PERFORMANCE COMPARISON OF A PERMISSIVE OVERREACH TRANSFER TRIP

(POTT) SCHEME OVER IEC 61850 AND HARD-WIRE

By

José Luis Ruiz

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ABSTRACT

The International Electrotechnical Commission (IEC) 61850 is a standard that allows communication integration of systems built from multivendor power protection relays. The standard describes the rules for integration of control, measurement, and protection functions within a power system network at the substation control levels. The standard was created with the idea of eliminating wiring in the substation and facilitating the communication between different relay vendors.

This study implemented IEC 61850 standard in a Permissive Overreach Transfer Trip (POTT) scheme to protect a 166 mile, 230 kV transmission line using Generic Object Oriented Substation Events (GOOSE) messaging in the laboratory. Two multivendor digital line protection relays were placed at each end of the line to protect the transmission line via the POTT communication scheme. Faults were simulated at different points on the line using two modern relay test sets.

A comparison of the POTT with IEC 61850 communication and a classic communication method, hard-wire, is made to determine the performance of the POTT with IEC 61850. It is observed that the maximum and minimum time delay between fault occurrence and the POTT operation with IEC 61850 communication is around 1.72 cycles (28.67 ms) and 1.50 cycles (25 ms), respectively, under laboratory conditions. The results on this research show that the POTT with IEC 61850 communication is faster or similar to the POTT with hard-wire communication.

DEDICATION

I would like to dedicate this research to my wife, Irene, whose help has been very important on pursuing this degree.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

A-G, Phase A to ground fault

ANSI, American National Standards Institute

BC, Phase B and C fault

BC-G, Phase B and C to ground fault

BKR, Breaker

CT, Current Transformer

DIST, Distance

FB, Function Block

GND, Ground

GOOSE, Generic Object Oriented Substation Event

HMI, Human-Machine Interface

IEC, International Electrotechnical Commission

IED, Intelligent Electronic Device

IEEE, Institute of Electrical and Electronics Engineers

ms, milliseconds

OP, Operate

PKP, Pick up

POTT, Permissive Overreach Transfer Trip

PU, Pick up

RCV, Received

SCADA, Supervisory Control and Data Acquisition

SNTP, Simple Network Time Protocol

TR, Technical Report

TS, Technical Specification

TVA, Tennessee Valley Authority

TX, Transmit

VT, Voltage Transformer

CHAPTER I

INTRODUCTION

Stability is very important in a power system. If a system works as a synchronous system, it has to keep its synchronization at all times. When a fault condition occurs, the system experiences instability and an immediate action is required.

Pilot protection schemes are an alternative to protect short transmission lines at all voltage levels [1], but it is mostly used to protect transmission lines of 69 kV and higher. Pilot protection schemes guarantee that the transmission line is fully protected and coordination with protection in other zones is not necessary.

If a disturbance occurs (fault) in a transmission line and a pilot protection scheme is implemented on it, it will guarantee a high-speed tripping [1]. If a high-speed tripping is achieved, the fault will be isolated from the system in a fastest way.

Distance relays, also known as impedance relays, are relays that use the measured voltage and current to calculate the impedance [1]. Modern pilot relays, such as microprocessor relays, incorporate the pilot scheme logic that before required complex electromechanical contacts making them slower at reacting [2]. But the use of digital communication systems on modern pilot protection schemes has improved its performance.

The introduction of IEC 61850 into the power system protection industry has changed the way information is exchanged between Intelligent Electronic Devices (IEDs) inside a substation. ([3] defines an IED as any device that has a processor with the capability of sending or receiving

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data/control from an external source). It is now going beyond the substation and is also used to exchange information between IEDs in different substations [4]. The considerable reduction in wiring required for the connection between IEDs is another important aspect of the utilization of this standard. The standard IEC 61850 was developed to cover most of the market requirements. The most relevant of which were interoperability, free architecture, and long-term stability [5].

Many IEC 61850 projects are in operation at this moment around the world, such as the first multivendor project in the United States of America with IEC 61850 developed by a group of engineers of the Tennessee Valley Authority (TVA) and manufacture representatives in the Bradley Substation which improved the IED multivendor interoperability after it [6]; La Venta II in Mexico, which is the world's first multivendor IEC 61850 project to prove multivendor interoperability [7]; and the substation Winznauschachen in Switzerland, which is the first world's first operating substation compliant with the standard IEC 61850 [8]. So far, IEC 61850 has been implemented in new substation projects and substation upgrades to communicate with IEDs inside the substation.

This thesis compares the performance of a Permissive Overreach Transfer Trip (POTT) scheme with IEC 61850 communication and a classic communication method, hard-wire. A simulated transmission line, 230 kV and 166 miles length, is protected by two multivendor relays on a POTT scheme. The hard-wire connection refers to the cable connected from one relay contact output to another relay contact input in order to provide the permissive signal required by the POTT.

The comparison performance of the POTT with IEC 61850 with hard-wire provides a better understanding of the relay's behavior when different communication channels are used. To accomplish this, this research has been divided into five chapters.

The current chapter –Chapter I– is a general overview of the importance of a pilot protection scheme and how the standard IEC 61850 has been implemented in real life projects around the world.

Chapter II is a literature review of the different papers related to this topic; most of them related to IEC 61850 and pilot protection schemes.

Chapter III gives a quick definition and introduction to the different topics addressed on this research: zones of protection, the POTT, and the standard IEC 61850; furthermore, the test set up is also explained in this chapter.

Chapter IV summarizes the results for the tests of IEC 61850 and hard-wire. Screenshots of the Comtrade files for the different simulated faults are also presented.

Chapter V is the conclusion of this research.

CHAPTER II

LITERATURE REVIEW

Different papers have been written and published about IEC 61850. The major parts of the standard were published in 2002 and 2003 [9]; however, only a few papers are related to protection schemes and Generic Object Oriented Substation Event (GOOSE) performance. However, no existing literature could be found that analyzes the performance of a POTT with IEC 61850 communication with multivendor relays.

[10] developed and tested a POTT scheme with IEC 61850 between two GE D90 Plus relays. GOOSE messages through an Ethernet-over-copper connection carried the permissive signal between the two remote simulated relays. Different faults were injected on different locations of the protected transmission line and the time from fault inception until trip operation was measured.

[11] compared a classical serial communication method using hard-wire contacts and IEC 61850 using Ethernet. The criteria set for this comparison was speed, control, usability, and reliability. A Human-Machine Interface (HMI) Supervisory Control and Data Acquisition (SCADA) system was setup using a Wonderware application to test controls of the relays.

[12] presents digital radio as a digital communication method to send permissive, blocking, and transfer trip signals. It discusses the factors affecting the reliability of digital radio path. It studies the path quality and performs analysis for fade margin. It also makes a

performance comparison between direct fiber, analog tone over analog microwave, digital channel through modem, and digital radio.

[13] discusses the time delay for GOOSE messages and proposes to implement packet scheduling techniques in the microprocessor relay itself rather than the switch. It also performs a comparison test between strict priority, round robin, and weighted round robin scheduling techniques.

The references mentioned above have only used IEC 61850 and hard-wire communication between relays of a single vendor only.

For this reason, this thesis work was performed, to provide results for two multivendor relays in a POTT protection scheme using hard-wire and IEC 61850 communication.

CHAPTER III

ACTUAL PROBLEM AND SOLUTION

A simulated transmission line, 230 kV and 166 miles in length, is presented. It was used to compare the performance of a POTT scheme with IEC 61850 and hard-wire communication.

Zones of Protection

A common practice is to divide the power system in zones [1]. If a fault occurs anywhere within a zone, the system components within the zone will be isolated. A zone is defined as the area from the current transformer (CT) connected to the line distance relay, until the defined reach of the zone.

In transmission line protection, it is common to use an underreaching zone (Zone 1) and an overreaching zone (Zone 2). A third zone, Zone 3, is also used in reverse or forward direction as a back protection of the prior or next transmission line, but it has not been used on this research since it is not required for a POTT scheme.

Figure 3.1 is an example of two zones of protection on the line distance relay A. The light gray area represents the first zone of protection, Zone 1, and the dark gray area the second zone of protection, Zone 2. The same zones are defined for relay B, but they are not represented on this figure.

Zone 1 is set to protect 80 to 90% of the transmission line [14]. It underreaches the remote end and does not have a time delay set to initiate a trip for any fault within the zone reach.

Zone 2 is set to protect at least 120% of the transmission line. Zone 2 covers all the line, including Zone 1's reach, and overreaches the remote end. A time delay of 15 to 30 cycles, 250 to 500 ms, is set to initiate a trip if a fault is detected anywhere within the zone.
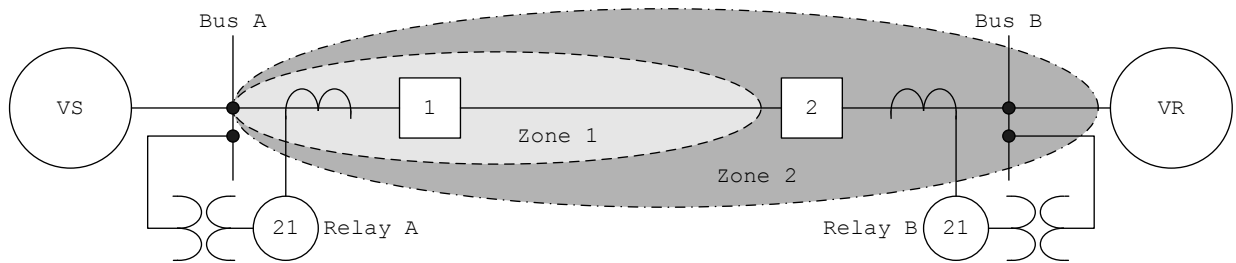
Figure 3.1 Zones of protection.

For this research a simulated medium-sized transmission line, 230 kV and 166 miles in length, is protected by two multivendor relays on a POTT scheme, Figure 3.2. Two modern test sets were used to simulate the voltage, a current that both relays would see on each end on the transmission line during the pre-fault and fault condition.

The protection zones for relay A and B start from Bus A and B respectively. Two zones of protection have been defined on each relay, Zone 1 and Zone 2. Zone 1 is set to protect 80% of the transmission line and Zone 2 is set to protect 120% of the transmission line. Relay A looks forward to Bus B and relay B looks forward to Bus A. The impedance positive-sequence (1) and zero-sequence (0) values of the transmission line, source S (VS), and source R (VR) are given as well as the voltage transformer ratio (VT) and current transformer ratio (CT). The circuit breaker 1 and 2 are governed by relay A and B respectively.

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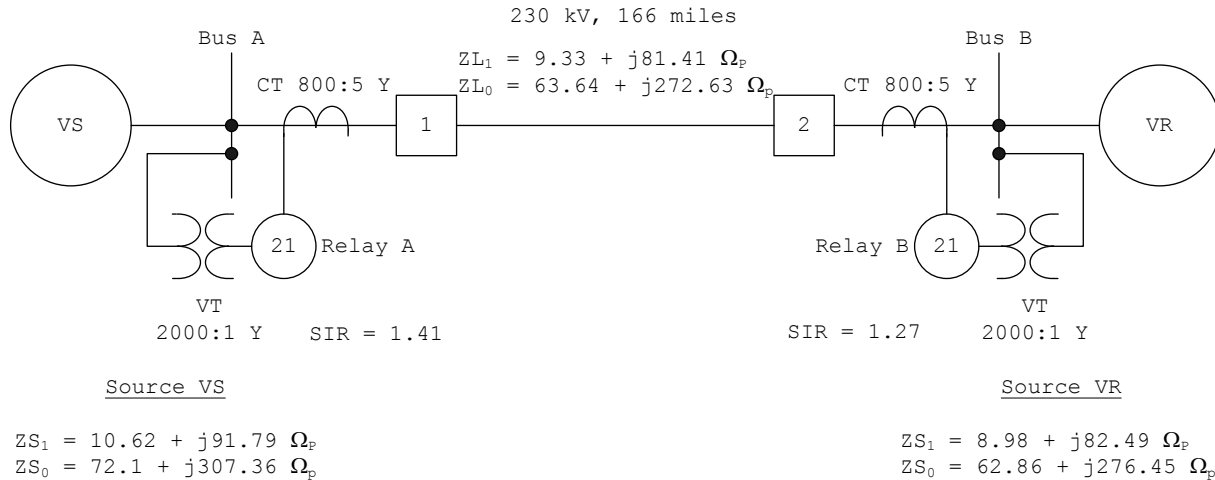
Figure 3.2 230 kV transmission line protected by two multivendor relays.

The relays used to protect the transmission line are distance relays. The ANSI/IEE has designated a number 21 to refer to a distance relay [15], as indicated in the figure.

Permissive Overreach Transfer Trip (POTT)

In a POTT scheme, when the relays on both terminals detect a fault on their overreach protected zone (Zone 2), they send a permissive signal to the remote terminal. This signal is compared with the internal overreaching function, Zone 2, to trip the breaker. For example on Figure 3.3, if Relay A detects a fault on Zone 1 and 2 it sends a permissive signal to relay B and initiate the trip operation for breaker 1. Breaker 1 is operated due to the fact that no time delay is associated to Zone 1. Relay B also detects the same fault in Zone 2 and sends a permissive signal to relay A. When a relay receives a permissive signal, the relay compares it with the Zone 2 function operation, pickup. If both signals −Zone 2 pickup and remote permissive signal− are present at the same time, the relay A and B initiate the trip operation for breaker 1 and 2, respectively.

On the previous example, one can notice that relay A does not require the permissive signal to operate its breaker while relay B does. In this case, POTT does not operate on the relay that detects the fault on its underreaching zone.
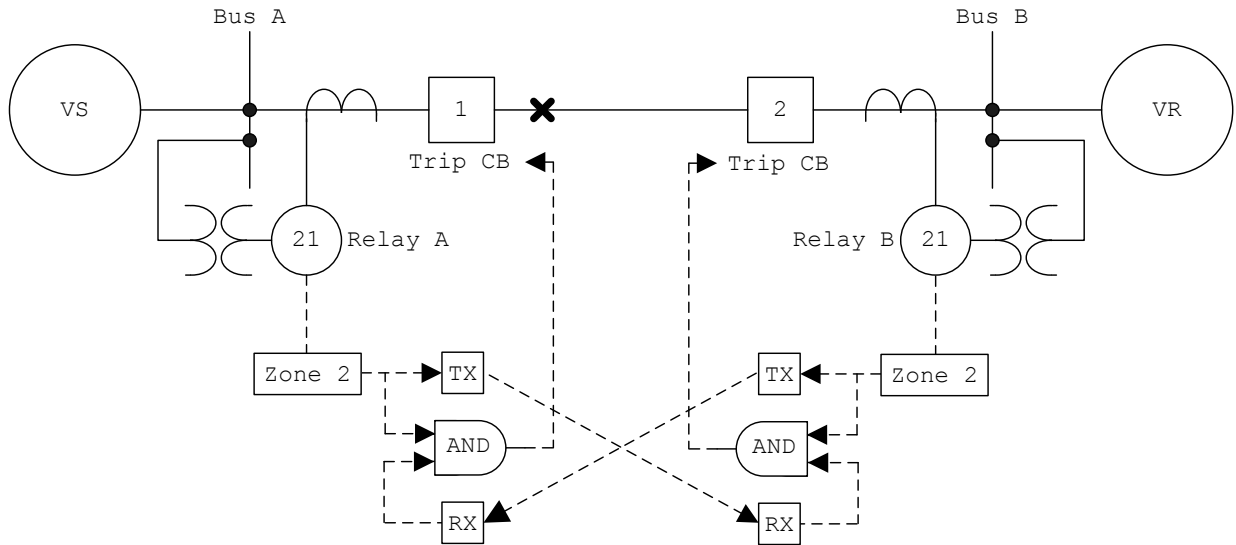
Figure 3.3 Permissive overreach transfer trip scheme function.

POTT schemes regularly communicate through audio frequency tones over telephone circuits or modulated on microwave channels [2]. In the United States, however, most of the pilot protection systems are digital using fiber optic or microwave as the channel.

If the communication channel is inoperative, the POTT scheme is very secure because it will not operate for any external fault, though it has the drawback that it will not operate for internal faults [14].

IEC 61850

The IEC 61850 standard was developed to address market requirements, the most relevant of which were interoperability, open architecture, and long-term stability [5]. It has been divided in a series of documents. Table 3.1 summarizes the different parts of the standard.

Table 3.1 IEC 61850 summary of documents

Document	Description
IEC/TR[1] 61850-1	Introduction and overview
IEC/TS[2] 61850-2	Glossary
IEC 61850-3	General requirements
IEC 61850-4	System and project management
IEC 61850-5	Communication requirements for functions and device models
IEC 61850-6	Configuration description language for communication in electrical substations related to IEDs
IEC 61850-7-1	Basic communication structure for substation and feeder equipment – Principles and models
IEC 61850-7-2	Basic communication structure for substation and feeder equipment – Abstract communication service interface (ACSI)
IEC 61850-7-3	Basic communication structure for substation and feeder equipment – Common data classes
IEC 61850-7-4	Basic communication structure for substation and feeder equipment – Compatible logical node classes and data classes
IEC 61850-7-410	Hydroelectric power plants – Communication for monitoring and control
IEC 61850-7-420	Basic communication structure – Distributed energy resources logical nodes
IEC 61850-8-1	Specific communication service mapping (SCSM) – Mappings to MMS (ISO/IEC 9506-1 and ISO/IEC 9506-2) and to ISO/IEC 8802-3
IEC 61850-9-1	Specific communication service mapping (SCSM) – Sampled values over serial unidirectional multidrop point to point link
IEC 61850-9-2	Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3
IEC 61850-10	Conformance testing
IEC/TS 61850-80-1	Guideline to exchanging information from a CDC-based data model using IEC 60870-5-101 or IEC 60870-5-104
IEC/TR 61850-90-1	Use of IEC 61850 for the communication between substations

[1] Technical Report.
[2] Technical Specification.

The scope of the standard was for communication inside the substation, but it has gone beyond the substation with applications that use different components of IEC 61850 for the communication from substation-to-substation [4]. As a result, the standard has also published a

technical report about the communication between substations and network control centers, IEC/TR 61850-90-1 [16], as one can see in Table 3.1.

In the case of a protection scheme, such as POTT, the permissive signal is sent to a remote device through a Generic Object Oriented System (GOOSE) message if IEC 61850 is been used for this purpose. A GOOSE message can also include information such as status changes, open or close circuit breaker, or blocking. Part 5 [17] of the standard IEC 61850 defines that the total transmission time for a trip signal with a performance of Class P1 shall be in the order of 10 ms and similarly a Class P2/3 shall be in the order of 3 ms.

Making a comparison of the transfer time on a classic communication method, such as −hard-wire,− and IEC 61850, one can see that in the case of Figure 3.4, time a and c, t_a and t_c, are the times it takes the relay contact output and input to send and receive a signal, respectively. Conventional relay contact inputs and outputs have response times of around 10 ms [16]. Time b, t_b, is the time it takes the signal to get from physical device 1 to 2. It is usually close to the speed of light if a direct link exists between both devices. The assumption is that the physical device 1 is sending a signal and the physical device 2 is receiving it.
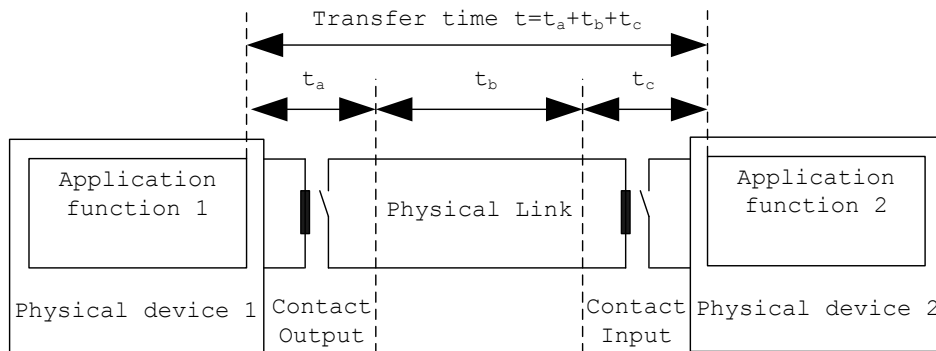
Figure 3.4 Transfer time using a relay contact output and input with hard-wire.

In the other hand, Figure 3.5 shows that the relay contacts have been replaced by a software communication stack running inside the relay. Similarly as in the case presented above, time *a* and *c* represent the times that take to code and decode a signal that will be transmitted through the physical link. The communication decoding in the stack can be done in less than 1 ms [18]. Time *b* represents the pure network transfer time.
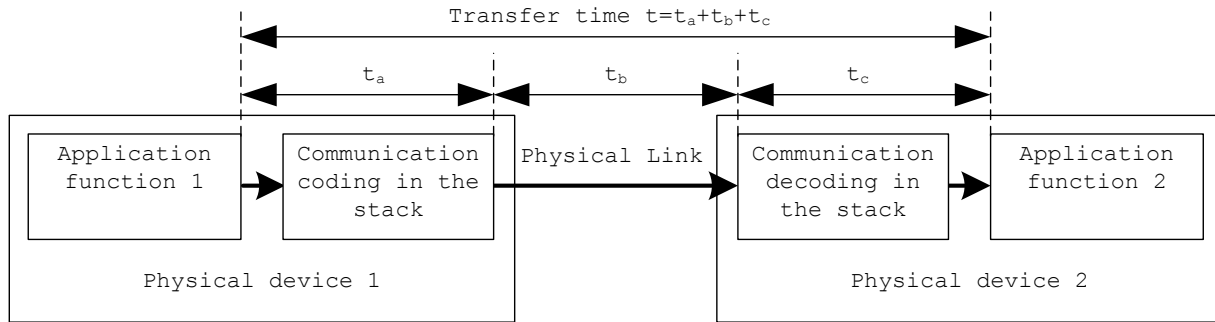
Figure 3.5 Transfer time using a serial communication with IEC 61850.

Test Setup

The IEC 61850 and hard-wire performance comparison for POTT scheme was divided into two parts.

