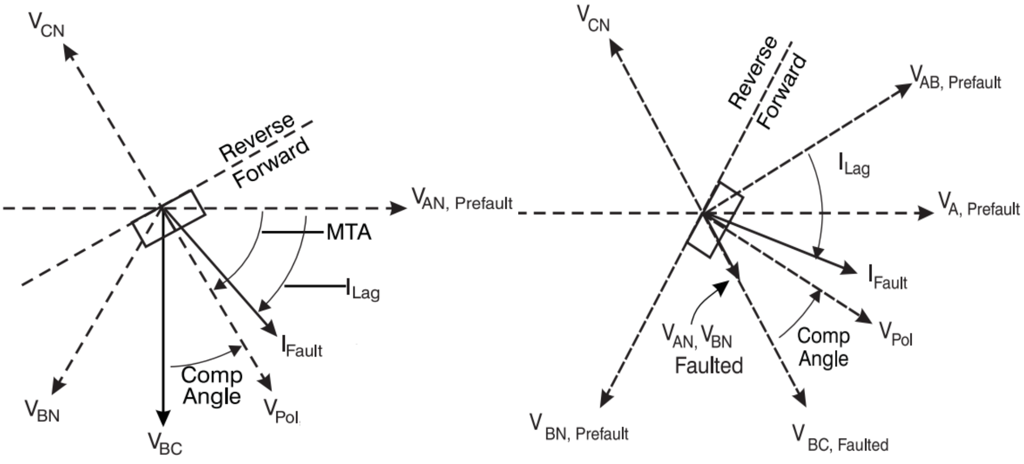
Figure 2.9: Setting the characteristic angle to 45° [37].

The setting values 30° and 60°correspond to the following applications [43]:

- RCA= 30° may be suitable for cables with large cross-sections.
- RCA= 45° may be suitable for all cases.
- RCA = 60° may be suitable for cables with small cross-sections.

2.2.5. Directional overcurrent protection response to balanced and unbalanced fault systems in case of quadratic connection:

Any of the three possible connection arrangements known (30°, 60°,90°) assures obtaining the maximum torque at a given angle for balanced three-phase short circuits. But the choice of connections for obtaining the correct directional decision for unbalanced short circuits (i.e. phase-to-phase, phase-to-ground, and two-phase-to-ground) is restricted to the 90° connection. The quadrature connection (90°) assures the independence of the voltage signals from the effects of any phase-to-ground and phase-to-phase fault. The response to a phase to ground fault is fairly apparent because the quadrature voltages are assumed to be relatively unaffected by the faulted phase currents [35]. However, for a phase to phase fault, the quadrature voltages are affected. We should study the diagram in Figure 2.10 to develop an understanding [35].



a) Phase to ground fault. b) Phase to phase fault.

Figure 2.10: Phasors in Classical Quadrature Directional Elements [35].

Basically, in the phase-to-phase fault, relative to phase-ground fault, note that both V_{BC} and faulted phase A current I_{Fault} have been shifted by 30°, so there is no net change in tendency of the element to operate when quadrature voltage is used, then V_{pol} is somewhat independent of the fault current, especially for a phase to ground fault. The angle by which current lags quadrature voltage is a factor of both source impedance as well as forward-looking line impedance, so a compromise value is utilized. An MTA in the range of 30° to 75° is common [35].

2.3. Directional Over Current Relay (67) Characteristics and settings:

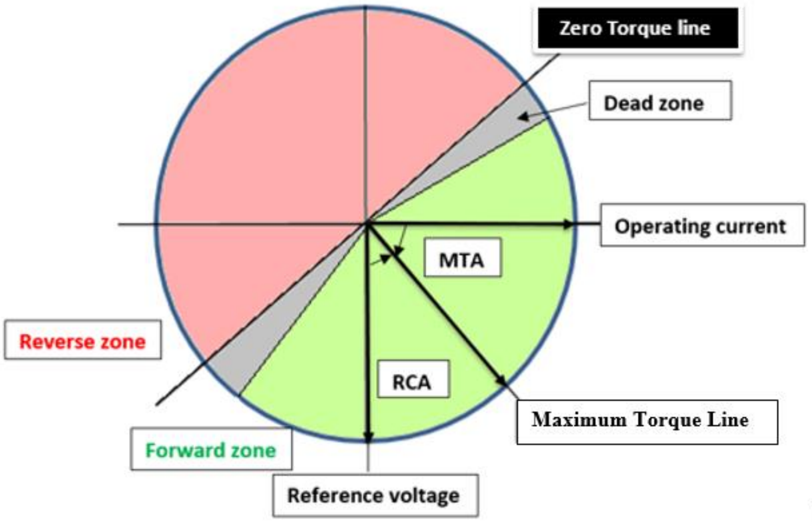


Figure 2.11: Directional overcurrent characteristics.

- **Reference Voltage:** Directional overcurrent relays needs a reference voltage to identify the direction of currents. This is the voltage taken from potential transformers and is called polarizing voltage. The relay operates for the defined direction when the fault current is in the same direction and exceeds the over current setting value [44].
- **Relay Characteristic Angle (RCA):** It is the phase displacement from the reference voltage vector to maximum torque line (polarizing voltage). It is limited to a range depending on the manufacturer. For example; ABB REL670 relay has an RCA limited between 40° and 65°, whereas the SIEMENS 7SA87 relay has a setting range from −180° to 180° [44]. ***RCA= 90º [Angle of Quadrature] + MTA*** (2.2)
- **Maximum Torque Angle (MTA): It is the angle shift from the operating current at (UPF)** to the maximum torque line. The usual characteristic angle values are 30°, 45° and 60° but generally set to 45° [44].
- **Center of Zone or Maximum Torque Line:** It is the line formed by RCA where the relay exhibits maximum sensitivity. At this line relay current is in phase with the reference or polarizing voltage [44].

$$Max\ Torque\ Line = Reference\ Voltage\ \angle RCA \qquad (2.3)$$

- **Zero Torque Line: It** is the boundary line which separates the plane into operating and non-operating regions.

- **Forward Zone:** Forward zone is +/- Relay Operating Angle (ROA) either side of the maximum torque line or center of forward zone line [44].
- **Relay Operating Angle:** It is the angle between the maximum torque line and one of the operating region boundaries.

$$ROA = Total\ Operating\ Zone\ angle/2 \quad (2.4)$$

- **Reverse Zone:** Reverse operate zone is the mirror image of the forward zone with respect to the zero torque line.
- **Dead Zone:** It is the zone between boundaries of the operating region and the zero torque line. In case the electrical fault is near the bus, the voltage available on PT secondary that depends on the location of the fault on line from the relaying point is not enough to produce an operating torque in directional relay. The minimum fault distance from the relay point for which the relay fails to operate is known as dead zone [34]. In numerical relays it is found to be a very small region compared to the electromechanical relays.

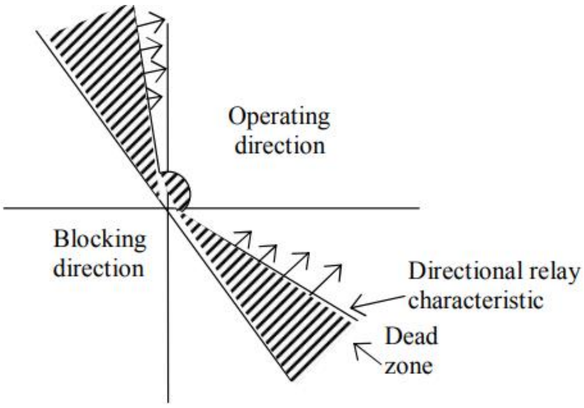


Figure 2.12: Directional relay characteristic [34].

- **Current threshold**: It is the minimum current for which the directional overcurrent relay may trip.
- **Time delay:** This is the operating time of the relay when a definite-time overcurrent relay (ANSI 51DT) is used in the directional overcurrent relay.

2.4. Application and importance of Directional Overcurrent Relays:

Directional phase protection element is complementary to overcurrent protection element, to enable a better discrimination of the faulty network section and assure the continuity of the power flow towards the loads. It is used in the following cases [38]:

- In systems with radial distribution.

- In a system with several sources.
- In closed loop or parallel-cabled systems (it should be put on each line).
- In isolated neutral systems for the feedback of capacitive currents.
- To detect an abnormal direction of flow of active or reactive power (generators).

Importance of directional phase overcurrent relay: assure selectivity when any type of fault occurs in the power network.

Figure 2.13 shows a parallel-cabled system of two feeders with a protection system consisting of overcurrent relays (ANSI 51), circuit breakers and a directional overcurrent relay (ANSI 67) at the source end of each line [37].

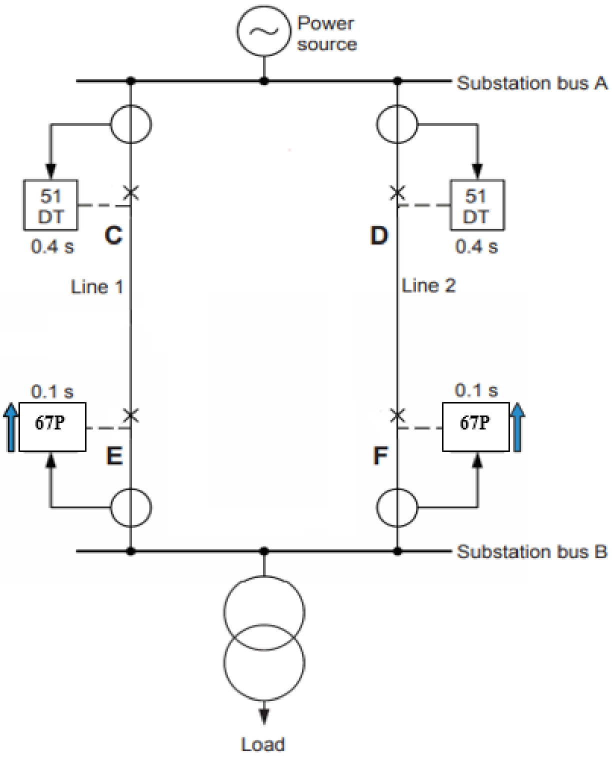


Figure 2.13: Parallel-cabled system with two feeders [37].

2.4.1. Application of Directional Phase Overcurrent Relay in Parallel Lines:

The use of lines in parallel is common in power networks, because it allows more power to be conveyed to a given location. Directional phase overcurrent relay is the best protection device for this type of distribution to disconnect the minimum amount of circuit and isolate any type of fault in case it happens.

To ease understanding the application of directional phase overcurrent relay in protecting parallel lines an example is proposed, which consist of a comparative study between protection system using only overcurrent relays (ANSI 51) and a protection system using directional phase overcurrent relay (ANSI 67) [37].

2.4.1.1. Protection of parallel power lines using overcurrent relays:

When a fault occurs on line 1, fault current I_{F1} flows through line 1, and fault current I_{F2} also flows through line 1 in the opposite direction after passing through line 2. This will cause both overcurrent relays (ANSI 51) to trip after 0.3s, thus opening both circuit breakers C and D, in other words, both the faulted line and the healthy line are opened. As a result, power is no longer available at substation bus B. Using overcurrent protection alone to protect power lines connected in parallel works, but is not discriminative.

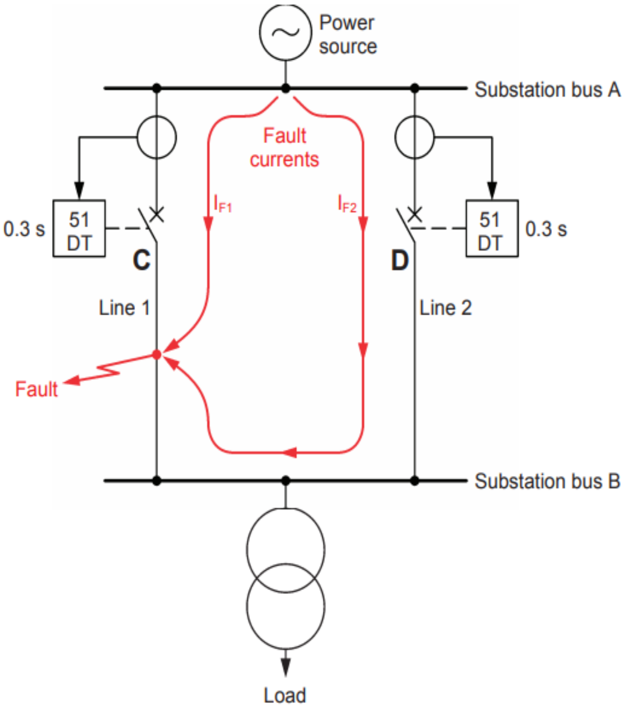


Figure 2.14: Protection of two parallel lines using overcurrent relays [37].

2.4.1.2. Directional overcurrent protection:

Because the fault current I_{F2} flows in the same direction as the direction set in the relay, the directional overcurrent relay at location E trips and opens the corresponding circuit breaker after 0.1s the fault occurred, thus I_{F2} is interrupted. Unfortunately, Fault current I_{F1} still flows through line 1 after the circuit breaker at location E opened. On an other hand, the directional overcurrent relay at location F does not trip, because fault current I_{F2} flows in the direction opposite to the direction set in the relay. However, the overcurrent relay at location C trips and opens the corresponding circuit breaker 0.4s after the fault occurred, thereby interrupting fault current I_{F1}.

As a result, the protection isolated the fault while achieving proper discrimination means that the faulty line (line 1) has been disconnected and the healthy line (line 2) has been left in service.

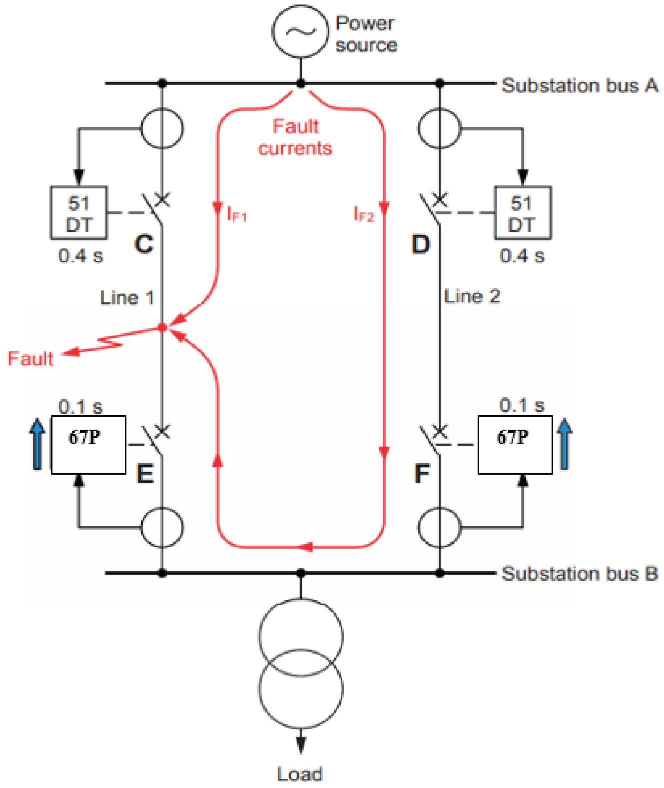


Figure 2.15: Protection of two parallel lines using directional phase overcurrent relays [37].

To achieve a proper fault discrimination, relay coordination using time grading is applied. Setting the overcurrent relay D time delay to 0.4s allows the directional overcurrent relay at location E to trip first when a fault occurs on line 1. This ensures the service continuity of line 2 when a fault occurs on line 1 [37].

2.5. Subtleties involved in the forward/reverse direction decision making:

There is a number of subtleties involved in the direction decision making, one should refer to the various relay manufacturers' instruction manuals. Some characteristics that can vary by manufacturer needs to be understood to avoid having unwanted results concerning the relay's response to any type of fault.

2.5.1. Memory Polarisation:

When a three phase (or close to) fault occur, the voltage at the relay may fall to near 0 which will directly affect the relay's 67 logic upon making a correct directional decision, and in some relay configurations, if the relay fails to determine the fault's direction, it does not trip at all, leading to heavy consequences. The creation a memory polarization scheme is the solution provided by numerical relay's manufacturer to avoid this problem from happening. The use of the memory polarisation scheme can be explained as the following: The relay constantly is reading the present voltage and using it to create a voltage vector (V1), if a fault occurs that suddenly drives voltage too low to be used for directional analysis, the relay reaches back to its memory and projects the past voltage vector into the present. The V1 voltage vector change very slowly in the normal power system, so a past V1 voltage vector is a good indication of the voltage vector that would exist if a fault had not occurred, and it is a reliable backup for directional analysis [35].

2.5.2. Close in to Fault Logic:

The Close in to Fault logic, is an alternate solution in case the polarization scheme fails to work. The Close in to Fault logic monitors for a breaker close and enables a high set three phase non-directional overcurrent sensing circuit for a short period of time [35].

2.5.3. Minimum Sensitivity:

The minimum current and voltage quantity limitations that are sufficient for a relay to make a correct directional decision is set by the manufacturer. The response of the relay to low voltage or current varies, but typically, the relay will default to a “neither forward nor reverse” status. In this case, there must be settings to define minimum quantities the relay needs to see and settings for how the relay responds when values are below the minimum [35].

2.5.4. Positive vs. Negative Torque Angles:

Each manufacturer has its own way of presenting certain data, for example some manufacturers interpret negative angles as forward and positive angles as reverse. In this case, a “-1” factor is entered into the relay’s impedance angle calculations [35].

2.5.5. Superimposed Components:

When heavy load flow occurs at the same time as a low level fault, the relay may face difficulties to separate out load flow currents from fault currents which can confuse the directional element. In this situation some manufacturers have implemented a scheme referred to as superimposed components. It is similar in application to memory polarization but involves both current and voltage from the past into the present, rather than just the voltage in order to separate the fault current from the overriding load current and, hence, improve the decision about where the fault is located [35].

2.6. Conclusion:

This chapter treated so far the operation principle of a directional phase overcurrent relay, including its main characteristics and settings that must be made to assure an effective directional decisions making for all types of faults. The main settings for directional phase overcurrent relay are: relay operating angle to define the tripping region, direction of current flow (forward or reverse), the current threshold, time delay only when a definite-time overcurrent relay is used and the relay characteristic angle which is generally set at 45° to ensure an optimal detection of the direction of current flow. The parallel power line configuration is widely used in modern power network because it allows more power to be conveyed to the consumer/load at any location.

The best protection used for this type of configuration network is the directional phase overcurrent relay since it achieves a proper fault discrimination in case any type of fault occurs and assures a continuous power flow towards the loads.

There are many factors that may affect the directional decision making. The main factor refers to various relay manufacturers' and their different relays' algorithms that we should take into consideration for a correct performance.

CHAPTER 3

TESTING of DIRECTIONAL PHASE OVERCURRENT PROTECTION RELAY AND RESULTS

3.1. Introduction:

Tests are performed in different ways and as relays evolved the testing technology have become more developed to lead to more accurate results. To minimize the failures of protection devices, it should be tested and maintained in a periodic way.

As nowadays manufacturers do not provide enough information to engineers about testing details of their relays and with the lack of resources it is essential to have a simple guide that helps in testing the fundamental directional phase overcurrent protection.

In this chapter, different testing types have been defined from type test to trouble shouting test, modern testing method and testing principles then the testing method of the directional phase overcurrent protection function of the line distance protection ABB REL670 IED numerical relay has been shown with a detailed results and discussion considering different RCA settings.

3.2. Testing Types:

The testing and verification process of protection devices introduces a number of issues. This happens because the main function of protection devices is related to the operation under fault conditions. Hence, these devices cannot be tested under normal operating conditions. This problem is worsened by the growing complexity of protection relay application with extensive software functionalities and the frequent use of Ethernet peer-to-peer logic. The testing and verification of relay protection devices can be divided into six groups [46]:

3.2.1. Type Tests:

Type tests are needed to prove that a protection relay meets the claimed specification and follows all relevant standards. Since the basic function of a protection relay is to correctly function under abnormal power conditions, it is crucial that the operation is evaluated under such conditions. Therefore, complex type tests simulating the working conditions are completed at the manufacturer's facilities during equipment development and certification. The standards that cover majority of relay performance aspects are IEC 60255 and IEEE C37.90. Nevertheless, compliance may also include consideration of the demands of IEC 61000, IEC 60068 and IEC 60529. Since type testing of a digital or numerical protection relay includes software and hardware testing, the type testing procedure is very complex and more challenging than a static or electromechanical relay [46].

3.2.2. Routine Factory Production Tests:

These tests are done to show that protection relays are free from defects during manufacturing process. Testing will be done at several stages during manufacture, to make sure problems are discovered at the earliest possible time and therefore minimize remedial work. The testing extent will be impacted by the relay complexity and past manufacturing experience [45].

3.2.3. Commissioning Test:

Commissioning tests are done to show that a particular protection configuration has been correctly used prior to setting to work. All aspects of the configuration are rigorously verified, from installation of the correct equipment through wiring verifications and operation checks of the equipment individual items, finishing with testing of the complete configuration [46].

3.2.4. Periodic Maintenance Tests:

These are needed to discover equipment failures and service degradation, so that corrective action can be taken. Because a protection configuration only works under fault conditions, defects may not be discovered for a substantial period of time, until a fault happens. Regular testing assists in discovering faults that would otherwise stay undetected until a fault happens [46].

3.2.5. Acceptance Testing:

This is a bench test performed either by the manufacturer or end-user to check the acceptability of the unit for sale or purchase [47].

3.2.6. Troubleshooting:

This kind of test comes into effect after a power system disturbance had occurred and relay acted in an unanticipated way. Assuming the responsible relay is known, the following information need to be evaluated [47]:

- Exact time at which relay created the disturbance & cleared it.
- Fundamental frequencies of currents and voltages during above times.
- Occurrences of relay trip signal, breaker opening, send/receive transfer signals etc.

Thereafter the data can be manipulated using an expert system to find the causes. For example, relay operation was slower, such as pick up was more than 4 cycles (set value).

3.3. Computer Aided Relay Testing Method:

Instead of testing a relay function manually a computer program is used. There are many reasons why the testers have changed from manual testing to automated [47], such as:

- Many modern microprocessor relays can’t be tested with slow speed of amplifier injection.
- Due to lack of speed, the relay will have to be in heat for a longer duration, results more stresses.
- Since the type of tests, test procedure, frequency etc. are decided by the computer, testing engineers are not required to be expert.
- Test report format is available

Computer aided test can be classified into two kinds:

- **Model specific:** This kind of program is used to check a particular type of relay. It actually checks all the functions of the particular relay produced by a certain manufacturer. The test’s results can be stored to find the trends.
- **Application specific**: This is a kind of program used to check the primary side of CT, i.e. the actual circuit relay is protecting the system around it. No focus is given to relay and its functions. The main drawbacks of automation of testing are lack of flexibility and high cost [47].

3.4. Testing Principles:

There are two main testing principles, which are primary injection and secondary injection.

3.4.1. Primary Injection:

High current is injected to primary side of the CT. Test carried out covers CT, conductors, relay and sometimes circuit breaker as well. The relay unit has to be isolated from the power system. Usually this principle is used at commissioning and also if the secondary of the CT is not accessible [48].

3.4.2. Secondary Injection:

Relay is disconnected from the CT and the stepped down current is directly injected to relay. Therefore, no need the primary side of the CT to be disconnected from the rest of the system [48].

3.5. Testing of the Directional Phase overcurrent function in the REL 670:

3.5.1. Equipment:

- CMC 256plus, Universal relay test set and commissioning tool (OMICRON).
- The Four Step Directional Phase Overcurrent Protection Function of the Line Distance Protection Relay REL670 relay (ABB).
- Leads, cables and Ethernet cable.

➢ **CMC 256plus, Universal relay test set and commissioning tool:**

The CMC 256plus is the first choice for applications requiring very high accuracy. This unit is not only an excellent test set for protection devices of all kinds but also a universal calibration tool. Its high precision allows the calibration of a wide range of measuring devices, including: energy meters of class 0.2S, measuring transducers, power quality measurement devices and phasor measurement units (PMU). Its unique accuracy and flexibility make the CMC 256plus ideal for protection and measurement equipment manufacturers for research and development, production and type testing [49].