The first part of the test was the POTT scheme with IEC 61850 communication. The wiring connections shown on Figure 3.6 were made between both multivendor relays and test sets. These wiring connections were used only for the analog inputs, voltage and current, a binary input signal, breaker status, and binary output signal, the breaker trip coil signal, on each relay. Each substation was simulated with a relay and a test set. The test set provided the voltage and current to the relay. The breaker trip coil signal from a relay contact output was hooked to a binary input of the test set to sense the time from fault inception until the relay sent the trip signal. The relays must know the breaker position and was handled by simulating the

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breaker position with the test set. The 52a circuit breaker contact was used for this purpose, which follows the status of the breaker; it is closed when the circuit breaker is closed and open when the circuit breaker is open.

A switch was used to start both test sets at the same time. It ensured the synchronization of both units.
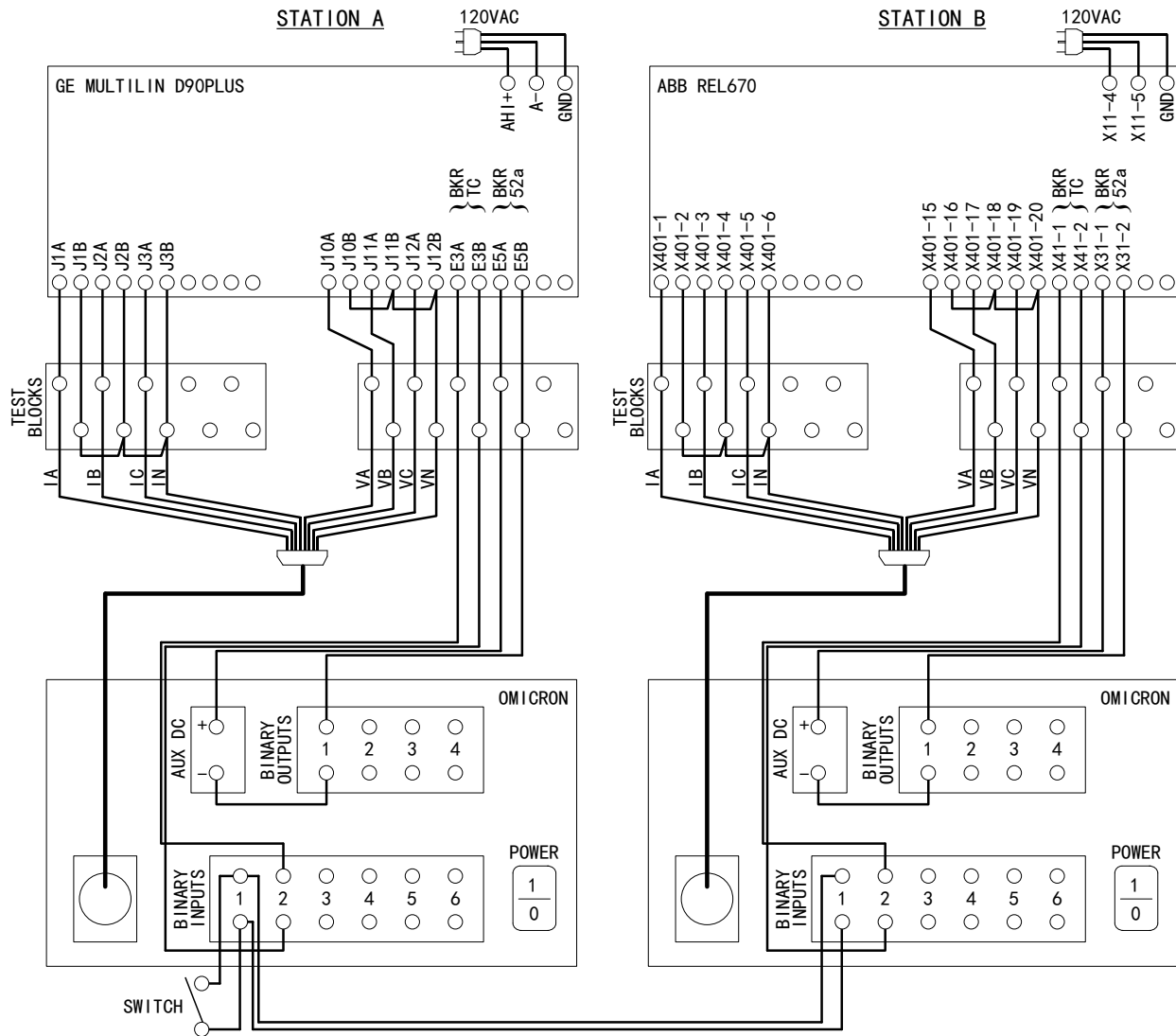
Figure 3.6 Analog inputs connection diagram for POTT with IEC 61850.

The communication connection diagram for this test is presented on Figure 3.7. An Ethernet switch was placed on each rack, racks A and B, to simulate a real condition where both substations are geographically separated. Ethernet over copper was used by the most with the only exception being relay B because the rear port of this relay is an Ethernet port over fiber. Only test set A had IEC 61850 capabilities and it was used to monitor the GOOSE messages with the permissive signal coming from both relays. A computer was configured to serve as a Simple Time Network Protocol (SNTP) server, to provide time synchronization for both relays.
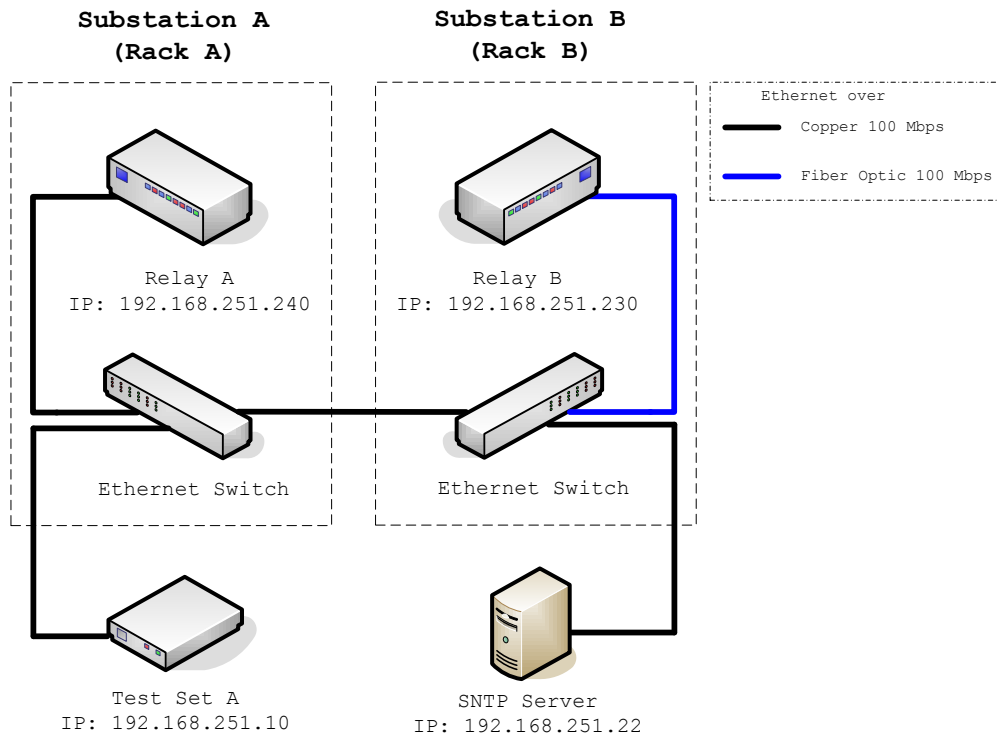
Figure 3.7 Communication connection diagram for POTT with IEC 61850.

The second part of the test was the POTT scheme with hard-wire communication. The wiring connection showed on Figure 3.8 corresponds to this part of the test and the communication section is included in this figure. The only difference with the first part of the

test is that a contact output and input was used to send and receive the permissive signal. The other wiring connections remained the same as in Figure 3.6
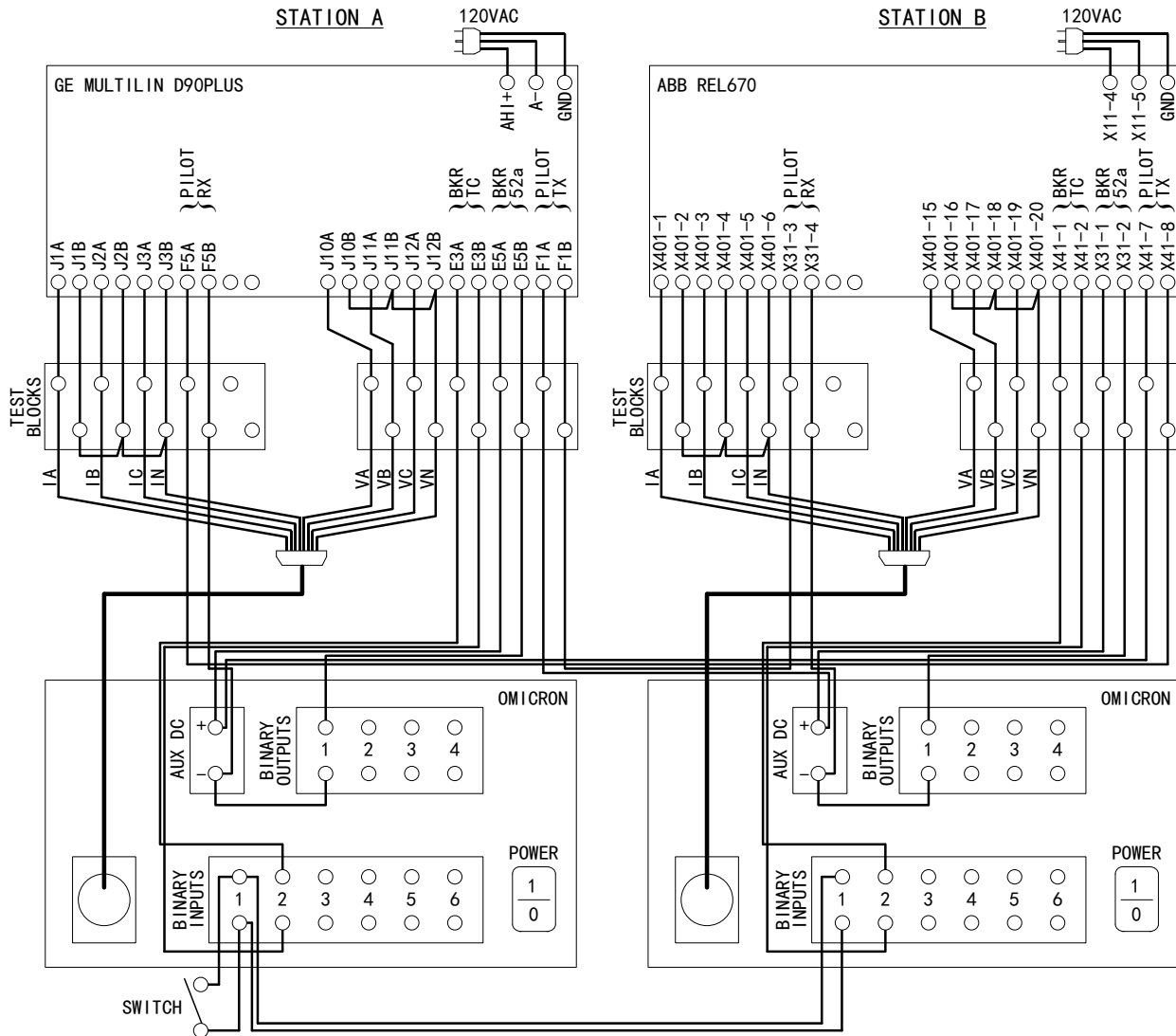
Figure 3.8 Connection diagram for POTT with hard-wire communication.

The test sets simulated different fault conditions in Zone 1 and 2 of each relay. The simulated fault conditions were as follows:

1. Single phase to ground fault. Phase A to ground fault (A-G)

2. Double line to ground fault. Phase B and C to ground fault (BC-G)

3.   Phase-to-phase fault. Phase B and C fault (BC)

The fault conditions were calculated with the method of symmetrical components. Appendix A shows the calculations for the pre-fault and fault conditions seen by each relay on the simulated substations. The tables in Appendix B are summaries of the pre-fault, fault, and post-fault conditions injected to the relays with the test sets during the test. For example, Table B.1 is the simulated A-G fault seen by relay A in Zone 1 and Table B.2 the simulated A-G fault seen by relay B in Zone 2. The simulated fault is the same fault seen from two different positions, relay A and B. The fault in Zone 1 of relay A and Zone 2 of relay B is simulated on each test set to recreate the fault condition. It means that voltage and current from the test A and B are injected into relay A and B respectively at the same time.

An example of the test sequences used is showed on Figure 3.9. There are four states. The first state is the synchronization state; the second one is the pre-fault condition state; the third one is the fault condition state; and the fourth, and last state, is the post-fault condition state. Notice that the simulated circuit breaker position, 52a, is closed during the first three states and it opens on the post-fault state. A delay of three cycles after trigger is set on the fault condition state, to simulate the time that takes to the circuit breaker to open after the trip signal is received.

Name	1 — Zero-frequency (Synchronization) T1		2 — Pre-Fault T1		3 — Fault T1		4 — Post-Fault T1	
V A-N	0.000 V	0.0000 Hz	66.15 V -3.59°	60.000 Hz	5.410 V 0.01°	60.000 Hz	66.15 V -3.59°	60.000 Hz
V B-N	0.000 V	0.0000 Hz	66.15 V -123.59°	60.000 Hz	81.34 V -141.34°	60.000 Hz	66.15 V -123.59°	60.000 Hz
V C-N	0.000 V	0.0000 Hz	66.15 V 116.41°	60.000 Hz	84.92 V 131.56°	60.000 Hz	66.15 V 116.41°	60.000 Hz
I A	0.000 A	0.0000 Hz	560.0 mA 1.46°	60.000 Hz	4.650 A -76.23°	60.000 Hz	0.000 A 0.00°	60.000 Hz
I B	0.000 A	0.0000 Hz	560.0 mA -118.54°	60.000 Hz	560.0 mA -118.54°	60.000 Hz	0.000 A 0.00°	60.000 Hz
I C	0.000 A	0.0000 Hz	560.0 mA 121.46°	60.000 Hz	560.0 mA 121.46°	60.000 Hz	0.000 A 0.00°	60.000 Hz
CMC Rel	1 output(s) active		1 output(s) active		1 output(s) active		1 output(s) active	
Trigger				240.0 cy				60.00 cy

Column 1 — Trigger tab

State termination
- Binary input(s) and/or timeout
  - ☑ Use binary trigger condition as specified below
  - ☐ Timeout:
- User interaction Define Instruction...
- Pulse from CMGPS connected to 'ext. Interf.'
- After number of IRIG-B pulses: 1

Delay after trigger: 0.000 cy

Binary trigger condition
Trigger logic: ○ AND ● OR

Input	Display Name	State
1	Start	1
2	Trip BRK1	X

Column 2 — Trigger tab

State termination
- Binary input(s) and/or timeout
  - ☐ Use binary trigger condition as specified below
  - ☑ Timeout: 240.0 cy
- User interaction Define Instruction...
- Pulse from CMGPS connected to 'ext. Interf.'
- After number of IRIG-B pulses: 1

Delay after trigger: 0.000 cy

Binary trigger condition
Trigger logic: ○ AND ● OR

Input	Display Name	State
1	Start	X
2	Trip BRK1	X

Column 3 — Trigger tab

State termination
- Binary input(s) and/or timeout
  - ☑ Use binary trigger condition as specified below
  - ☐ Timeout:
- User interaction Define Instruction...
- Pulse from CMGPS connected to 'ext. Interf.'
- After number of IRIG-B pulses: 1

Delay after trigger: 3.000 cy

Binary trigger condition
Trigger logic: ○ AND ● OR

Input	Display Name	State
1	Start	X
2	Trip BRK1	1

Column 4 — Trigger tab

State termination
- Binary input(s) and/or timeout
  - ☑ Use binary trigger condition as specified below
  - ☑ Timeout: 60.00 cy
- User interaction Define Instruction...
- Pulse from CMGPS connected to 'ext. Interf.'
- After number of IRIG-B pulses: 1

Delay after trigger: 7.000 cy

Binary trigger condition
Trigger logic: ○ AND ● OR

Input	Display Name	State
1	Start	X
2	Trip BRK1	X

Binary Out tabs

Output	Display Name	
1	CB 52a	

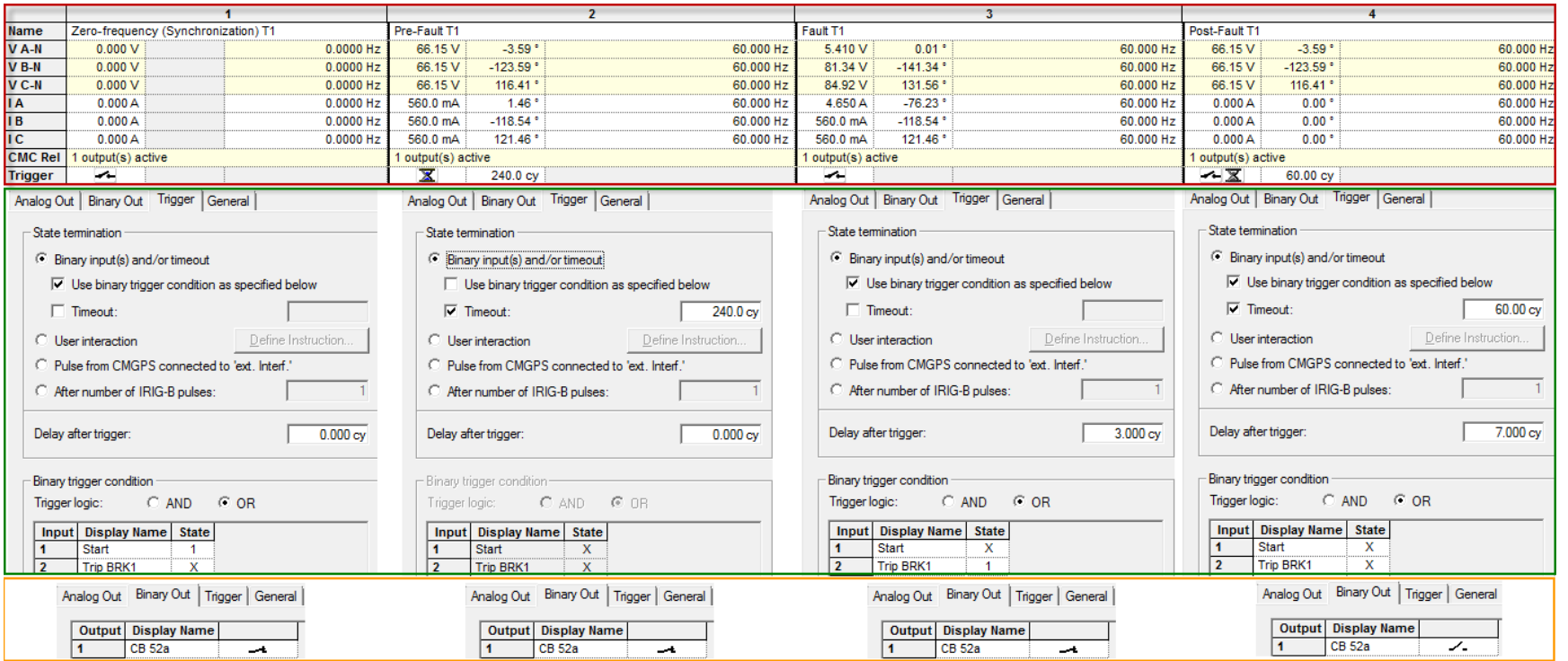Figure 3.9 Test set sequence example.

CHAPTER IV

RESULTS

Six different tests on each station were performed for testing a POTT with IEC61850 and hard-wire communication. Each test was run 10 times and an average of the time result was gathered for POTT with IEC61850 and hard-wire communication.

The tests were as follows:

1. Phase A to ground fault (A-G) in Zone 1 of relay A and Zone 2 of relay B

2. Phase A to ground fault (A-G) in Zone 2 of relay A and Zone 1 of relay B

3. Phase B and C to ground fault (BC-G) in Zone 1 of relay A and Zone 2 of relay B

4. Phase B and C to ground fault (BC-G) in Zone 2 of relay A and Zone 1 of relay B

5. Phase B and C fault (BC) in Zone 1 of relay A and Zone 2 of relay B

6. Phase B and C fault (BC) in Zone 2 of relay A and Zone 1 of relay B

The Zone 1 distance element was expected to operate on both relays for all faults located in Zone 1. But the Zone 2 distance element only to pick up, because the reach of Zone 2 includes Zone 1.

The Zone 2 distance element was expected to pick up and not to operate for faults located in Zone 2 only. The relays behaved as expected on all the tests.

POTT with IEC61850 Communication Test

A-G Fault

Figure 4.1 shows that the relay A ground distance element picks up on Zone 1 (GND DIST Z1 PKP) and 2 (GND DIST Z2 PKP) at the same time and Zone 1 operates (GND DIST Z1 OP) immediately after Zone 1 picks up with no delay; therefore, the relay trips (Trip On). When Zone 2 picks up on this relay, a permissive signal (POTT TX1) is sent to the remote device.

It is expected that the relay A ground distance element picks up on Zone 1 and 2 because a phase-to-ground fault is applied at 10% of the transmission line from relay A.
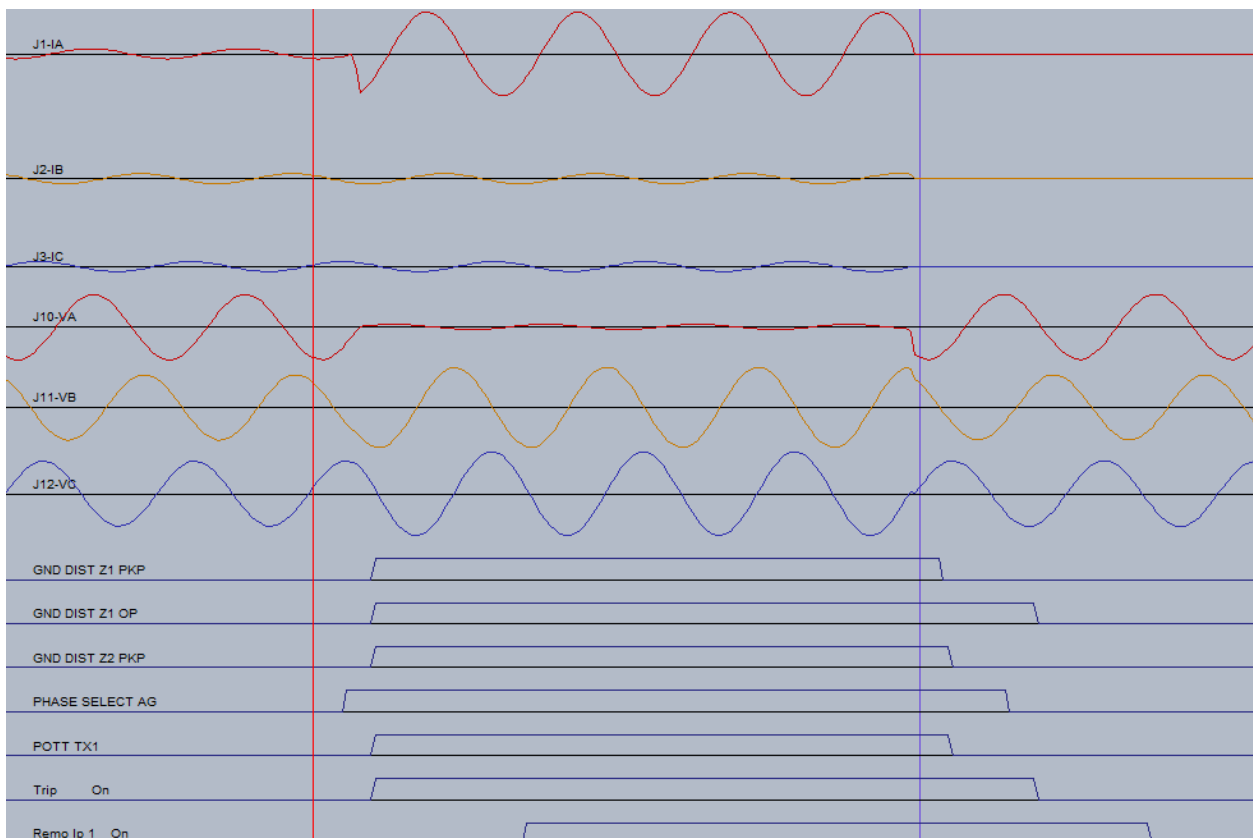

Figure 4.1 Relay A – Zone 1 AG fault.

Figure 4.2 shows that a permissive signal (CHANNEL RCV 1) has been received and when the distance element picks up on Zone 2 (ZONE2 MHO PU), the pilot scheme element operates (PILOT TRIP); therefore, the relay trips (TRIP BKR1) the circuit breaker.

It is expected that the relay B distance element picks up on Zone 2, because a phase-to-ground fault is applied at 90% of the transmission line from relay B and a time delay is set on this Zone which causes it to trip when the permissive signal is received.
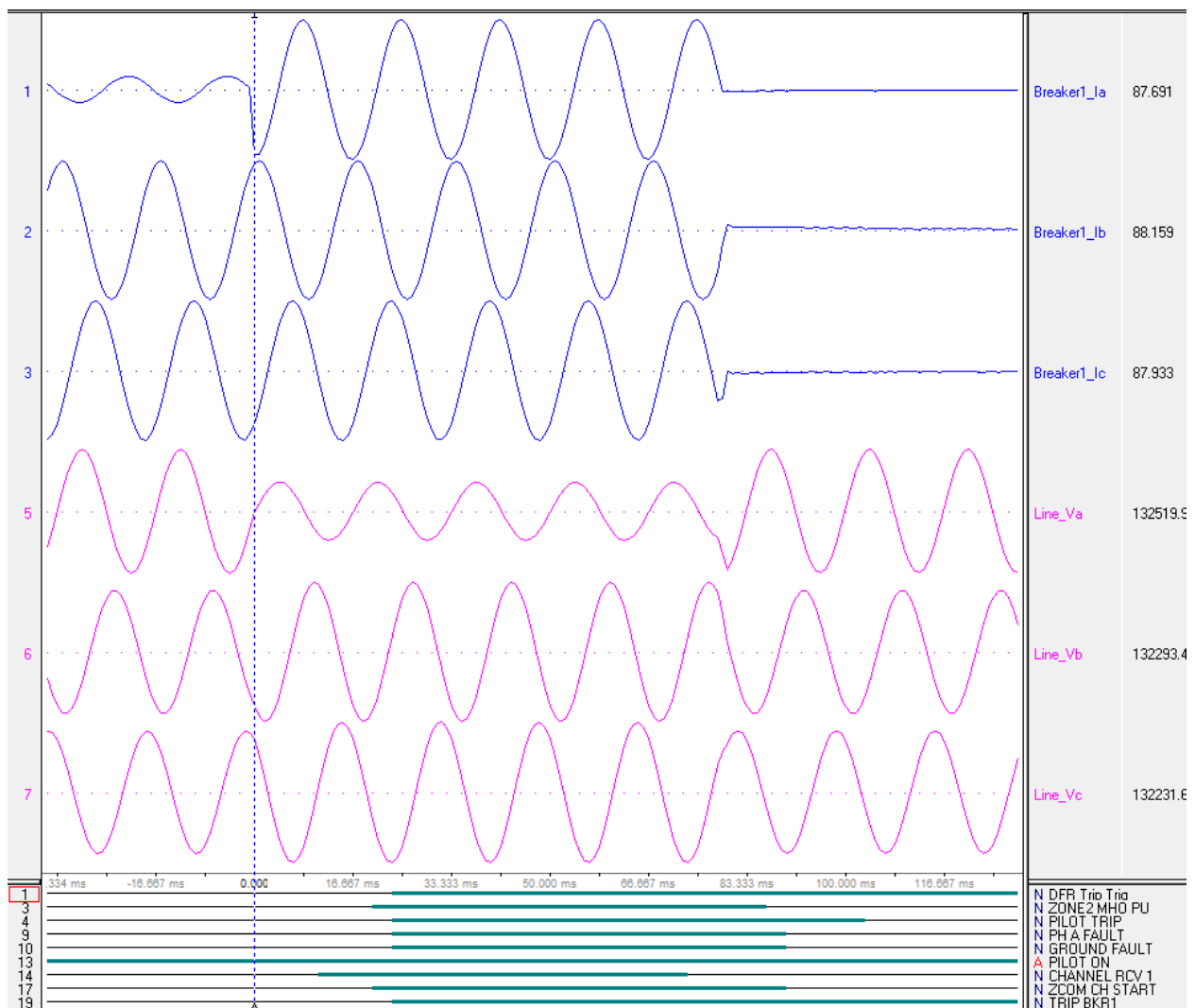

Figure 4.2 Relay B − Zone 2 AG fault.

The test set captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.3. The relay A trip signal (Trip BRK1) is the first to operate followed by the relay B trip signal (Trip BRK2). One can see that the remote permissive signal (Pilot A C1) is received and after some time the relay B trips as mentioned above. The permissive signal (Pilot B C1) from relay B is also displayed on this figure, but it is not required by relay A to trip since the fault is located on its Zone 1.

Figure 4.3 Test set – AG fault in Zone 1 of relay A.
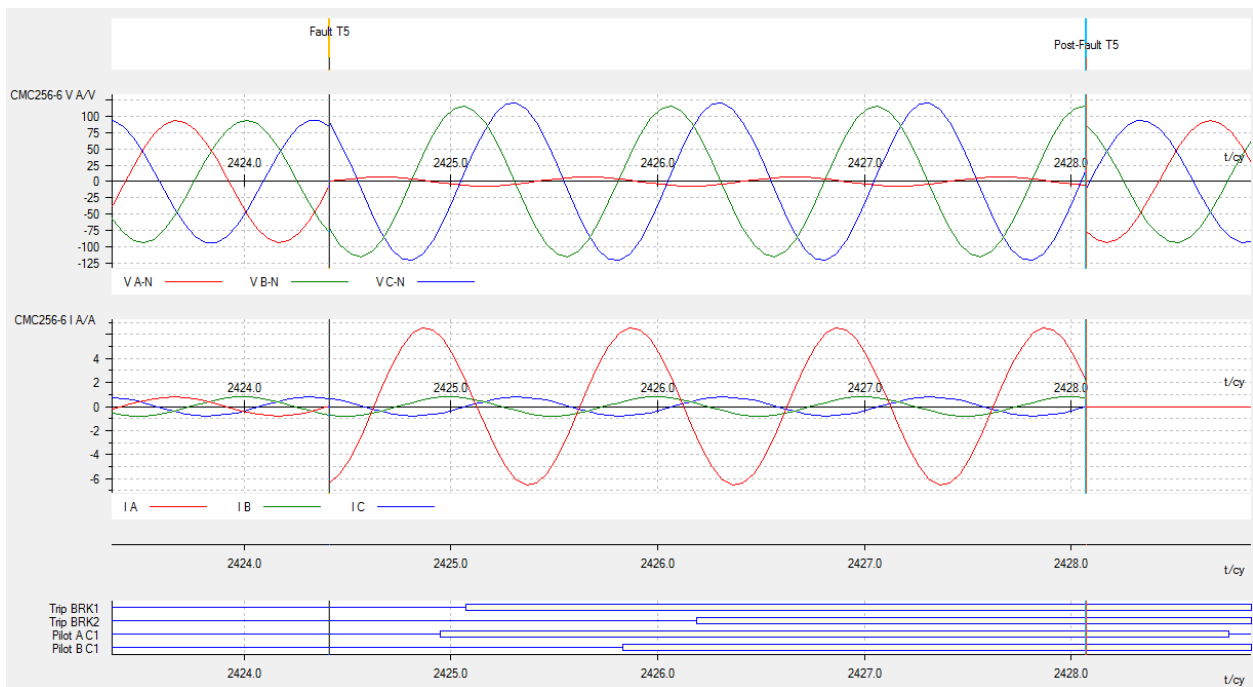
Figure 4.4 shows that only the relay A ground distance element Zone 2 picks up (GND DIST Z2 PKP). When the remote permissive signal (Remo Ip 1 On) is received, the POTT operates (POTT OP) and the relay trips (Trip On).

It is expected that the relay A ground distance element Zone 2 picks up, because a phase-to-ground fault is applied at 90% of the transmission line from relay A.

Figure 4.4 Relay A – Zone 2 AG fault.

Figure 4.5 shows that the relay B phase distance element Zone 1 trips (ZONE1 MHO TRP) and at the same time the phase distance element Zone 2 (ZONE2 MHO PU) picks up and sends a permissive signal (ZCOM CH START) to relay A.

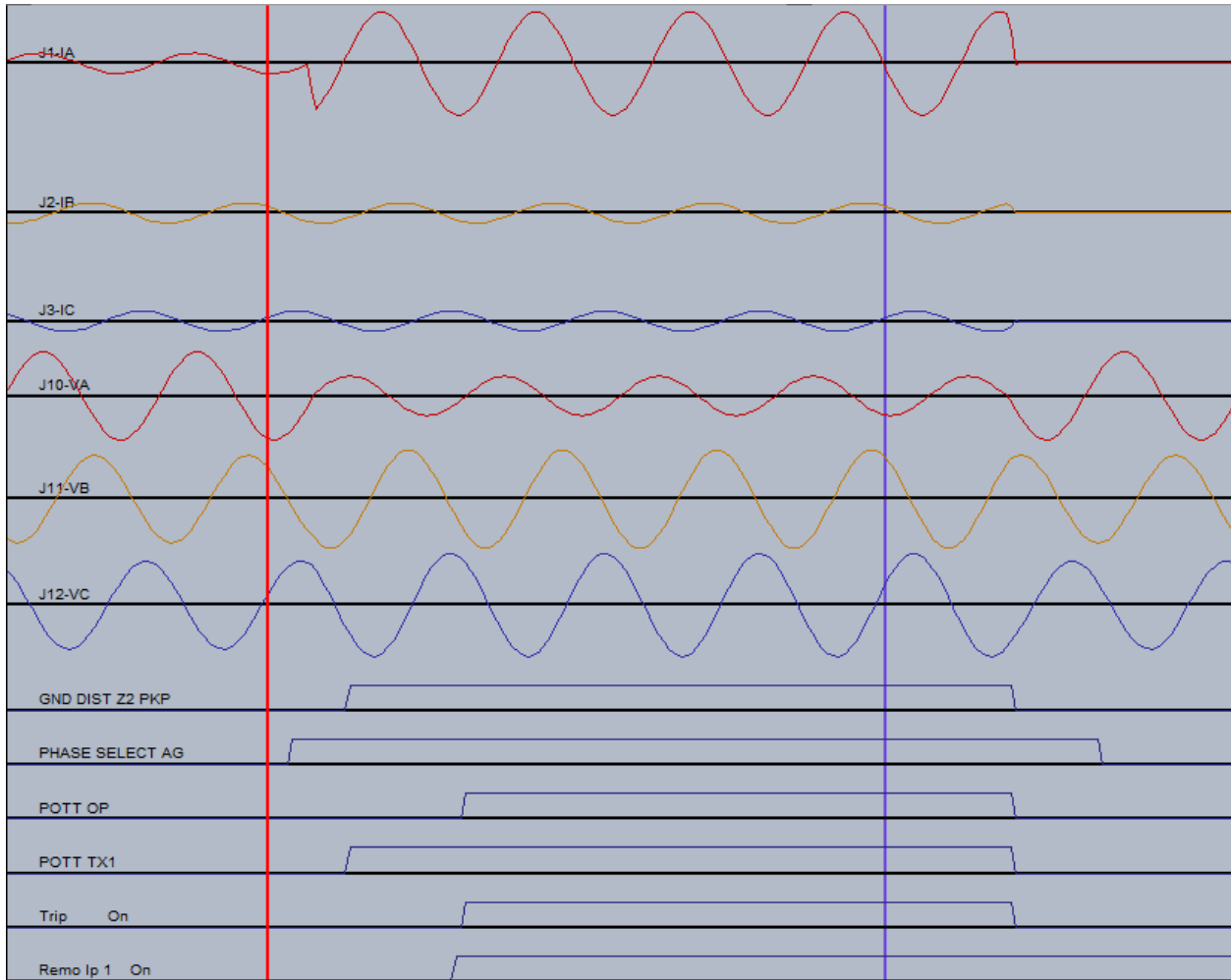It is expected that the relay B phase distance element Zone 1 trips, because a phase-to-ground fault is applied at 10% of the transmission line from relay B and there is not a time delay set associated to Zone 1.
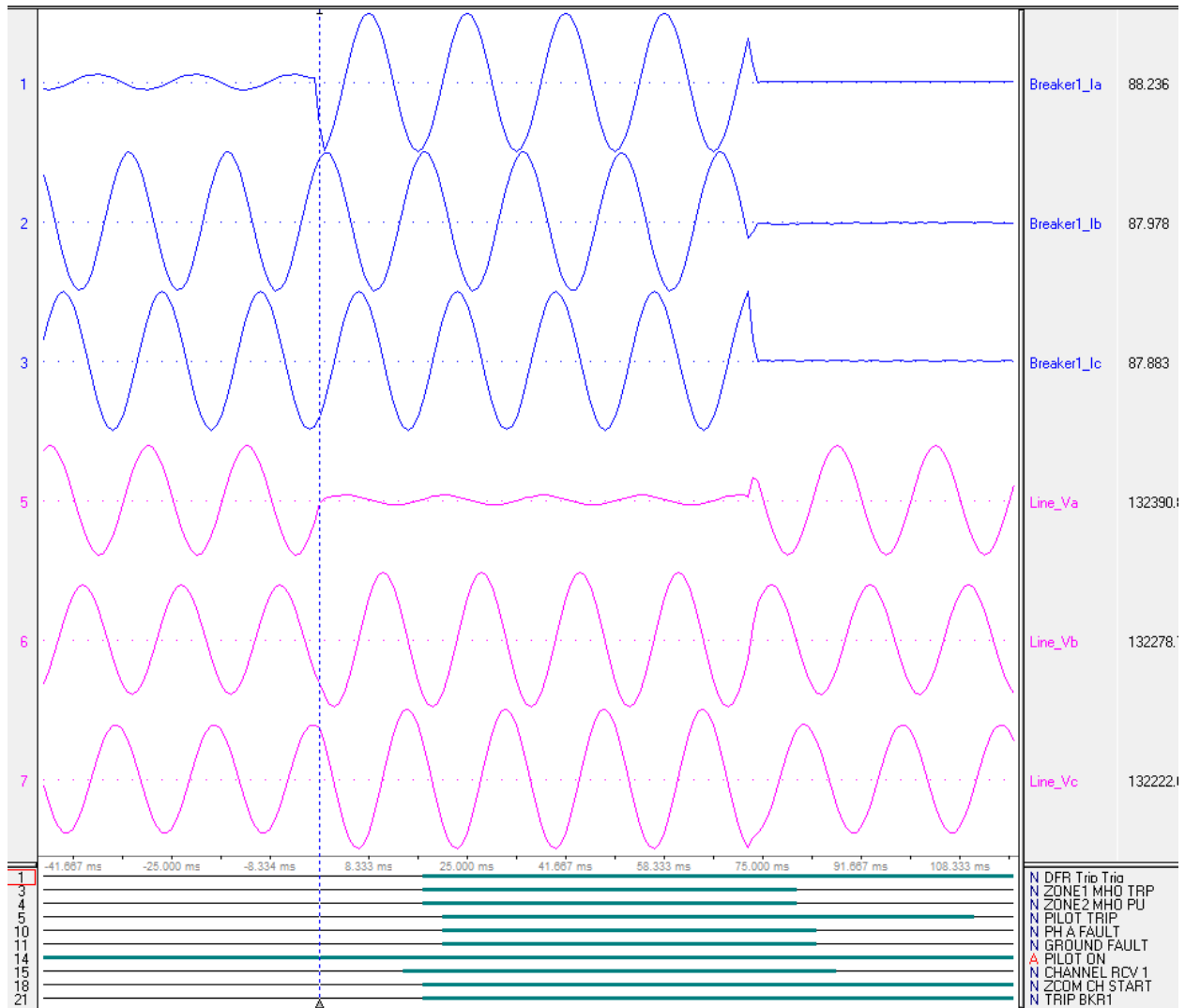
Figure 4.5 Relay B – Zone 1 AG fault.

The test set captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.6. The relay B trip signal (Trip BRK2) is the first to operate followed by the relay A trip signal (Trip BRK1). One can see that the remote permissive signal (Pilot B C1) is received and after some time the relay A trips as mentioned above. The permissive signal (Pilot A C1) from relay A is also displayed on this figure, but it is not required by relay A to trip since the fault is located on Zone 1.

Figure 4.6 Test set – AG fault in Zone 2 of relay A.

BC-G Fault

Figure 4.7 shows that the relay A phase distance element picks up on Zone 1 (PH DIST Z1 PKP) and 2 (PH DIST Z2 PKP), but the phase distance element Zone 1 operates (PH DIST Z1 OP). The relay trips (Trip On) as a result of the phase distance element Zone 1 operation. A permissive signal (POTT TX1) is sent at the same time that the phase distance Zone 2 picks up.

It is expected that the relay A phase distance element Zone 1 operates, because a double line-to-ground fault is applied at 10% of the transmission line from relay A.
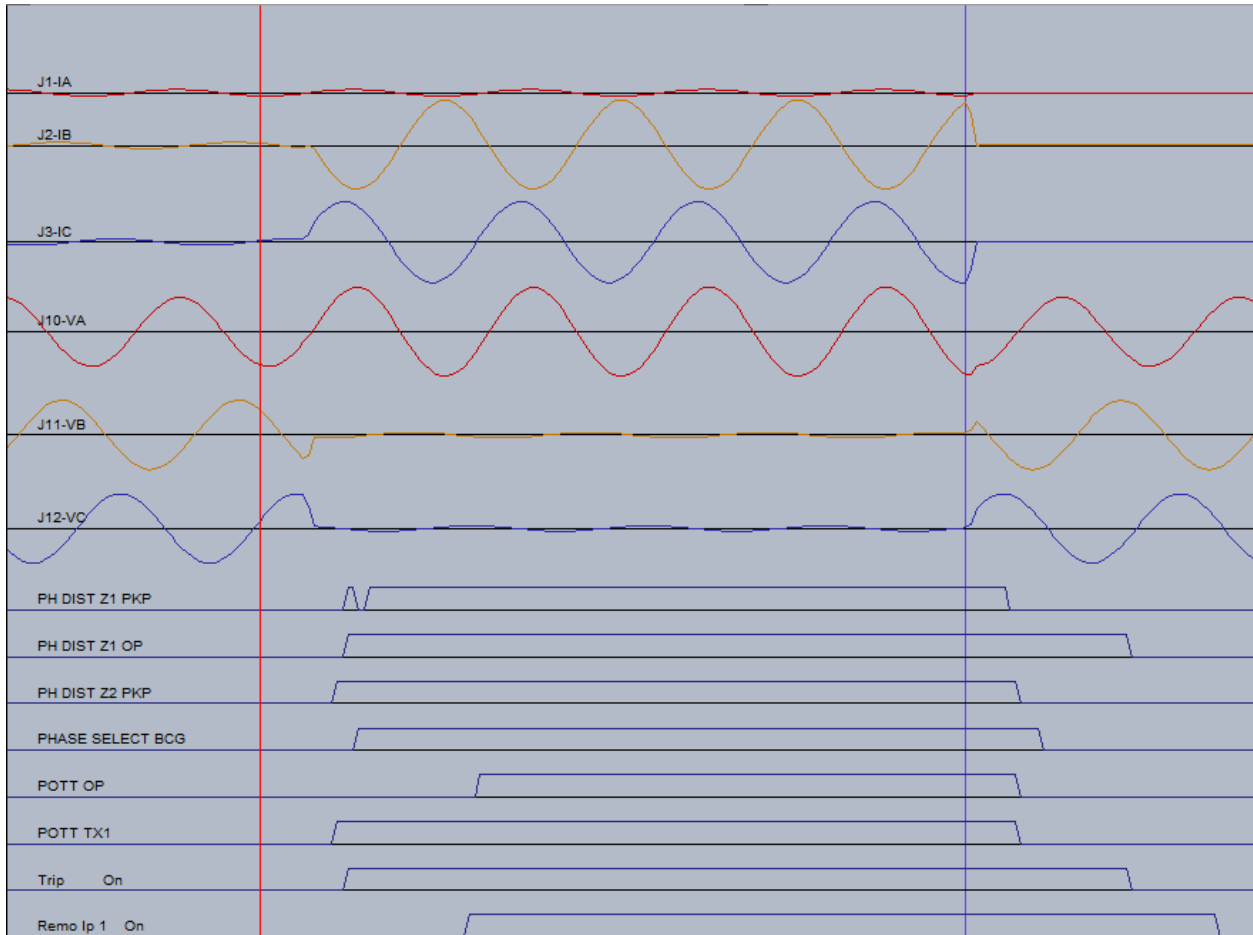
Figure 4.7 Relay A – Zone 1 BC-G fault.