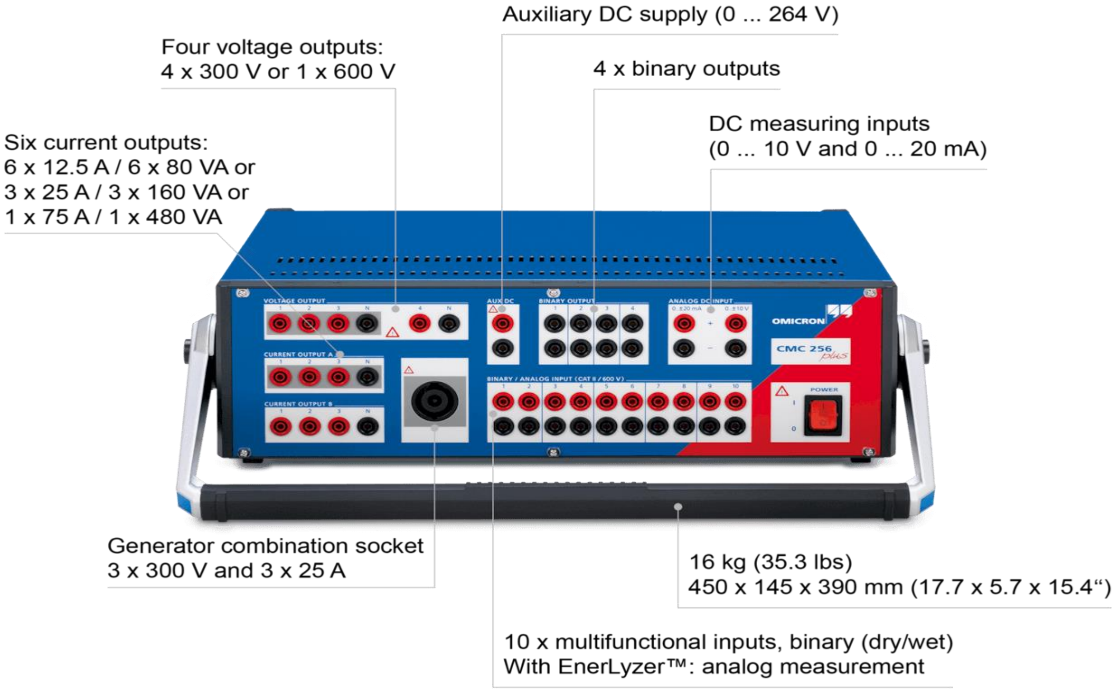


Figure 3.1: OMICRON CMC 256plus Electrical Testing Equipment [47].

- **Line Distance Protection Relay ABB REL670 IED relay:**

REL670 IED (Intelligent Electronic Device) is a numerical line distance relay used for the protection, control and monitoring of overhead lines with maximum flexibility, high sensitivity and low requirement on remote end communication. The IED can be used up to the high voltage levels. It is suitable for the protection of heavily loaded lines and multi-terminal lines where the requirement for tripping is one- and/or three-pole. It provides various functions that can be used simultaneously and independently (or dependently if wanted). We can find the following main functions: High set instantaneous phase and ground overcurrent, Distance Phase and Ground fault protection and the main function that we will be heavily focused on, the Four Step Directional or Non-Directional Phase and Ground Overcurrent [50].

- **The Four Step Directional Phase Overcurrent Protection Function of REL670 relay:**

The four step phase overcurrent protection function OC4PTOC has an inverse or definite time delay independent for step 1 and 4 separately. Step 2 and 3 are always definite time delayed. All IEC and ANSI inverse time characteristics are available together with an optional user defined time characteristic. The directional function is voltage polarized with memory. The function can be set to be directional or non-directional independently for each of the steps. Second harmonic blocking level can be set for the function and can be used to block each step individually [50].

Figure 3.2: The REL670 relay, ABB [50].

The following table represents the main characteristics of the directional overcurrent function ANSI 51-67 of this relay:

Function	Setting range	Accuracy
Operate current	(1-2500)% of Ibase	± 1.0% of In at I ≤ In ± 1.0% of I at I > In
Min. operating current	(1-100)% of Ibase	± 1.0% of In
Relay characteristic angle	(40.0–65.0) degrees	± 2.0 degrees
Maximum forward angle	(40.0–70.0) degrees	± 2.0 degrees
Minimum forward angle	(75.0–90.0) degrees	± 2.0 degrees
Independent time delay	(0.000-60.000) s	± 0.5% ± 10 ms
Minimum operate time	(0.000-60.000) s	± 0.5% ± 10 ms
Characteristics	19 curve types	--

Table 3.1: Characteristics of the four step phase overcurrent protection [50].

3.5.2. Software:

- ***Test Universe:***

This software is designed by Omicron to support the test set with different options based to test protective and measurement devices in power systems. It is the most powerful and convenient for its detailed various packages consisting on precise settings of faults and measurements. It offers a wide range of functions for manual and automated protection testing, with an excellent reliability in the functional assessment of protection relays and other secondary measurement instruments [51].

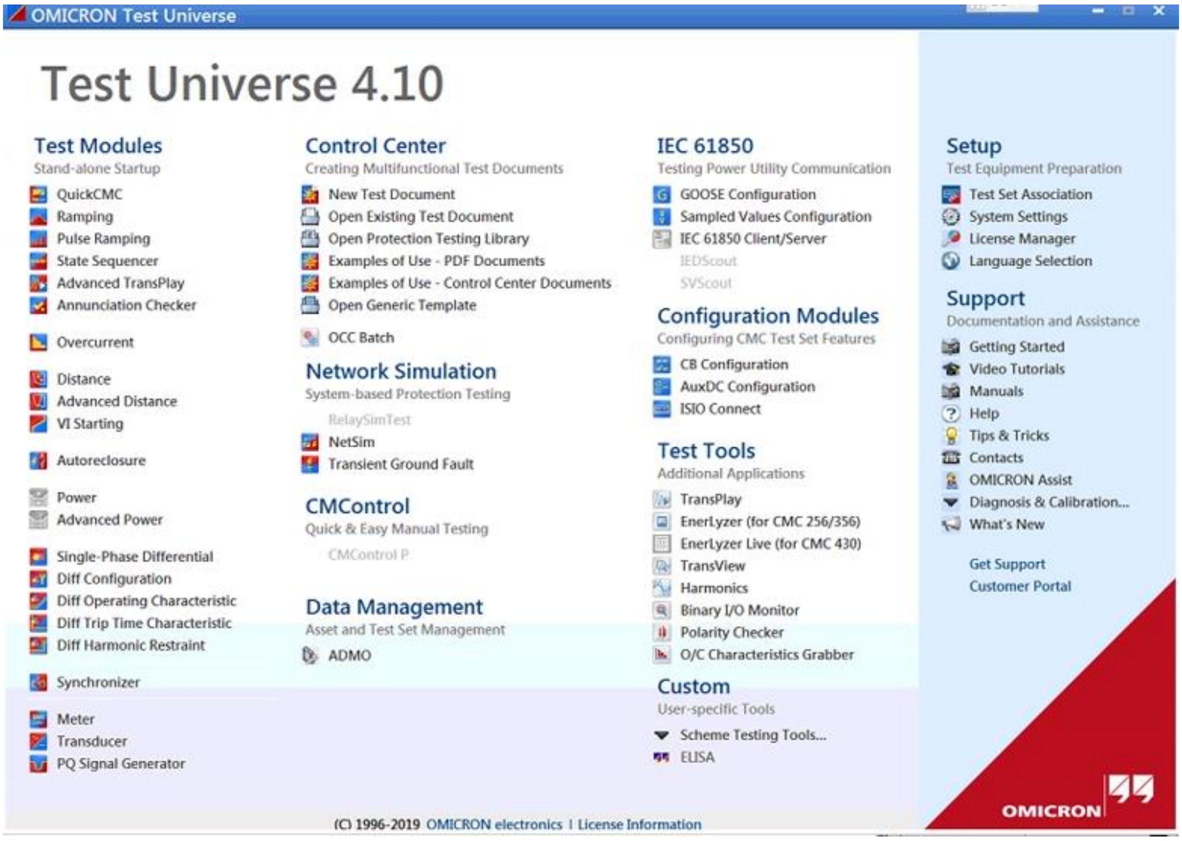


Figure 3.3: OMICRON Test Universe 4.10 Launch menu.

- **PCM600:**

It is ABB's protection and control IED manager software. It provides efficient functionality for application configuration and communication engineering. With an intuitive and well-structured user interface PCM600 offers easy-to-use configuration capabilities for I/O mapping and signal mapping. The user interface, workflow and the IEC 61850 based data model in PCM600 are designed according to the same philosophy as the IED itself, ensuring smooth and seamless integration between the tool and the IEDs [51].

Welcome to ABB's Protection and Control IED Manager PCM600. PCM600 provides versatile functionalities for the entire lifecycle of ABB's protection and control IED applications. PCM600 helps you manage your protection and control equipment all the way from configuration to maintenance.

Copyright 2005-2018 ABB. All rights reserved.

Figure 3.4: Opening window of PCM600 software Version 2.9.

3.5.3 Equipments Connection:

- We started by connecting the equipments as shown in Figure 3.5.

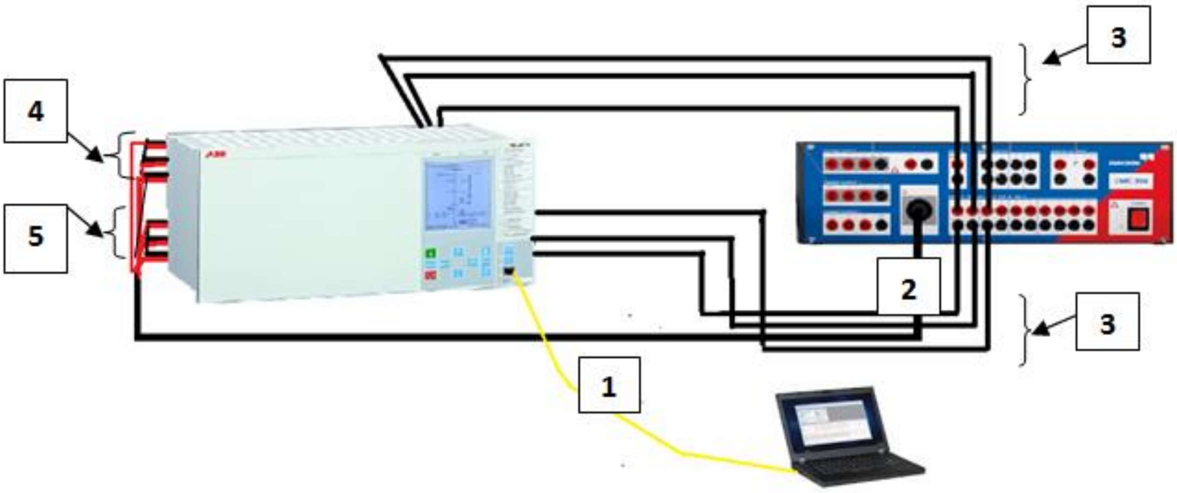


Figure 3.5: Connection diagram of ANSI 67 testing in REL670

1) Ethernet cable from PC to IED **2)** Generator socket **3)** Binary inputs
4) CTs connection **5)** VTs connection

For CTs and VTs connections on the back of the relay:

I/O ports 1, 3, 5 are for CT currents while ports 2, 4, 6 are for the neutral.

I/O ports 7, 9, 11 are for VT voltages while ports 8, 10, 12 are for the neutral.

Figure 3.6: Equipments Connections in The Lab.

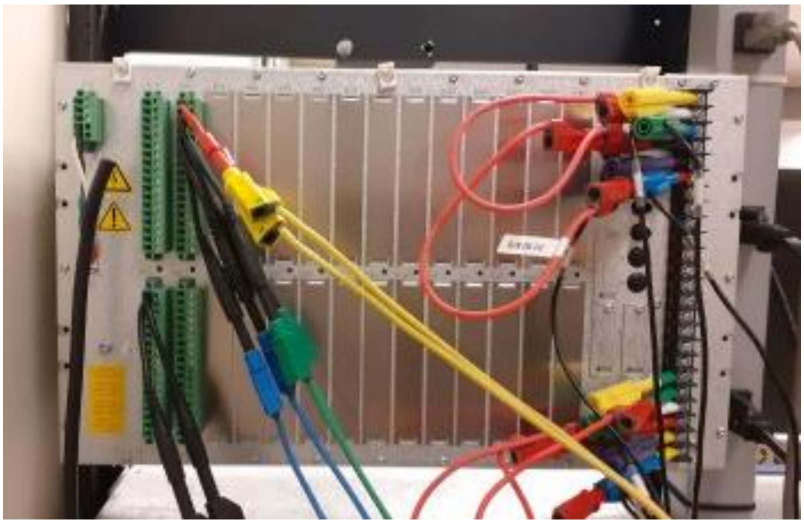


Figure 3.7: Back of the Relay.

Figure 3.8: Front of the Relay**.**

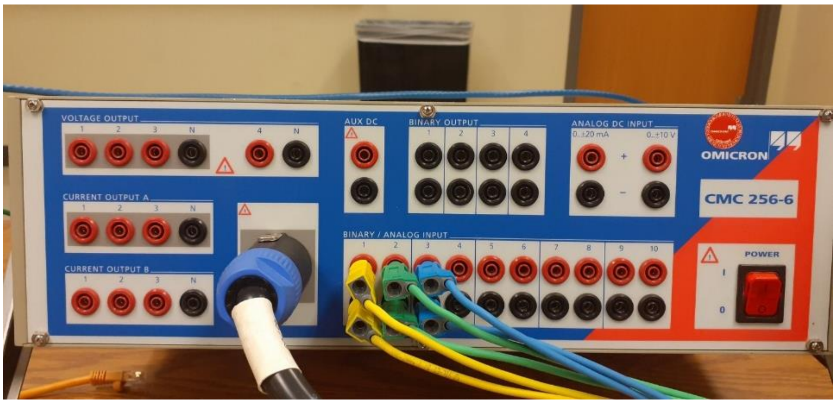


Figure 3.9: OMICRON CMC 256plus.

- We created a new project in the PCM 600 Software, and then to make the communication between the PC and the relay. We selected the online configuration mode as shown below:

REL670 Configuration Wizard

Configuration Mode Selection Page

This wizard helps you to create configuration for your relays. Configuration wizard sets the basic hardware and communication properties. The configuration can be made either offline or online.

Configuration Mode

● Online Configuration

○ Offline Configuration

Figure 3.10: Configuration mode for the communication setting.

3.5.4. The CT and VT test:

We tested current transformer and voltage transformer to verify the wiring, polarity and ratio of these units. The purpose of these testes is to check the CT and VT operations:

- We first injected phase voltage magnitudes 30V, 60V, and 90V with their respective phases 0°, -120°, 120°. We set phase currents to 0, and then we recorded from the relay screen the displayed secondary values.
- We then injected phase current magnitudes 100mA, 200mA, 300mA with their respective phases 0°, -120°, 120°, and we set phase voltages to 0. Then we recorded from the relay screen the displayed secondary values.
- We finally injected both values of voltages and currents respectively 30V,60V,90V, 100mA,200mA,300mA with the following phases respectively 0°, -120° ,120°. Then we recorded from the relay screen the displayed secondary values.

At the end we found that the CT and VT ratios are as indicated in the relay settings which are 1A/ 3000A, 400kV/1V respectively.

3.5.5. Directional Characteristic Test:

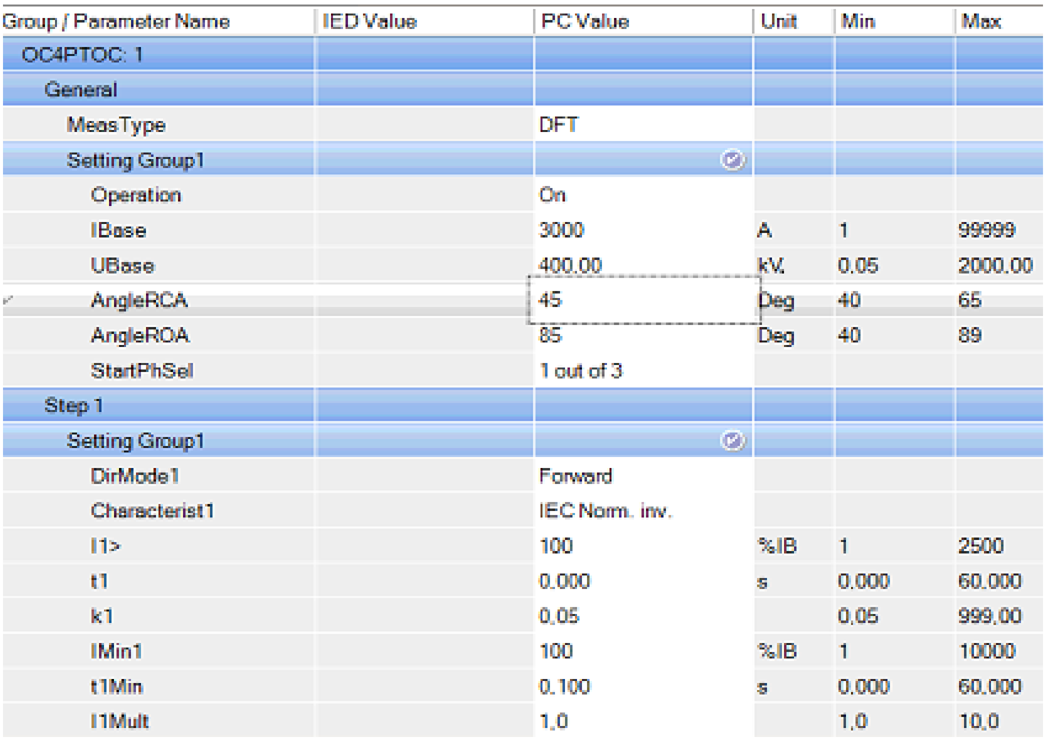
The objective of this test is to confirm the tripping zone angle of the directional characteristic. The testing points should be placed on both sides of the directional characteristic lines. In order to get a correct assessment, they should be placed just outside of the angle tolerance.

Note: A three phase fault is recommended for this test. The angle between current and voltage for each phase is the same for this fault type. This ensures a proper assessment of the test.

3.6 Directional Tests and Results with RCA=45°:

We set the relay parameters as the following:

Operation: On	**Angle RCA**: 45°	**I1**>100 %IB
Ibase: 3000 A	**Angle ROA**: 85	**IMin1**:100%IB
Ubase: 400 kV	**characterist1**: IEC Norm.Inv	



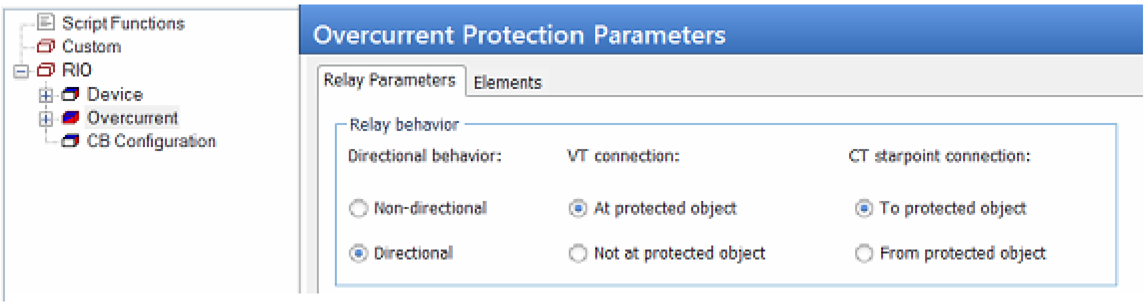
Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
OC4PTOC: 1					
General					
MeasType		DFT			
Setting Group1					
Operation		On			
IBase		3000	A	1	99999
UBase		400.00	kV	0.05	2000.00
AngleRCA		45	Deg	40	65
AngleROA		85	Deg	40	89
StartPhSel		1 out of 3			
Step 1					
Setting Group1					
DirMode1		Forward			
Characterist1		IEC Norm. inv.			
I1>		100	%IB	1	2500
t1		0.000	s	0.000	60.000
k1		0.05		0.05	999.00
IMin1		100	%IB	1	10000
t1Min		0.100	s	0.000	60.000
I1Mult		1.0		1.0	10.0

Figure 3.11: Setting Parameters of the Directional Phase Overcurrent Relay.

We open Test Universe software, in the test modules we choose **overcurrent** module, then we set the same parameters as in the relay software PCM600:

IEC Norm.Inv **MTA**=RCA-90° = 45°-90°= -45° **I pick up:** 1.0 Iref

We obtained the following characteristic of curve and phasor of the ANSI 51-67 protection:



Overcurrent Protection Parameters

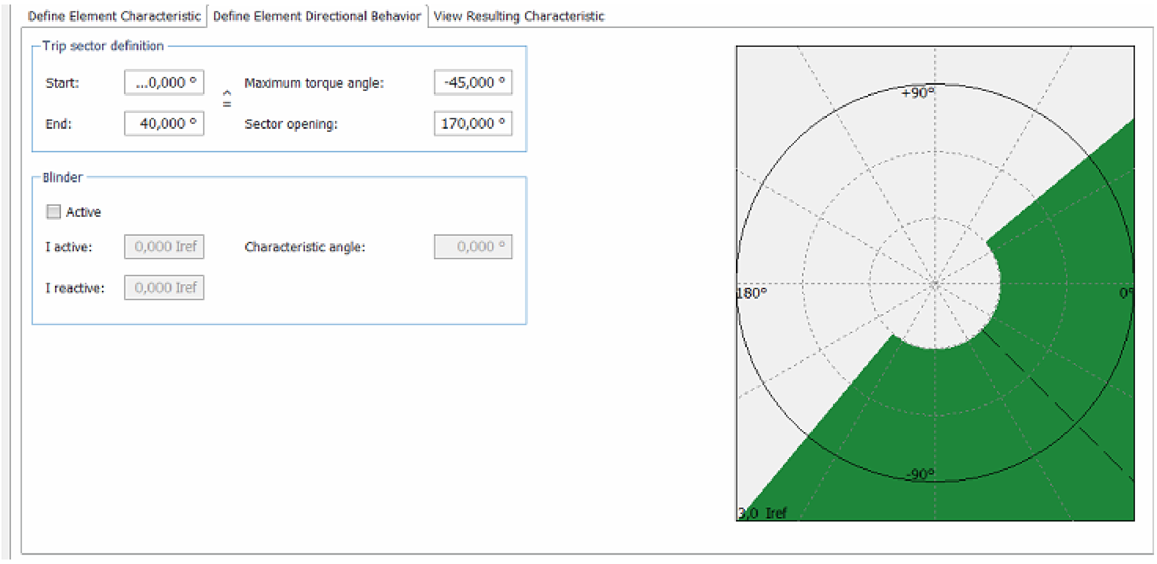
Relay behavior

Directional behavior:
○ Non-directional
● Directional

VT connection:
● At protected object
○ Not at protected object

CT starpoint connection:
● To protected object
○ From protected object

Figure 3.12: Overcurrent Protection Parameters viewed in Test Universe.



Trip sector definition

Start: ...0,000 °

Maximum torque angle: -45,000 °

End: 40,000 °

Sector opening: 170,000 °

Blinder

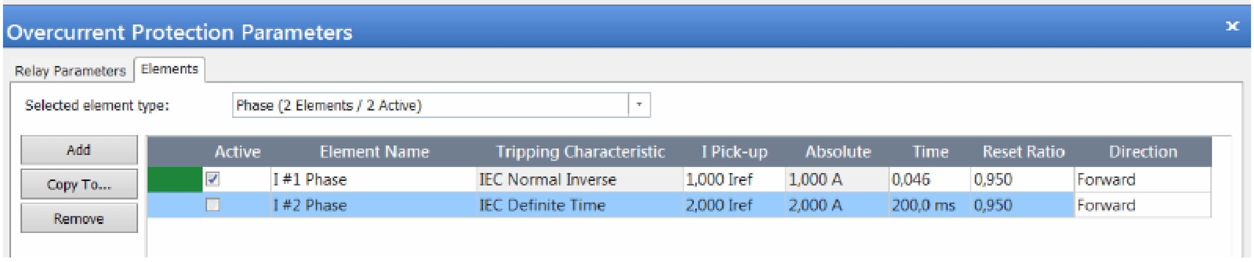
☐ Active

I active: 0,000 Iref

Characteristic angle: 0,000 °

I reactive: 0,000 Iref

Figure 3.13: MTA Setting in Test Universe.



Selected element type: Phase (2 Elements / 2 Active)

Active	Element Name	Tripping Characteristic	I Pick-up	Absolute	Time	Reset Ratio	Direction
🟩 ☑	I #1 Phase	IEC Normal Inverse	1,000 Iref	1,000 A	0,046	0,950	Forward
☐	I #2 Phase	IEC Definite Time	2,000 Iref	2,000 A	200,0 ms	0,950	Forward

Figure 3.14: Overcurrent Protection Parameters Elements Window.

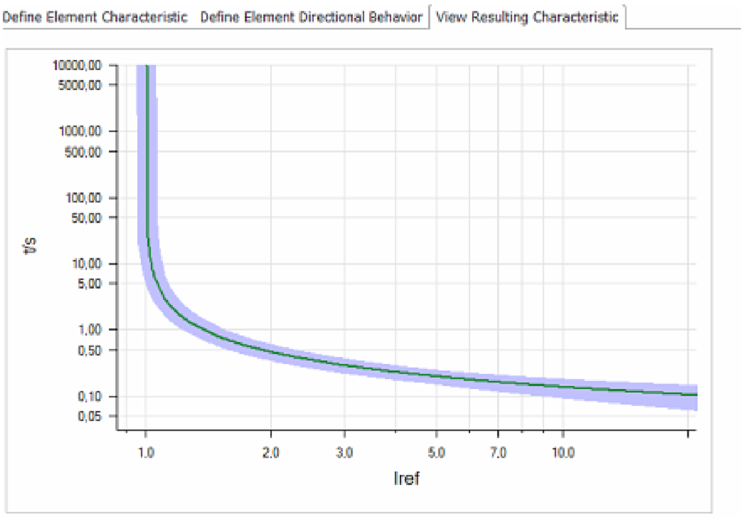


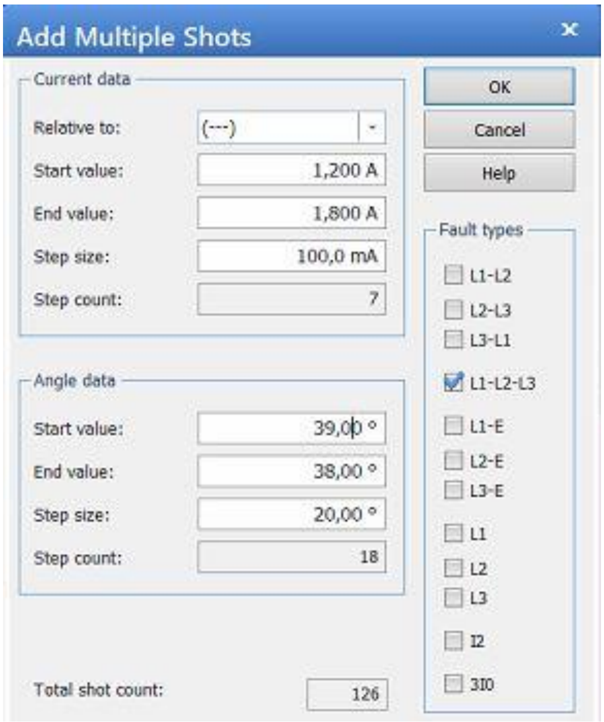
Figure 3.15: IEC Norm.Inv Characteristic curve.