Figure 4.8 shows that the relay B distance element Zone 2 picks up (ZONE2 MHO PU) and when the remote permissive signal (CHANNEL RCV1) is received, the pilot protection scheme operates (PILOT TRIP) and the relay trips (TRIP BKR1).

It is expected that the relay B distance element Zone 2 picks up, because a double line-to-ground fault is applied at 90% of the transmission line from relay B.

Figure 4.8 Relay B – Zone 2 BC-G fault.

The test set captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.9. The relay A trip signal (Trip BRK1) operates first followed by the relay B trip signal (Trip BRK2). One can see that the remote permissive signal (Pilot A C1) has been received before the relay B senses the fault. The permissive signal (Pilot B C1) from relay B is also displayed on this figure, but it is not required by relay A to trip since the fault is located on relay's A Zone 1.
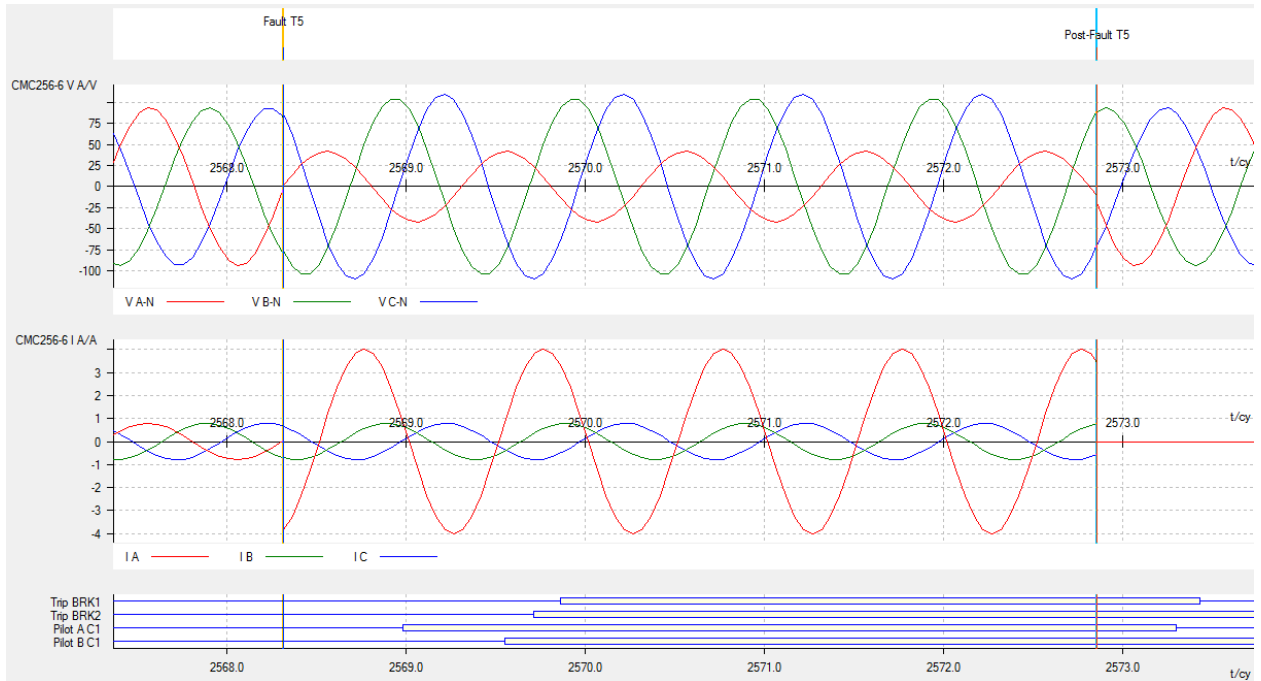
Figure 4.9 Test set – BC-G fault in Zone 1 of relay A.

Figure 4.10 shows that the relay A phase distance element Zone 2 (PH DIST Z2 PKP) picks up, a remote permissive signal (Remo Ip 1 On) is received, and after this permissive signal is received the pilot protection scheme (POTT OP) operates; therefore, the relay trips (Trip On).

It is expected that the relay A phase distance element Zone 2 picks up, because a double line-to-ground fault is applied at 90% of the transmission line from relay A.

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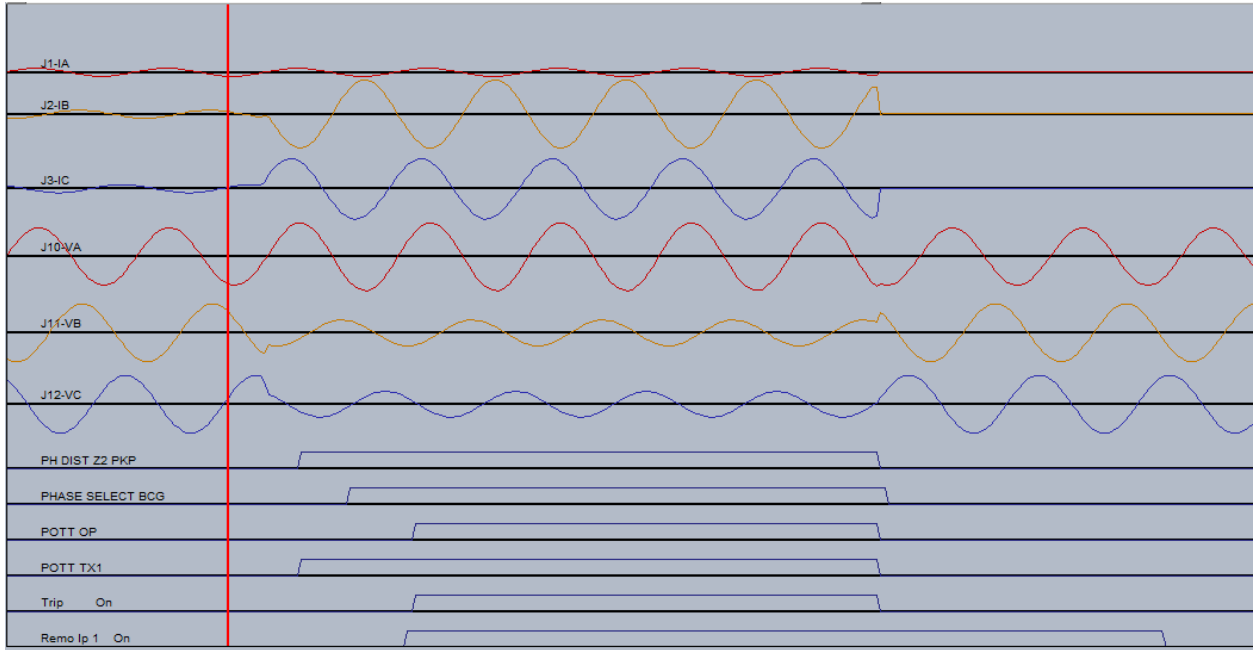
Figure 4.10 Relay A – Zone 2 BC-G fault.

Figure 4.11 shows that the relay B distance element Zone 1 (ZONE1 MHO TRP) operates and immediately it trips (TRIP BKR1); the distance element Zone 2 (ZONE2 MHO PU) picks up and a permissive signal (ZCOM CH START) is sent as result of it.

It is expected that the relay B distance element trips on Zone 1, because a double line-to-ground fault is applied at 10% of the transmission line from relay B and there is not a time delay set associated to Zone 1.
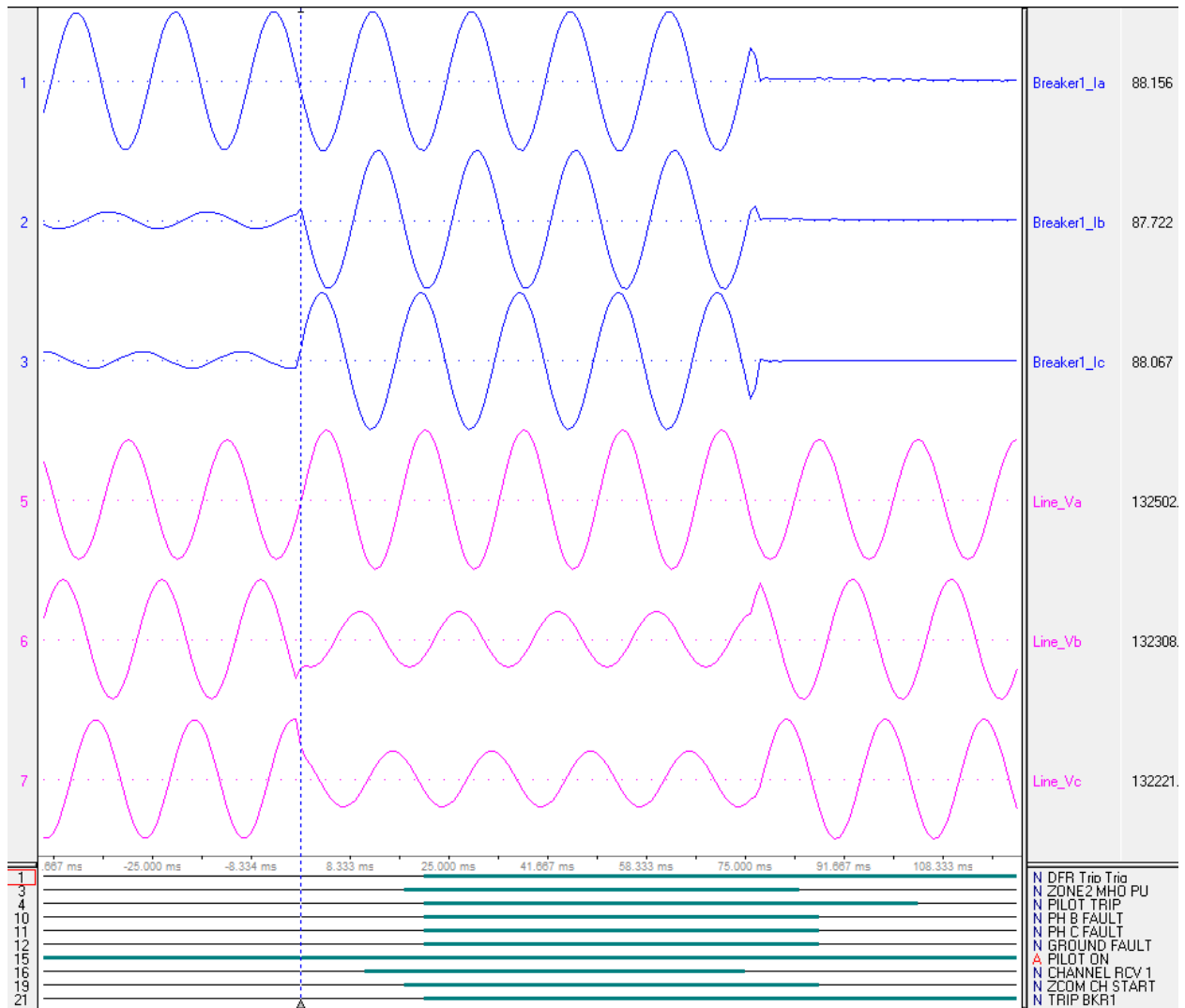
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Figure 4.11 Relay B – Zone 1 BC-G fault.

The test set captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.12. The relay B trip signal (Trip BRK2) is the first to operate followed by the relay A trip signal (Trip BRK1). One can see that the remote permissive signal (Pilot B C1) is received and after some time the relay A trips as mentioned above. The permissive signal (Pilot A C1) from relay A is also displayed on this figure, but it is not required by relay B to trip since the fault is located on Zone 1.
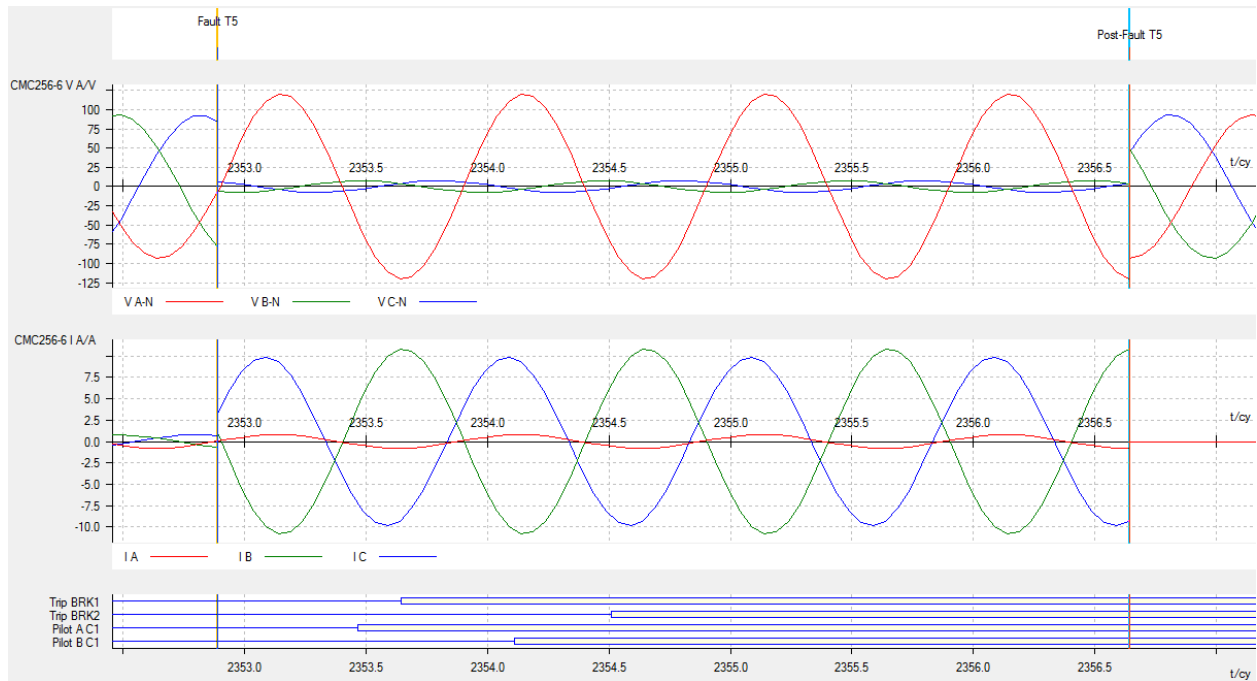
Figure 4.12 Test set – BC-G fault in Zone 2 of relay A.

BC Fault

Figure 4.13 shows that the relay A phase distance element picks up on Zone 1 (PH DIST Z1 PKP) and 2 (PH DIST Z2 PKP), but the phase distance element Zone 1 operates (PH DIST Z1 OP). The relay trips (Trip On) as a result of the phase distance element Zone 1 operation. A permissive signal (POTT TX1) is sent at the same time to the remote relay B.

It is expected that the relay A phase distance element Zone 1 operates, because a phase-to-phase fault is applied at 10% of the transmission line from relay A.

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Figure 4.13 Relay A – Zone 1 BC fault.

Figure 4.14 shows that the relay B distance element Zone 2 (ZONE2 MHO PU) picks up.
The pilot scheme element (PILOT TRIP) operates once Zone 2 picks up, because a permissive
signal (CHANNEL RCV1) has been previously received from relay A. As a result of PILOT
TRIP operation, the relay trips (TRIP BKR1).

It is expected that the relay B distance element Zone 2 picks up, because a phase-to-phase
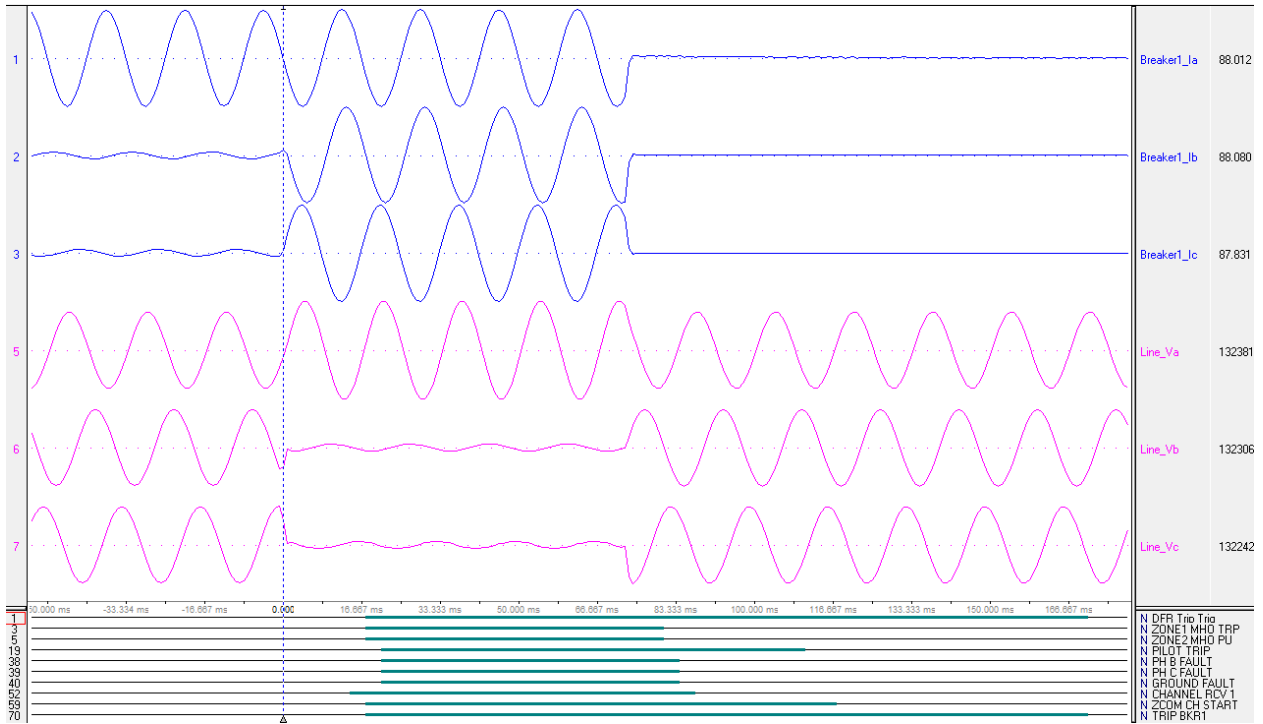fault is applied at 90% of the transmission line from relay B.

Figure 4.14 Relay B – Zone 2 BC fault.