3.6.1. Directional Characteristic Test for Three Phase Fault:

3.6.1.1. *Forward Characteristic Test 1*:

We set the DirMode to forward in the relay parameters, we then go to our Test Universe window, we selected the three phase fault injection, and then entered the testing points in Figure 3.16 to be tested. The testing points are illustrated by a grey point in Figure 3.17.

In order to test most of forward tripping zone, for each angle tested we varied the injected fault current from 1.2A to 1.8A with a step of 100 mA.



Current data

Relative to: (---)

Start value: 1,200 A

End value: 1,800 A

Step size: 100,0 mA

Step count: 7

Angle data

Start value: 39,00 °

End value: 38,00 °

Step size: 20,00 °

Step count: 18

Total shot count: 126

Fault types

☐ L1-L2
☐ L2-L3
☐ L3-L1
☑ L1-L2-L3
☐ L1-E
☐ L2-E
☐ L3-E
☐ L1
☐ L2
☐ L3
☐ I2
☐ 3I0

Figure 3.16: “Add Multiple “Test Universe window.

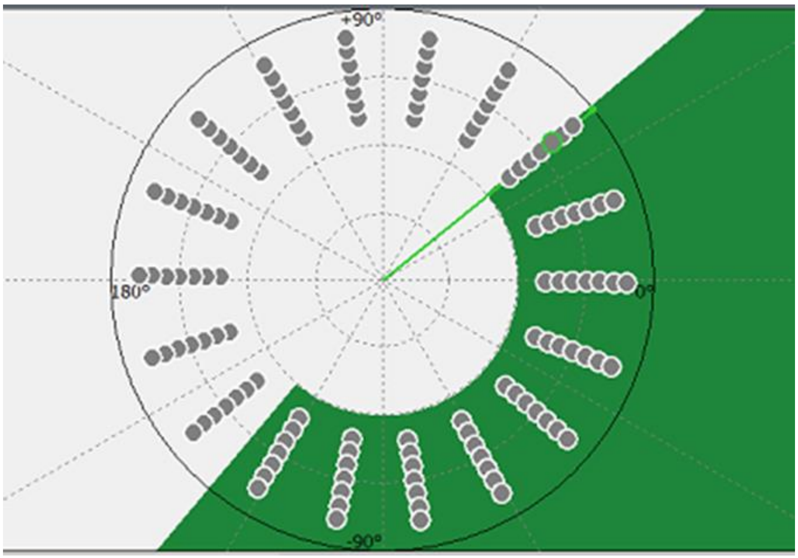


Figure 3.17: Testing Points in Test Universe window.

The following table summarize the total points set to be tested:

Type	Magnitude	Angle	tnom	tmin	Tmax
L1-L2-L3	1,200 A	39,00 °	1,763 s	1,112 s	2,945 s
L1-L2-L3	1,300 A	39,00 °	1,224 s	825,3 ms	1,827 s
L1-L2-L3	1,400 A	39,00 °	953,8 ms	666,1 ms	1,351 s
L1-L2-L3	1,500 A	39,00 °	790,9 ms	564,5 ms	1,087 s
L1-L2-L3	1,600 A	39,00 °	681,9 ms	494,0 ms	919,0 ms
L1-L2-L3	1,700 A	39,00 °	603,6 ms	442,0 ms	802,3 ms
L1-L2-L3	1,800 A	39,00 °	544,6 ms	402,1 ms	716,4 ms
L1-L2-L3	1.200 A to 1.800 A step of 100mA	59° to -141° with a step of 20°	No trip	No trip	No trip
L1-L2-L3	1.200 A to 1.800 A	121° to 19°	As in the 39° angle case	As in the 39° angle case	As in the 39° angle case

Table 3.2: Three Phase (L1-L2-L3) Fault Test Points.

The final results of the test are illustrated in Figure 3.18 and Figure 3.19.

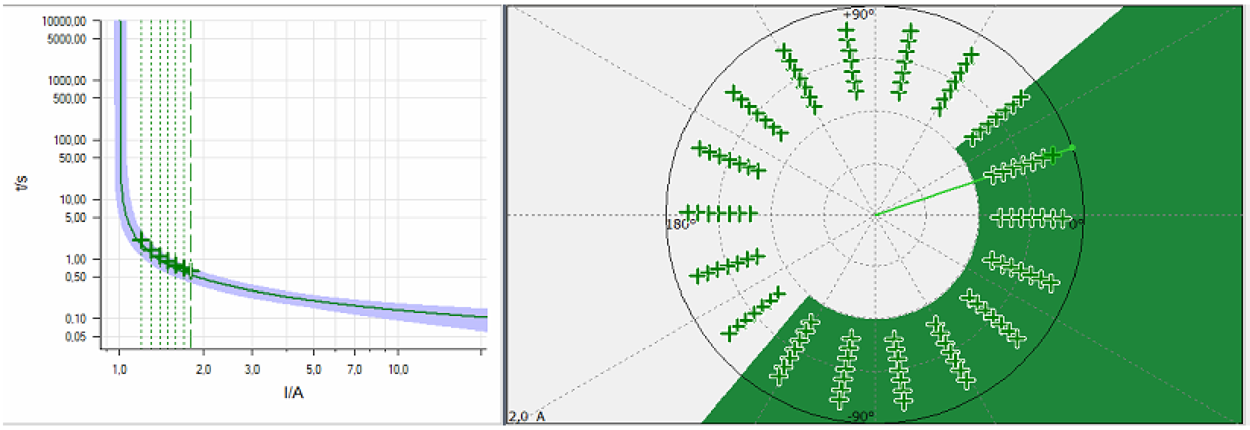


Figure 3.18: Three Phase Fault (L1-L2-L3) Test Result for RCA =45° in Directional Region.

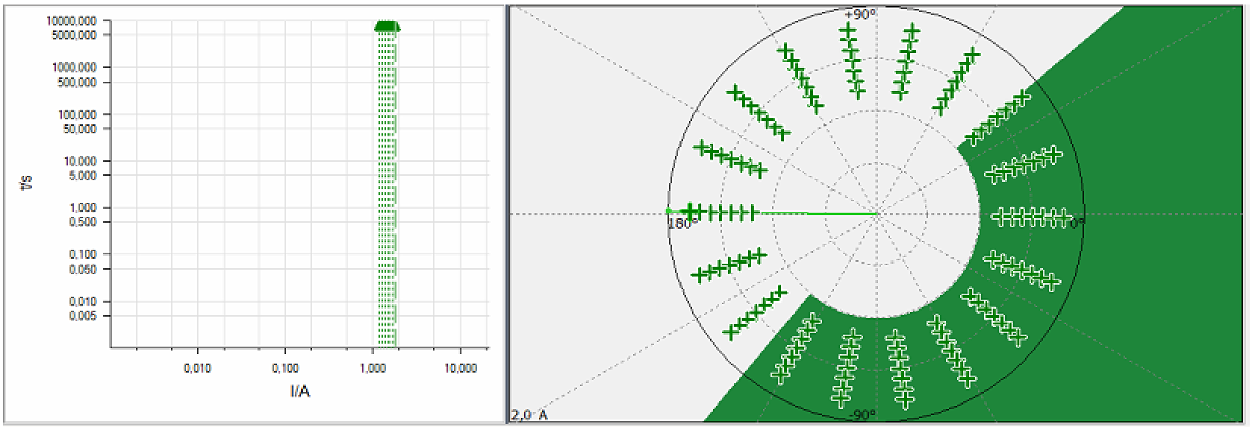


Figure 3.19: Three Phase Fault (L1-L2-L3) Test Result for RCA =45° in Non-Directional Region.

we obtained the following curve and phasor results for test angle 39°,59° with a three phase fault (L1-L2-L3):

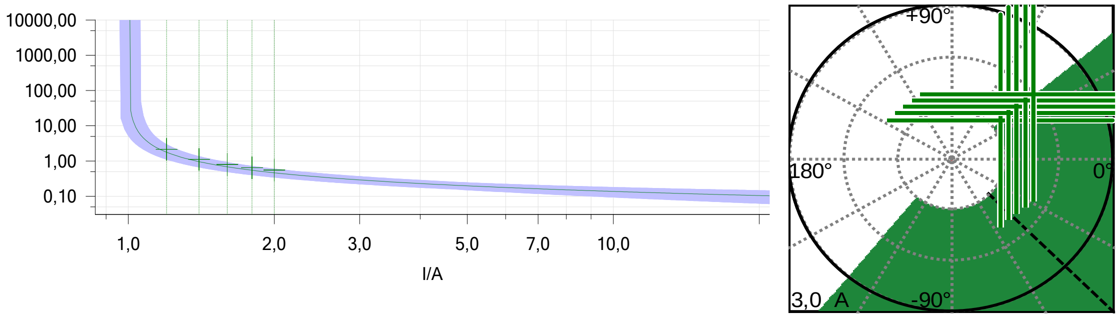


Figure 3.20: Three Phase (L1-L2-L3) Fault Test 1 Results in the Tripping Forward Zone for RCA =45°.

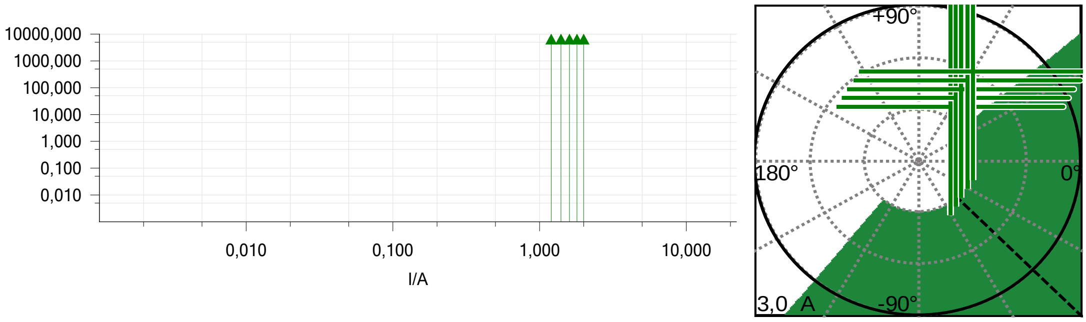


Figure 3.21: Three Phase (L1-L2-L3) Fault Test 1 Results in the Non-Tripping Zone for RCA =45°.

The Table 3.3 summarizes a part of the three phase (L1-L2-L3) fault test 1 results, the total test results are found in Table B.1 Appendix B.

Type	Magnitude	Angle	tnom	tact	Deviation	Result
L1-L2-L3	1,200 A	39°	1,763 s	2,094 s	18,78 %	Passed
L1-L2-L3	1,300 A	39°	1,224 s	1,432 s	16,99 %	Passed
L1-L2-L3	1,400 A	39°	953,8 ms	1,122 s	17,67 %	Passed
L1-L2-L3	1,500 A	39°	790,9 ms	932,9 ms	17,95 %	Passed
L1-L2-L3	1,600 A	39°	681,9 ms	793,4 ms	16,35 %	Passed
L1-L2-L3	1,700 A	39°	603,6 ms	716,3 ms	18,67 %	Passed
L1-L2-L3	1,800 A	39°	544,6 ms	647,0 ms	18,80 %	Passed
L1-L2-L3	1.200 A to 1.800 A	59° to - 141°	No trip	No trip	n/a	Passed

Table 3.3: Results of the Three Phase (L1-L2-L3) Fault test 1 for RCA =45°.

3.6.1.2. Forward Characteristic Test 2:

We set the DirMode to Non-directional in the relay parameters with keeping the testing tool setting directional. We go to our Test Universe window; we selected the three phase fault setting, then entered the same points of the previous test to check the forward directional characteristics of ANSI 51-67 protection, as shown in Table 3.4.

We obtained the Figure 3.22 that illustrate fault forward directional overcurrent Test 2 results.

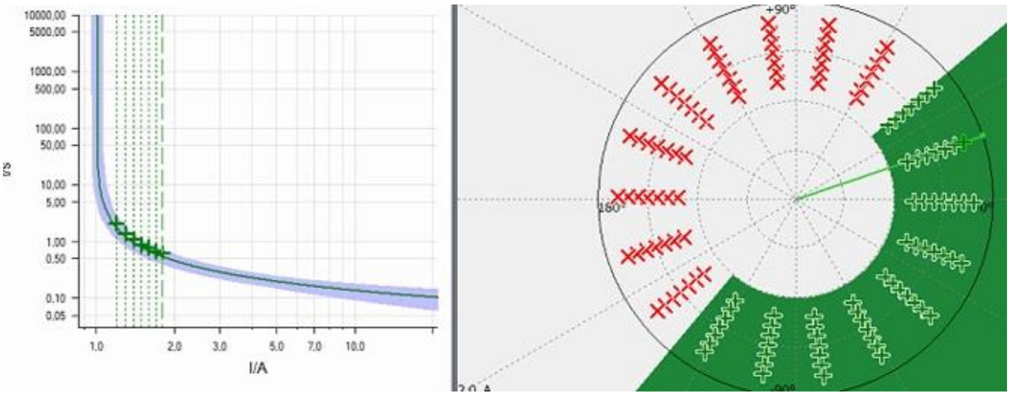


Figure 3.22: Three Phase (L1-L2-L3) Fault Forward Directional Overcurrent Test 2 Results for RCA =45°.

The table below summarizes a part of the three phase (L1-L2-L3) fault test 2 results, the total test results can be found in Table B.2 in Appendix B.

Type	Magnitude	Angle	tnom	tact	Deviation	Result
L1-L2-L3	1,200 A	39°	1,763 s	2,081 s	18,05 %	Passed
L1-L2-L3	1,300 A	39°	1,224 s	1,417 s	15,73 %	Passed
L1-L2-L3	1,400 A	39°	953,8 ms	1,102 s	15,50 %	Passed
L1-L2-L3	1,500 A	39°	790,9 ms	905,6 ms	14,50 %	Passed
L1-L2-L3	1,600 A	39°	681,9 ms	778,9 ms	14,23 %	Passed
L1-L2-L3	1,700 A	39°	603,6 ms	686,2 ms	13,68 %	Passed
L1-L2-L3	1,800 A	39°	544,6 ms	632,6 ms	16,16 %	Passed
L1-L2-L3	1.200 A to 1.800 A	59° to -141°	No trip	No trip	n/a	Passed

Table 3.4: Result of Three Phase (L1-L2-L3) Fault Test 2 for RCA =45°.

3.6.1.3. Non directional characteristic test:

We kept the DirMode as Non directional in the relay parameters and modified the testing tool setting non-directional. We selected the three phase fault setting, then entered the same points as the previous test to check the forward directional characteristics of ANSI 51-67 protection, as shown in Table 3.5.

We obtained the curve results shown in Figure 3.23.

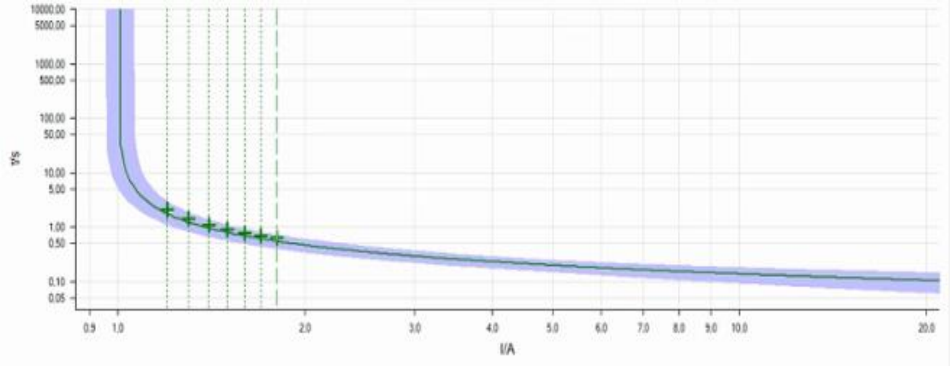


Figure 3.23: Three Phase (L1-L2-L3) Fault Non-Directional Overcurrent Test Result.

Type	Magnitude	Angle	tnom	tact	Deviation	Overland	Result
L1-L2-L3	1,200 A	n/a	1,763 s	2,084 s	18,23 %	No	Passed
L1-L2-L3	1,300 A	n/a	1,224 s	1,414 s	15,51 %	No	Passed
L1-L2-L3	1,400 A	n/a	953,8 ms	1,094 s	14,72 %	No	Passed
L1-L2-L3	1,500 A	n/a	790,9 ms	905,2 ms	14,45 %	No	Passed
L1-L2-L3	1,600 A	n/a	681,9 ms	782,7 ms	14,78 %	No	Passed
L1-L2-L3	1,700 A	n/a	603,6 ms	700,6 ms	16,07 %	No	Passed
L1-L2-L3	1,800 A	n/a	544,6 ms	628,2 ms	15,35 %	No	Passed

Table 3.5: Three Phase (L1-L2-L3) Fault Non-Directional Overcurrent Test Result.

3.6.2. Forward Directional Characteristic Test for Phase to Phase Fault:

We select the phase to phase fault type to be tested, then, entered the point’s magnitudes and angles. We obtained the following curve and phasor results:

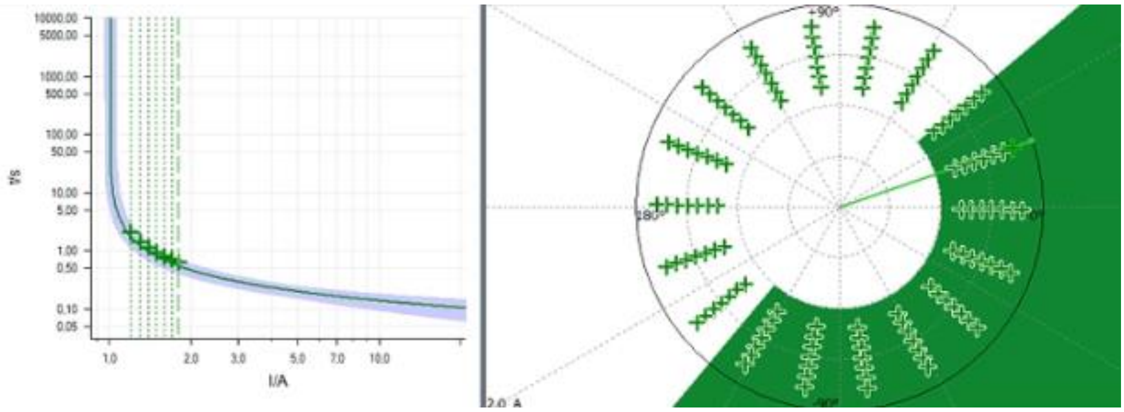


Figure 3.24: Phase to Phase (L1-L2) Fault Test Results for RCA =45°.

The Table 3.6 summarizes a part of the phase to phase (L1-L2) fault test results. The total test results can be found in Table B.3 in Appendix B.

Type	Magnitude	Angle	tnom	tact	Deviation	Result
L1-L2	1,200 A	39,00 °	1,763 s	2,109 s	19,61 %	Passed
L1-L2	1,300 A	39,00 °	1,224 s	1,452 s	18,62 %	Passed
L1-L2	1,400 A	39,00 °	953,8 ms	1,135 s	19,04 %	Passed
L1-L2	1,500 A	39,00 °	790,9 ms	927,8 ms	17,30 %	Passed
L1-L2	1,600 A	39,00 °	681,9 ms	813,2 ms	19,26 %	Passed
L1-L2	1,700 A	39,00 °	603,6 ms	726,2 ms	20,31 %	Passed
L1-L2	1,800 A	39,00 °	544,6 ms	645,9 ms	18,60 %	Passed
L1-L2	1,200 A To 1.800 A	59,00 ° To 119°	No trip	No trip	n/a	Passed

Table 3.6: Result of Phase to Phase (L1-L2) Fault Test for RCA =45°.

3.6.3. Forward Directional Characteristic Test for a Phase to Earth Fault:

We select the single phase to earth fault type to be tested; then we entered the same point's magnitudes and angles as we did in the previous tests.

Note: Phase to ground faults can be sensed using a directional phase overcurrent relay ANSI 67P, but compared to the ground directional overcurrent relay ANSI 67G performance, it is slower in detecting and isolating this type of fault.

We obtained the following curve and phasor results:

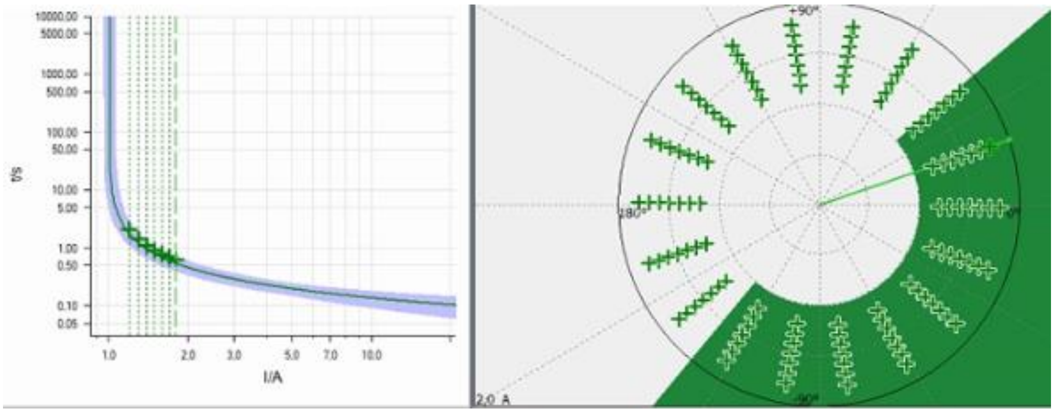


Figure 3.25: Phase to Earth (L-E) Fault Test Results.

The Table 3.8 summarizes a part of the phase to earth (L1-E) fault test results. The complete results can be found on Table B.4 in Appendix B.

Type	Magnitude	Angle	tnom	tact	Deviation	Result
L1-E	1,200 A	39,00 °	1,763 s	2,109 s	19,61 %	Passed
L1-E	1,300 A	39,00 °	1,224 s	1,452 s	18,62 %	Passed
L1-E	1,400 A	39,00 °	953,8 ms	1,135 s	19,04 %	Passed
L1-E	1,500 A	39,00 °	790,9 ms	927,8 ms	17,30 %	Passed
L1-E	1,600 A	39,00 °	681,9 ms	813,2 ms	19,26 %	Passed
L1-E	1,700 A	39,00 °	603,6 ms	726,2 ms	20,31 %	Passed
L1-E	1,800 A	39,00 °	544,6 ms	645,9 ms	18,60 %	Passed
L1-E	1,200 A To 1.800 A	59,00 ° To 119°	No trip	No trip	n/a	Passed

Table 3.7: Results of Phase to Earth (L1-E) Fault Test.

3.6.4. Discussion:

- In the first test **“forward characteristic test 1”,** we remark that the test illustrated in Figure 3.18 and Figure 3.19 was successful, and the results satisfy our expectations, in other words we confirmed that under three phase fault condition the relay will trip and operates to open the circuit breaker for a fault current I that is **greater** than **I pick up**=1A flowing in the **forward direction** (at time duration close to the nominal tripping time with small deviation).
- In the second test “**forward characteristic test 2**”, we remark that the result satisfies our expectations. As we can see in the Figure 3.22 the test passes in the forward directional zone and in the non-operating zone the tested points are shown in red colour (red cross) in the testing software which indicates the failure of the test at these points. This is because the relay is set to the non-directional mode but the testing tool is still checking the directional overcurrent function. Hence the test fails for a current that is out of the forward directional tripping zone.
- In the third test” **Non directional characteristic test”**, we remark that the result satisfies our expectations. We notice from Figure 3.23 which represents the characteristic of the definite time curve of the overcurrent protection function that it tripped at the three phase fault current I_{fault}=1.2 A (at each phase) which is greater than $I_{pick\ up}$ =1 A (at time

duration close to the nominal tripping time with small deviation). Since we are testing the non-directional characteristic the protection function ANSI 67 is made off and only the protection function ANSI 51 is operating in this test.

- From the phase to phase (L1-L2) fault and the single phase to earth (LE) fault tests we have done, we remark that the results found are satisfactory. The relay tripped under fault current $I > I_{\text{pick up}}$ in the forward direction assigned (at time duration close to the nominal tripping time with small deviation) to open the circuit breaker and isolate the fault.
- When the RCA is set to 45° and the directional element is correctly activated, we can see that all type of faults (three phase, phase to phase and single phase to ground fault) are detected, which is illustrated by a green cross and shown in the test's result table. The use of 45° as a universal RCA setting for any given system and for any fault condition assures a wide coverage of forward and reverse regions, as well as a fast response.

3.7. Directional Tests and Results with RCA=40° and RCA=65° Respectively:

The objective of this test is to study, discuss and compare the relay's behaviour and performances at the limit RCA settings for the relay ABB REL670 which are set to minimum 40° and maximum 65°.

3.7.1. Directional Tests with RCA=40°:

- **Forward Directional Characteristic Test for Three Phase Fault:**

We followed the same steps shown previously in the RCA 45° tests, but this time we changed RCA to an angle equal to 40°. For this case the maximum torque angle is found 50°:

$$\mathbf{MTA} = \mathbf{RCA} - 90° = 40° - 90° = -50°$$

The result of the directional testes for three phase faults, phase to phase faults and single phase to ground faults are illustrated in Figure 3.26, Figure 3.27 and Figure 3.28 respectively.

Note: The full results of the three phase faults, phase to phase faults and single phase to ground faults for RCA=40° are presented in Table B.5, Table B.6 and Table B.7 in Appendix B respectively.

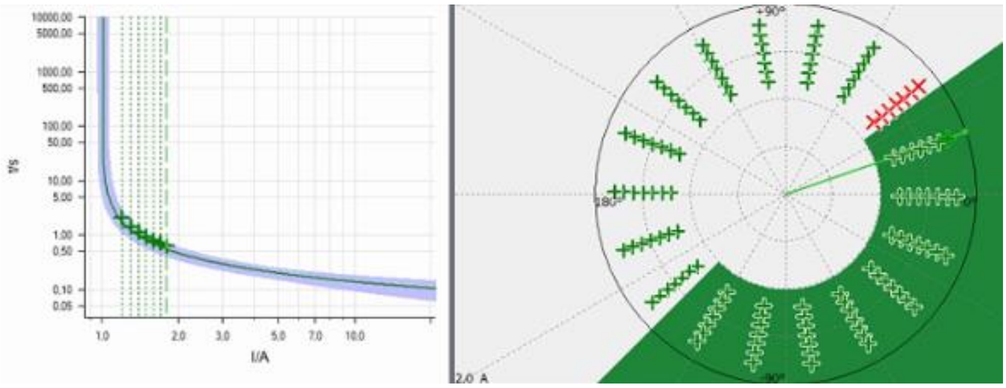


Figure 3.26: Three Phase (L1-L2-L3) Fault Forward Directional Overcurrent Test for RCA=40°.

- **Forward Directional Characteristic Test for Phase to Phase Fault:**

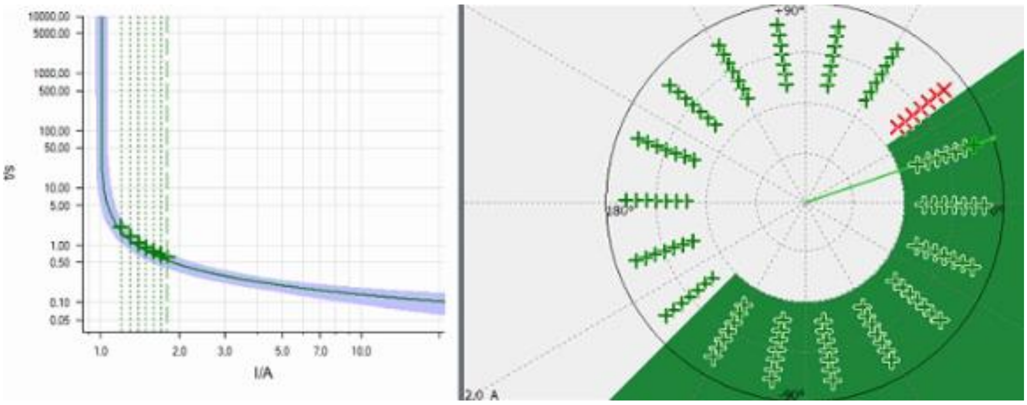


Figure 3.27: Phase to Phase (L1-L2) Fault Forward Directional Overcurrent Test for RCA=40°.

- **Forward Directional Characteristic Test for Single Phase to Earth Fault:**

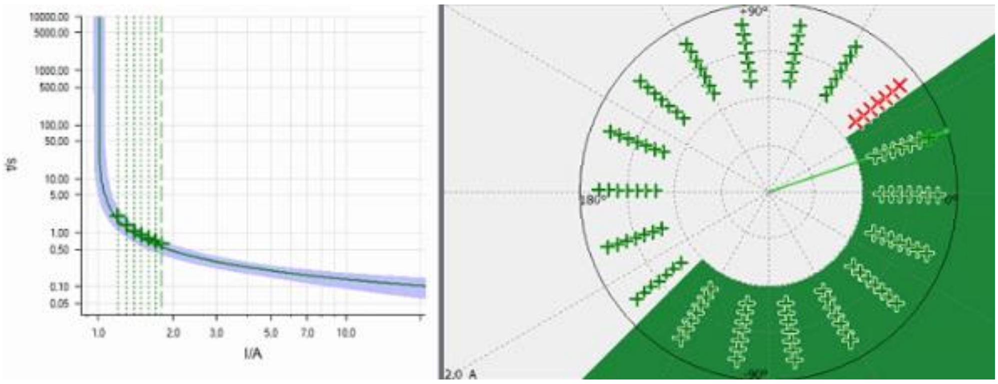


Figure 3.28: Phase to Earth (L1-E) Fault Forward Directional Overcurrent Test for RCA=40°.

3.7.2. Directional Tests and Results with RCA=65°:

We followed the same steps presented above but this time we changed RCA to an angle equal to 65°. For this case the maximum torque angle is found 65°:

MTA =**RCA**- 90° = 65°- 90°=25°

Note: The full results of the three phase faults, phase to phase faults and phase to earth fault for RCA=65° tests are all presented in Table B.8, Table B.9 and Table B.10 in appendix B respectively.

- **Forward Directional Characteristic Test for Three Phase Fault:**

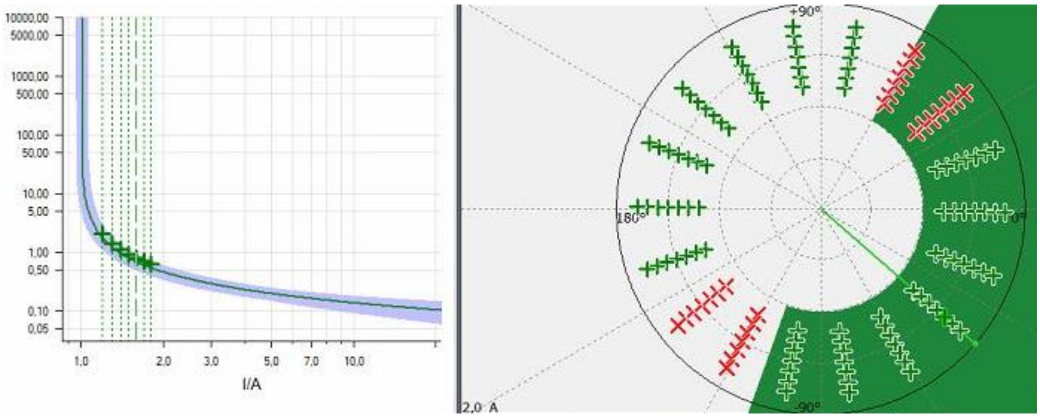


Figure 3.29: Three Phase (L1-L2-L3) Fault Forward Directional Overcurrent Test for RCA=65°.

- **Forward Directional Characteristic Test for Phase to Phase Fault:**

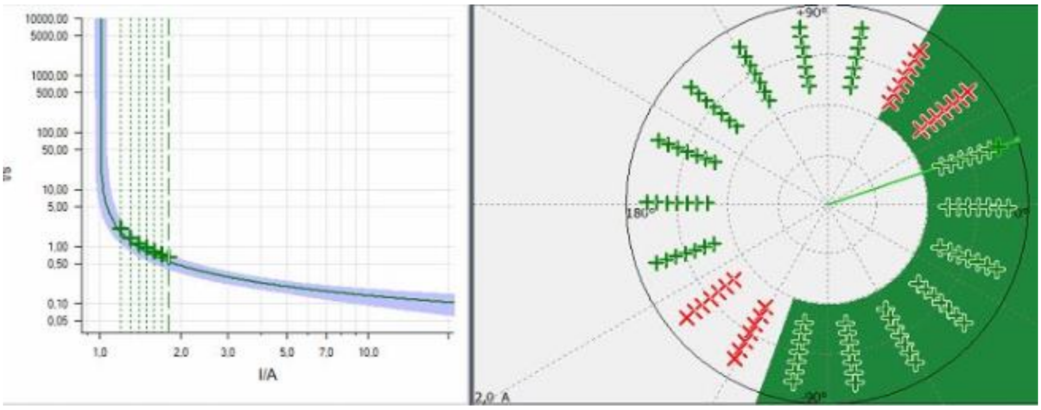


Figure 3.30: Phase to Phase (L1-L2) Fault Forward Directional Overcurrent Test for RCA=65°.

- **Forward Directional Characteristic Test for Phase to Earth Fault:**

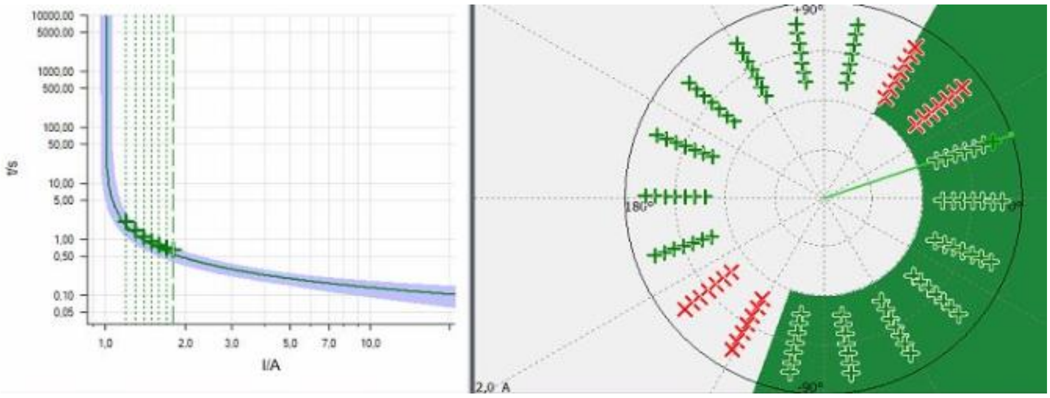


Figure 3.31: Phase to earth L1-E fault forward directional overcurrent test for RCA=65°.

3.7.3. Discussion:

- When we set RCA to 40°, we can see from Figure 3.26, Figure 3.27 and Figure 3.28 that for all the types of faults testes, there are 7 points failed out of 126 points tested which are illustrated by a red cross. When we set RCA to 65°, we can see from Figure 3.29, Figure 3.30 and Figure 3.31 that for all the types of faults testes, there are 28 points failed out of 126 points tested.
- The closer the RCA setting is to the actual limit (40° or 65°), the higher the risk of obtaining nuisance tripping of such protective elements, especially when they are subjected to current transformer saturation, harmonic content, DC components and other short-circuit related phenomena, affecting the accurate measure of the relevant system variables on which the reliability of the protective functions relies. This is why the proposed settings for all the protective functions must be properly justified and validated for the particularities of every protected system [41].
- Relay manufacturers and studies have recommended a setting of 45° for the RCA, and even state that there is no way the relay can fail to determine the correct direction of the fault with this setting [41].

3.8. The use of COMTRADE for Fault Inspection

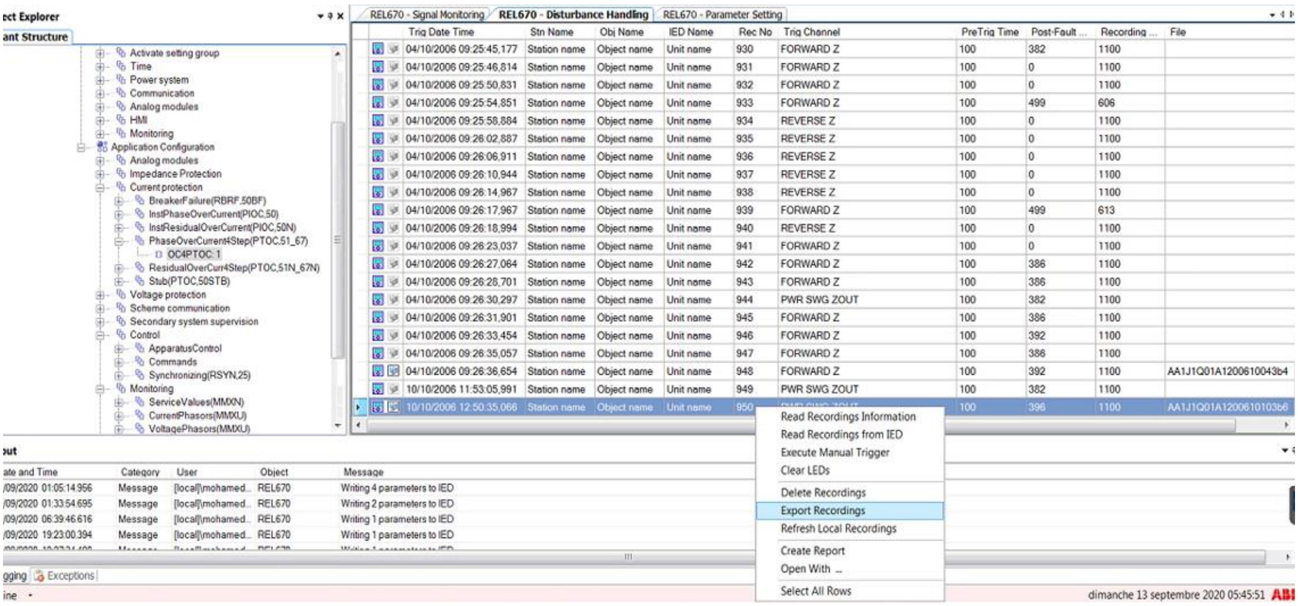
A relay tester is capable of producing uploaded current and voltage waveforms. COMTRADE and PL4-files are the most used file formats. The waveforms can be recorded events from a relay/IED. Relay testing using waveforms from a real fault scenario can be very interesting.

This is a useful feature as the user can verify relay's reliability. The relay tester can play back a scenario where the relay tripped when it was not supposed to, giving the user an opportunity to locate the reasoning behind the misoperation and improve the protection systems security in future events, whether it was a hardware, software error, or simply an error in the setting of the relay. Another significant event is when a relay does not trip for a fault it was supposed to trip.

It means the relays dependability was not sufficient. Studies of such scenarios are important to improve the overall reliability of protection systems [51].

3.8.1. The Steps to Get the Comtrade File:

In the PCM 600 software we right clicked to select "Disturbance Handling "we went to the event that concerns the inspected fault which is selected thanks to the date and time of its occurrence, then we right clicked and selected "Exporting Recordings".



Trig Date Time	Stn Name	Obj Name	IED Name	Rec No	Trig Channel	PreTrig Time	Post-Fault ...	Recording ...	File
04/10/2006 09:25:45,177	Station name	Object name	Unit name	930	FORWARD Z	100	382	1100	
04/10/2006 09:25:46,814	Station name	Object name	Unit name	931	FORWARD Z	100	0	1100	
04/10/2006 09:25:50,831	Station name	Object name	Unit name	932	FORWARD Z	100	0	1100	
04/10/2006 09:25:54,851	Station name	Object name	Unit name	933	FORWARD Z	100	499	606	
04/10/2006 09:25:58,884	Station name	Object name	Unit name	934	REVERSE Z	100	0	1100	
04/10/2006 09:26:02,887	Station name	Object name	Unit name	935	REVERSE Z	100	0	1100	
04/10/2006 09:26:06,911	Station name	Object name	Unit name	936	REVERSE Z	100	0	1100	
04/10/2006 09:26:10,944	Station name	Object name	Unit name	937	REVERSE Z	100	0	1100	
04/10/2006 09:26:14,967	Station name	Object name	Unit name	938	REVERSE Z	100	0	1100	
04/10/2006 09:26:17,967	Station name	Object name	Unit name	939	FORWARD Z	100	499	613	
04/10/2006 09:26:18,994	Station name	Object name	Unit name	940	REVERSE Z	100	0	1100	
04/10/2006 09:26:23,037	Station name	Object name	Unit name	941	FORWARD Z	100	0	1100	
04/10/2006 09:26:27,064	Station name	Object name	Unit name	942	FORWARD Z	100	386	1100	
04/10/2006 09:26:28,701	Station name	Object name	Unit name	943	FORWARD Z	100	386	1100	
04/10/2006 09:26:30,297	Station name	Object name	Unit name	944	PWR SWG ZOUT	100	382	1100	
04/10/2006 09:26:31,901	Station name	Object name	Unit name	945	FORWARD Z	100	386	1100	
04/10/2006 09:26:33,454	Station name	Object name	Unit name	946	FORWARD Z	100	392	1100	
04/10/2006 09:26:35,057	Station name	Object name	Unit name	947	FORWARD Z	100	386	1100	
04/10/2006 09:26:36,654	Station name	Object name	Unit name	948	FORWARD Z	100	392	1100	AA1J1Q01A1200610043b4
10/10/2006 11:53:05,991	Station name	Object name	Unit name	949	PWR SWG ZOUT	100	382	1100	
10/10/2006 12:50:35,066	Station name	Object name	Unit name	950	[illegible]	100	396	1100	AA1J1Q01A1200610103b6

ate and Time	Category	User	Object	Message
/09/2020 01:05:14.956	Message	[local]\mohamed...	REL670	Writing 4 parameters to IED
/09/2020 01:33:54.695	Message	[local]\mohamed...	REL670	Writing 2 parameters to IED
/09/2020 06:39:46.616	Message	[local]\mohamed...	REL670	Writing 1 parameters to IED
/09/2020 19:23:00.394	Message	[local]\mohamed...	REL670	Writing 1 parameters to IED

Figure 3.32: Disturbance Handling window.

We opened the Test Universe software and we selected among the Test Tools "Transplay" as shown in figure below:

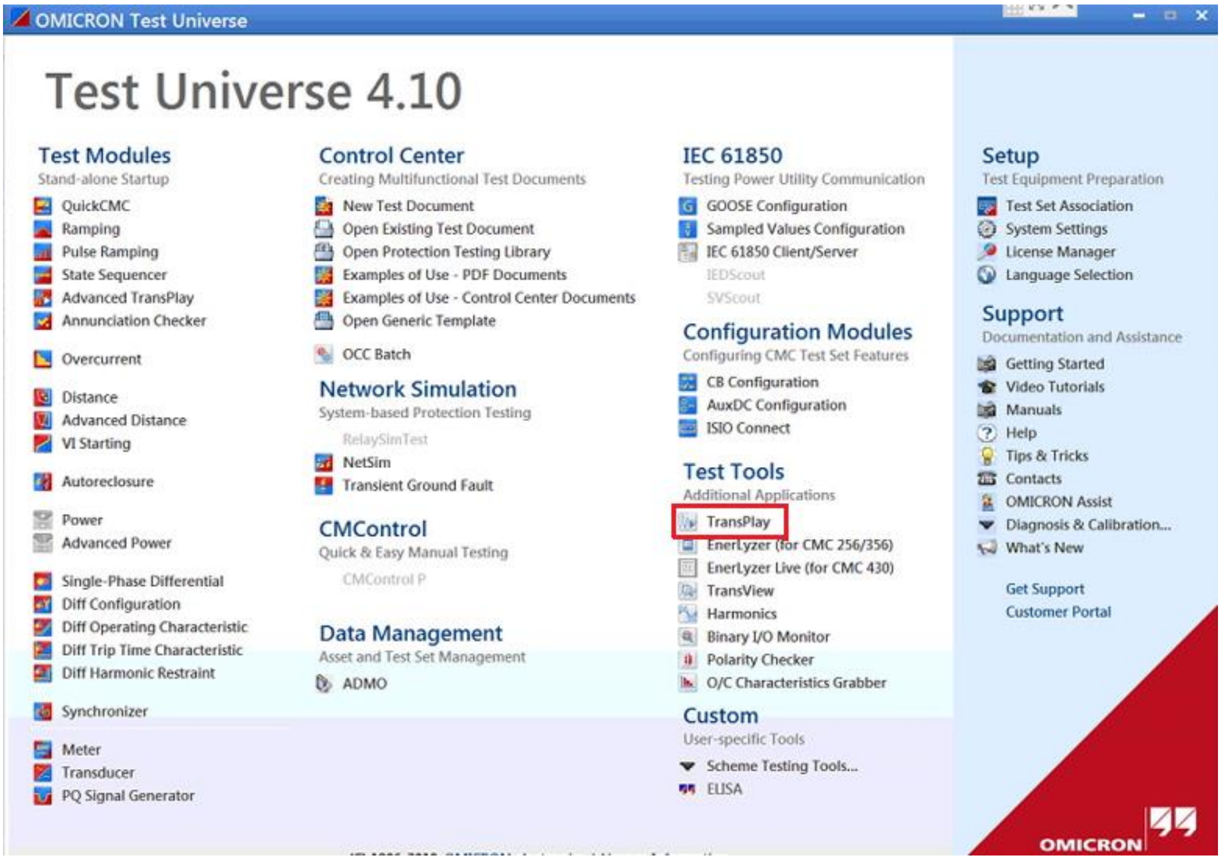
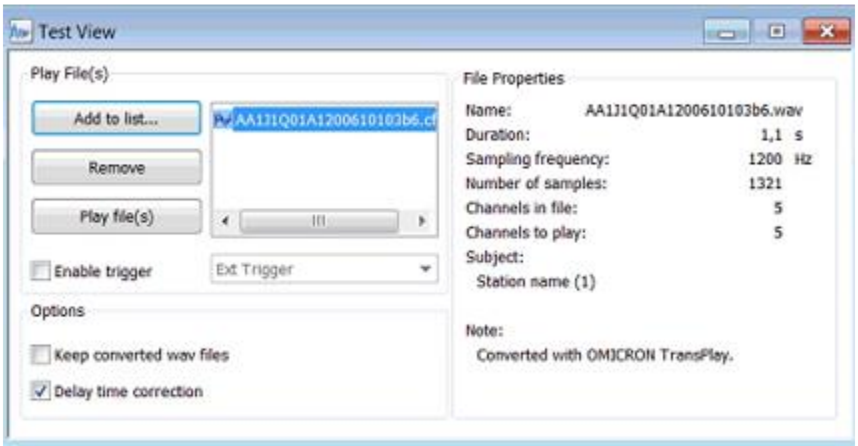


Figure 3.33: The Transplay tool selection.

We then selected test view from the tool bar and we selected the event registered in the PC previously:



☐ Enable trigger

☐ Keep converted wav files

☑ Delay time correction

Name: AA1J1Q01A1200610103b6.wav
Duration: 1,1 s
Sampling frequency: 1200 Hz
Number of samples: 1321
Channels in file: 5
Channels to play: 5
Subject:
Station name (1)

Note:
Converted with OMICRON TransPlay.

Figure 3.34: The Transplay tool selection test view.

We clicked on "Play file(s)" then the event made a replay automatically to repeat the scenario of the inspected fault to check why it behaved differently than expected.

3.9. Conclusion:

This chapter presented a simplified guide on how to test the directional phase overcurrent relay ABB REL670 as well discussing the response of the relay once subjected to different RCA settings under symmetrical and asymmetrical faults.

Before starting the directional test, it is important to go through some basic yet essential tests to make sure the equipments used is functioning properly during the test process. This assures avoiding unwanted testing results. From those basic routine tests we find: type tests, commissioning test, periodic maintenance tests, troubleshooting etc.

The RCA setting plays an essential role for a correct directional decision making. The 45° setting for the RCA is universal standard setting for any given system and for any fault condition, because it allows the relay to work properly for a wide coverage of forward and reverse regions. Setting the RCA closer to the actual limit is not advised, because it raises the risk of obtaining nuisance tripping of such protective elements.

The results of the testing successfully showcased the main conditions that must be satisfied for a correct directional decision making, we proved that the relay trips whenever the current is higher than a certain current pick up value in a defined direction (forward, reverse or non-directional). We proved as well, that the choice of the relay characteristic angle may affect the relay direction determination hence the tripping decision (40°, 45° or 65° or any other value in the RCA relay range).

CONCLUSION:

In this project, the directional phase over current relay was studied and was subjected to different tests in *Tennessee University of* U.S. state Chattanooga laboratory.

General definitions and background knowledge concerning the power system protection has been presented first. The analysis of the different types of faults that can disturb the power system network has been discussed including its causes and consequences. The operation of necessary protection devices was presented and explained. As the relays are the main protection devices that are widely used, it is important to understand the relaying concepts of these lasts, as well as being able to test its performance with respect to their main settings.