The test set A captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.15. The relay A trip signal (Trip BRK1) is the first to operate followed by the relay B trip signal (Trip BRK2). One can see that the remote permissive signal (Pilot A C1) is received and after some time the relay B trips as mentioned above. The permissive signal (Pilot B C1) from relay B is also displayed on this figure, but it is not required by relay A to trip since the fault is located on Zone 1.
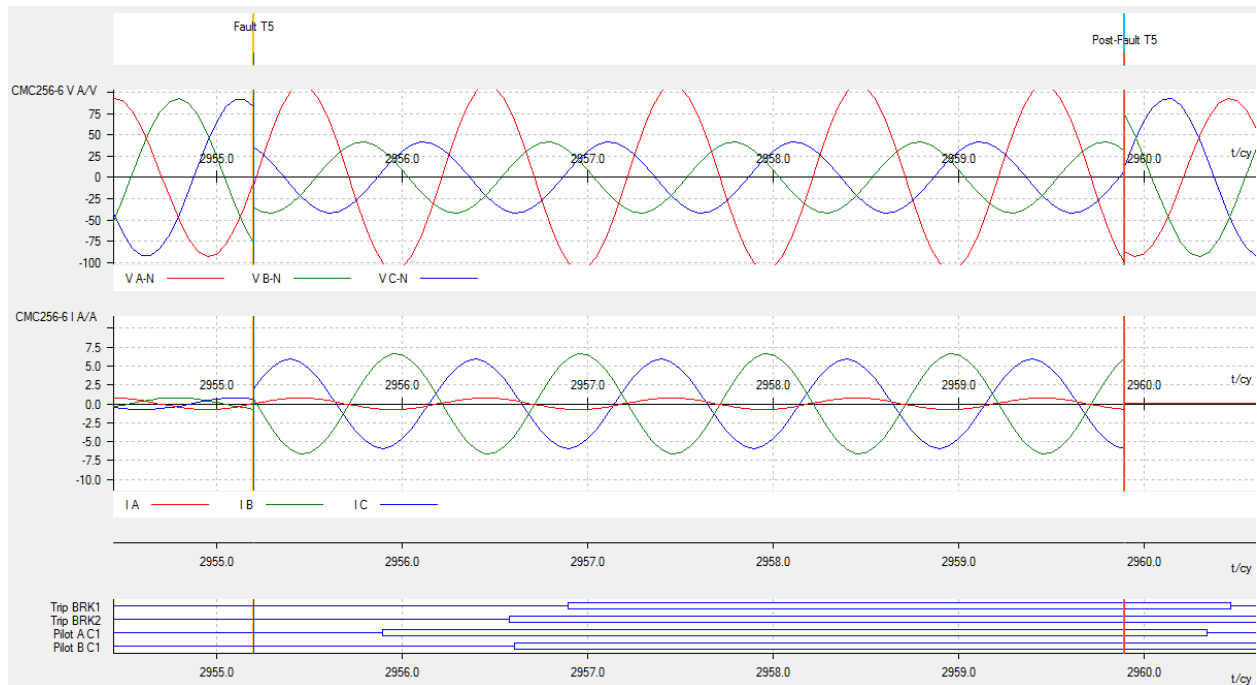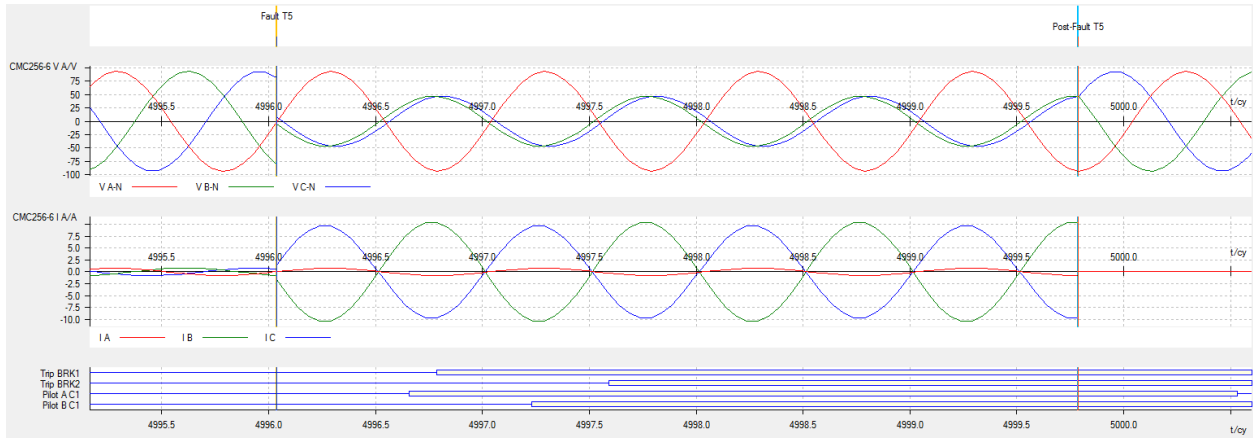
Figure 4.15 Test set – BC fault in Zone 1 of relay A.

Figure 4.16 shows that the relay A phase distance element picks up on Zone 2 (PH DIST Z2 PKP) and it trips (Trip On) after it receives the remote permissive signal (Remo Ip 1 On) from relay B. Relay A also sends a permissive signal (POTT TX1) as soon as the phase distance element picks up on Zone 2.

It is expected that the relay A phase distance element picks up on Zone 2, because a phase-to-phase fault is applied at 90% of the transmission line from relay A.

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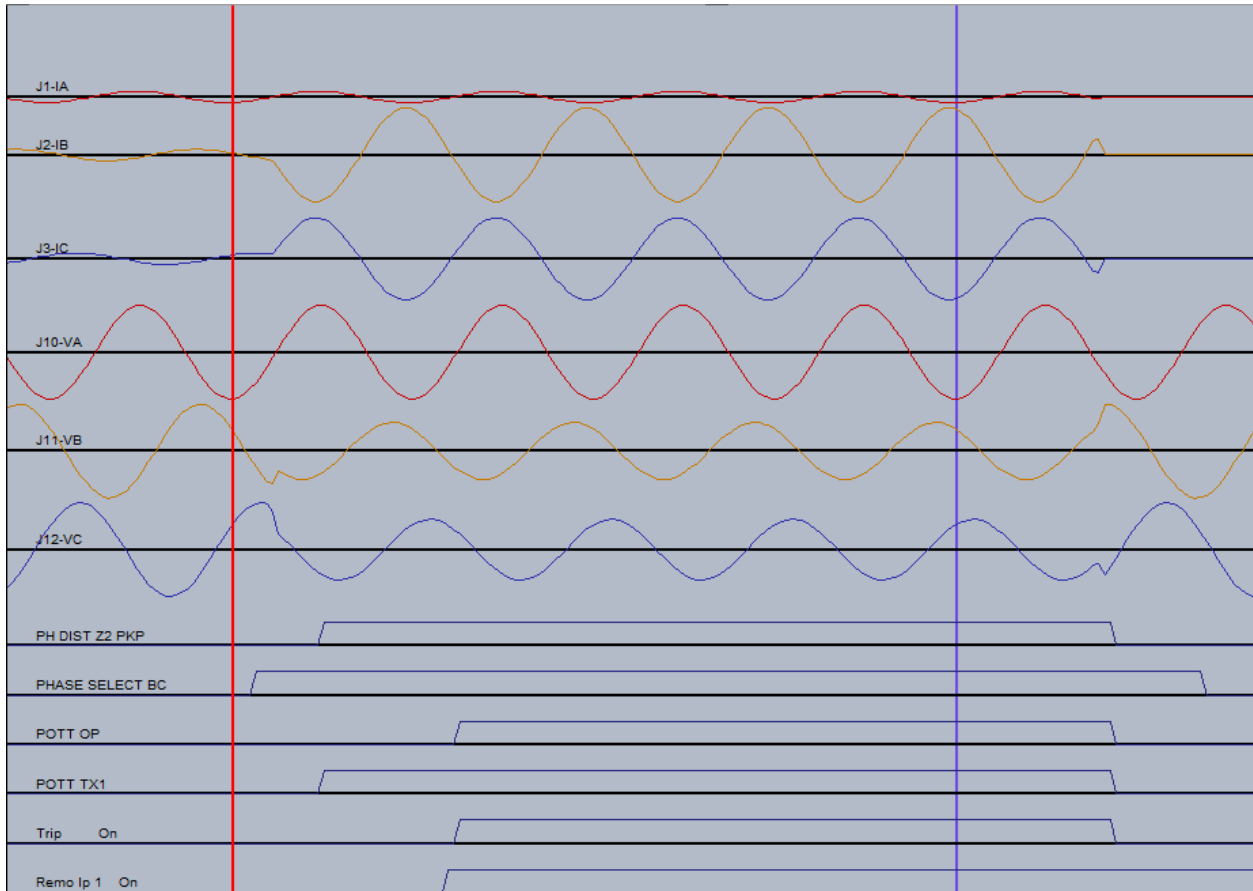
Figure 4.16 Relay A – Zone 2 BC fault.

Figure 4.17 shows that the relay B distance element Zone 2 (ZONE2 MHO PU) picks up and a permissive signal (ZCOM CH START) is sent to the remote relay, but the distance element Zone 1 (ZONE1 MHO TRP) operates. Once Zone 1 operates, the relay trips (TRIP BKR1).

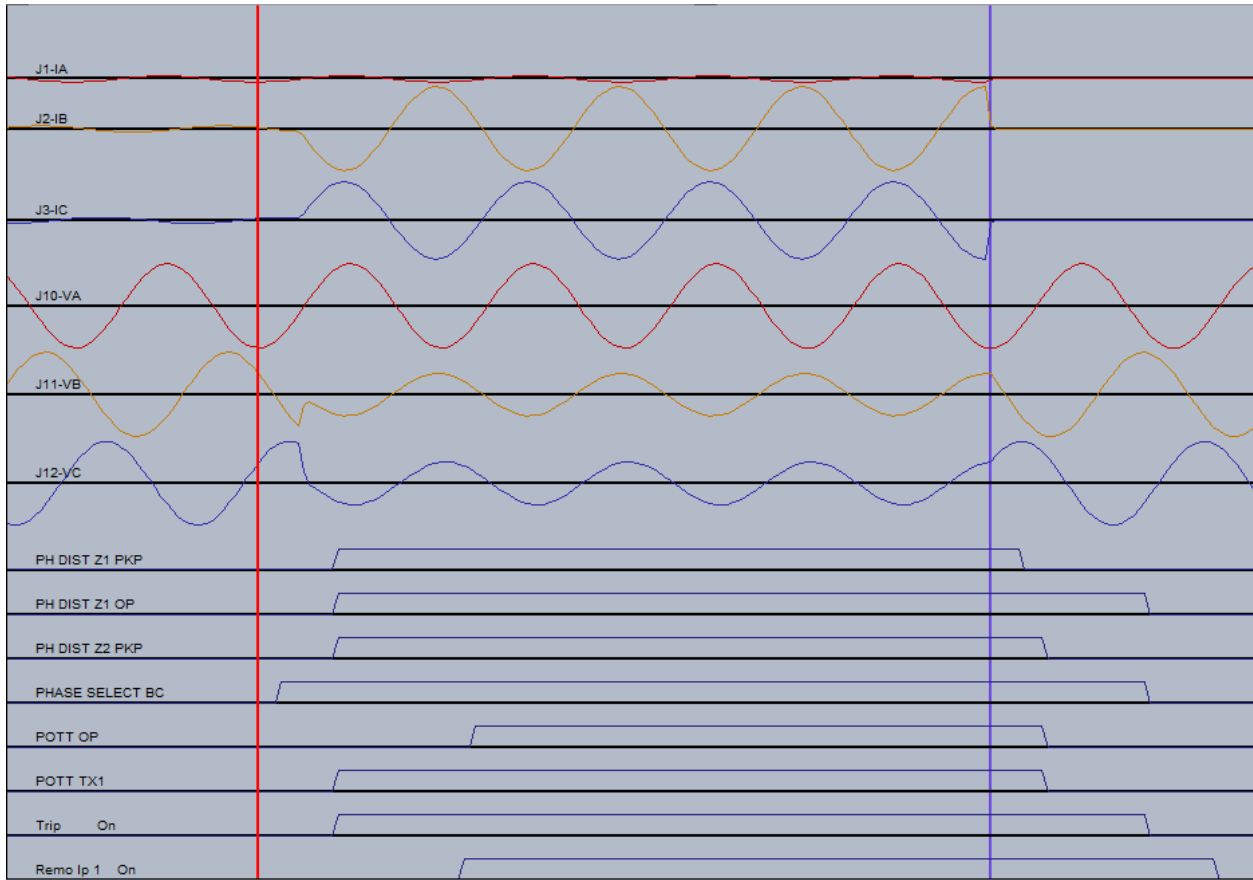It is expected that the relay B distance element Zone 1trips, because a phase-to-phase fault is applied at 10% of the transmission line from relay B and there is not a time delay set associated to Zone 1.
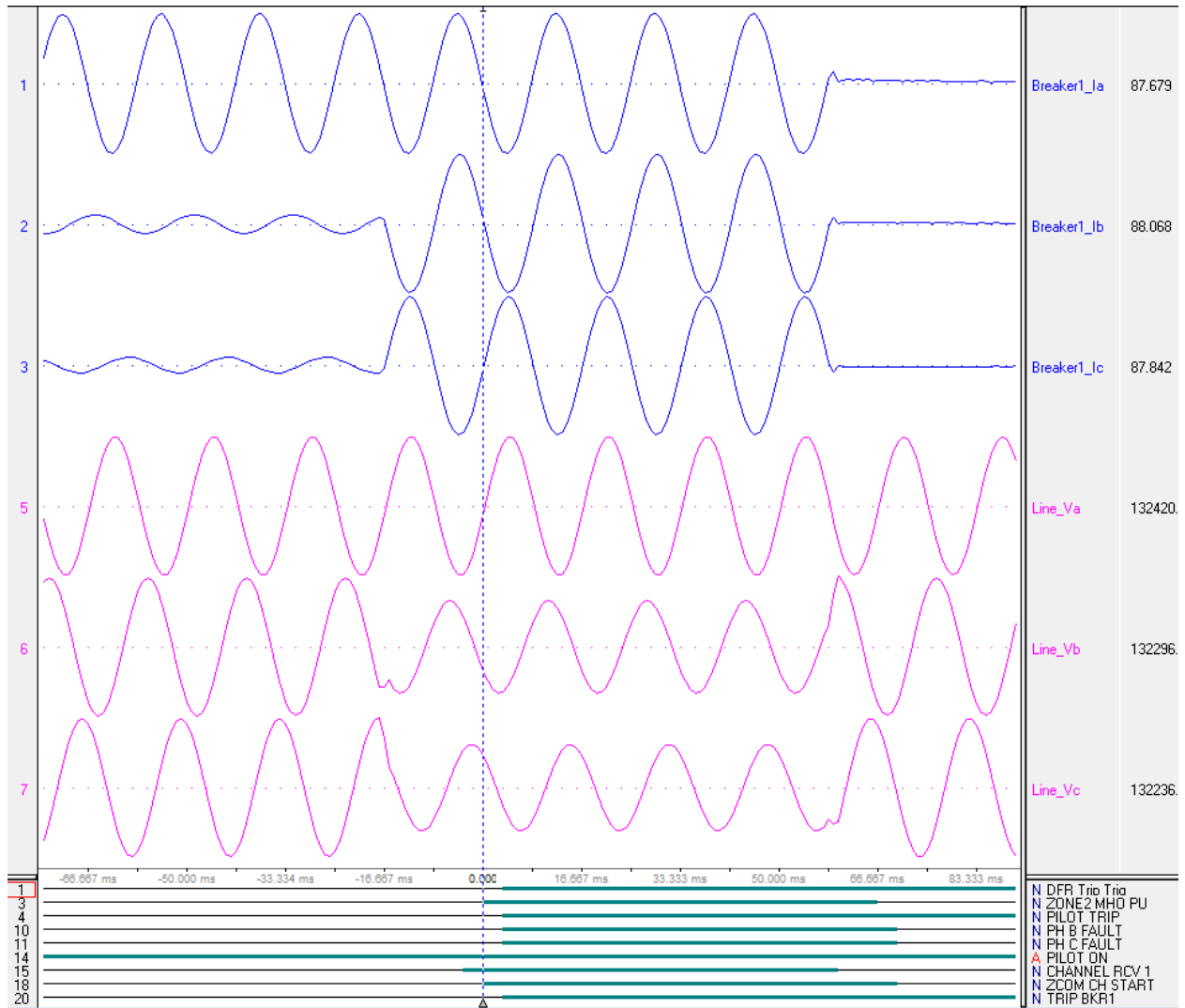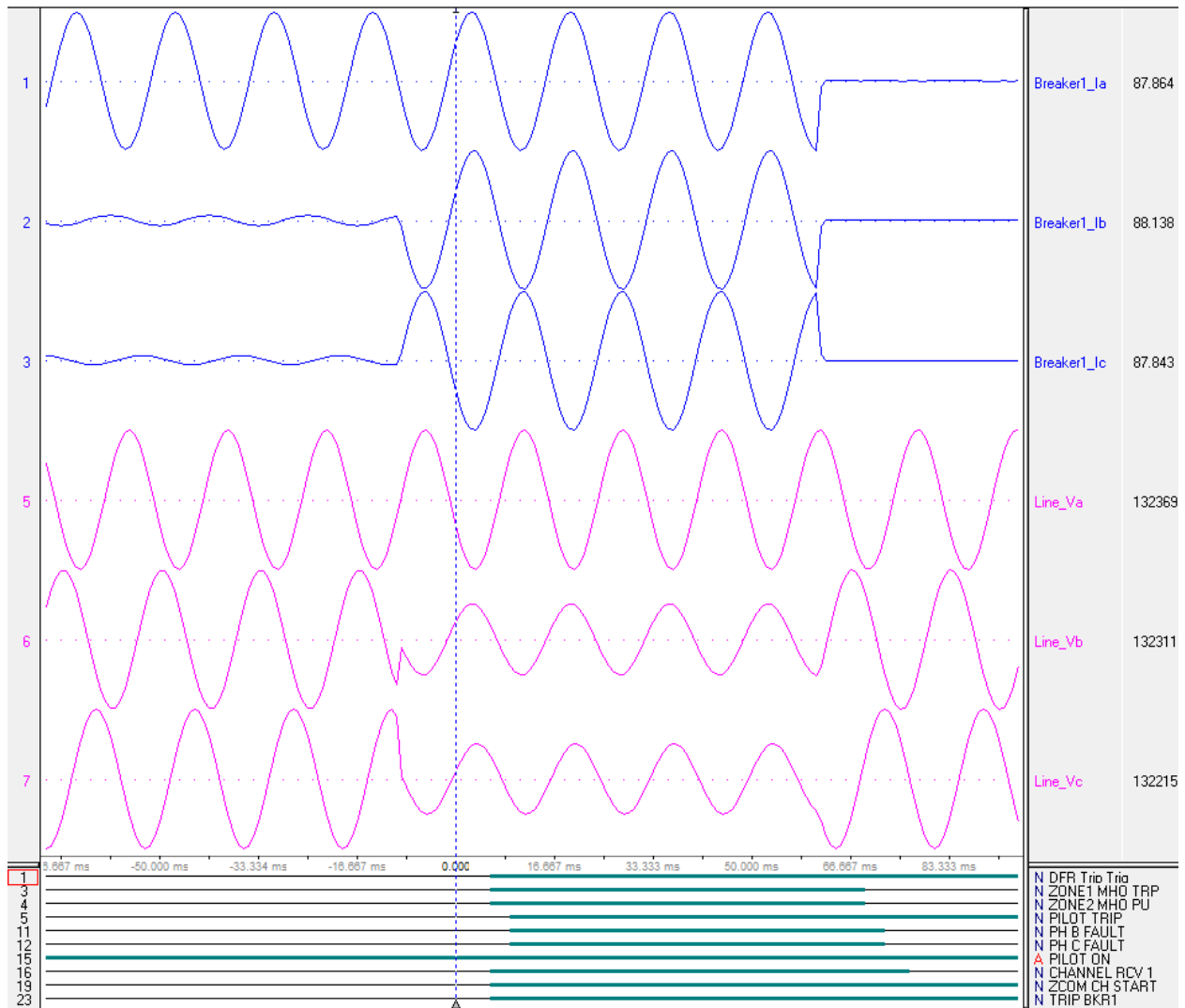
Figure 4.17 Relay B – Zone 1 BC fault.

The test set A captures the trip and permissive signals from relay A and B to compare the trip signal operation from both relays, Figure 4.18. The relay B trip signal (Trip BRK2) is the first to operate followed by the relay A trip signal (Trip BRK1). One can see that the remote permissive signal (Pilot B C1) is received and after some time the relay A trips as mentioned above. The permissive signal (Pilot A C1) from relay A is also displayed on this figure, but it is not required by relay B to trip since the fault is located on Zone 1.

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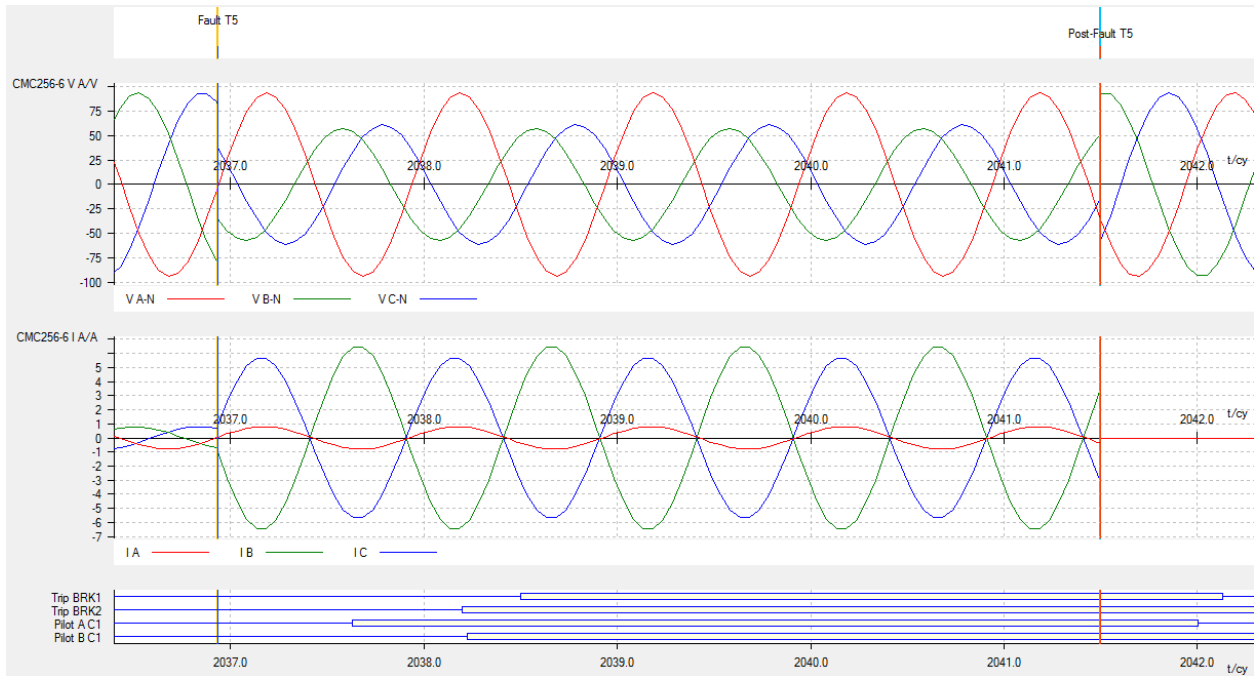
Figure 4.18 Test set − BC fault in Zone 2 of relay A.

Table 4.1 summarizes the average result, in cycles, of the six different tests run on this part of the experiment. The table also shows the maximum and minimum values obtained out of the 10 times of each test. The fault location is referring to its respective relay. It is understood that an A-G fault located in Zone 1 of relay A, 10% of the transmission line from relay A, during a test is seen in Zone 2 of relay B; it is 90% of the transmission line from relay B.