The study of directional phase overcurrent relay was the main focus of this thesis, as it is mainly used in multiple source network, parallel distribution lines and in mesh distribution network protection. The directional phase over current relay responds to an excessive fault current in a particular pre-determined direction of the power flow. It is characterized by its RCA and MTA which define the operation zone of the relay as well as its performance quality.

Various set of tests were performed on the Four Step Directional Phase Overcurrent Protection Function of the Line Distance Protection Relay ABB REL670 IED (Intelligent Electronic Device) relay, in order to showcase its relaying concept.

The first part of the testing experiment consisted on subjecting the relay to different types of faults (symmetrical and asymmetrical) for RCA=45° and emphasizing on the correct was to set the relay to obtain correct results. The final results showed that in case of a wrong setting, the relay will underperform and malfunction, this showcases the importance of the directional and non-directional setting.

The second part of the test consisted on subjecting the relay to different types of faults under RCA limits (RCA=40° and RCA=65°). The results obtained are compared to the results of the 45° RCA test. The compresence proves that the relay behaviour and quality performance is heavily influenced by the RCA setting. It will show the best and fast and the most sensitive and accurate performance under 45° RCA. The closer RCA was to the relay's setting limits, the higher the risk of obtaining nuisance tripping of such protective elements.

The testing procedure followed in this thesis was carefully explained step by step, in order to provide fundamental knowledge in testing the directional function of the ABB REL670 IED, as well refer to the results found and discussed in this last.

FUTURE WORK:

A future work will cover the coordination of the directional phase overcurrent protection relay with another protection type like the distance protection which is used for protecting transmission lines. It should also include an application of the presented methodology with specific cases for the evaluation of the RCA setting but with different relay functions, that can be named as “The neutral directional overcurrent and ground protection”, which are used to protect capacitive feeders with a capacitive current of the same order of magnitude as earthing fault current.

Besides this thesis, which is mainly a technical one, another simplified guide should be done to cover all the directional overcurrent protection types (67P,67N,67G,67Ns,67Q).

References:

[1] Power System Relaying Committee: “Performance of Generator Protection During Major System Disturbances”, IEEE Transactions in Power Delivery, 2003.

[2] Power System Relay Committee: “Coordination of Generator Protection with Generator Excitation Control and Generator Capability”, IEEE Power Engineering Society General Meeting, 2007.

[3] Dr M. Electrical, "power system grid", 2020. [Online]. Available: http://electrical-engineering-course.blogspot.com/2011/06/power-system-grid.html, [Accessed: 20- Feb-2020]

[4] B. Ummels, *wind integration; Power System Operation with Large-Scale Wind Power in Liberalised Environments*. Netherlands, 2009.

[5] P. BERTRAND, *Directional Protection Equipment*. France, 2020.

[6] “What are the Different Types of Faults in Power System - Circuit Globe", *Circuit Globe*, 2020. [Online]. Available : https://circuitglobe.com/types-of-faults-in-power-system.html, [Accessed : 12- Mar- 2020].

[7] A. Al Ameri, “Méthodes analytiques d’étude pour la diminution des pertes de puissance dans les réseaux électriques maillés en utilisant des techniques d’optimisation pour le dimensionnement et l’emplacement des générateurs décentralisés”, Normandie Université, France, 2017.

[8] K. Andrew, "Integration of Distributed Generation", The National University of Ireland, Ireland, Jan. 2007.

[9] "Wisconsin Fundamentals of Electricity", *C03.apogee.net*, 2020. [Online]. Available: https://c03.apogee.net/mvc/home/hes/land/el?spc=foe&id=4481&utilityname=wppi, [Accessed: 02- Feb- 2020].

[10] "What are the Different Types of Faults in Power System? - Circuit Globe", *Circuit Globe*, 2020. [Online]. Available: https://circuitglobe.com/types-of-faults-in-power-system.html, [Accessed: 15- Mar- 2020].

[11] "Types of Faults in Electrical Power Systems", *Electronics Hub*, 2015. [Online]. Available : https://www.electronicshub.org/types-of-faults-in-electrical-power-systems/, [Accessed : 24- Mar- 2020].

[12] "Electrical Power Systems", *Electronics Hub*, 2020. [Online]. Available: https://www.electronicshub.org, [Accessed: 30- Nov- 2020].

[13] "Short Circuit - Causes and Effects", *StudyElectrical.Com*, 2018. [Online]. Available:https://studyelectrical.com/2016/03/short-circuit-causes-and-effects-application.html# : ~ :text=by%20public%20etc.-, Effects%20of%20Short%2DCircuit, result%20in%20fire%20or%20explosion. [Accessed : 25- Mar- 2020].

[14] "Short Circuit in Power System | Short Circuit Currents | Faults in Power System", *EEEGUIDE.COM*, 2018. [Online]. Available : https://www.eeeguide.com/short-circuit-in-power-system, [Accessed : 22- Mar- 2020].

[15] E. Csanyi, "Arriving at the scene of a power substation fire. What to do?", *EEP - Electrical Engineering Portal*, 2014. [Online]. Available: https://electrical-engineering-portal.com/arriving-at-the-scene-of-a-power-substation-fire-what-to-do. [Accessed: 19- Apr- 2020].

[16] F. ALAM, S. SAIF, H. ALI, “Short Circuit Current Calculation and Prevention in High Voltage Power nets “, Karlskrona, Sweden, June 2014.

[17] E.A. DYRSTAD, “Relay Lab at NTNU”, Norwegian University of Science and Technology, June 2014

[18] P.M. Anderson: *Power System Protection,* John Wiley & Sons, Inc., New York, 1999.

[19] Yu-Ting Huang, “Investigating The Performance of Generator Protection Relays Using a Real-Time Simulator”, University of KwaZulu-Natal, Durban, South Africa, November 2013.

[20] A. Gomez, A. Conejo, C. Canizares: *Electric Energy Systems Analysis and Operation*, Taylor and Francis Group, LLC, 2009

[21] GE Digital Energy, *Instrument Transformer Basic Technical Information and Application*. Florida, USA, 2014.

[22] "Electrical Protection Device - Types of Circuit Protection Devices", *ElProCus - Electronic Projects for Engineering Students*, 2020. [Online]. Available:

https://www.elprocus.com/what-is-a-protection-device-different-types-of-protection-devices/, [Accessed: 15- Apr- 2020].

[23] A. Wright and C. Christopoulos: *Electrical Power System Protection. Chapman & Hall*, First edition, 1993.

[24] J. A. Martínez-Velasco, J. Martín-Arnedo, and F. CastroAranda. “Modeling Protective Devices for Distribution Systems with Distributed Generation Using an EMTP-Type Tool”, August 2010.

[25] "Fundamentals of recloser | Eaton", *Eaton*, 2020. [Online]. Available: https://www.eaton.com/us/en-us/products/medium-voltage-power-distribution-control-systems/reclosers/reclosers--fundamentals-of-reclosers.html. [Accessed: 15- Apr- 2020].

[26] E. Csanyi, "4 Factors To Consider When Selecting a Sectionalizer | EEP", *EEP - Electrical Engineering Portal*, 2015. [Online]. Available: https://electrical-engineering-portal.com/4-factors-to-consider-when-selecting-a-sectionalizer. [Accessed: 16- Apr- 2020].

[27] B. Heffernan, J. Donev, J. Toor, K. Stenhouse, J. Hanania and J. Jenden, "Electrical safety devices - Energy Education", *Energyeducation.ca*, 2020. [Online]. Available: https://energyeducation.ca/encyclopedia/Electrical_safety_devices, [Accessed: 28- Jun- 2020].

[28] SEL, *Differential protection principle*. 2018.

[29] "TRANSMISSION LINES DISTANCE RELAY BASICS AND TUTORIALS", *Transmission-line.net*, 2020. [Online]. Available: http://www.transmission-line.net/2012/03/transmission-lines-distance-relay.html, [Accessed: 18- Jun- 2020].

[30] G. Ziegler, “Numerical Distance Protection principles and applications”, Berlin: Siemens, 2008.

[31] G. Baruti, "The Basics of Overcurrent Protection", in *Razdelilna in industrijska omrežja*, 2020, pp. 9-11

[32] B. Bridger, “Directional Overcurrent and Directional Power Relays”, [Online]. Available: http://www.powellind.com, May 24,1991.

[33] E. Csanyi, “Protection Relay ANSI Standards”. [Online]. Available : https://electrical-engineering-portal.com, June 2020

[34] “ANSI Standard Device Numbers & Common Acronyms”. [Online]. Available: https://www.gegridsolutions.com.

[35] Anonymous Source: “CHAPTER 3: A NEW DIRECTIONAL OVER CURRENT RELAYING SCHEME FOR DISTRIBUTION FEEDERS IN THE PRESENCE OF DG”.

[36] J. Horak, "Directional Overcurrent Relaying (67) Concepts", *Myprotectionguide.com*, 2001. [Online]. Available: https://www.myprotectionguide.com/uploads/7/3/0/1/73017921/directionaloc.pdf. [Accessed: 12- July- 2020].

[37] K. Zimmerman and D. Costello, "Fundamentals and Improvements for Directional Relays", in *37th Annual Western Protective Relay Conference*, Texas, 2010.

[38] The staff of Festo Didactic, *Electricity and New Energy Directional Protection courseware sample*, 1st ed. Quebec, Canada: www.festo-didactic.com, 2016.

[39] P. BERTRAND, *Directional Protection Equipment*. France, 2020. (Applications), Available: https://www.studiecd.dk/cahiers_techniques/Directional_protection_equipment.pdf.

[40] R. Hughes, "Directional protection characteristic angle", *Ideology.atlassian.net*, 2020. [Online]. Available:https://ideology.atlassian.net/wiki/spaces/AP/pages/32604170/Directional+protection+characteristic+angle. [Accessed: 20- Apr- 2020].

[41] J. López-Lezama and J. Serna, "Alternative Methodology to Calculate the Directional Characteristic Settings of Directional Overcurrent Relays in Transmission and Distribution Networks". Colombia, 2019. [Online] Available : https://www.mdpi.com/1996-1073/12/19/3779/htm.

[42] R. Hughes, "Rod Hughes Consulting Pty Ltd", *Ideology.atlassian.net*, 2020. [Online]. Available:https://ideology.atlassian.net/wiki/spaces/AP/pages/32604170/Directional+protection+characteristic+angle, [Accessed: 21- Jul- 2020]

[43] “CURRENT, VOLTAGE, DIRECTIONAL, CURRENT (OR VOLTAGE)-BALANCE, AND DIFFERENTIAL RELAYS” [Online]. Available : https://www.gegridsolutions.com/multilin/notes/artsci/art03.pdf.

[44] J. Appleyard and Power Systems Relaying Committee, *Considerations in Choosing Directional Polarizing Methods for Ground Overcurrent Elements in Line Protection Applications*. May 2015.

[45] "Directional Over Current Relay [67]: Numerical Relays", *ELECTRICAL ENGINEERING MATERIALS*, 2019. [Online]. Available: https://electengmaterials.com/directional-over-current-relay-67/, [Accessed: 05- Jul- 2020].

[46] V. Lackovic, "E-058 Protection Relay Testing and Commissioning", Mexico, 2020.

[47] *Type Testing Offer Safety and Reliability*, 1st ed. Schneider Electric, 2020, p. 495.

[48] D. Wijeratne, "Protective Relay Testing", 2020.

[49] *CMC 256plus Brochure - Omicron*. Omicron, 2020, pp. 2-3.

[50] *Line distance protection IED REL 670 pre-configured Product guide*. MEXICO: ABB, 2020, pp. 12-42.

[51] *Omicron testing solutions for protection and measurement systems- Omicron*. Omicron, 2013, p.7.

Appendix A - Symmetrical Components

three phase system line currents and voltages can be represented by a phasor sum of a balanced negative sequence vectors (ACB), a balanced positive sequence vectors (ABC), and an identical zero sequence vectors, as shown in Figure A.1. It is defined as symmetrical components.

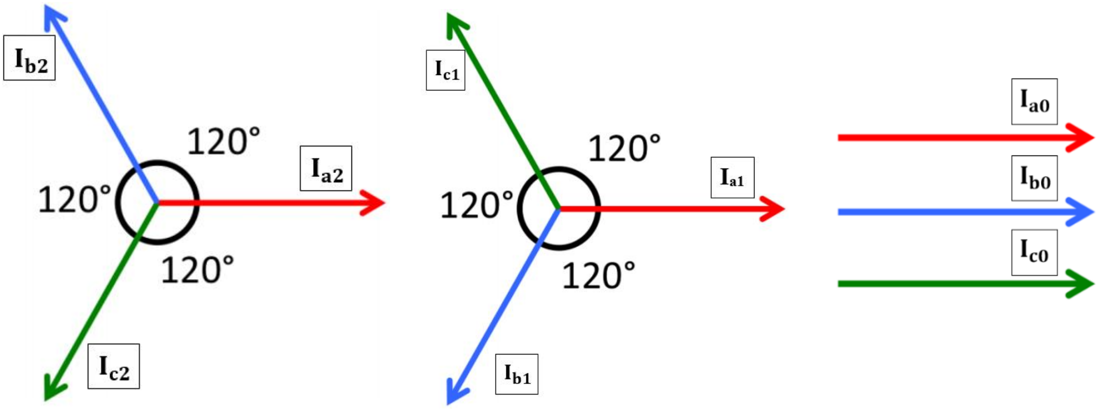


Figure A.1: Negative, Positive and Zero Sequence Vectors.

Any set of phase quantities can be converted into symmetrical components and likewise, a set of symmetrical components can also be converted into phase quantities. The sequence equations, Equation A.1 and A.2, are used to go from one representation to the other, where a is defined as 1∠120°, and a^2 is defined as 1∠240° :

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{A.1}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{A.2}$$

where $\mathrm{I_0}$, $\mathrm{I_1}$ and $\mathrm{I_2}$ are the zero sequence, positive sequence, and negative sequence currents components, respectively. While $\mathrm{I_a}$, $\mathrm{I_b}$ and $\mathrm{I_c}$ are three phase line currents components.

Appendix B - Testing Results

- ## For the case of RCA=45°:

<u>Three phase forward fault test 1 results:</u>

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2-L3	n/a	1,200 A	39,00 °	1,763 s	2,094 s	18,78 %	No	Passed
L1-L2-L3	n/a	1,300 A	39,00 °	1,224 s	1,432 s	16,99 %	No	Passed
L1-L2-L3	n/a	1,400 A	39,00 °	953,8 ms	1,122 s	17,67 %	No	Passed
L1-L2-L3	n/a	1,500 A	39,00 °	790,9 ms	932,9 ms	17,95 %	No	Passed
L1-L2-L3	n/a	1,600 A	39,00 °	681,9 ms	793,4 ms	16,35 %	No	Passed
L1-L2-L3	n/a	1,700 A	39,00 °	603,6 ms	716,3 ms	18,67 %	No	Passed
L1-L2-L3	n/a	1,800 A	39,00 °	544,6 ms	647,0 ms	18,80 %	No	Passed
L1-L2-L3	n/a	1,200 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed

L1-L2-L3	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-121,00 °	1,763 s	2,069 s	17,34 %	No	Passed
L1-L2-L3	n/a	1,300 A	-121,00 °	1,224 s	1,423 s	16,22 %	No	Passed
L1-L2-L3	n/a	1,400 A	-121,00 °	953,8 ms	1,107 s	16,03 %	No	Passed
L1-L2-L3	n/a	1,500 A	-121,00 °	790,9 ms	922,3 ms	16,61 %	No	Passed
L1-L2-L3	n/a	1,600 A	-121,00 °	681,9 ms	802,3 ms	17,66 %	No	Passed
L1-L2-L3	n/a	1,700 A	-121,00 °	603,6 ms	704,0 ms	16,63 %	No	Passed
L1-L2-L3	n/a	1,800 A	-121,00 °	544,6 ms	648,5 ms	19,08 %	No	Passed
L1-L2-L3	n/a	1,200 A	-101,00 °	1,763 s	2,069 s	17,36 %	No	Passed
L1-L2-L3	n/a	1,300 A	-101,00 °	1,224 s	1,429 s	16,70 %	No	Passed
L1-L2-L3	n/a	1,400 A	-101,00 °	953,8 ms	1,105 s	15,89 %	No	Passed
L1-L2-L3	n/a	1,500 A	-101,00 °	790,9 ms	929,0 ms	17,46 %	No	Passed
L1-L2-L3	n/a	1,600 A	-101,00 °	681,9 ms	803,5 ms	17,83 %	No	Passed
L1-L2-L3	n/a	1,700 A	-101,00 °	603,6 ms	707,4 ms	17,19 %	No	Passed
L1-L2-L3	n/a	1,800 A	-101,00 °	544,6 ms	639,2 ms	17,37 %	No	Passed
L1-L2-L3	n/a	1,200 A	-81,00 °	1,763 s	2,070 s	17,40 %	No	Passed
L1-L2-L3	n/a	1,300 A	-81,00 °	1,224 s	1,422 s	16,19 %	No	Passed
L1-L2-L3	n/a	1,400 A	-81,00 °	953,8 ms	1,108 s	16,15 %	No	Passed
L1-L2-L3	n/a	1,500 A	-81,00 °	790,9 ms	923,6 ms	16,77 %	No	Passed
L1-L2-L3	n/a	1,600 A	-81,00 °	681,9 ms	797,9 ms	17,01 %	No	Passed
L1-L2-L3	n/a	1,700 A	-81,00 °	603,6 ms	704,8 ms	16,76 %	No	Passed
L1-L2-L3	n/a	1,800 A	-81,00 °	544,6 ms	641,7 ms	17,83 %	No	Passed
L1-L2-L3	n/a	1,200 A	-61,00 °	1,763 s	2,070 s	17,41 %	No	Passed
L1-L2-L3	n/a	1,300 A	-61,00 °	1,224 s	1,423 s	16,26 %	No	Passed
L1-L2-L3	n/a	1,400 A	-61,00 °	953,8 ms	1,104 s	15,77 %	No	Passed
L1-L2-L3	n/a	1,500 A	-61,00 °	790,9 ms	925,6 ms	17,03 %	No	Passed
L1-L2-L3	n/a	1,600 A	-61,00 °	681,9 ms	796,7 ms	16,84 %	No	Passed
L1-L2-L3	n/a	1,700 A	-61,00 °	603,6 ms	709,3 ms	17,51 %	No	Passed
L1-L2-L3	n/a	1,800 A	-61,00 °	544,6 ms	639,1 ms	17,35 %	No	Passed
L1-L2-L3	n/a	1,200 A	-41,00 °	1,763 s	2,081 s	18,04 %	No	Passed
L1-L2-L3	n/a	1,300 A	-41,00 °	1,224 s	1,425 s	16,43 %	No	Passed
L1-L2-L3	n/a	1,400 A	-41,00 °	953,8 ms	1,108 s	16,19 %	No	Passed
L1-L2-L3	n/a	1,500 A	-41,00 °	790,9 ms	924,1 ms	16,84 %	No	Passed
L1-L2-L3	n/a	1,600 A	-41,00 °	681,9 ms	796,8 ms	16,85 %	No	Passed
L1-L2-L3	n/a	1,700 A	-41,00 °	603,6 ms	705,0 ms	16,80 %	No	Passed
L1-L2-L3	n/a	1,800 A	-41,00 °	544,6 ms	641,8 ms	17,85 %	No	Passed
L1-L2-L3	n/a	1,200 A	-21,00 °	1,763 s	2,078 s	17,87 %	No	Passed
L1-L2-L3	n/a	1,300 A	-21,00 °	1,224 s	1,429 s	16,76 %	No	Passed
L1-L2-L3	n/a	1,400 A	-21,00 °	953,8 ms	1,107 s	16,09 %	No	Passed
L1-L2-L3	n/a	1,500 A	-21,00 °	790,9 ms	920,2 ms	16,34 %	No	Passed
L1-L2-L3	n/a	1,600 A	-21,00 °	681,9 ms	801,3 ms	17,51 %	No	Passed
L1-L2-L3	n/a	1,700 A	-21,00 °	603,6 ms	707,2 ms	17,16 %	No	Passed
L1-L2-L3	n/a	1,800 A	-21,00 °	544,6 ms	650,7 ms	19,48 %	No	Passed
L1-L2-L3	n/a	1,200 A	-1,00 °	1,763 s	2,073 s	17,57 %	No	Passed
L1-L2-L3	n/a	1,300 A	-1,00 °	1,224 s	1,423 s	16,21 %	No	Passed
L1-L2-L3	n/a	1,400 A	-1,00 °	953,8 ms	1,104 s	15,71 %	No	Passed
L1-L2-L3	n/a	1,500 A	-1,00 °	790,9 ms	924,7 ms	16,91 %	No	Passed
L1-L2-L3	n/a	1,600 A	-1,00 °	681,9 ms	801,7 ms	17,57 %	No	Passed

L1-L2-L3	n/a	1,700 A	-1,00 °	603,6 ms	703,3 ms	16,51 %	No	Passed
L1-L2-L3	n/a	1,800 A	-1,00 °	544,6 ms	639,8 ms	17,48 %	No	Passed
L1-L2-L3	n/a	1,200 A	19,00 °	1,763 s	2,083 s	18,14 %	No	Passed
L1-L2-L3	n/a	1,300 A	19,00 °	1,224 s	1,424 s	16,32 %	No	Passed
L1-L2-L3	n/a	1,400 A	19,00 °	953,8 ms	1,114 s	16,83 %	No	Passed
L1-L2-L3	n/a	1,500 A	19,00 °	790,9 ms	920,2 ms	16,34 %	No	Passed
L1-L2-L3	n/a	1,600 A	19,00 °	681,9 ms	794,8 ms	16,56 %	No	Passed
L1-L2-L3	n/a	1,700 A	19,00 °	603,6 ms	707,2 ms	17,16 %	No	Passed
L1-L2-L3	n/a	1,800 A	19,00 °	544,6 ms	636,0 ms	16,78 %	No	Passed

Table B.1: Three Phase Fault test 1 Result using RCA=45°

<u>Three phase forward fault test 2 results</u>:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2-L3	n/a	1,200 A	39,00 °	1,763 s	2,081 s	18,05 %	No	Passed
L1-L2-L3	n/a	1,300 A	39,00 °	1,224 s	1,417 s	15,73 %	No	Passed
L1-L2-L3	n/a	1,400 A	39,00 °	953,8 ms	1,102 s	15,50 %	No	Passed
L1-L2-L3	n/a	1,500 A	39,00 °	790,9 ms	905,6 ms	14,50 %	No	Passed
L1-L2-L3	n/a	1,600 A	39,00 °	681,9 ms	778,9 ms	14,23 %	No	Passed
L1-L2-L3	n/a	1,700 A	39,00 °	603,6 ms	686,2 ms	13,68 %	No	Passed
L1-L2-L3	n/a	1,800 A	39,00 °	544,6 ms	632,6 ms	16,16 %	No	Passed
L1-L2-L3	n/a	1,200 A	59,00 °	No trip	2,068 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	59,00 °	No trip	1,416 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	59,00 °	No trip	1,096 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	59,00 °	No trip	903,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	59,00 °	No trip	779,0 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	59,00 °	No trip	697,0 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	59,00 °	No trip	627,1 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	79,00 °	No trip	2,055 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	79,00 °	No trip	1,404 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	79,00 °	No trip	1,085 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	79,00 °	No trip	909,0 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	79,00 °	No trip	785,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	79,00 °	No trip	685,1 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	79,00 °	No trip	631,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	99,00 °	No trip	2,060 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	99,00 °	No trip	1,407 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	99,00 °	No trip	1,094 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	99,00 °	No trip	910,8 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	99,00 °	No trip	779,4 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	99,00 °	No trip	690,8 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	99,00 °	No trip	624,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	119,00 °	No trip	2,055 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	119,00 °	No trip	1,405 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	119,00 °	No trip	1,097 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	119,00 °	No trip	905,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	119,00 °	No trip	778,4 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	119,00 °	No trip	689,8 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	119,00 °	No trip	621,1 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	139,00 °	No trip	2,062 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	139,00 °	No trip	1,409 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	139,00 °	No trip	1,091 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	139,00 °	No trip	903,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	139,00 °	No trip	780,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	139,00 °	No trip	686,0 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	139,00 °	No trip	622,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	159,00 °	No trip	2,060 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	159,00 °	No trip	1,409 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	159,00 °	No trip	1,092 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	159,00 °	No trip	903,4 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	159,00 °	No trip	785,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	159,00 °	No trip	691,0 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	159,00 °	No trip	620,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	179,00 °	No trip	2,054 s	n/a	No	Failed