For example, in the first fault result, A-G Zone 1, the average time test on relay A is 0.68 cycles (11.33 ms); and in relay B, where the POTT operates, the average time for the same fault, seen by it in Zone 2, is 1.72 cycles (28.67 ms). The gray area on the Table helps to visualize these results.

Table 4.1 POTT with IEC61850 communication - time assessment in cycles.

Fault Type and Location	TEST SET TIME ASSESMENT					
	Relay A			Relay B		
	Average Time (cycles)	Max Time (cycles)	Minimum Time (cycles)	Average Time (cycles)	Max Time (cycles)	Minimum Time (cycles)
A-G Zone 1	0.68	0.71	0.65	1.41	1.48	1.31
BC-G Zone 1	0.76	0.79	0.74	1.36	1.43	1.28
BC Zone 1	0.76	0.78	0.74	1.31	1.39	1.27
A-G Zone 2	1.60	1.79	1.46	1.72	1.79	1.66
BC-G Zone 2	1.59	1.72	1.45	1.56	1.66	1.46
BC Zone 2	1.50	1.63	1.39	1.57	1.63	1.50

Table 4.2 shows the same test results as in Table 4.1, but in milliseconds.

Table 4.2 POTT with IEC61850 communication - time assessment in milliseconds.

Fault Type and Location	TEST SET TIME ASSESMENT					
	Relay A			Relay B		
	Average Time (ms)	Max Time (ms)	Minimum Time (ms)	Average Time (ms)	Max Time (ms)	Minimum Time (ms)
A-G Zone 1	11.33	11.83	10.83	23.50	24.67	21.83
BC-G Zone 1	12.67	13.17	12.33	22.67	23.83	21.33
BC Zone 1	12.67	13.00	12.33	21.83	23.17	21.17
A-G Zone 2	26.67	29.83	24.33	28.67	29.83	27.67
BC-G Zone 2	26.50	28.67	24.17	26.00	27.67	24.33
BC Zone 2	25.00	27.17	23.17	26.17	27.17	25.00

POTT with Hardwire Communication Test

The same previous 6 tests used on the POTT with IEC 61850 communication were applied to this experiment with the only difference that the communication system used for the permissive signal was hard-wire.

Table 4.3 shows the results in cycles. The format is the same as in Table 4.1. The relay A's performance for faults located in Zone 1 is very close to the ones presented in Table 4.1, with a very slight difference of 0.01 cycles (0.17 ms) for BC faults. Similarly, the relay B performance for the same fault location, Zone 1, is 0.04 cycles (0.67 ms) different for BC-G faults and 0.02 cycles (0.33 ms) for BC faults. With this in mind, a comparison between the results in Table 4.1 and Table 4.3 or Table 4.2 and Table 4.4 can be done for POTT with IEC 61850 or hard-wire communication.

A maximum time difference between IEC 61850 and hard-wire communication of 0.22 cycles (3.67 ms) and a minimum of 0.11 cycles (1.83 ms) is observed on relay A's results for faults located in Zone 2. The maximum time difference, 0.22 cycles, is close to the operation time of a regular contact output. In this case, the POTT communication with IEC 61850 is faster than the one with hard-wire.

The relay B time difference between IEC 61850 and hard-wire communication has a maximum value of 0.04 cycles (0.66 ms) and a minimum of 0.01 cycles (0.17 ms). The faster, in this case, is hard-wire; but one can notice that the time difference is not even close to 1 ms.

The performance of the POTT with IEC 61850 communication on relay B is similar to the POTT with hard-wire communication. There are two possible causes behind it. First, relay A detects the fault faster than relay B. It means that the permissive signal from relay A is the first input of the AND logic of the POTT on relay B, permissive signal and Zone 2 pick up. In

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this case, the POTT performance depends only on how fast relay B detects the fault. Second, it was detected that during the engineering stage of the IEC 61850 logic on relay B, the order of the used function blocks (FBs) was not taken into consideration. A function block is defined as a graphical programming language that process variables inputs to produce a result on a variable output [19].

Three function blocks were involved on it. The first FB (FB1) received the GOOSE message with the permissive signal; the second FB (FB2) was an AND logic gate; and the third FB a binary input FB (FB3). Ideally, the execution order of the FBs should be FB1-FB2-FB3, but in this case it was FB1-FB3-FB2. The exchanged on the execution order of the FB2 and FB3 caused a time delay around 3 ms on the permissive signal to be received by relay B on the POTT with IEC 61850 communication.

As one can see, using IEC 61850 communication for the permissive signal could speed up the POTT operation by a quarter of cycle. Hard-wire communication has been used for years and speeding the POTT operation does not affect the protection. It could have consequences, if using IEC 61850 would delay the POTT operation.

Table 4.3 POTT with hard-wire communication - time assessment in cycles.

Fault Type and Location	TEST SET TIME ASSESMENT					
	Relay A			Relay B		
	Average Time (cycles)	Max Time (cycles)	Minimum Time (cycles)	Average Time (cycles)	Max Time (cycles)	Minimum Time (cycles)
A-G Zone 1	0.68	0.71	0.65	1.41	1.51	1.31
BC-G Zone 1	0.76	0.79	0.74	1.32	1.42	1.25
BC Zone 1	0.77	0.78	0.76	1.33	1.44	1.24
A-G Zone 2	1.80	1.93	1.66	1.68	1.76	1.58
BC-G Zone 2	1.70	1.85	1.63	1.55	1.62	1.45
BC Zone 2	1.72	1.81	1.63	1.53	1.60	1.46

Table 4.4 shows the same results as in Table 4.3 in milliseconds.

Table 4.4 POTT with hard-wire communication - time assessment in milliseconds.

Fault Type and Location	TEST SET TIME ASSESMENT					
	Relay A			Relay B		
	Average Time (ms)	Max Time (ms)	Minimum Time (ms)	Average Time (ms)	Max Time (ms)	Minimum Time (ms)
A-G Zone 1	11.33	11.83	10.83	23.50	25.17	21.83
BC-G Zone 1	12.67	13.17	12.33	22.00	23.67	20.83
BC Zone 1	12.83	13.00	12.67	22.17	24.00	20.67
A-G Zone 2	30.00	32.17	27.67	28.00	29.33	26.33
BC-G Zone 2	28.33	30.83	27.17	25.83	27.00	24.17
BC Zone 2	28.67	30.17	27.17	25.50	26.67	24.33

CHAPTER V

CONCLUSION

The POTT pilot protection scheme has become common in the field to protect transmission lines; and guarantee a fast trip operation of the relays assigned to protect them during fault conditions. New applications of the IEC 61850 standard for communication between substations have pushed the standard to reconsider of the initial focus on only communication inside a substation. This new focus has been applied in this research, using IEC 61850 to receive the permissive signal required by the POTT scheme to operate. In the same way, a hard-wire communication was used for this purpose as a comparison.

The two Ethernet switches used to connect the two relays to the network provided a more realistic scenario. The more devices added to the network the more time delay would be added to the GOOSE message to reach the relay that was subscribed to it.

The relay's Ethernet ports were also considered to connect the relays to the network. It was known that both relay B's Ethernet ports, front and rear, supported IEC 61850 communication, but the front port did not have the highest priority on the inside logic of the relay for GOOSE messages going through it. In this case, the rear port was the manufacturer's suggested port for GOOSE messages. A wrong port selection would change the test results.

A test set with IEC 61850 capability was not required to measure the time since fault inception until the POTT operated, but it helped to visualize the permissive signal during the test of the POTT with IEC 61850 communication, as one can see on Chapter IV.

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The experiment was not intended to compare relay A and B performance under different fault conditions, but to compare the POTT performance with the classic communication method, hard-wire, and IEC61850. Comparing relay A average value's results in Table 4.1 and Table 4.3 for the three different faults located in Zone 2, one can see that a maximum time difference between IEC 61850 and hard-wire communication of 0.22 cycles (3.67 ms) and a minimum of 0.11 cycles (1.83 ms) is observed. The maximum time difference, 0.22 cycles, is close to the operation time of a regular contact output. In this case, the POTT communication with IEC 61850 is faster than the one with hard-wire.

Similarly, comparing relay's B results between both Tables mentioned above, they have a maximum time difference of 0.04 cycles (0.66 ms) and a minimum of 0.01 cycles (0.17 ms). The faster, in this case, is hard-wire; but one can notice that the time difference is not even close to 1 ms.

Base on the comparison done above, once can say that the POTT with an IEC 61850 communication has a similar or better performance than a hard-wire communication.

It is very important to have a good understanding of the relay's application and setting before implementing logic on the relay and placing settings in it.

This research has showed a multivendor communication with IEC 6850 could be extended to a further study of GOOSE messages with traffic conditions on the network in the future. The effect of the traffic on the network on the GOOSE messages could be analyzed under different conditions, such as GOOSE messages with no priority and GOOSE messages with a priority setting.

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APPENDIX A

PRE-FAULT AND FAULT CALCULATION

PRE-FAULT CALCULATION

The pre-fault condition is calculated using Figure A.1 as a reference. The current flows from Bus A to B and relay A's forward direction is toward Bus B while relay B's forward direction is in opposite way to relay A; it is from Bus B to A. The amount of current that flows from Bus A to B is based on the phase angle difference between these two buses.
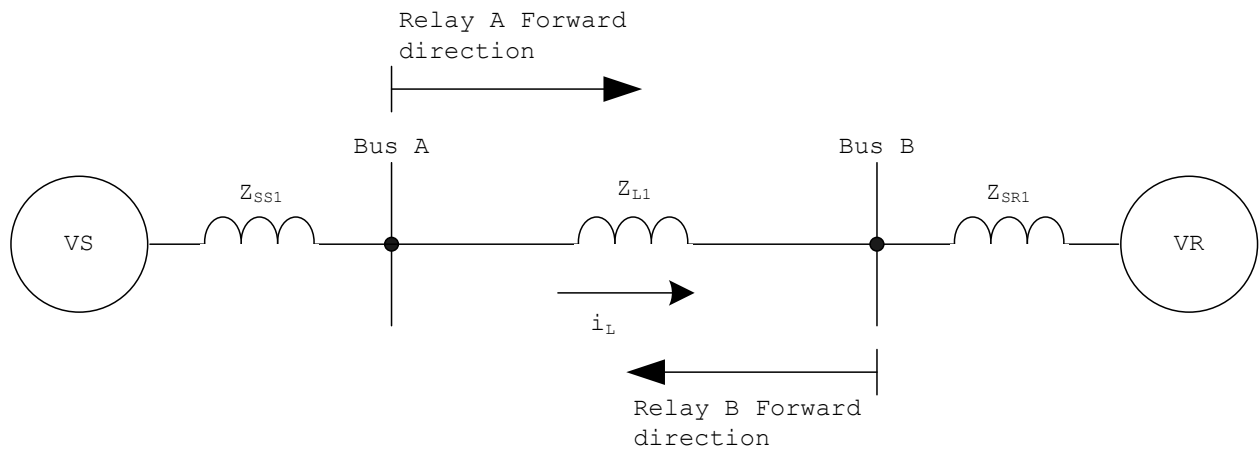
Figure A.1 Positive sequence diagram for pre-fault calculation.

Common parameters:

$V_S = 230000\angle 0° \ V$

$V_R = 230000\angle -10° \ V$

$PT = 2000$

$CT = 160$

$Z_{L1} = 81.94\angle 83.46° \ \Omega$

$Z_{SS1} = 92.4\angle 83.4° \ \Omega$

$Z_{SR1} = 82.98\angle 83.79° \ \Omega$

Solution:

$$V_{S\_phase} = \frac{V_S}{\sqrt{3}}$$

$$V_{R\_phase} = \frac{V_R}{\sqrt{3}}$$

$$i_L = \frac{V_{S_{phase}} - V_{R_{phase}}}{Z_{SS1} + Z_{L1} + Z_{SR1}}$$

$$i_L = 89.95\angle 1.46° \text{ A}$$

$$i_{Load} = \begin{bmatrix} i_L \\ i_L \cdot 1\angle 240° \\ i_L \cdot 1\angle 120° \end{bmatrix}$$

$$i_{Load} = \begin{bmatrix} 89.95\angle 1.46° \\ 89.95\angle -118.54° \\ 89.95\angle 121.46° \end{bmatrix} A$$

Relay A pre-fault primary values

$$V_{A\_pref} = \begin{bmatrix} V_{S\_phase} - i_L \cdot Z_{SS1} \\ (V_{S\_phase} - i_L \cdot Z_{SS1}) \cdot (1\angle 240°) \\ (V_{S\_phase} - i_L \cdot Z_{SS1}) \cdot (1\angle 120°) \end{bmatrix}$$

$$V_{A\_pref} = \begin{bmatrix} 132304.45\angle -3.59° \\ 132304.45\angle -123.59° \\ 132304.45\angle 116.41° \end{bmatrix} V$$

$$i_{Load\_A} = i_{Load}$$

$$i_{Load\_A} = \begin{bmatrix} 89.95\angle 1.46° \\ 89.95\angle -118.54° \\ 89.95\angle 121.46° \end{bmatrix} A$$

Relay A pre-fault secondary values

$$V_{A\_pref\_sec} = \frac{V_{A\_pref}}{PT}$$

$$V_{A\_pref\_sec} = \begin{bmatrix} 66.15\angle -3.59° \\ 66.15\angle -123.59° \\ 66.15\angle 116.41° \end{bmatrix} V$$

$$i_{Load\_A\_sec} = \frac{i_{Load\_A}}{CT}$$

$$i_{Load\_A\_sec} = \begin{bmatrix} 0.56\angle 1.46° \\ 0.56\angle -118.54° \\ 0.56\angle 121.46° \end{bmatrix} A$$

Relay B pre-fault primary values

$$V_{B\_pref} = \begin{bmatrix} V_{R\_phase} + i_L \cdot Z_{SR1} \\ (V_{R\_phase} + i_L \cdot Z_{SR1}) \cdot (1\angle 240°) \\ (V_{R\_phase} + i_L \cdot Z_{SR1}) \cdot (1\angle 120°) \end{bmatrix}$$

$$V_{B\_pref} = \begin{bmatrix} 132317.14\angle -6.78° \\ 132317.14\angle -126.78° \\ 132317.14\angle 113.22° \end{bmatrix} V$$

$$i_{Load\_B} = i_{Load} \cdot 1\angle 180°$$

$$i_{Load\_B} = \begin{bmatrix} 89.95\angle -178.54° \\ 89.95\angle 61.46° \\ 89.95\angle -58.54° \end{bmatrix} A$$

Relay B pre-fault secondary values

$$V_{B\_pref\_sec} = \frac{V_{B\_pref}}{PT}$$

$$V_{B\_pref\_sec} = \begin{bmatrix} 66.16\angle -6.78° \\ 66.16\angle -126.78° \\ 66.16\angle 113.22° \end{bmatrix} V$$

$$i_{Load\_B\_sec} = \frac{i_{Load\_B}}{CT}$$

$$i_{Load\_B\_sec} = \begin{bmatrix} 0.56\angle -178.54° \\ 0.56\angle 61.46° \\ 0.56\angle -58.54° \end{bmatrix} A$$

FAULT CALCULATION

Two different cases are considered on each fault calculation: A-G, BC-G, and BC. The first one is when the fault location (FL) is at 10% of the transmission line from relay A and the second one when the fault location is at 90%.

Common parameters:

$V_S = 230000\angle 0° \ V$

$V_R = 230000\angle -10° \ V$

$PT = 2000$

$CT = 160$

$Z_{L1} = 81.94\angle 83.46° \ \Omega$

$Z_{L2} = 81.94\angle 83.46° \ \Omega$

$Z_{L0} = 279.93\angle 76.86° \ \Omega$

$Z_{SS1} = 92.4\angle 83.4° \ \Omega$

$Z_{SS2} = 92.4\angle 83.4° \ \Omega$

$Z_{SS0} = 315.7\angle 76.8° \ \Omega$

$Z_{SR1} = 82.98\angle 83.79° \ \Omega$

$Z_{SR2} = 82.98\angle 83.79° \ \Omega$

$Z_{SR0} = 283.51\angle 77.19° \ \Omega$

$FL = 0.1 \ and \ 0.9$

Note: The fault location (FL) on this calculation is referring from the position of relay A, Bus A, to the fault. Relay B sees the same fault at $1 - FL$ from its position, Bus B.

Solution:

$$V_{S\_phase} = \frac{V_S}{\sqrt{3}}$$

$$V_{S\_phase} = 132790.56 \angle 0° \, V$$

$$V_{R\_phase} = \frac{V_R}{\sqrt{3}}$$

$$V_{R\_phase} = 132790.56 \angle -10° \, V$$

A-G Fault (FL = 0.1)
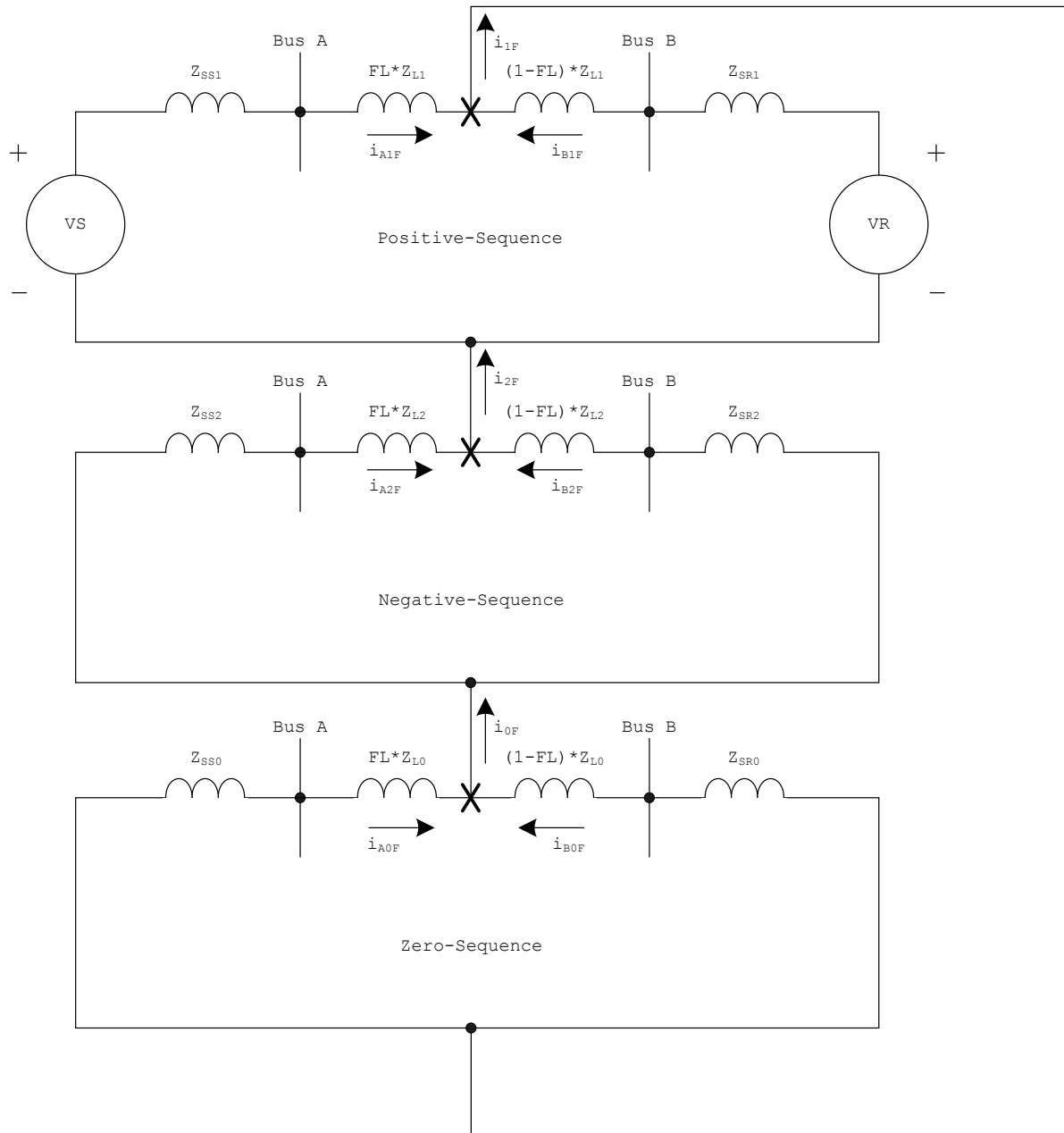
Figure A.2 A-G fault sequence diagram connection.