L1-L2-L3	n/a	1,300 A	179,00 °	No trip	1,407 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	179,00 °	No trip	1,091 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	179,00 °	No trip	902,7 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	179,00 °	No trip	781,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	179,00 °	No trip	691,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	179,00 °	No trip	623,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	-161,00 °	No trip	2,059 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	-161,00 °	No trip	1,411 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	-161,00 °	No trip	1,101 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	-161,00 °	No trip	908,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	-161,00 °	No trip	782,8 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	-161,00 °	No trip	689,7 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	-161,00 °	No trip	619,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	-141,00 °	No trip	2,055 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	-141,00 °	No trip	1,405 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	-141,00 °	No trip	1,089 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	-141,00 °	No trip	907,2 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	-141,00 °	No trip	781,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	-141,00 °	No trip	685,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	-141,00 °	No trip	622,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	-121,00 °	1,763 s	2,054 s	16,50 %	No	Passed
L1-L2-L3	n/a	1,300 A	-121,00 °	1,224 s	1,411 s	15,27 %	No	Passed
L1-L2-L3	n/a	1,400 A	-121,00 °	953,8 ms	1,085 s	13,75 %	No	Passed
L1-L2-L3	n/a	1,500 A	-121,00 °	790,9 ms	903,1 ms	14,18 %	No	Passed
L1-L2-L3	n/a	1,600 A	-121,00 °	681,9 ms	778,1 ms	14,11 %	No	Passed
L1-L2-L3	n/a	1,700 A	-121,00 °	603,6 ms	690,3 ms	14,36 %	No	Passed
L1-L2-L3	n/a	1,800 A	-121,00 °	544,6 ms	622,7 ms	14,34 %	No	Passed
L1-L2-L3	n/a	1,200 A	-101,00 °	1,763 s	2,061 s	16,89 %	No	Passed
L1-L2-L3	n/a	1,300 A	-101,00 °	1,224 s	1,402 s	14,57 %	No	Passed
L1-L2-L3	n/a	1,400 A	-101,00 °	953,8 ms	1,091 s	14,38 %	No	Passed
L1-L2-L3	n/a	1,500 A	-101,00 °	790,9 ms	908,8 ms	14,90 %	No	Passed
L1-L2-L3	n/a	1,600 A	-101,00 °	681,9 ms	780,4 ms	14,45 %	No	Passed
L1-L2-L3	n/a	1,700 A	-101,00 °	603,6 ms	690,4 ms	14,38 %	No	Passed
L1-L2-L3	n/a	1,800 A	-101,00 °	544,6 ms	623,6 ms	14,51 %	No	Passed
L1-L2-L3	n/a	1,200 A	-81,00 °	1,763 s	2,054 s	16,53 %	No	Passed
L1-L2-L3	n/a	1,300 A	-81,00 °	1,224 s	1,404 s	14,71 %	No	Passed
L1-L2-L3	n/a	1,400 A	-81,00 °	953,8 ms	1,087 s	13,93 %	No	Passed
L1-L2-L3	n/a	1,500 A	-81,00 °	790,9 ms	907,1 ms	14,69 %	No	Passed
L1-L2-L3	n/a	1,600 A	-81,00 °	681,9 ms	778,0 ms	14,10 %	No	Passed
L1-L2-L3	n/a	1,700 A	-81,00 °	603,6 ms	691,5 ms	14,56 %	No	Passed
L1-L2-L3	n/a	1,800 A	-81,00 °	544,6 ms	621,1 ms	14,05 %	No	Passed
L1-L2-L3	n/a	1,200 A	-61,00 °	1,763 s	2,058 s	16,72 %	No	Passed
L1-L2-L3	n/a	1,300 A	-61,00 °	1,224 s	1,403 s	14,64 %	No	Passed
L1-L2-L3	n/a	1,400 A	-61,00 °	953,8 ms	1,093 s	14,59 %	No	Passed
L1-L2-L3	n/a	1,500 A	-61,00 °	790,9 ms	902,9 ms	14,16 %	No	Passed
L1-L2-L3	n/a	1,600 A	-61,00 °	681,9 ms	783,7 ms	14,93 %	No	Passed
L1-L2-L3	n/a	1,700 A	-61,00 °	603,6 ms	689,2 ms	14,18 %	No	Passed
L1-L2-L3	n/a	1,800 A	-61,00 °	544,6 ms	621,6 ms	14,14 %	No	Passed
L1-L2-L3	n/a	1,200 A	-41,00 °	1,763 s	2,058 s	16,74 %	No	Passed
L1-L2-L3	n/a	1,300 A	-41,00 °	1,224 s	1,409 s	15,11 %	No	Passed
L1-L2-L3	n/a	1,400 A	-41,00 °	953,8 ms	1,099 s	15,18 %	No	Passed
L1-L2-L3	n/a	1,500 A	-41,00 °	790,9 ms	905,7 ms	14,51 %	No	Passed
L1-L2-L3	n/a	1,600 A	-41,00 °	681,9 ms	783,0 ms	14,83 %	No	Passed
L1-L2-L3	n/a	1,700 A	-41,00 °	603,6 ms	685,7 ms	13,60 %	No	Passed
L1-L2-L3	n/a	1,800 A	-41,00 °	544,6 ms	618,5 ms	13,57 %	No	Passed
L1-L2-L3	n/a	1,200 A	-21,00 °	1,763 s	2,053 s	16,44 %	No	Passed
L1-L2-L3	n/a	1,300 A	-21,00 °	1,224 s	1,403 s	14,62 %	No	Passed
L1-L2-L3	n/a	1,400 A	-21,00 °	953,8 ms	1,087 s	13,95 %	No	Passed
L1-L2-L3	n/a	1,500 A	-21,00 °	790,9 ms	909,0 ms	14,93 %	No	Passed
L1-L2-L3	n/a	1,600 A	-21,00 °	681,9 ms	776,2 ms	13,83 %	No	Passed
L1-L2-L3	n/a	1,700 A	-21,00 °	603,6 ms	686,2 ms	13,68 %	No	Passed
L1-L2-L3	n/a	1,800 A	-21,00 °	544,6 ms	620,9 ms	14,01 %	No	Passed
L1-L2-L3	n/a	1,200 A	-1,00 °	1,763 s	2,054 s	16,49 %	No	Passed
L1-L2-L3	n/a	1,300 A	-1,00 °	1,224 s	1,408 s	15,04 %	No	Passed
L1-L2-L3	n/a	1,400 A	-1,00 °	953,8 ms	1,090 s	14,29 %	No	Passed

L1-L2-L3	n/a	1,500 A	-1,00 °	790,9 ms	903,9 ms	14,28 %	No	Passed
L1-L2-L3	n/a	1,600 A	-1,00 °	681,9 ms	781,8 ms	14,65 %	No	Passed
L1-L2-L3	n/a	1,700 A	-1,00 °	603,6 ms	693,1 ms	14,83 %	No	Passed
L1-L2-L3	n/a	1,800 A	-1,00 °	544,6 ms	624,0 ms	14,58 %	No	Passed
L1-L2-L3	n/a	1,200 A	19,00 °	1,763 s	2,062 s	16,98 %	No	Passed
L1-L2-L3	n/a	1,300 A	19,00 °	1,224 s	1,405 s	14,76 %	No	Passed
L1-L2-L3	n/a	1,400 A	19,00 °	953,8 ms	1,093 s	14,56 %	No	Passed
L1-L2-L3	n/a	1,500 A	19,00 °	790,9 ms	902,1 ms	14,06 %	No	Passed
L1-L2-L3	n/a	1,600 A	19,00 °	681,9 ms	780,0 ms	14,39 %	No	Passed
L1-L2-L3	n/a	1,700 A	19,00 °	603,6 ms	692,4 ms	14,71 %	No	Passed
L1-L2-L3	n/a	1,800 A	19,00 °	544,6 ms	631,8 ms	16,01 %	No	Passed

Table B.2: Three Phase Fault Test 2 result using RCA=45°

Phase to phase forward fault test results:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2	n/a	1,200 A	39,00 °	1,763 s	2,109 s	19,61 %	No	Passed
L1-L2	n/a	1,300 A	39,00 °	1,224 s	1,452 s	18,62 %	No	Passed
L1-L2	n/a	1,400 A	39,00 °	953,8 ms	1,135 s	19,04 %	No	Passed
L1-L2	n/a	1,500 A	39,00 °	790,9 ms	927,8 ms	17,30 %	No	Passed
L1-L2	n/a	1,600 A	39,00 °	681,9 ms	813,2 ms	19,26 %	No	Passed
L1-L2	n/a	1,700 A	39,00 °	603,6 ms	726,2 ms	20,31 %	No	Passed
L1-L2	n/a	1,800 A	39,00 °	544,6 ms	645,9 ms	18,60 %	No	Passed
L1-L2	n/a	1,200 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed

L1-L2	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-121,00 °	1,763 s	2,056 s	16,60 %	No	Passed
L1-L2	n/a	1,300 A	-121,00 °	1,224 s	1,419 s	15,90 %	No	Passed
L1-L2	n/a	1,400 A	-121,00 °	953,8 ms	1,107 s	16,10 %	No	Passed
L1-L2	n/a	1,500 A	-121,00 °	790,9 ms	921,0 ms	16,44 %	No	Passed
L1-L2	n/a	1,600 A	-121,00 °	681,9 ms	797,7 ms	16,98 %	No	Passed
L1-L2	n/a	1,700 A	-121,00 °	603,6 ms	712,2 ms	17,99 %	No	Passed
L1-L2	n/a	1,800 A	-121,00 °	544,6 ms	644,9 ms	18,42 %	No	Passed
L1-L2	n/a	1,200 A	-101,00 °	1,763 s	2,068 s	17,33 %	No	Passed
L1-L2	n/a	1,300 A	-101,00 °	1,224 s	1,423 s	16,22 %	No	Passed
L1-L2	n/a	1,400 A	-101,00 °	953,8 ms	1,111 s	16,53 %	No	Passed
L1-L2	n/a	1,500 A	-101,00 °	790,9 ms	924,8 ms	16,93 %	No	Passed
L1-L2	n/a	1,600 A	-101,00 °	681,9 ms	797,4 ms	16,94 %	No	Passed
L1-L2	n/a	1,700 A	-101,00 °	603,6 ms	707,6 ms	17,23 %	No	Passed
L1-L2	n/a	1,800 A	-101,00 °	544,6 ms	641,4 ms	17,77 %	No	Passed
L1-L2	n/a	1,200 A	-81,00 °	1,763 s	2,056 s	16,63 %	No	Passed
L1-L2	n/a	1,300 A	-81,00 °	1,224 s	1,420 s	16,03 %	No	Passed
L1-L2	n/a	1,400 A	-81,00 °	953,8 ms	1,111 s	16,52 %	No	Passed
L1-L2	n/a	1,500 A	-81,00 °	790,9 ms	924,8 ms	16,93 %	No	Passed
L1-L2	n/a	1,600 A	-81,00 °	681,9 ms	797,5 ms	16,96 %	No	Passed
L1-L2	n/a	1,700 A	-81,00 °	603,6 ms	705,3 ms	16,85 %	No	Passed
L1-L2	n/a	1,800 A	-81,00 °	544,6 ms	642,6 ms	17,99 %	No	Passed
L1-L2	n/a	1,200 A	-61,00 °	1,763 s	2,057 s	16,67 %	No	Passed
L1-L2	n/a	1,300 A	-61,00 °	1,224 s	1,412 s	15,33 %	No	Passed
L1-L2	n/a	1,400 A	-61,00 °	953,8 ms	1,104 s	15,76 %	No	Passed
L1-L2	n/a	1,500 A	-61,00 °	790,9 ms	926,3 ms	17,11 %	No	Passed
L1-L2	n/a	1,600 A	-61,00 °	681,9 ms	797,6 ms	16,97 %	No	Passed
L1-L2	n/a	1,700 A	-61,00 °	603,6 ms	704,1 ms	16,65 %	No	Passed
L1-L2	n/a	1,800 A	-61,00 °	544,6 ms	636,5 ms	16,87 %	No	Passed
L1-L2	n/a	1,200 A	-41,00 °	1,763 s	2,068 s	17,29 %	No	Passed
L1-L2	n/a	1,300 A	-41,00 °	1,224 s	1,416 s	15,68 %	No	Passed
L1-L2	n/a	1,400 A	-41,00 °	953,8 ms	1,107 s	16,08 %	No	Passed
L1-L2	n/a	1,500 A	-41,00 °	790,9 ms	921,1 ms	16,46 %	No	Passed
L1-L2	n/a	1,600 A	-41,00 °	681,9 ms	794,3 ms	16,49 %	No	Passed
L1-L2	n/a	1,700 A	-41,00 °	603,6 ms	705,4 ms	16,86 %	No	Passed
L1-L2	n/a	1,800 A	-41,00 °	544,6 ms	636,5 ms	16,87 %	No	Passed
L1-L2	n/a	1,200 A	-21,00 °	1,763 s	2,065 s	17,16 %	No	Passed
L1-L2	n/a	1,300 A	-21,00 °	1,224 s	1,413 s	15,43 %	No	Passed
L1-L2	n/a	1,400 A	-21,00 °	953,8 ms	1,110 s	16,33 %	No	Passed
L1-L2	n/a	1,500 A	-21,00 °	790,9 ms	921,5 ms	16,51 %	No	Passed
L1-L2	n/a	1,600 A	-21,00 °	681,9 ms	795,9 ms	16,72 %	No	Passed
L1-L2	n/a	1,700 A	-21,00 °	603,6 ms	705,7 ms	16,91 %	No	Passed
L1-L2	n/a	1,800 A	-21,00 °	544,6 ms	642,1 ms	17,90 %	No	Passed
L1-L2	n/a	1,200 A	-1,00 °	1,763 s	2,066 s	17,20 %	No	Passed

L1-L2	n/a	1,300 A	-1,00 °	1,224 s	1,413 s	15,43 %	No	Passed
L1-L2	n/a	1,400 A	-1,00 °	953,8 ms	1,105 s	15,90 %	No	Passed
L1-L2	n/a	1,500 A	-1,00 °	790,9 ms	917,7 ms	16,03 %	No	Passed
L1-L2	n/a	1,600 A	-1,00 °	681,9 ms	795,1 ms	16,60 %	No	Passed
L1-L2	n/a	1,700 A	-1,00 °	603,6 ms	705,2 ms	16,83 %	No	Passed
L1-L2	n/a	1,800 A	-1,00 °	544,6 ms	640,1 ms	17,53 %	No	Passed
L1-L2	n/a	1,200 A	19,00 °	1,763 s	2,060 s	16,86 %	No	Passed
L1-L2	n/a	1,300 A	19,00 °	1,224 s	1,426 s	16,45 %	No	Passed
L1-L2	n/a	1,400 A	19,00 °	953,8 ms	1,109 s	16,26 %	No	Passed
L1-L2	n/a	1,500 A	19,00 °	790,9 ms	925,3 ms	16,99 %	No	Passed
L1-L2	n/a	1,600 A	19,00 °	681,9 ms	795,5 ms	16,66 %	No	Passed
L1-L2	n/a	1,700 A	19,00 °	603,6 ms	706,4 ms	17,03 %	No	Passed
L1-L2	n/a	1,800 A	19,00 °	544,6 ms	639,5 ms	17,42 %	No	Passed

Table B.3: Phase to Phase Fault Test Result using RCA=45°

Phase to Ground forward fault test results:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-E	n/a	1,200 A	39,00 °	1,763 s	2,180 s	23,65 %	No	Passed
L1-E	n/a	1,300 A	39,00 °	1,224 s	1,441 s	17,69 %	No	Passed
L1-E	n/a	1,400 A	39,00 °	953,8 ms	1,121 s	17,53 %	No	Passed
L1-E	n/a	1,500 A	39,00 °	790,9 ms	930,4 ms	17,63 %	No	Passed
L1-E	n/a	1,600 A	39,00 °	681,9 ms	801,8 ms	17,59 %	No	Passed
L1-E	n/a	1,700 A	39,00 °	603,6 ms	719,6 ms	19,22 %	No	Passed
L1-E	n/a	1,800 A	39,00 °	544,6 ms	658,7 ms	20,95 %	No	Passed
L1-E	n/a	1,200 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed

L1-E	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-121,00 °	1,763 s	2,073 s	17,61 %	No	Passed
L1-E	n/a	1,300 A	-121,00 °	1,224 s	1,420 s	15,96 %	No	Passed
L1-E	n/a	1,400 A	-121,00 °	953,8 ms	1,107 s	16,09 %	No	Passed
L1-E	n/a	1,500 A	-121,00 °	790,9 ms	926,7 ms	17,17 %	No	Passed
L1-E	n/a	1,600 A	-121,00 °	681,9 ms	797,3 ms	16,93 %	No	Passed
L1-E	n/a	1,700 A	-121,00 °	603,6 ms	709,2 ms	17,49 %	No	Passed
L1-E	n/a	1,800 A	-121,00 °	544,6 ms	641,4 ms	17,77 %	No	Passed
L1-E	n/a	1,200 A	-101,00 °	1,763 s	2,078 s	17,89 %	No	Passed
L1-E	n/a	1,300 A	-101,00 °	1,224 s	1,423 s	16,23 %	No	Passed
L1-E	n/a	1,400 A	-101,00 °	953,8 ms	1,106 s	15,97 %	No	Passed
L1-E	n/a	1,500 A	-101,00 °	790,9 ms	919,9 ms	16,31 %	No	Passed
L1-E	n/a	1,600 A	-101,00 °	681,9 ms	798,7 ms	17,13 %	No	Passed
L1-E	n/a	1,700 A	-101,00 °	603,6 ms	709,4 ms	17,53 %	No	Passed
L1-E	n/a	1,800 A	-101,00 °	544,6 ms	642,0 ms	17,88 %	No	Passed
L1-E	n/a	1,200 A	-81,00 °	1,763 s	2,080 s	18,01 %	No	Passed
L1-E	n/a	1,300 A	-81,00 °	1,224 s	1,426 s	16,52 %	No	Passed
L1-E	n/a	1,400 A	-81,00 °	953,8 ms	1,104 s	15,74 %	No	Passed
L1-E	n/a	1,500 A	-81,00 °	790,9 ms	919,4 ms	16,24 %	No	Passed
L1-E	n/a	1,600 A	-81,00 °	681,9 ms	798,6 ms	17,12 %	No	Passed
L1-E	n/a	1,700 A	-81,00 °	603,6 ms	707,9 ms	17,28 %	No	Passed
L1-E	n/a	1,800 A	-81,00 °	544,6 ms	638,9 ms	17,31 %	No	Passed
L1-E	n/a	1,200 A	-61,00 °	1,763 s	2,081 s	18,03 %	No	Passed
L1-E	n/a	1,300 A	-61,00 °	1,224 s	1,425 s	16,43 %	No	Passed
L1-E	n/a	1,400 A	-61,00 °	953,8 ms	1,104 s	15,70 %	No	Passed
L1-E	n/a	1,500 A	-61,00 °	790,9 ms	923,4 ms	16,75 %	No	Passed
L1-E	n/a	1,600 A	-61,00 °	681,9 ms	800,4 ms	17,38 %	No	Passed
L1-E	n/a	1,700 A	-61,00 °	603,6 ms	708,7 ms	17,41 %	No	Passed
L1-E	n/a	1,800 A	-61,00 °	544,6 ms	636,0 ms	16,78 %	No	Passed
L1-E	n/a	1,200 A	-41,00 °	1,763 s	2,073 s	17,59 %	No	Passed
L1-E	n/a	1,300 A	-41,00 °	1,224 s	1,420 s	16,01 %	No	Passed
L1-E	n/a	1,400 A	-41,00 °	953,8 ms	1,102 s	15,57 %	No	Passed
L1-E	n/a	1,500 A	-41,00 °	790,9 ms	927,0 ms	17,20 %	No	Passed
L1-E	n/a	1,600 A	-41,00 °	681,9 ms	793,1 ms	16,31 %	No	Passed
L1-E	n/a	1,700 A	-41,00 °	603,6 ms	702,4 ms	16,37 %	No	Passed
L1-E	n/a	1,800 A	-41,00 °	544,6 ms	637,9 ms	17,13 %	No	Passed
L1-E	n/a	1,200 A	-21,00 °	1,763 s	2,069 s	17,35 %	No	Passed
L1-E	n/a	1,300 A	-21,00 °	1,224 s	1,431 s	16,90 %	No	Passed
L1-E	n/a	1,400 A	-21,00 °	953,8 ms	1,114 s	16,82 %	No	Passed
L1-E	n/a	1,500 A	-21,00 °	790,9 ms	921,8 ms	16,55 %	No	Passed
L1-E	n/a	1,600 A	-21,00 °	681,9 ms	792,6 ms	16,24 %	No	Passed
L1-E	n/a	1,700 A	-21,00 °	603,6 ms	707,2 ms	17,16 %	No	Passed

L1-E	n/a	1,800 A	-21,00 °	544,6 ms	636,4 ms	16,86 %	No	Passed
L1-E	n/a	1,200 A	-1,00 °	1,763 s	2,076 s	17,76 %	No	Passed
L1-E	n/a	1,300 A	-1,00 °	1,224 s	1,424 s	16,29 %	No	Passed
L1-E	n/a	1,400 A	-1,00 °	953,8 ms	1,103 s	15,59 %	No	Passed
L1-E	n/a	1,500 A	-1,00 °	790,9 ms	925,7 ms	17,04 %	No	Passed
L1-E	n/a	1,600 A	-1,00 °	681,9 ms	795,6 ms	16,68 %	No	Passed
L1-E	n/a	1,700 A	-1,00 °	603,6 ms	709,8 ms	17,59 %	No	Passed
L1-E	n/a	1,800 A	-1,00 °	544,6 ms	641,4 ms	17,77 %	No	Passed
L1-E	n/a	1,200 A	19,00 °	1,763 s	2,072 s	17,51 %	No	Passed
L1-E	n/a	1,300 A	19,00 °	1,224 s	1,430 s	16,79 %	No	Passed
L1-E	n/a	1,400 A	19,00 °	953,8 ms	1,105 s	15,85 %	No	Passed

Table B.4: Single Phase to Earth Fault Test Result using RCA=45°

- ## For the case of RCA=40°:

Three phase forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2-L3	n/a	1,200 A	39,00 °	No trip	2,090 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	39,00 °	No trip	1,431 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	39,00 °	No trip	1,109 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	39,00 °	No trip	923,2 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	39,00 °	No trip	800,3 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	39,00 °	No trip	705,4 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	39,00 °	No trip	644,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed

L1-L2-L3	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-121,00 °	1,763 s	2,069 s	17,34 %	No	Passed
L1-L2-L3	n/a	1,300 A	-121,00 °	1,224 s	1,434 s	17,14 %	No	Passed
L1-L2-L3	n/a	1,400 A	-121,00 °	953,8 ms	1,107 s	16,01 %	No	Passed
L1-L2-L3	n/a	1,500 A	-121,00 °	790,9 ms	925,2 ms	16,98 %	No	Passed
L1-L2-L3	n/a	1,600 A	-121,00 °	681,9 ms	802,7 ms	17,72 %	No	Passed
L1-L2-L3	n/a	1,700 A	-121,00 °	603,6 ms	710,6 ms	17,72 %	No	Passed
L1-L2-L3	n/a	1,800 A	-121,00 °	544,6 ms	652,1 ms	19,74 %	No	Passed
L1-L2-L3	n/a	1,200 A	-101,00 °	1,763 s	2,074 s	17,65 %	No	Passed
L1-L2-L3	n/a	1,300 A	-101,00 °	1,224 s	1,423 s	16,23 %	No	Passed
L1-L2-L3	n/a	1,400 A	-101,00 °	953,8 ms	1,110 s	16,40 %	No	Passed
L1-L2-L3	n/a	1,500 A	-101,00 °	790,9 ms	928,3 ms	17,37 %	No	Passed
L1-L2-L3	n/a	1,600 A	-101,00 °	681,9 ms	805,0 ms	18,05 %	No	Passed
L1-L2-L3	n/a	1,700 A	-101,00 °	603,6 ms	710,2 ms	17,66 %	No	Passed
L1-L2-L3	n/a	1,800 A	-101,00 °	544,6 ms	639,8 ms	17,48 %	No	Passed
L1-L2-L3	n/a	1,200 A	-81,00 °	1,763 s	2,080 s	17,98 %	No	Passed
L1-L2-L3	n/a	1,300 A	-81,00 °	1,224 s	1,420 s	16,04 %	No	Passed
L1-L2-L3	n/a	1,400 A	-81,00 °	953,8 ms	1,121 s	17,49 %	No	Passed
L1-L2-L3	n/a	1,500 A	-81,00 °	790,9 ms	919,8 ms	16,29 %	No	Passed
L1-L2-L3	n/a	1,600 A	-81,00 °	681,9 ms	807,2 ms	18,38 %	No	Passed
L1-L2-L3	n/a	1,700 A	-81,00 °	603,6 ms	702,7 ms	16,42 %	No	Passed
L1-L2-L3	n/a	1,800 A	-81,00 °	544,6 ms	643,1 ms	18,09 %	No	Passed
L1-L2-L3	n/a	1,200 A	-61,00 °	1,763 s	2,069 s	17,38 %	No	Passed
L1-L2-L3	n/a	1,300 A	-61,00 °	1,224 s	1,424 s	16,32 %	No	Passed
L1-L2-L3	n/a	1,400 A	-61,00 °	953,8 ms	1,104 s	15,75 %	No	Passed
L1-L2-L3	n/a	1,500 A	-61,00 °	790,9 ms	925,8 ms	17,05 %	No	Passed
L1-L2-L3	n/a	1,600 A	-61,00 °	681,9 ms	794,9 ms	16,57 %	No	Passed
L1-L2-L3	n/a	1,700 A	-61,00 °	603,6 ms	710,3 ms	17,67 %	No	Passed
L1-L2-L3	n/a	1,800 A	-61,00 °	544,6 ms	643,5 ms	18,16 %	No	Passed
L1-L2-L3	n/a	1,200 A	-41,00 °	1,763 s	2,064 s	17,08 %	No	Passed
L1-L2-L3	n/a	1,300 A	-41,00 °	1,224 s	1,423 s	16,27 %	No	Passed
L1-L2-L3	n/a	1,400 A	-41,00 °	953,8 ms	1,106 s	15,96 %	No	Passed
L1-L2-L3	n/a	1,500 A	-41,00 °	790,9 ms	925,7 ms	17,04 %	No	Passed
L1-L2-L3	n/a	1,600 A	-41,00 °	681,9 ms	801,5 ms	17,54 %	No	Passed
L1-L2-L3	n/a	1,700 A	-41,00 °	603,6 ms	719,4 ms	19,18 %	No	Passed
L1-L2-L3	n/a	1,800 A	-41,00 °	544,6 ms	638,1 ms	17,17 %	No	Passed
L1-L2-L3	n/a	1,200 A	-21,00 °	1,763 s	2,064 s	17,06 %	No	Passed

L1-L2-L3	n/a	1,300 A	-21,00 °	1,224 s	1,425 s	16,40 %	No	Passed
L1-L2-L3	n/a	1,400 A	-21,00 °	953,8 ms	1,115 s	16,86 %	No	Passed
L1-L2-L3	n/a	1,500 A	-21,00 °	790,9 ms	924,3 ms	16,86 %	No	Passed
L1-L2-L3	n/a	1,600 A	-21,00 °	681,9 ms	794,7 ms	16,54 %	No	Passed
L1-L2-L3	n/a	1,700 A	-21,00 °	603,6 ms	706,9 ms	17,11 %	No	Passed
L1-L2-L3	n/a	1,800 A	-21,00 °	544,6 ms	641,0 ms	17,70 %	No	Passed
L1-L2-L3	n/a	1,200 A	-1,00 °	1,763 s	2,064 s	17,10 %	No	Passed
L1-L2-L3	n/a	1,300 A	-1,00 °	1,224 s	1,421 s	16,07 %	No	Passed
L1-L2-L3	n/a	1,400 A	-1,00 °	953,8 ms	1,105 s	15,88 %	No	Passed
L1-L2-L3	n/a	1,500 A	-1,00 °	790,9 ms	920,7 ms	16,41 %	No	Passed
L1-L2-L3	n/a	1,600 A	-1,00 °	681,9 ms	798,2 ms	17,06 %	No	Passed
L1-L2-L3	n/a	1,700 A	-1,00 °	603,6 ms	702,6 ms	16,40 %	No	Passed
L1-L2-L3	n/a	1,800 A	-1,00 °	544,6 ms	641,8 ms	17,85 %	No	Passed
L1-L2-L3	n/a	1,200 A	19,00 °	1,763 s	2,062 s	16,97 %	No	Passed
L1-L2-L3	n/a	1,300 A	19,00 °	1,224 s	1,421 s	16,11 %	No	Passed
L1-L2-L3	n/a	1,400 A	19,00 °	953,8 ms	1,102 s	15,56 %	No	Passed
L1-L2-L3	n/a	1,500 A	19,00 °	790,9 ms	924,3 ms	16,86 %	No	Passed
L1-L2-L3	n/a	1,600 A	19,00 °	681,9 ms	800,3 ms	17,37 %	No	Passed
L1-L2-L3	n/a	1,700 A	19,00 °	603,6 ms	702,4 ms	16,37 %	No	Passed
L1-L2-L3	n/a	1,800 A	19,00 °	544,6 ms	643,5 ms	18,16 %	No	Passed

Table B.5: Three Phase Fault Test Result using RCA=40°

Phase to phase forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2	n/a	1,200 A	39,00 °	No trip	2,083 s	n/a	No	Failed
L1-L2	n/a	1,300 A	39,00 °	No trip	1,424 s	n/a	No	Failed
L1-L2	n/a	1,400 A	39,00 °	No trip	1,102 s	n/a	No	Failed
L1-L2	n/a	1,500 A	39,00 °	No trip	920,3 ms	n/a	No	Failed
L1-L2	n/a	1,600 A	39,00 °	No trip	796,0 ms	n/a	No	Failed
L1-L2	n/a	1,700 A	39,00 °	No trip	711,4 ms	n/a	No	Failed
L1-L2	n/a	1,800 A	39,00 °	No trip	639,9 ms	n/a	No	Failed
L1-L2	n/a	1,200 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	59,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed

L1-L2	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	-141,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-121,00 °	1,763 s	2,064 s	17,09 %	No	Passed
L1-L2	n/a	1,300 A	-121,00 °	1,224 s	1,420 s	16,00 %	No	Passed
L1-L2	n/a	1,400 A	-121,00 °	953,8 ms	1,113 s	16,69 %	No	Passed
L1-L2	n/a	1,500 A	-121,00 °	790,9 ms	928,1 ms	17,34 %	No	Passed
L1-L2	n/a	1,600 A	-121,00 °	681,9 ms	800,7 ms	17,42 %	No	Passed
L1-L2	n/a	1,700 A	-121,00 °	603,6 ms	712,1 ms	17,97 %	No	Passed
L1-L2	n/a	1,800 A	-121,00 °	544,6 ms	641,0 ms	17,70 %	No	Passed
L1-L2	n/a	1,200 A	-101,00 °	1,763 s	2,061 s	16,90 %	No	Passed
L1-L2	n/a	1,300 A	-101,00 °	1,224 s	1,424 s	16,36 %	No	Passed
L1-L2	n/a	1,400 A	-101,00 °	953,8 ms	1,113 s	16,66 %	No	Passed
L1-L2	n/a	1,500 A	-101,00 °	790,9 ms	928,4 ms	17,38 %	No	Passed
L1-L2	n/a	1,600 A	-101,00 °	681,9 ms	810,0 ms	18,79 %	No	Passed
L1-L2	n/a	1,700 A	-101,00 °	603,6 ms	708,9 ms	17,44 %	No	Passed
L1-L2	n/a	1,800 A	-101,00 °	544,6 ms	645,8 ms	18,58 %	No	Passed
L1-L2	n/a	1,200 A	-81,00 °	1,763 s	2,054 s	16,54 %	No	Passed
L1-L2	n/a	1,300 A	-81,00 °	1,224 s	1,414 s	15,47 %	No	Passed
L1-L2	n/a	1,400 A	-81,00 °	953,8 ms	1,105 s	15,88 %	No	Passed
L1-L2	n/a	1,500 A	-81,00 °	790,9 ms	928,8 ms	17,43 %	No	Passed
L1-L2	n/a	1,600 A	-81,00 °	681,9 ms	796,8 ms	16,85 %	No	Passed
L1-L2	n/a	1,700 A	-81,00 °	603,6 ms	705,5 ms	16,88 %	No	Passed
L1-L2	n/a	1,800 A	-81,00 °	544,6 ms	644,8 ms	18,40 %	No	Passed
L1-L2	n/a	1,200 A	-61,00 °	1,763 s	2,056 s	16,60 %	No	Passed
L1-L2	n/a	1,300 A	-61,00 °	1,224 s	1,422 s	16,18 %	No	Passed
L1-L2	n/a	1,400 A	-61,00 °	953,8 ms	1,107 s	16,06 %	No	Passed
L1-L2	n/a	1,500 A	-61,00 °	790,9 ms	918,3 ms	16,10 %	No	Passed
L1-L2	n/a	1,600 A	-61,00 °	681,9 ms	796,2 ms	16,76 %	No	Passed
L1-L2	n/a	1,700 A	-61,00 °	603,6 ms	703,3 ms	16,51 %	No	Passed
L1-L2	n/a	1,800 A	-61,00 °	544,6 ms	632,5 ms	16,14 %	No	Passed
L1-L2	n/a	1,200 A	-41,00 °	1,763 s	2,061 s	16,91 %	No	Passed
L1-L2	n/a	1,300 A	-41,00 °	1,224 s	1,420 s	16,02 %	No	Passed
L1-L2	n/a	1,400 A	-41,00 °	953,8 ms	1,110 s	16,39 %	No	Passed
L1-L2	n/a	1,500 A	-41,00 °	790,9 ms	920,9 ms	16,43 %	No	Passed
L1-L2	n/a	1,600 A	-41,00 °	681,9 ms	801,7 ms	17,57 %	No	Passed
L1-L2	n/a	1,700 A	-41,00 °	603,6 ms	709,4 ms	17,53 %	No	Passed
L1-L2	n/a	1,800 A	-41,00 °	544,6 ms	636,8 ms	16,93 %	No	Passed
L1-L2	n/a	1,200 A	-21,00 °	1,763 s	2,062 s	16,96 %	No	Passed
L1-L2	n/a	1,300 A	-21,00 °	1,224 s	1,421 s	16,06 %	No	Passed
L1-L2	n/a	1,400 A	-21,00 °	953,8 ms	1,108 s	16,17 %	No	Passed
L1-L2	n/a	1,500 A	-21,00 °	790,9 ms	935,6 ms	18,29 %	No	Passed
L1-L2	n/a	1,600 A	-21,00 °	681,9 ms	803,1 ms	17,78 %	No	Passed
L1-L2	n/a	1,700 A	-21,00 °	603,6 ms	708,7 ms	17,41 %	No	Passed
L1-L2	n/a	1,800 A	-21,00 °	544,6 ms	639,0 ms	17,33 %	No	Passed
L1-L2	n/a	1,200 A	-1,00 °	1,763 s	2,054 s	16,51 %	No	Passed
L1-L2	n/a	1,300 A	-1,00 °	1,224 s	1,419 s	15,96 %	No	Passed
L1-L2	n/a	1,400 A	-1,00 °	953,8 ms	1,105 s	15,83 %	No	Passed
L1-L2	n/a	1,500 A	-1,00 °	790,9 ms	918,6 ms	16,14 %	No	Passed
L1-L2	n/a	1,600 A	-1,00 °	681,9 ms	795,9 ms	16,72 %	No	Passed
L1-L2	n/a	1,700 A	-1,00 °	603,6 ms	706,1 ms	16,98 %	No	Passed

L1-L2	n/a	1,800 A	-1,00 °	544,6 ms	636,0 ms	16,78 %	No	Passed
L1-L2	n/a	1,200 A	19,00 °	1,763 s	2,063 s	17,00 %	No	Passed
L1-L2	n/a	1,300 A	19,00 °	1,224 s	1,425 s	16,42 %	No	Passed
L1-L2	n/a	1,400 A	19,00 °	953,8 ms	1,103 s	15,67 %	No	Passed
L1-L2	n/a	1,500 A	19,00 °	790,9 ms	923,6 ms	16,77 %	No	Passed
L1-L2	n/a	1,600 A	19,00 °	681,9 ms	797,6 ms	16,97 %	No	Passed
L1-L2	n/a	1,700 A	19,00 °	603,6 ms	705,2 ms	16,83 %	No	Passed
L1-L2	n/a	1,800 A	19,00 °	544,6 ms	639,3 ms	17,39 %	No	Passed

Table B.6: Phase to Phase Fault Test Result using RCA=40°

Phase to ground forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-E	n/a	1,200 A	39,00 °	No trip	2,095 s	n/a	No	Failed
L1-E	n/a	1,300 A	39,00 °	No trip	1,439 s	n/a	No	Failed
L1-E	n/a	1,400 A	39,00 °	No trip	1,120 s	n/a	No	Failed
L1-E	n/a	1,500 A	39,00 °	No trip	923,1 ms	n/a	No	Failed
L1-E	n/a	1,600 A	39,00 °	No trip	799,5 ms	n/a	No	Failed
L1-E	n/a	1,700 A	39,00 °	No trip	713,6 ms	n/a	No	Failed
L1-E	n/a	1,800 A	39,00 °	No trip	650,0 ms	n/a	No	Failed
L1-E	n/a	1,200 A	59,00 °	No trip	2,083 s	n/a	No	Failed
L1-E	n/a	1,300 A	59,00 °	No trip	1,429 s	n/a	No	Failed
L1-E	n/a	1,400 A	59,00 °	No trip	1,120 s	n/a	No	Failed
L1-E	n/a	1,500 A	59,00 °	No trip	925,8 ms	n/a	No	Failed
L1-E	n/a	1,600 A	59,00 °	No trip	798,5 ms	n/a	No	Failed
L1-E	n/a	1,700 A	59,00 °	No trip	717,4 ms	n/a	No	Failed
L1-E	n/a	1,800 A	59,00 °	No trip	650,5 ms	n/a	No	Failed
L1-E	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed

L1-E	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-141,00 °	No trip	2,073 s	n/a	No	Failed
L1-E	n/a	1,300 A	-141,00 °	No trip	1,429 s	n/a	No	Failed
L1-E	n/a	1,400 A	-141,00 °	No trip	1,107 s	n/a	No	Failed
L1-E	n/a	1,500 A	-141,00 °	No trip	924,9 ms	n/a	No	Failed
L1-E	n/a	1,600 A	-141,00 °	No trip	798,4 ms	n/a	No	Failed
L1-E	n/a	1,700 A	-141,00 °	No trip	711,2 ms	n/a	No	Failed
L1-E	n/a	1,800 A	-141,00 °	No trip	640,3 ms	n/a	No	Failed
L1-E	n/a	1,200 A	-121,00 °	1,763 s	2,077 s	17,80 %	No	Passed
L1-E	n/a	1,300 A	-121,00 °	1,224 s	1,423 s	16,22 %	No	Passed
L1-E	n/a	1,400 A	-121,00 °	953,8 ms	1,113 s	16,71 %	No	Passed
L1-E	n/a	1,500 A	-121,00 °	790,9 ms	929,8 ms	17,56 %	No	Passed
L1-E	n/a	1,600 A	-121,00 °	681,9 ms	800,5 ms	17,40 %	No	Passed
L1-E	n/a	1,700 A	-121,00 °	603,6 ms	710,9 ms	17,77 %	No	Passed
L1-E	n/a	1,800 A	-121,00 °	544,6 ms	641,5 ms	17,79 %	No	Passed
L1-E	n/a	1,200 A	-101,00 °	1,763 s	2,073 s	17,60 %	No	Passed
L1-E	n/a	1,300 A	-101,00 °	1,224 s	1,423 s	16,24 %	No	Passed
L1-E	n/a	1,400 A	-101,00 °	953,8 ms	1,108 s	16,21 %	No	Passed
L1-E	n/a	1,500 A	-101,00 °	790,9 ms	927,2 ms	17,23 %	No	Passed
L1-E	n/a	1,600 A	-101,00 °	681,9 ms	798,7 ms	17,13 %	No	Passed
L1-E	n/a	1,700 A	-101,00 °	603,6 ms	710,7 ms	17,74 %	No	Passed
L1-E	n/a	1,800 A	-101,00 °	544,6 ms	637,8 ms	17,11 %	No	Passed
L1-E	n/a	1,200 A	-81,00 °	1,763 s	2,081 s	18,02 %	No	Passed
L1-E	n/a	1,300 A	-81,00 °	1,224 s	1,428 s	16,67 %	No	Passed
L1-E	n/a	1,400 A	-81,00 °	953,8 ms	1,107 s	16,02 %	No	Passed
L1-E	n/a	1,500 A	-81,00 °	790,9 ms	927,1 ms	17,22 %	No	Passed
L1-E	n/a	1,600 A	-81,00 °	681,9 ms	803,1 ms	17,78 %	No	Passed
L1-E	n/a	1,700 A	-81,00 °	603,6 ms	706,2 ms	17,00 %	No	Passed
L1-E	n/a	1,800 A	-81,00 °	544,6 ms	636,7 ms	16,91 %	No	Passed
L1-E	n/a	1,200 A	-61,00 °	1,763 s	2,079 s	17,92 %	No	Passed
L1-E	n/a	1,300 A	-61,00 °	1,224 s	1,419 s	15,94 %	No	Passed
L1-E	n/a	1,400 A	-61,00 °	953,8 ms	1,109 s	16,23 %	No	Passed
L1-E	n/a	1,500 A	-61,00 °	790,9 ms	925,0 ms	16,95 %	No	Passed
L1-E	n/a	1,600 A	-61,00 °	681,9 ms	800,0 ms	17,32 %	No	Passed
L1-E	n/a	1,700 A	-61,00 °	603,6 ms	709,6 ms	17,56 %	No	Passed
L1-E	n/a	1,800 A	-61,00 °	544,6 ms	652,4 ms	19,79 %	No	Passed
L1-E	n/a	1,200 A	-41,00 °	1,763 s	2,084 s	18,20 %	No	Passed
L1-E	n/a	1,300 A	-41,00 °	1,224 s	1,421 s	16,10 %	No	Passed
L1-E	n/a	1,400 A	-41,00 °	953,8 ms	1,111 s	16,47 %	No	Passed
L1-E	n/a	1,500 A	-41,00 °	790,9 ms	927,6 ms	17,28 %	No	Passed
L1-E	n/a	1,600 A	-41,00 °	681,9 ms	799,5 ms	17,25 %	No	Passed
L1-E	n/a	1,700 A	-41,00 °	603,6 ms	709,2 ms	17,49 %	No	Passed
L1-E	n/a	1,800 A	-41,00 °	544,6 ms	645,6 ms	18,54 %	No	Passed
L1-E	n/a	1,200 A	-21,00 °	1,763 s	2,083 s	18,18 %	No	Passed
L1-E	n/a	1,300 A	-21,00 °	1,224 s	1,426 s	16,46 %	No	Passed
L1-E	n/a	1,400 A	-21,00 °	953,8 ms	1,117 s	17,13 %	No	Passed
L1-E	n/a	1,500 A	-21,00 °	790,9 ms	925,0 ms	16,95 %	No	Passed
L1-E	n/a	1,600 A	-21,00 °	681,9 ms	799,9 ms	17,31 %	No	Passed
L1-E	n/a	1,700 A	-21,00 °	603,6 ms	709,1 ms	17,48 %	No	Passed
L1-E	n/a	1,800 A	-21,00 °	544,6 ms	641,9 ms	17,87 %	No	Passed
L1-E	n/a	1,200 A	-1,00 °	1,763 s	2,084 s	18,20 %	No	Passed
L1-E	n/a	1,300 A	-1,00 °	1,224 s	1,434 s	17,17 %	No	Passed
L1-E	n/a	1,400 A	-1,00 °	953,8 ms	1,110 s	16,38 %	No	Passed
L1-E	n/a	1,500 A	-1,00 °	790,9 ms	923,2 ms	16,72 %	No	Passed
L1-E	n/a	1,600 A	-1,00 °	681,9 ms	799,0 ms	17,18 %	No	Passed

L1-E	n/a	1,700 A	-1,00 °	603,6 ms	707,1 ms	17,14 %	No	Passed
L1-E	n/a	1,800 A	-1,00 °	544,6 ms	648,4 ms	19,06 %	No	Passed
L1-E	n/a	1,200 A	19,00 °	1,763 s	2,085 s	18,27 %	No	Passed
L1-E	n/a	1,300 A	19,00 °	1,224 s	1,426 s	16,50 %	No	Passed
L1-E	n/a	1,400 A	19,00 °	953,8 ms	1,105 s	15,81 %	No	Passed
L1-E	n/a	1,500 A	19,00 °	790,9 ms	919,1 ms	16,20 %	No	Passed
L1-E	n/a	1,600 A	19,00 °	681,9 ms	799,4 ms	17,23 %	No	Passed
L1-E	n/a	1,700 A	19,00 °	603,6 ms	706,6 ms	17,06 %	No	Passed
L1-E	n/a	1,800 A	19,00 °	544,6 ms	648,9 ms	19,15 %	No	Passed

Table B.7: Single Phase to Earth Fault Test Result using RCA=40°

- **For the case of RCA=65°:**

Three phase forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2-L3	n/a	1,200 A	39,00 °	1,763 s	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	39,00 °	1,224 s	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	39,00 °	953,8 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	39,00 °	790,9 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	39,00 °	681,9 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	39,00 °	603,6 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	39,00 °	544,6 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	59,00 °	1,763 s	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	59,00 °	1,224 s	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	59,00 °	953,8 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	59,00 °	790,9 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	59,00 °	681,9 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	59,00 °	603,6 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	59,00 °	544,6 ms	No trip	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed

L1-L2-L3	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2-L3	n/a	1,200 A	-141,00 °	No trip	2,062 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	-141,00 °	No trip	1,425 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	-141,00 °	No trip	1,106 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	-141,00 °	No trip	924,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	-141,00 °	No trip	809,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	-141,00 °	No trip	704,7 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	-141,00 °	No trip	641,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	-121,00 °	No trip	2,068 s	n/a	No	Failed
L1-L2-L3	n/a	1,300 A	-121,00 °	No trip	1,425 s	n/a	No	Failed
L1-L2-L3	n/a	1,400 A	-121,00 °	No trip	1,103 s	n/a	No	Failed
L1-L2-L3	n/a	1,500 A	-121,00 °	No trip	923,9 ms	n/a	No	Failed
L1-L2-L3	n/a	1,600 A	-121,00 °	No trip	801,5 ms	n/a	No	Failed
L1-L2-L3	n/a	1,700 A	-121,00 °	No trip	709,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,800 A	-121,00 °	No trip	635,6 ms	n/a	No	Failed
L1-L2-L3	n/a	1,200 A	-101,00 °	1,763 s	2,064 s	17,05 %	No	Passed
L1-L2-L3	n/a	1,300 A	-101,00 °	1,224 s	1,425 s	16,43 %	No	Passed
L1-L2-L3	n/a	1,400 A	-101,00 °	953,8 ms	1,107 s	16,02 %	No	Passed
L1-L2-L3	n/a	1,500 A	-101,00 °	790,9 ms	925,7 ms	17,04 %	No	Passed
L1-L2-L3	n/a	1,600 A	-101,00 °	681,9 ms	798,4 ms	17,09 %	No	Passed
L1-L2-L3	n/a	1,700 A	-101,00 °	603,6 ms	704,0 ms	16,63 %	No	Passed
L1-L2-L3	n/a	1,800 A	-101,00 °	544,6 ms	641,5 ms	17,79 %	No	Passed
L1-L2-L3	n/a	1,200 A	-81,00 °	1,763 s	2,063 s	17,02 %	No	Passed
L1-L2-L3	n/a	1,300 A	-81,00 °	1,224 s	1,425 s	16,38 %	No	Passed
L1-L2-L3	n/a	1,400 A	-81,00 °	953,8 ms	1,108 s	16,16 %	No	Passed
L1-L2-L3	n/a	1,500 A	-81,00 °	790,9 ms	923,8 ms	16,80 %	No	Passed
L1-L2-L3	n/a	1,600 A	-81,00 °	681,9 ms	798,0 ms	17,03 %	No	Passed
L1-L2-L3	n/a	1,700 A	-81,00 °	603,6 ms	708,7 ms	17,41 %	No	Passed
L1-L2-L3	n/a	1,800 A	-81,00 °	544,6 ms	638,6 ms	17,26 %	No	Passed
L1-L2-L3	n/a	1,200 A	-61,00 °	1,763 s	2,065 s	17,15 %	No	Passed
L1-L2-L3	n/a	1,300 A	-61,00 °	1,224 s	1,421 s	16,12 %	No	Passed
L1-L2-L3	n/a	1,400 A	-61,00 °	953,8 ms	1,107 s	16,04 %	No	Passed
L1-L2-L3	n/a	1,500 A	-61,00 °	790,9 ms	930,7 ms	17,67 %	No	Passed
L1-L2-L3	n/a	1,600 A	-61,00 °	681,9 ms	799,6 ms	17,26 %	No	Passed
L1-L2-L3	n/a	1,700 A	-61,00 °	603,6 ms	708,5 ms	17,38 %	No	Passed
L1-L2-L3	n/a	1,800 A	-61,00 °	544,6 ms	639,8 ms	17,48 %	No	Passed
L1-L2-L3	n/a	1,200 A	-41,00 °	1,763 s	2,074 s	17,62 %	No	Passed
L1-L2-L3	n/a	1,300 A	-41,00 °	1,224 s	1,421 s	16,11 %	No	Passed
L1-L2-L3	n/a	1,400 A	-41,00 °	953,8 ms	1,105 s	15,90 %	No	Passed
L1-L2-L3	n/a	1,500 A	-41,00 °	790,9 ms	923,0 ms	16,70 %	No	Passed
L1-L2-L3	n/a	1,600 A	-41,00 °	681,9 ms	796,9 ms	16,87 %	No	Passed
L1-L2-L3	n/a	1,700 A	-41,00 °	603,6 ms	706,4 ms	17,03 %	No	Passed
L1-L2-L3	n/a	1,800 A	-41,00 °	544,6 ms	638,1 ms	17,17 %	No	Passed
L1-L2-L3	n/a	1,200 A	-21,00 °	1,763 s	2,066 s	17,17 %	No	Passed
L1-L2-L3	n/a	1,300 A	-21,00 °	1,224 s	1,428 s	16,65 %	No	Passed
L1-L2-L3	n/a	1,400 A	-21,00 °	953,8 ms	1,106 s	15,95 %	No	Passed