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 100.59\angle 83.4° \, \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 156.73\angle 83.63° \ \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 100.59\angle 83.4° \ \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 156.73\angle 83.63° \ \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 61.27\angle 83.49° \ \Omega$$

$$Z_{0\_eq1} = Z_{SS0} + Z_{L0} \cdot FL$$

$$Z_{0\_eq1} = 343.69\angle 76.8° \ \Omega$$

$$Z_{0\_eq2} = Z_{SR0} + Z_{L0} \cdot (1 - FL)$$

$$Z_{0\_eq2} = 535.48\angle 77.03° \ \Omega$$

$$Z_{0TH} = \frac{Z_{0_{eq1}} \cdot Z_{0_{eq2}}}{Z_{0_{eq1}} + Z_{0_{eq2}}}$$

$$Z_{0\_TH} = 209.33\angle 76.89° \ \Omega$$

$$Z_{20\_eq} = Z_{2\_TH} + Z_{0\_TH}$$

$$Z_{20\_eq} = 270.29\angle 78.39° \ \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot (Z_{1\_eq1} + Z_{20\_eq}) + i_{B1F} \cdot Z_{20\_eq}$$

$$V_{R\_phase} = i_{A1F} \cdot Z_{20\_eq} + i_{B1F} \cdot \left(Z_{1\_eq2} + Z_{20\_eq}\right)$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{20\_eq} & Z_{20\_eq} \\ Z_{20\_eq} & Z_{1\_eq2} + Z_{20\_eq} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 370.6\angle 79.75° & 270.29\angle 78.39° \\ 270.29\angle 78.39° & 426.6\angle 80.31° \end{bmatrix} \begin{bmatrix} 132790.56\angle 0° \\ 132790.56\angle - 10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 2667.08\angle - 63.56° \\ 172.98\angle - 114.57° \end{bmatrix}$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 399.23\angle - 83.24° \ A$$

$$i_{2F} = i_{1F}$$

$$i_{2F} = 399.23\angle - 83.24° \ A$$

$$i_{0F} = i_{2F}$$

$$i_{0F} = 399.23\angle - 83.24° \ A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 243.16\angle - 83.15° \ A$$

$$i_{A0F} = i_{0F} \cdot \frac{Z_{0\_eq2}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{A0F} = 243.16\angle - 83.15° \ A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$
\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 243.16\angle-83.15° \\ 243.16\angle-83.15° \\ 243.16\angle-83.15° \end{bmatrix}
$$

$$
\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 743.35\angle-76.23° \\ 89.95\angle-118.54° \\ 89.95\angle121.46° \end{bmatrix} A
$$

$$
V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}
$$

$$
V_{A1F} = 109897.48\angle-4.37° \; V
$$

$$
V_{A2F} = -i_{A2F} \cdot Z_{SS2}
$$

$$
V_{A2F} = 22467.71\angle-179.75° \; V
$$

$$
V_{A0F} = -i_{A0F} \cdot Z_{SS0}
$$

$$
V_{A0F} = 76764.21\angle173.65° \; V
$$

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}
$$

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 76764.21\angle173.65° \\ 109897.48\angle-4.37° \\ 22467.71\angle-179.75° \end{bmatrix}
$$

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 10816.61\angle0.06° \\ 162671.81\angle-141.34° \\ 169840.74\angle131.56° \end{bmatrix} V
$$

Fault seen by relay A in secondary values

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 10816.61\angle0.06° \\ 162671.81\angle-141.34° \\ 169840.74\angle131.56° \end{bmatrix} \cdot \frac{1}{PT}
$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 5.41\angle 0.06° \\ 81.34\angle -141.34° \\ 81.92\angle 131.56° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 743.35\angle -76.23° \\ 89.95\angle -118.54° \\ 89.95\angle 121.46° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 4.65\angle -76.23° \\ 0.56\angle -118.54° \\ 0.56\angle 121.46° \end{bmatrix} A$$

Fault seen by relay B in primary values

$$i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{B2F} = 156.07\angle -83.38° \ A$$

$$i_{B0F} = i_{0F} \cdot \frac{Z_{0\_eq1}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{B0F} = 156.07\angle -83.38° \ A$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 156.07\angle -83.38° \\ 156.07\angle -83.38° \\ 156.07\angle -83.38° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 468.75\angle -94.4° \\ 89.95\angle 61.46° \\ 89.95\angle -58.54° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 119479.35\angle - 7.56° \, V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 12950.69\angle - 179.59° \, V$$

$$V_{B0F} = -i_{B0F} \cdot Z_{SR0}$$

$$V_{B0F} = 44247.94\angle173.81° \, V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 44247.94\angle173.81° \\ 119479.35\angle - 7.56° \\ 12950.69\angle - 179.59° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 62483.65\angle - 10.17° \\ 149607.86\angle - 137.48° \\ 151380.42\angle123.34° \end{bmatrix} \, V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 62483.65\angle - 10.17° \\ 149607.86\angle - 137.48° \\ 151380.42\angle123.34° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 31.24\angle - 10.17° \\ 74.8\angle - 137.48° \\ 75.69\angle123.34° \end{bmatrix} \, V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 468.75\angle - 94.4° \\ 89.95\angle61.46° \\ 89.95\angle - 58.54° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 2.93\angle - 94.4° \\ 0.56\angle61.46° \\ 0.56\angle - 58.54° \end{bmatrix} \, A$$

A-G Fault (FL = 0.9)

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 166.15 \angle 83.43° \, \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 91.17 \angle 83.76° \, \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 166.15 \angle 83.43° \, \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 91.17 \angle 83.76° \, \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 58.87 \angle 83.64° \, \Omega$$

$$Z_{0\_eq1} = Z_{SS0} + Z_{L0} \cdot FL$$

$$Z_{0\_eq1} = 567.66 \angle 76.83° \, \Omega$$

$$Z_{0\_eq2} = Z_{SR0} + Z_{L0} \cdot (1 - FL)$$

$$Z_{0\_eq2} = 311.51 \angle 77.16° \, \Omega$$

$$Z_{0TH} = \frac{Z_{0eq1} \cdot Z_{0eq2}}{Z_{0eq1} + Z_{0eq2}}$$

$$Z_{0\_TH} = 201.14 \angle 77.04° \, \Omega$$

$$Z_{20\_eq} = Z_{2\_TH} + Z_{0\_TH}$$

$$Z_{20\_eq} = 259.7\angle78.54° \ \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot (Z_{1\_eq1} + Z_{20\_eq}) + i_{B1F} \cdot Z_{20\_eq}$$

$$V_{R\_phase} = i_{A1F} \cdot Z_{20\_eq} + i_{B1F} \cdot (Z_{1\_eq2} + Z_{20\_eq})$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{20\_eq} & Z_{20\_eq} \\ Z_{20\_eq} & Z_{1\_eq2} + Z_{20\_eq} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 425.48\angle80.44° & 259.7\angle78.54° \\ 259.7\angle78.54° & 350.6\angle79.89° \end{bmatrix} \begin{bmatrix} 132790.56\angle0° \\ 132790.56\angle-10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 176.28\angle-55.08° \\ 279.25\angle-104.83° \end{bmatrix}$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 415.53\angle-85.94° \ A$$

$$i_{2F} = i_{1F}$$

$$i_{2F} = 415.53\angle-85.94° \ A$$

$$i_{0F} = i_{2F}$$

$$i_{0F} = 415.53\angle-85.94° \ A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 147.23\angle-85.72° \ A$$

$$i_{A0F} = i_{0F} \cdot \frac{Z_{0\_eq2}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{A0F} = 147.23\angle -85.72° \, A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 147.23\angle -85.72° \\ 243.16\angle -83.15° \\ 147.23\angle -85.72° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 455.08\angle -74.34° \\ 89.95\angle -118.54° \\ 89.95\angle121.46° \end{bmatrix} A$$

$$V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}$$

$$V_{A1F} = 118703.9\angle -3.73° \, V$$

$$V_{A2F} = -i_{A2F} \cdot Z_{SS2}$$

$$V_{A2F} = 13604.24\angle -177.68° \, V$$

$$V_{A0F} = -i_{A0F} \cdot Z_{SS0}$$

$$V_{A0F} = 46480.88\angle171.08° \, V$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 46480.88\angle171.08° \\ 118703.9\angle -3.73° \\ 13604.24\angle -177.68° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 58940.78\angle 0.03° \\ 147844.3\angle -135.54° \\ 154843.59\angle 126.07° \end{bmatrix} V$$

Fault seen by relay A in secondary values

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 58940.78\angle 0.03° \\ 147844.3\angle -135.54° \\ 154843.59\angle 126.07° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 29.47\angle 0.03° \\ 73.92\angle -135.54° \\ 77.42\angle 126.07° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 455.08\angle -74.34° \\ 89.95\angle -118.54° \\ 89.95\angle 121.46° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 2.84\angle -74.34° \\ 0.56\angle -118.54° \\ 0.56\angle 121.46° \end{bmatrix} A$$

Fault seen by relay B in primary values

$$i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{B2F} = 268.3\angle -86.06° A$$

$$i_{B0F} = i_{0F} \cdot \frac{Z_{0\_eq1}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{B0F} = 268.3\angle -86.06° A$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 268.3\angle - 86.06° \\ 279.25\angle - 104.83° \\ 268.3\angle - 86.06° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 806.02\angle - 92.46° \\ 89.95\angle61.46° \\ 89.95\angle - 58.54° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 110136.5\angle - 7.69° \; V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 22263.59\angle177.73° \; V$$

$$V_{B0F} = -i_{B0F} \cdot Z_{SR0}$$

$$V_{B0F} = 76066.81\angle171.13° \; V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 76066.81\angle171.13° \\ 110136.5\angle - 7.69° \\ 22263.59\angle177.73° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 11934.18\angle - 10.3° \\ 162819.52\angle - 144.25° \\ 169065.09\angle128.43° \end{bmatrix} V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 11934.18\angle - 10.3° \\ 162819.52\angle - 144.25° \\ 169065.09\angle128.43° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 5.97\angle -10.3° \\ 81.41\angle -144.25° \\ 84.53\angle 128.43° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 806.02\angle -92.46° \\ 89.95\angle 61.46° \\ 89.95\angle -58.54° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 5.04\angle -92.46° \\ 0.56\angle 61.46° \\ 0.56\angle -58.54° \end{bmatrix} A$$

BC-G Fault (FL = 0.1)
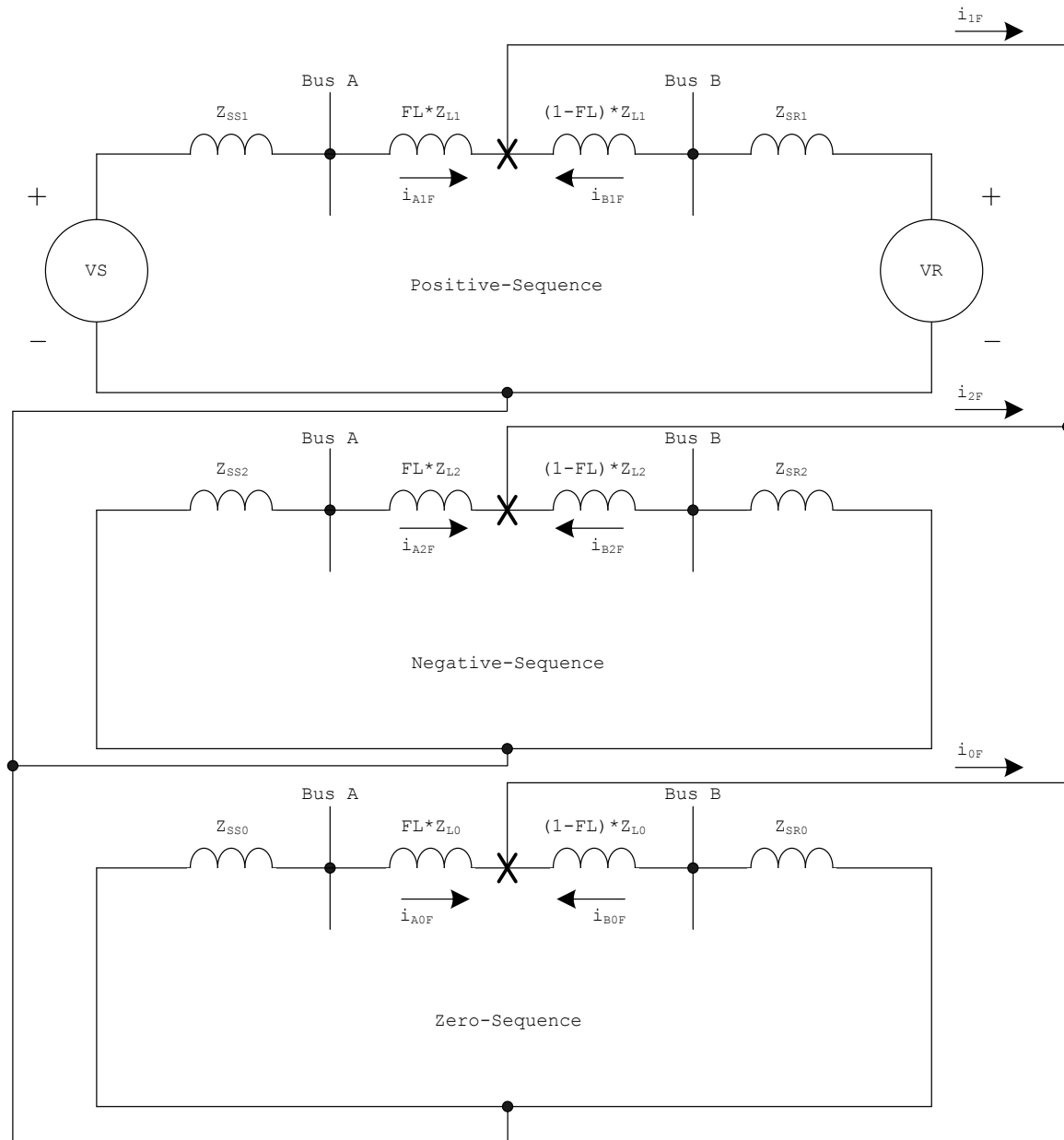
Figure A.3 BC-G fault sequence diagram connection.

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 100.59\angle 83.4° \ \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 156.73 \angle 83.63° \ \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 100.59 \angle 83.4° \ \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 156.73 \angle 83.63° \ \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 61.27 \angle 83.49° \ \Omega$$

$$Z_{0\_eq1} = Z_{SS0} + Z_{L0} \cdot FL$$

$$Z_{0\_eq1} = 343.69 \angle 76.8° \ \Omega$$

$$Z_{0\_eq2} = Z_{SR0} + Z_{L0} \cdot (1 - FL)$$

$$Z_{0\_eq2} = 535.48 \angle 77.03° \ \Omega$$

$$Z_{0TH} = \frac{Z_{0_{eq1}} \cdot Z_{0_{eq2}}}{Z_{0_{eq1}} + Z_{0_{eq2}}}$$

$$Z_{0\_TH} = 209.33 \angle 76.89° \ \Omega$$

$$Z_{20\_eq} = \frac{Z_{2\_TH} \cdot Z_{0\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$Z_{20\_eq} = 47.45 \angle 82° \ \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot (Z_{1\_eq1} + Z_{20\_eq}) + i_{B1F} \cdot Z_{20\_eq}$$

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$$V_{R\_phase} = i_{A1F} \cdot Z_{20\_eq} + i_{B1F} \cdot (Z_{1\_eq2} + Z_{20\_eq})$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{20\_eq} & Z_{20\_eq} \\ Z_{20\_eq} & Z_{1\_eq2} + Z_{20\_eq} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 370.6\angle 79.75° & 270.29\angle 78.39° \\ 270.29\angle 78.39° & 426.6\angle 80.31° \end{bmatrix} \begin{bmatrix} 132790.56\angle 0° \\ 132790.56\angle -10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 749.53\angle -79.77° \\ 481.58\angle -97.65° \end{bmatrix} A$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 1216.87\angle -86.75° \, A$$

$$i_{2F} = -i_{1F} \cdot \frac{Z_{0\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$i_{2F} = 942.44\angle 91.76° \, A$$

$$i_{0F} = -i_{1F} \cdot \frac{Z_{2\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$i_{0F} = 275.84\angle 98.36° \, A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 574.01\angle 91.85° \, A$$

$$i_{A0F} = i_{0F} \cdot \frac{Z_{0\_eq2}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{A0F} = 168.01\angle 98.45° \, A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 168.01\angle 98.45° \\ 749.53\angle -79.77° \\ 574.01\angle 91.85° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 1223.22\angle 174.52° \\ 1119.9\angle 19.8° \end{bmatrix} A$$

$$V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}$$

$$V_{A1F} = 63823.86\angle -3.94° \, V$$

$$V_{A2F} = -i_{A2F} \cdot Z_{SS2}$$

$$V_{A2F} = 53038.87\angle -4.75° \, V$$

$$V_{A0F} = -i_{A0F} \cdot Z_{SS0}$$

$$V_{A0F} = 53038.87\angle -4.75° \, V$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 53038.87\angle -4.75° \\ 63823.86\angle -3.94° \\ 53038.87\angle -4.75° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 169897.59\angle -4.45° \\ 10816.61\angle -119.94° \\ 10816.61\angle 120.06° \end{bmatrix} V$$

Fault seen by relay A in secondary values

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 169897.59\angle - 4.45° \\ 10816.61\angle - 119.94° \\ 10816.61\angle 120.06° \end{bmatrix} \cdot \frac{1}{PT}
$$

$$
\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 84.95\angle - 4.45° \\ 5.41\angle - 119.94° \\ 5.41\angle 120.06° \end{bmatrix} V
$$

$$
\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 1223.22\angle 174.52° \\ 1119.9\angle 19.8° \end{bmatrix} \cdot \frac{1}{CT}
$$

$$
\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 0.56\angle 1.46° \\ 7.65\angle 174.52° \\ 7\angle 19.8° \end{bmatrix} A
$$

Fault seen by relay B in primary values

$$
i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}
$$

$$
i_{B2F} = 368.43\angle 91.62° \, A
$$

$$
i_{B0F} = i_{0F} \cdot \frac{Z_{0\_eq1}}{Z_{0\_eq1} + Z_{0\_eq2}}
$$

$$
i_{B0F} = 107.83\angle 98.22° \, A
$$

$$
\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}
$$

$$
\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 107.83\angle 98.22° \\ 481.58\angle - 97.65° \\ 368.43\angle 91.62° \end{bmatrix}
$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 740.2\angle 163.7° \\ 762.81\angle 8.65° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 92958.58\angle - 8.34° \, V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 30572.33\angle - 4.59° \, V$$

$$V_{B0F} = -i_{B0F} \cdot Z_{SR0}$$

$$V_{B0F} = 30572.33\angle - 4.59° \, V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 30572.33\angle - 4.59° \\ 92958.58\angle - 8.34° \\ 30572.33\angle - 4.59° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 154024.3\angle - 6.85° \\ 62483.65\angle - 130.17° \\ 62483.65\angle 109.83° \end{bmatrix} V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 154024.3\angle - 6.85° \\ 62483.65\angle - 130.17° \\ 62483.65\angle 109.83° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 77.01\angle - 6.85° \\ 31.24\angle - 130.17° \\ 31.24\angle 109.83° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 740.2\angle 163.7° \\ 762.81\angle 8.65° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 0.56\angle - 178.54° \\ 4.63\angle 163.7° \\ 4.77\angle 8.65° \end{bmatrix} A$$

BC-G Fault (FL = 0.9)

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 166.15\angle 83.43° \, \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 91.17\angle 83.76° \, \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 166.15\angle 83.43° \, \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 91.17\angle 83.76° \, \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 58.87\angle 83.64° \, \Omega$$

$$Z_{0\_eq1} = Z_{SS0} + Z_{L0} \cdot FL$$

$$Z_{0\_eq1} = 567.66\angle 76.83° \, \Omega$$

$$Z_{0\_eq2} = Z_{SR0} + Z_{L0} \cdot (1 - FL)$$

$$Z_{0\_eq2} = 311.51\angle 77.16° \ \Omega$$

$$Z_{0TH} = \frac{Z_{0_{eq1}} \cdot Z_{0_{eq2}}}{Z_{0_{eq1}} + Z_{0_{eq2}}}$$

$$Z_{0\_TH} = 201.14\angle 77.04° \ \Omega$$

$$Z_{20\_eq} = \frac{Z_{2\_TH} \cdot Z_{0\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$Z_{20\_eq} = 45.59\angle 82.15° \ \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot \left(Z_{1\_eq1} + Z_{20\_eq}\right) + i_{B1F} \cdot Z_{20\_eq}$$

$$V_{R\_phase} = i_{A1F} \cdot Z_{20\_eq} + i_{B1F} \cdot \left(Z_{1\_eq2} + Z_{20\_eq}\right)$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{20\_eq} & Z_{20\_eq} \\ Z_{20\_eq} & Z_{1\_eq2} + Z_{20\_eq} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 211.73\angle 83.15° & 45.59\angle 82.15° \\ 45.59\angle 82.15° & 136.75\angle 83.22° \end{bmatrix} \begin{bmatrix} 132790.56\angle 0° \\ 132790.56\angle -10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 456.63\angle -77.88° \\ 824.33\angle -95.83° \end{bmatrix} \ A$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 1266.56\angle -89.45° \ A$$

$$i_{2F} = -i_{1F} \cdot \frac{Z_{0\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$i_{2F} = 980.93\angle 89.06° \ A$$

$$i_{0F} = -i_{1F} \cdot \frac{Z_{2\_TH}}{Z_{2\_TH} + Z_{0\_TH}}$$

$$i_{0F} = 287.1\angle 95.66° \ A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 347.57\angle 89.27° \; A$$

$$i_{A0F} = i_{0F} \cdot \frac{Z_{0\_eq2}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{A0F} = 101.73\angle 95.87° \; A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 101.73\angle 95.87° \\ 456.63\angle -77.88° \\ 347.57\angle 89.27° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 751.58\angle 174.55° \\ 667.85\angle 20.13° \end{bmatrix} A$$

$$V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}$$

$$V_{A1F} = 90884.39\angle -2.56° \; V$$

$$V_{A2F} = -i_{A2F} \cdot Z_{SS2}$$

$$V_{A2F} = 32115.14\angle -7.33° \; V$$

$$V_{A0F} = -i_{A0F} \cdot Z_{SS0}$$

$$V_{A0F} = 32115.14\angle -7.33° \; V$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 32115.14\angle-7.33° \\ 90884.39\angle-2.56° \\ 32115.14\angle-7.33° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 154984.46\angle-4.54° \\ 58940.78\angle-119.97° \\ 58940.78\angle120.03° \end{bmatrix} V$$

Fault seen by relay A in secondary values

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 154984.46\angle-4.54° \\ 58940.78\angle-119.97° \\ 58940.78\angle120.03° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 77.49\angle-4.54° \\ 29.47\angle-119.97° \\ 29.47\angle120.03° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 89.95\angle1.46° \\ 751.58\angle174.55° \\ 667.85\angle20.13° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 0.56\angle1.46° \\ 4.7\angle174.55° \\ 4.17\angle20.13° \end{bmatrix} A$$

Fault seen by relay B in primary values

$$i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{B2F} = 633.37\angle88.94° \, A$$

$$i_{B0F} = i_{0F} \cdot \frac{Z_{0\_eq1}}{Z_{0\_eq1} + Z_{0\_eq2}}$$

$$i_{B0F} = 185.38\angle95.54° \; A$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 185.38\angle95.54° \\ 824.33\angle-95.83° \\ 633.37\angle88.94° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle-178.54° \\ 1291.84\angle163.79° \\ 1291.57\angle8.69° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 64477.62\angle-7.83° \; V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 52557.02\angle-7.27° \; V$$

$$V_{B0F} = -i_{B0F} \cdot Z_{SR0}$$

$$V_{B0F} = 52557.02\angle-7.27° \; V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 52557.02\angle-7.27° \\ 64477.62\angle-7.83° \\ 52557.02\angle-7.27° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 169589.75\angle-7.49° \\ 11934.18\angle-130.3° \\ 11934.18\angle109.7° \end{bmatrix} V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 169589.75\angle - 7.49° \\ 11934.18\angle - 130.3° \\ 11934.18\angle 109.7° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 84.79\angle - 7.49° \\ 5.97\angle - 130.3° \\ 5.97\angle 109.7° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 1291.84\angle 163.79° \\ 1291.57\angle 8.69° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 0.56\angle - 178.54° \\ 8.07\angle 163.79° \\ 8.07\angle 8.69° \end{bmatrix} A$$

BC Fault (FL = 0.1)
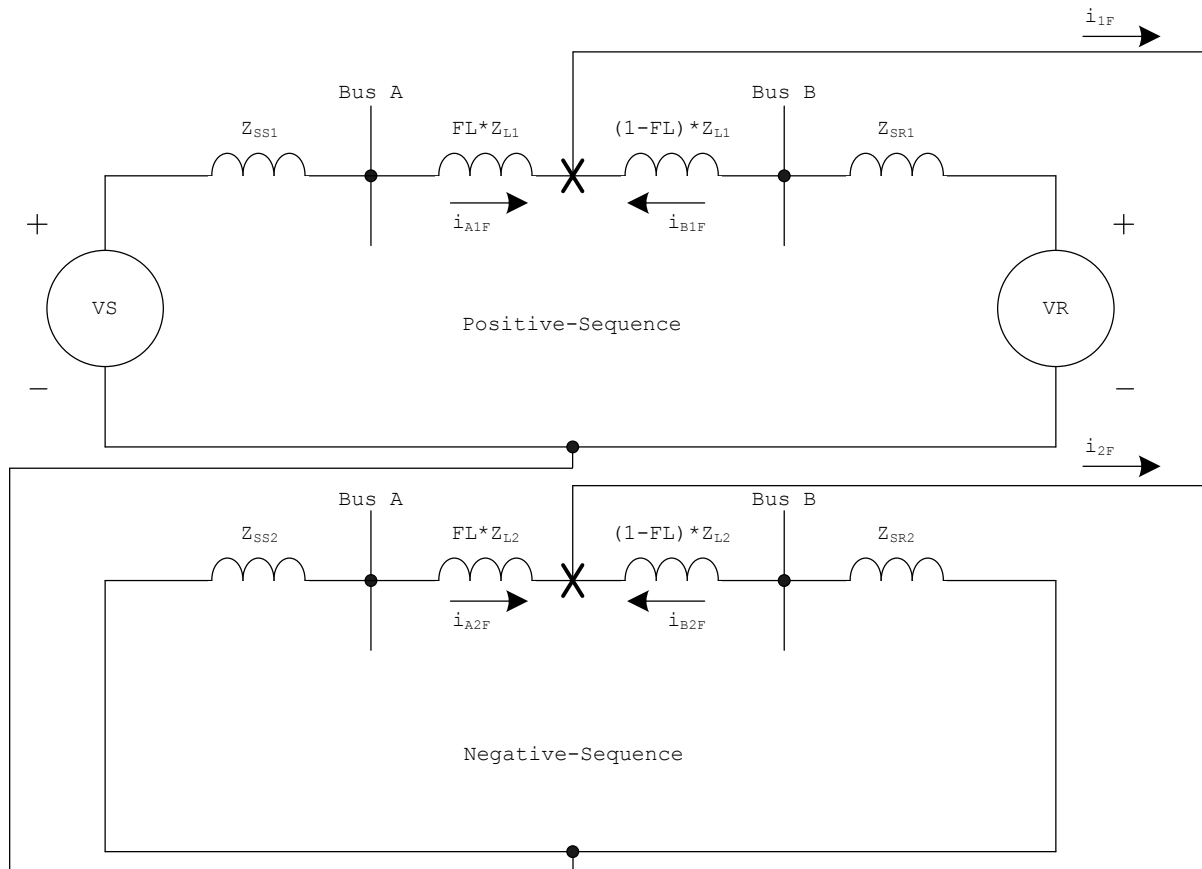
Figure A.4 BC fault sequence diagram connection.

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 100.59\angle83.4°\ \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 156.73\angle83.63°\ \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 100.59\angle83.4°\ \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 156.73\angle83.63° \ \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 61.27\angle83.49° \ \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot (Z_{1\_eq1} + Z_{2\_TH}) + i_{B1F} \cdot Z_{2\_TH}$$

$$V_{R\_phase} = i_{A1F} \cdot Z_{2\_TH} + i_{B1F} \cdot (Z_{1\_eq2} + Z_{2\_TH})$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{2\_TH} & Z_{2\_TH} \\ Z_{2\_TH} & Z_{1\_eq2} + Z_{2\_TH} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 161.86\angle83.43° & 61.27\angle83.49° \\ 61.27\angle83.49° & 218\angle83.59° \end{bmatrix} \begin{bmatrix} 132790.56\angle0° \\ 132790.56\angle-10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 665.57\angle-79.55° \\ 429.97\angle-99.62° \end{bmatrix} A$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 1079.56\angle-87.4° \ A$$

$$i_{2F} = -i_{1F}$$

$$i_{2F} = 1079.56\angle-92.6° \ A$$

$$i_{0F} = 0 \ A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 657.53\angle92.69° \ A$$

$$i_{A0F} = 0 \ A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 665.57\angle -79.55° \\ 657.53\angle 92.69° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 1188.01\angle -173.6° \\ 1098.42\angle 6.81° \end{bmatrix} A$$

$$V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}$$

$$V_{A1F} = 71550.43\angle -3.31° \ V$$

$$V_{A2F} = -i_{A2F} \cdot Z_{SS2}$$

$$V_{A2F} = 60755.82\angle -3.91° \ V$$

$$V_{A0F} = 0 \ V$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 71550.43\angle -3.31° \\ 60755.82\angle -3.91° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 132304.45\angle -3.59° \\ 66220.31\angle -175.47° \\ 67398.83\angle 168.44° \end{bmatrix} V$$

Fault seen by relay A in secondary values

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 132304.45\angle - 3.59° \\ 66220.31\angle - 175.47° \\ 67398.83\angle 168.44° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 66.15\angle - 3.59° \\ 33.11\angle - 175.47° \\ 33.7\angle 168.44° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 1188.01\angle - 173.6° \\ 1098.42\angle 6.81° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 0.56\angle 1.46° \\ 7.43\angle - 173.6° \\ 6.87\angle 6.81° \end{bmatrix} A$$

Fault seen by relay B in primary values

$$i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{B2F} = 422.04\angle 92.46° \ A$$

$$i_{B0F} = 0 \ A$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 429.97\angle - 99.62° \\ 422.04\angle 92.46° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 688.98\angle 176.03° \\ 778.58\angle - 3.34° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 97363.14\angle - 7.87° \ V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 35020.48\angle - 3.75° \ V$$

$$V_{B0F} = 0 \ V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle240° & 1\angle120° \\ 1 & 1\angle120° & 1\angle240° \end{bmatrix} \begin{bmatrix} 0 \\ 97363.14\angle - 7.87° \\ 35020.48\angle - 3.75° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 132317.14\angle - 6.78° \\ 87915.5\angle - 148.87° \\ 82952.32\angle132.59° \end{bmatrix} V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 132317.14\angle - 6.78° \\ 87915.5\angle - 148.87° \\ 82952.32\angle132.59° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 66.16\angle - 6.78° \\ 43.96\angle - 148.87° \\ 41.48\angle132.59° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 688.98\angle176.03° \\ 778.58\angle - 3.34° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 0.56\angle - 178.54° \\ 4.31\angle176.03° \\ 4.87\angle - 3.34° \end{bmatrix} A$$

BC Fault (FL = 0.9)

$$Z_{1\_eq1} = Z_{SS1} + Z_{L1} \cdot FL$$

$$Z_{1\_eq1} = 166.15\angle83.43° \; \Omega$$

$$Z_{1\_eq2} = Z_{SR1} + Z_{L1} \cdot (1 - FL)$$

$$Z_{1\_eq2} = 91.17\angle83.76° \; \Omega$$

$$Z_{2\_eq1} = Z_{SS2} + Z_{L2} \cdot FL$$

$$Z_{2\_eq1} = 166.15\angle83.43° \; \Omega$$

$$Z_{2\_eq2} = Z_{SR2} + Z_{L2} \cdot (1 - FL)$$

$$Z_{2\_eq2} = 91.17\angle83.76° \; \Omega$$

$$Z_{2\_TH} = \frac{Z_{2\_eq1} \cdot Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$Z_{2\_TH} = 58.87\angle83.64° \; \Omega$$

$$V_{S\_phase} = i_{A1F} \cdot (Z_{1\_eq1} + Z_{2\_TH}) + i_{B1F} \cdot Z_{2\_TH}$$

$$V_{R\_phase} = i_{A1F} \cdot Z_{2\_TH} + i_{B1F} \cdot (Z_{1\_eq2} + Z_{2\_TH})$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} Z_{1\_eq1} + Z_{2\_TH} & Z_{2\_TH} \\ Z_{2\_TH} & Z_{1\_eq2} + Z_{2\_TH} \end{bmatrix} \begin{bmatrix} V_{S\_phase} \\ V_{R\_phase} \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 225.02\angle83.48° & 58.87\angle83.64° \\ 58.87\angle83.64° & 150.04\angle83.71° \end{bmatrix} \begin{bmatrix} 132790.56\angle0° \\ 132790.56\angle-10° \end{bmatrix}$$

$$\begin{bmatrix} i_{A1F} \\ i_{B1F} \end{bmatrix} = \begin{bmatrix} 406.11\angle-77.09° \\ 733.68\angle-97.26° \end{bmatrix} A$$

$$i_{1F} = i_{A1F} + i_{B1F}$$

$$i_{1F} = 1123.65 \angle - 90.1° \, A$$

$$i_{2F} = -i_{1F}$$

$$i_{2F} = 1123.65 \angle 89.9° \, A$$

$$i_{0F} = 0 \, A$$

Fault seen by relay A in primary values

$$i_{A2F} = i_{2F} \cdot \frac{Z_{2\_eq2}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{A2F} = 398.14 \angle 90.11° \, A$$

$$i_{A0F} = i_{0F}$$

$$i_{A0F} = 0 \, A$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{A0F} \\ i_{A1F} \\ i_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 406.11 \angle - 77.09° \\ 398.14 \angle 90.11° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayA\_A} \\ i_{relayA\_B} \\ i_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 89.95 \angle 1.46° \\ 736.97 \angle - 173.74° \\ 647.38 \angle 6.93° \end{bmatrix} A$$

$$V_{A1F} = V_{S\_phase} - i_{A1F} \cdot Z_{SS1}$$

$$V_{A1F} = 95581.91 \angle - 2.47° \, V$$

$$V_{A2F} = -i_{A2F} \cdot Z_{SS2}$$

$$V_{A2F} = 36787.77 \angle - 6.49° \, V$$

$$V_{A0F} = 0 \ V$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} V_{A0F} \\ V_{A1F} \\ V_{A2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 95581.91\angle -2.47° \\ 36787.77\angle -6.49° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 132304.45\angle -3.59° \\ 80963.85\angle -144.6° \\ 86070.39\angle 140.12° \end{bmatrix} V$$

Fault seen by relay A in secondary values

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 132304.45\angle -3.59° \\ 80963.85\angle -144.6° \\ 86070.39\angle 140.12° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayA\_A} \\ V_{relayA\_B} \\ V_{relayA\_C} \end{bmatrix} = \begin{bmatrix} 66.15\angle -3.59° \\ 40.48\angle -144.6° \\ 43.04\angle 140.12° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 89.95\angle 1.46° \\ 736.97\angle -173.74° \\ 647.38\angle 6.93° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayA\_A\_sec} \\ i_{relayA\_B\_sec} \\ i_{relayA\_C\_sec} \end{bmatrix} = \begin{bmatrix} 0.56\angle 1.46° \\ 4.61\angle -173.74° \\ 4.05\angle 6.93° \end{bmatrix} A$$

Fault seen by relay B in primary values

$$i_{B2F} = i_{2F} \cdot \frac{Z_{2\_eq1}}{Z_{2\_eq1} + Z_{2\_eq2}}$$

$$i_{B2F} = 725.52\angle 89.78° \ A$$

$$i_{B0F} = i_{0F}$$

$$i_{B0F} = 0 \ A$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} i_{B0F} \\ i_{B1F} \\ i_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 733.68\angle - 97.26° \\ 725.52\angle 89.78° \end{bmatrix}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 1216.54\angle 176.05° \\ 1306.12\angle - 3.58° \end{bmatrix} A$$

$$V_{B1F} = V_{R\_phase} - i_{B1F} \cdot Z_{SR1}$$

$$V_{B1F} = 72115.33\angle - 7.07° \ V$$

$$V_{B2F} = -i_{B2F} \cdot Z_{SR2}$$

$$V_{B2F} = 60203.85\angle - 6.43° \ V$$

$$V_{B0F} = 0 \ V$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} V_{B0F} \\ V_{B1F} \\ V_{B2F} \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240° & 1\angle 120° \\ 1 & 1\angle 120° & 1\angle 240° \end{bmatrix} \begin{bmatrix} 0 \\ 72115.33\angle - 7.07° \\ 60203.85\angle - 6.43° \end{bmatrix}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 132317.14\angle - 6.78° \\ 67585.17\angle - 178° \\ 66330.95\angle 164.27° \end{bmatrix} V$$

Fault seen by relay B in secondary values

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 132317.14\angle - 6.78° \\ 67585.17\angle - 178° \\ 66330.95\angle164.27° \end{bmatrix} \cdot \frac{1}{PT}$$

$$\begin{bmatrix} V_{relayB\_A} \\ V_{relayB\_B} \\ V_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 66.16\angle - 6.78° \\ 33.79\angle - 178° \\ 33.17\angle164.27° \end{bmatrix} V$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 89.95\angle - 178.54° \\ 1216.54\angle176.05° \\ 1306.12\angle - 3.58° \end{bmatrix} \cdot \frac{1}{CT}$$

$$\begin{bmatrix} i_{relayB\_A} \\ i_{relayB\_B} \\ i_{relayB\_C} \end{bmatrix} = \begin{bmatrix} 0.56\angle - 178.54° \\ 7.6\angle176.05° \\ 8.16\angle - 3.58° \end{bmatrix} A$$

APPENDIX B

TEST SET FAULT VALUES

Table B.1 Relay A – Zone 1 A-G fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	5.41	V	0.01	°	66.15	V	-3.59	°
66.15	V	-123.59	°	81.34	V	-141.34	°	66.15	V	-123.59	°
66.15	V	116.41	°	84.92	V	131.56	°	66.15	V	116.41	°
0.56	A	1.46	°	4.65	A	-76.23	°	0.00	A	0.00	°
0.56	A	-118.54	°	0.56	A	-118.54	°	0.00	A	0.00	°
0.56	A	121.46	°	0.56	A	121.46	°	0.00	A	0.00	°

Table B.2 Relay B – Zone 2 A-G fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	31.24	V	-10.17	°	66.16	V	-6.78	°
66.16	V	-126.78	°	74.80	V	-137.48	°	66.16	V	-126.78	°
66.16	V	113.22	°	75.69	V	123.34	°	66.16	V	113.22	°
0.56	A	-178.54	°	2.93	A	-94.40	°	0.00	A	0.00	°
0.56	A	61.46	°	0.56	A	61.46	°	0.00	A	0.00	°
0.56	A	-58.54	°	0.56	A	-58.54	°	0.00	A	0.00	°

Table B.3 Relay A – Zone 1 BC-G fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	84.95	V	-4.45	°	66.15	V	-3.59	°
66.15	V	-123.59	°	5.41	V	-119.94	°	66.15	V	-123.59	°
66.15	V	116.41	°	5.41	V	120.06	°	66.15	V	116.41	°
0.56	A	1.46	°	0.56	A	1.46	°	0.00	A	0.00	°
0.56	A	-118.54	°	7.65	A	174.52	°	0.00	A	0.00	°
0.56	A	121.46	°	7.00	A	19.80	°	0.00	A	0.00	°

Table B.4 Relay B – Zone 2 BC-G fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	77.01	V	-6.85	°	66.16	V	-6.78	°
66.16	V	-126.78	°	31.24	V	-130.17	°	66.16	V	-126.78	°
66.16	V	113.22	°	31.24	V	109.83	°	66.16	V	113.22	°
0.56	A	-178.54	°	0.56	A	-178.54	°	0.00	A	0.00	°
0.56	A	61.46	°	4.63	A	163.70	°	0.00	A	0.00	°
0.56	A	-58.54	°	4.77	A	8.65	°	0.00	A	0.00	°

Table B.5 Relay A – Zone 1 BC fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	66.15	V	-3.59	°	66.15	V	-3.59	°
66.15	V	-123.59	°	33.11	V	-175.47	°	66.15	V	-123.59	°
66.15	V	116.41	°	33.70	V	168.44	°	66.15	V	116.41	°
0.56	A	1.46	°	0.56	A	1.46	°	0.00	A	0.00	°
0.56	A	-118.54	°	7.43	A	-173.6	°	0.00	A	0.00	°
0.56	A	121.46	°	6.87	A	6.81	°	0.00	A	0.00	°

Table B.6 Relay B – Zone 2 BC fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	66.16	V	-6.78	°	66.16	V	-6.78	°
66.16	V	-126.78	°	43.96	V	-148.87	°	66.16	V	-126.78	°
66.16	V	113.22	°	41.48	V	132.59	°	66.16	V	113.22	°
0.56	A	-178.54	°	0.56	A	-178.54	°	0.00	A	0.00	°
0.56	A	61.46	°	4.31	A	176.63	°	0.00	A	0.00	°
0.56	A	-58.54	°	4.87	A	-3.34	°	0.00	A	0.00	°

Table B.7 Relay A – Zone 2 A-G fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	29.47	V	0.03	°	66.15	V	-3.59	°
66.15	V	-123.59	°	73.92	V	-135.54	°	66.15	V	-123.59	°
66.15	V	116.41	°	77.42	V	126.07	°	66.15	V	116.41	°
0.56	A	1.46	°	2.84	A	-74.34	°	0.00	A	0.00	°
0.56	A	-118.54	°	0.56	A	-118.54	°	0.00	A	0.00	°
0.56	A	121.46	°	0.56	A	121.46	°	0.00	A	0.00	°

Table B.8 Relay B – Zone 1 A-G fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	5.97	V	-10.30	°	66.16	V	-6.78	°
66.16	V	-126.78	°	81.41	V	-144.25	°	66.16	V	-126.78	°
66.16	V	113.22	°	84.53	V	128.43	°	66.16	V	113.22	°
0.56	A	-178.54	°	5.04	A	-92.46	°	0.00	A	0.00	°
0.56	A	61.46	°	0.56	A	61.46	°	0.00	A	0.00	°
0.56	A	-58.54	°	0.56	A	-58.54	°	0.00	A	0.00	°

Table B.9 Relay A – Zone 2 BC-G fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	77.49	V	-4.54	°	66.15	V	-3.59	°
66.15	V	-123.59	°	29.47	V	-119.97	°	66.15	V	-123.59	°
66.15	V	116.41	°	29.47	V	120.03	°	66.15	V	116.41	°
0.56	A	1.46	°	0.56	A	1.46	°	0.00	A	0.00	°
0.56	A	-118.54	°	4.70	A	174.55	°	0.00	A	0.00	°
0.56	A	121.46	°	4.17	A	20.13	°	0.00	A	0.00	°

Table B.10 Relay B – Zone 1 BC-G fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	84.79	V	-7.49	°	66.16	V	-6.78	°
66.16	V	-126.78	°	5.97	V	-130.30	°	66.16	V	-126.78	°
66.16	V	113.22	°	5.97	V	109.70	°	66.16	V	113.22	°
0.56	A	-178.54	°	0.56	A	-178.54	°	0.00	A	0.00	°
0.56	A	61.46	°	8.07	A	163.79	°	0.00	A	0.00	°
0.56	A	-58.54	°	8.07	A	8.69	°	0.00	A	0.00	°

Table B.11 Relay A – Zone 2 BC fault

Pre-Fault				Fault				Post-Fault			
66.15	V	-3.59	°	66.15	V	-3.59	°	66.15	V	-3.59	°
66.15	V	-123.59	°	40.48	V	-144.60	°	66.15	V	-123.59	°
66.15	V	116.41	°	43.04	V	140.12	°	66.15	V	116.41	°
0.56	A	1.46	°	0.56	A	1.46	°	0.00	A	0.00	°
0.56	A	-118.54	°	4.61	A	-173.74	°	0.00	A	0.00	°
0.56	A	121.46	°	4.05	A	6.93	°	0.00	A	0.00	°

Table B.12 Relay B – Zone 1 BC fault

Pre-Fault				Fault				Post-Fault			
66.16	V	-6.78	°	66.16	V	-6.78	°	66.16	V	-6.78	°
66.16	V	-126.78	°	33.79	V	-178.00	°	66.16	V	-126.78	°
66.16	V	113.22	°	33.17	V	164.27	°	66.16	V	113.22	°
0.56	A	-178.54	°	0.56	A	-178.54	°	0.00	A	0.00	°
0.56	A	61.46	°	7.60	A	176.05	°	0.00	A	0.00	°
0.56	A	-58.54	°	8.16	A	-3.58	°	0.00	A	0.00	°

VITA

José Ruiz was born in Ecuador. He received his Bachelors of Science in Electronic Engineering from the Universidad Politécnica Salesiana in Cuenca, Ecuador in 2007. He joined ABB Inc. in 2011 as a Protection Application Engineer where he keeps improving his knowledge on protection relaying up to the date.

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