L1-L2-L3	n/a	1,500 A	-21,00 °	790,9 ms	922,8 ms	16,67 %	No	Passed
L1-L2-L3	n/a	1,600 A	-21,00 °	681,9 ms	796,6 ms	16,82 %	No	Passed
L1-L2-L3	n/a	1,700 A	-21,00 °	603,6 ms	703,9 ms	16,61 %	No	Passed
L1-L2-L3	n/a	1,800 A	-21,00 °	544,6 ms	642,2 ms	17,92 %	No	Passed
L1-L2-L3	n/a	1,200 A	-1,00 °	1,763 s	2,073 s	17,60 %	No	Passed
L1-L2-L3	n/a	1,300 A	-1,00 °	1,224 s	1,418 s	15,80 %	No	Passed
L1-L2-L3	n/a	1,400 A	-1,00 °	953,8 ms	1,103 s	15,69 %	No	Passed
L1-L2-L3	n/a	1,500 A	-1,00 °	790,9 ms	922,5 ms	16,63 %	No	Passed
L1-L2-L3	n/a	1,600 A	-1,00 °	681,9 ms	799,5 ms	17,25 %	No	Passed
L1-L2-L3	n/a	1,700 A	-1,00 °	603,6 ms	705,2 ms	16,83 %	No	Passed
L1-L2-L3	n/a	1,800 A	-1,00 °	544,6 ms	641,7 ms	17,83 %	No	Passed
L1-L2-L3	n/a	1,200 A	19,00 °	1,763 s	2,064 s	17,06 %	No	Passed
L1-L2-L3	n/a	1,300 A	19,00 °	1,224 s	1,424 s	16,32 %	No	Passed
L1-L2-L3	n/a	1,400 A	19,00 °	953,8 ms	1,108 s	16,16 %	No	Passed
L1-L2-L3	n/a	1,500 A	19,00 °	790,9 ms	925,9 ms	17,06 %	No	Passed
L1-L2-L3	n/a	1,600 A	19,00 °	681,9 ms	798,1 ms	17,04 %	No	Passed
L1-L2-L3	n/a	1,700 A	19,00 °	603,6 ms	707,5 ms	17,21 %	No	Passed
L1-L2-L3	n/a	1,800 A	19,00 °	544,6 ms	638,3 ms	17,20 %	No	Passed

Table B.8: Three Phase Fault Test using RCA=65°

Phase to phase forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-L2	n/a	1,200 A	39,00 °	1,763 s	No trip	n/a	No	Failed
L1-L2	n/a	1,300 A	39,00 °	1,224 s	No trip	n/a	No	Failed
L1-L2	n/a	1,400 A	39,00 °	953,8 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,500 A	39,00 °	790,9 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,600 A	39,00 °	681,9 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,700 A	39,00 °	603,6 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,800 A	39,00 °	544,6 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,200 A	59,00 °	1,763 s	No trip	n/a	No	Failed
L1-L2	n/a	1,300 A	59,00 °	1,224 s	No trip	n/a	No	Failed
L1-L2	n/a	1,400 A	59,00 °	953,8 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,500 A	59,00 °	790,9 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,600 A	59,00 °	681,9 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,700 A	59,00 °	603,6 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,800 A	59,00 °	544,6 ms	No trip	n/a	No	Failed
L1-L2	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed

L1-L2	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-L2	n/a	1,200 A	-141,00 °	No trip	2,057 s	n/a	No	Failed
L1-L2	n/a	1,300 A	-141,00 °	No trip	1,415 s	n/a	No	Failed
L1-L2	n/a	1,400 A	-141,00 °	No trip	1,107 s	n/a	No	Failed
L1-L2	n/a	1,500 A	-141,00 °	No trip	927,6 ms	n/a	No	Failed
L1-L2	n/a	1,600 A	-141,00 °	No trip	799,4 ms	n/a	No	Failed
L1-L2	n/a	1,700 A	-141,00 °	No trip	708,4 ms	n/a	No	Failed
L1-L2	n/a	1,800 A	-141,00 °	No trip	642,6 ms	n/a	No	Failed
L1-L2	n/a	1,200 A	-121,00 °	No trip	2,055 s	n/a	No	Failed
L1-L2	n/a	1,300 A	-121,00 °	No trip	1,414 s	n/a	No	Failed
L1-L2	n/a	1,400 A	-121,00 °	No trip	1,106 s	n/a	No	Failed
L1-L2	n/a	1,500 A	-121,00 °	No trip	914,6 ms	n/a	No	Failed
L1-L2	n/a	1,600 A	-121,00 °	No trip	798,4 ms	n/a	No	Failed
L1-L2	n/a	1,700 A	-121,00 °	No trip	707,2 ms	n/a	No	Failed
L1-L2	n/a	1,800 A	-121,00 °	No trip	640,2 ms	n/a	No	Failed
L1-L2	n/a	1,200 A	-101,00 °	1,763 s	2,062 s	16,94 %	No	Passed
L1-L2	n/a	1,300 A	-101,00 °	1,224 s	1,417 s	15,75 %	No	Passed
L1-L2	n/a	1,400 A	-101,00 °	953,8 ms	1,111 s	16,53 %	No	Passed
L1-L2	n/a	1,500 A	-101,00 °	790,9 ms	921,2 ms	16,47 %	No	Passed
L1-L2	n/a	1,600 A	-101,00 °	681,9 ms	797,0 ms	16,88 %	No	Passed
L1-L2	n/a	1,700 A	-101,00 °	603,6 ms	707,3 ms	17,18 %	No	Passed
L1-L2	n/a	1,800 A	-101,00 °	544,6 ms	644,6 ms	18,36 %	No	Passed
L1-L2	n/a	1,200 A	-81,00 °	1,763 s	2,059 s	16,77 %	No	Passed
L1-L2	n/a	1,300 A	-81,00 °	1,224 s	1,423 s	16,25 %	No	Passed
L1-L2	n/a	1,400 A	-81,00 °	953,8 ms	1,104 s	15,75 %	No	Passed
L1-L2	n/a	1,500 A	-81,00 °	790,9 ms	922,5 ms	16,63 %	No	Passed
L1-L2	n/a	1,600 A	-81,00 °	681,9 ms	794,8 ms	16,56 %	No	Passed
L1-L2	n/a	1,700 A	-81,00 °	603,6 ms	715,8 ms	18,59 %	No	Passed
L1-L2	n/a	1,800 A	-81,00 °	544,6 ms	642,8 ms	18,03 %	No	Passed
L1-L2	n/a	1,200 A	-61,00 °	1,763 s	2,057 s	16,65 %	No	Passed
L1-L2	n/a	1,300 A	-61,00 °	1,224 s	1,421 s	16,10 %	No	Passed
L1-L2	n/a	1,400 A	-61,00 °	953,8 ms	1,104 s	15,72 %	No	Passed
L1-L2	n/a	1,500 A	-61,00 °	790,9 ms	925,2 ms	16,98 %	No	Passed
L1-L2	n/a	1,600 A	-61,00 °	681,9 ms	802,1 ms	17,63 %	No	Passed
L1-L2	n/a	1,700 A	-61,00 °	603,6 ms	703,0 ms	16,47 %	No	Passed
L1-L2	n/a	1,800 A	-61,00 °	544,6 ms	638,9 ms	17,31 %	No	Passed
L1-L2	n/a	1,200 A	-41,00 °	1,763 s	2,062 s	16,98 %	No	Passed
L1-L2	n/a	1,300 A	-41,00 °	1,224 s	1,416 s	15,65 %	No	Passed
L1-L2	n/a	1,400 A	-41,00 °	953,8 ms	1,110 s	16,40 %	No	Passed
L1-L2	n/a	1,500 A	-41,00 °	790,9 ms	924,0 ms	16,82 %	No	Passed
L1-L2	n/a	1,600 A	-41,00 °	681,9 ms	796,4 ms	16,79 %	No	Passed
L1-L2	n/a	1,700 A	-41,00 °	603,6 ms	708,6 ms	17,39 %	No	Passed
L1-L2	n/a	1,800 A	-41,00 °	544,6 ms	644,5 ms	18,34 %	No	Passed
L1-L2	n/a	1,200 A	-21,00 °	1,763 s	2,065 s	17,14 %	No	Passed
L1-L2	n/a	1,300 A	-21,00 °	1,224 s	1,417 s	15,77 %	No	Passed
L1-L2	n/a	1,400 A	-21,00 °	953,8 ms	1,108 s	16,15 %	No	Passed
L1-L2	n/a	1,500 A	-21,00 °	790,9 ms	925,9 ms	17,06 %	No	Passed
L1-L2	n/a	1,600 A	-21,00 °	681,9 ms	797,1 ms	16,90 %	No	Passed
L1-L2	n/a	1,700 A	-21,00 °	603,6 ms	705,5 ms	16,88 %	No	Passed
L1-L2	n/a	1,800 A	-21,00 °	544,6 ms	637,5 ms	17,06 %	No	Passed
L1-L2	n/a	1,200 A	-1,00 °	1,763 s	2,058 s	16,73 %	No	Passed
L1-L2	n/a	1,300 A	-1,00 °	1,224 s	1,427 s	16,54 %	No	Passed

L1-L2	n/a	1,400 A	-1,00 °	953,8 ms	1,113 s	16,68 %	No	Passed
L1-L2	n/a	1,500 A	-1,00 °	790,9 ms	930,2 ms	17,61 %	No	Passed
L1-L2	n/a	1,600 A	-1,00 °	681,9 ms	798,9 ms	17,16 %	No	Passed
L1-L2	n/a	1,700 A	-1,00 °	603,6 ms	706,7 ms	17,08 %	No	Passed
L1-L2	n/a	1,800 A	-1,00 °	544,6 ms	638,9 ms	17,31 %	No	Passed
L1-L2	n/a	1,200 A	19,00 °	1,763 s	2,088 s	18,43 %	No	Passed
L1-L2	n/a	1,300 A	19,00 °	1,224 s	1,438 s	17,44 %	No	Passed
L1-L2	n/a	1,400 A	19,00 °	953,8 ms	1,129 s	18,34 %	No	Passed
L1-L2	n/a	1,500 A	19,00 °	790,9 ms	952,7 ms	20,45 %	No	Passed
L1-L2	n/a	1,600 A	19,00 °	681,9 ms	826,1 ms	21,15 %	No	Passed
L1-L2	n/a	1,700 A	19,00 °	603,6 ms	737,4 ms	22,16 %	No	Passed
L1-L2	n/a	1,800 A	19,00 °	544,6 ms	655,0 ms	20,27 %	No	Passed

Table B.9: Phase to Phase Fault Test using RCA=65°

Phase to ground forward fault test:

Type	Factor	Magnitude	Angle	tnom	tact	Deviation	Overload	Result
L1-E	n/a	1,200 A	39,00 °	1,763 s	No trip	n/a	No	Failed
L1-E	n/a	1,300 A	39,00 °	1,224 s	No trip	n/a	No	Failed
L1-E	n/a	1,400 A	39,00 °	953,8 ms	No trip	n/a	No	Failed
L1-E	n/a	1,500 A	39,00 °	790,9 ms	No trip	n/a	No	Failed
L1-E	n/a	1,600 A	39,00 °	681,9 ms	No trip	n/a	No	Failed
L1-E	n/a	1,700 A	39,00 °	603,6 ms	No trip	n/a	No	Failed
L1-E	n/a	1,800 A	39,00 °	544,6 ms	No trip	n/a	No	Failed
L1-E	n/a	1,200 A	59,00 °	1,763 s	No trip	n/a	No	Failed
L1-E	n/a	1,300 A	59,00 °	1,224 s	No trip	n/a	No	Failed
L1-E	n/a	1,400 A	59,00 °	953,8 ms	No trip	n/a	No	Failed
L1-E	n/a	1,500 A	59,00 °	790,9 ms	No trip	n/a	No	Failed
L1-E	n/a	1,600 A	59,00 °	681,9 ms	No trip	n/a	No	Failed
L1-E	n/a	1,700 A	59,00 °	603,6 ms	No trip	n/a	No	Failed
L1-E	n/a	1,800 A	59,00 °	544,6 ms	No trip	n/a	No	Failed
L1-E	n/a	1,200 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	79,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	99,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	119,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	139,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	159,00 °	No trip	No trip	n/a	No	Passed

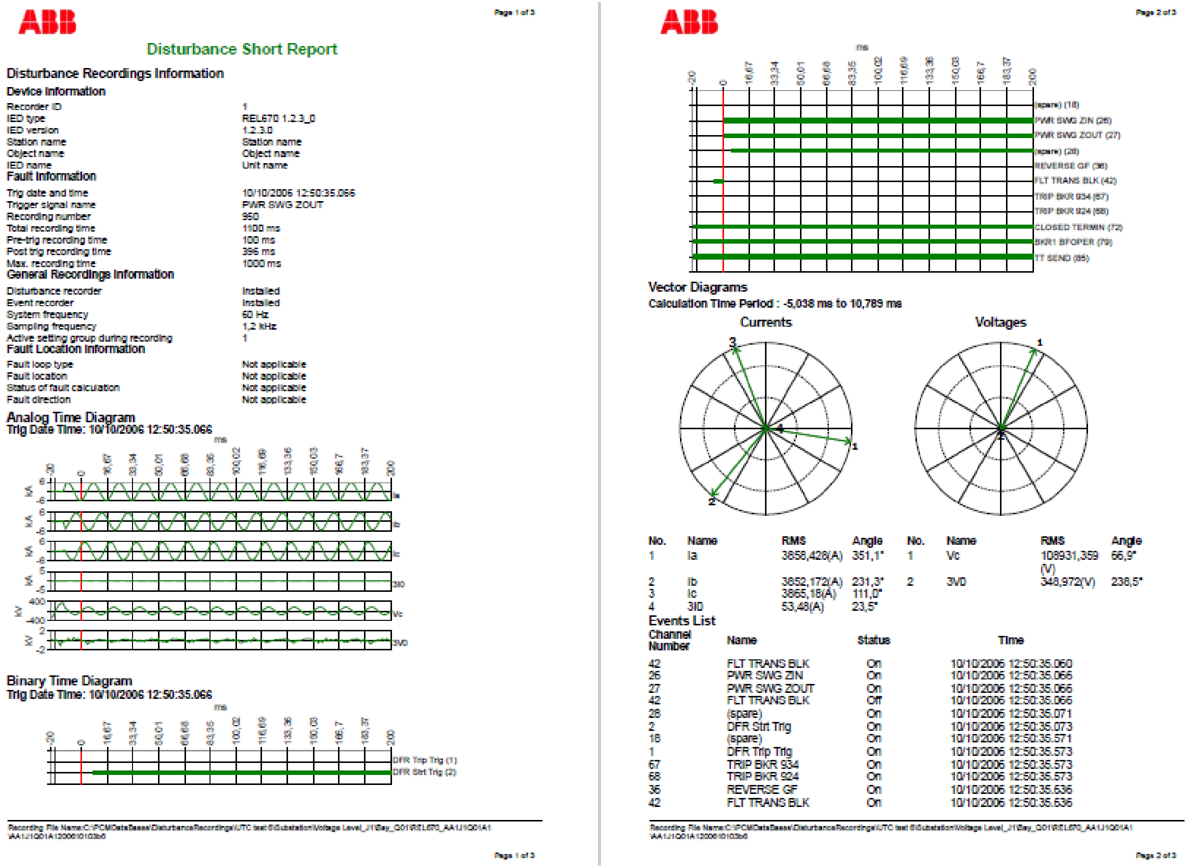
L1-E	n/a	1,700 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	159,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	179,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,300 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,400 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,500 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,600 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,700 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,800 A	-161,00 °	No trip	No trip	n/a	No	Passed
L1-E	n/a	1,200 A	-141,00 °	No trip	2,071 s	n/a	No	Failed
L1-E	n/a	1,300 A	-141,00 °	No trip	1,426 s	n/a	No	Failed
L1-E	n/a	1,400 A	-141,00 °	No trip	1,109 s	n/a	No	Failed
L1-E	n/a	1,500 A	-141,00 °	No trip	924,1 ms	n/a	No	Failed
L1-E	n/a	1,600 A	-141,00 °	No trip	796,9 ms	n/a	No	Failed
L1-E	n/a	1,700 A	-141,00 °	No trip	704,7 ms	n/a	No	Failed
L1-E	n/a	1,800 A	-141,00 °	No trip	646,2 ms	n/a	No	Failed
L1-E	n/a	1,200 A	-121,00 °	No trip	2,075 s	n/a	No	Failed
L1-E	n/a	1,300 A	-121,00 °	No trip	1,426 s	n/a	No	Failed
L1-E	n/a	1,400 A	-121,00 °	No trip	1,107 s	n/a	No	Failed
L1-E	n/a	1,500 A	-121,00 °	No trip	925,2 ms	n/a	No	Failed
L1-E	n/a	1,600 A	-121,00 °	No trip	796,6 ms	n/a	No	Failed
L1-E	n/a	1,700 A	-121,00 °	No trip	704,4 ms	n/a	No	Failed
L1-E	n/a	1,800 A	-121,00 °	No trip	644,9 ms	n/a	No	Failed
L1-E	n/a	1,200 A	-101,00 °	1,763 s	2,074 s	17,65 %	No	Passed
L1-E	n/a	1,300 A	-101,00 °	1,224 s	1,420 s	16,01 %	No	Passed
L1-E	n/a	1,400 A	-101,00 °	953,8 ms	1,108 s	16,14 %	No	Passed
L1-E	n/a	1,500 A	-101,00 °	790,9 ms	925,7 ms	17,04 %	No	Passed
L1-E	n/a	1,600 A	-101,00 °	681,9 ms	794,4 ms	16,50 %	No	Passed
L1-E	n/a	1,700 A	-101,00 °	603,6 ms	705,9 ms	16,95 %	No	Passed
L1-E	n/a	1,800 A	-101,00 °	544,6 ms	637,7 ms	17,09 %	No	Passed
L1-E	n/a	1,200 A	-81,00 °	1,763 s	2,064 s	17,10 %	No	Passed
L1-E	n/a	1,300 A	-81,00 °	1,224 s	1,419 s	15,90 %	No	Passed
L1-E	n/a	1,400 A	-81,00 °	953,8 ms	1,108 s	16,20 %	No	Passed
L1-E	n/a	1,500 A	-81,00 °	790,9 ms	921,6 ms	16,52 %	No	Passed
L1-E	n/a	1,600 A	-81,00 °	681,9 ms	797,8 ms	17,00 %	No	Passed
L1-E	n/a	1,700 A	-81,00 °	603,6 ms	705,8 ms	16,93 %	No	Passed
L1-E	n/a	1,800 A	-81,00 °	544,6 ms	637,4 ms	17,04 %	No	Passed
L1-E	n/a	1,200 A	-61,00 °	1,763 s	2,074 s	17,63 %	No	Passed
L1-E	n/a	1,300 A	-61,00 °	1,224 s	1,427 s	16,56 %	No	Passed
L1-E	n/a	1,400 A	-61,00 °	953,8 ms	1,109 s	16,22 %	No	Passed
L1-E	n/a	1,500 A	-61,00 °	790,9 ms	923,9 ms	16,81 %	No	Passed
L1-E	n/a	1,600 A	-61,00 °	681,9 ms	801,7 ms	17,57 %	No	Passed
L1-E	n/a	1,700 A	-61,00 °	603,6 ms	704,1 ms	16,65 %	No	Passed
L1-E	n/a	1,800 A	-61,00 °	544,6 ms	643,0 ms	18,07 %	No	Passed
L1-E	n/a	1,200 A	-41,00 °	1,763 s	2,070 s	17,40 %	No	Passed
L1-E	n/a	1,300 A	-41,00 °	1,224 s	1,424 s	16,31 %	No	Passed
L1-E	n/a	1,400 A	-41,00 °	953,8 ms	1,111 s	16,44 %	No	Passed
L1-E	n/a	1,500 A	-41,00 °	790,9 ms	920,3 ms	16,36 %	No	Passed
L1-E	n/a	1,600 A	-41,00 °	681,9 ms	795,3 ms	16,63 %	No	Passed
L1-E	n/a	1,700 A	-41,00 °	603,6 ms	709,1 ms	17,48 %	No	Passed
L1-E	n/a	1,800 A	-41,00 °	544,6 ms	638,0 ms	17,15 %	No	Passed
L1-E	n/a	1,200 A	-21,00 °	1,763 s	2,071 s	17,45 %	No	Passed
L1-E	n/a	1,300 A	-21,00 °	1,224 s	1,425 s	16,45 %	No	Passed
L1-E	n/a	1,400 A	-21,00 °	953,8 ms	1,107 s	16,03 %	No	Passed
L1-E	n/a	1,500 A	-21,00 °	790,9 ms	918,5 ms	16,13 %	No	Passed
L1-E	n/a	1,600 A	-21,00 °	681,9 ms	801,1 ms	17,48 %	No	Passed
L1-E	n/a	1,700 A	-21,00 °	603,6 ms	706,9 ms	17,11 %	No	Passed
L1-E	n/a	1,800 A	-21,00 °	544,6 ms	640,6 ms	17,63 %	No	Passed

L1-E	n/a	1,200 A	-1,00 °	1,763 s	2,076 s	17,73 %	No	Passed
L1-E	n/a	1,300 A	-1,00 °	1,224 s	1,423 s	16,25 %	No	Passed
L1-E	n/a	1,400 A	-1,00 °	953,8 ms	1,106 s	15,98 %	No	Passed
L1-E	n/a	1,500 A	-1,00 °	790,9 ms	922,8 ms	16,67 %	No	Passed
L1-E	n/a	1,600 A	-1,00 °	681,9 ms	802,1 ms	17,63 %	No	Passed
L1-E	n/a	1,700 A	-1,00 °	603,6 ms	708,6 ms	17,39 %	No	Passed
L1-E	n/a	1,800 A	-1,00 °	544,6 ms	644,9 ms	18,42 %	No	Passed
L1-E	n/a	1,200 A	19,00 °	1,763 s	2,100 s	19,13 %	No	Passed
L1-E	n/a	1,300 A	19,00 °	1,224 s	1,446 s	18,13 %	No	Passed
L1-E	n/a	1,400 A	19,00 °	953,8 ms	1,117 s	17,08 %	No	Passed
L1-E	n/a	1,500 A	19,00 °	790,9 ms	928,9 ms	17,44 %	No	Passed
L1-E	n/a	1,600 A	19,00 °	681,9 ms	807,3 ms	18,39 %	No	Passed
L1-E	n/a	1,700 A	19,00 °	603,6 ms	719,8 ms	19,25 %	No	Passed
L1-E	n/a	1,800 A	19,00 °	544,6 ms	648,2 ms	19,02 %	No	Passed

Table B.10: Single Phase to Earth Fault Test using RCA=65°

Appendix C – Disturbance Handling report

This report shown in Figure C.1 is an example result obtained when using COMTRADE for fault inspection.



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Disturbance Short Report

Disturbance Recordings Information

Device Information

Recorder ID	1
IED type	REL670 1.2.3_0
IED version	1.2.3.0
Station name	Station name
Object name	Object name
IED name	Unit name

Fault Information

Trig date and time	10/10/2006 12:50:35.066
Trigger signal name	PWR SWG ZOUT
Recording number	950
Total recording time	1100 ms
Pre-trig recording time	100 ms
Post trig recording time	396 ms
Max. recording time	1000 ms

General Recordings Information

Disturbance recorder	Installed
Event recorder	Installed
System frequency	60 Hz
Sampling frequency	1,2 kHz
Active setting group during recording	1

Fault Location Information

Fault loop type	Not applicable
Fault location	Not applicable
Status of fault calculation	Not applicable
Fault direction	Not applicable

Analog Time Diagram
Trig Date Time: 10/10/2006 12:50:35.066

Binary Time Diagram
Trig Date Time: 10/10/2006 12:50:35.066

Recording File Name:C:\PCM\DataBases\DisturbanceRecordings\UTC test 6\Substation\Voltage Level_J1\Bay_Q01\REL670_AA1J1Q01A1\AA1J1Q01A1200610103b6

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Vector Diagrams
Calculation Time Period : -5,038 ms to 10,789 ms

No.	Name	RMS	Angle	No.	Name	RMS	Angle
1	Ia	3858,428(A)	351,1°	1	Vc	108931,359 (V)	66,9°
2	Ib	3852,172(A)	231,3°	2	3V0	348,972(V)	236,5°
3	Ic	3865,18(A)	111,0°				
4	3I0	53,48(A)	23,5°				

Events List

Channel Number	Name	Status	Time
42	FLT TRANS BLK	On	10/10/2006 12:50:35.060
26	PWR SWG ZIN	On	10/10/2006 12:50:35.066
27	PWR SWG ZOUT	On	10/10/2006 12:50:35.066
42	FLT TRANS BLK	Off	10/10/2006 12:50:35.066
28	(spare)	On	10/10/2006 12:50:35.071
2	DFR Strt Trig	On	10/10/2006 12:50:35.073
18	(spare)	On	10/10/2006 12:50:35.571
1	DFR Trip Trig	On	10/10/2006 12:50:35.573
67	TRIP BKR 934	On	10/10/2006 12:50:35.573
68	TRIP BKR 924	On	10/10/2006 12:50:35.573
36	REVERSE GF	On	10/10/2006 12:50:35.636
42	FLT TRANS BLK	On	10/10/2006 12:50:35.636

Recording File Name:C:\PCM\DataBases\DisturbanceRecordings\UTC test 6\Substation\Voltage Level_J1\Bay_Q01\REL670_AA1J1Q01A1\AA1J1Q01A1200610103b6

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Figure C.1: Disturbance handling report of REL670 LINE Distance Protection.