Cape Peninsula University of Technology

HARDWARE IN THE LOOP SIMULATION AND TESTING OF VOLTS PER HERTZ PROTECTION SCHEME FOR A GENERATOR OVEREXCITATION SYSTEM

By

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DECLARATION

I, Khangwelo Loyd Rathogwa, certify that the information contained in this thesis or dissertation is entirely my own original work and has never before been submitted for academic review in order to obtain a degree. The views expressed here are also solely mine and do not necessarily reflect those of Cape Peninsula University of Technology.

Signed ____________________

09 December 2022
Date

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ABSTRACT

A power plant's large generators are essential components for ensuring the steady production and delivery of electric power for a variety of purposes. A power system's stability is greatly impacted by the generator protection system. It has recently become necessary to think about upgrading the existing protective devices due to a rise in power demand and their aging. The over-excitation, overvoltage, and under-voltage circumstances that affect generators as well as their protection mechanisms were the subject of this study. The analyses of the various method used for generator protection is conducted in this research as part of the literature review. The research developed a logic design and algorithm for volts per hertz protection strategy for overexcited generators. The logic design of over and under-voltage conditions is also developed. The implementation of the current differential and overcurrent protection schemes for generator using DIgSILENT power factory simulation environment is performed and the simulation results are studied for both normal and abnormal conditions for both current differential and overcurrent protection schemes. The lab scale test bench to test volts per hertz, a backup overcurrent, over and under voltage protection schemes for a generator is implemented using SEL 700G IED and simulation results are analysed and presented. The hardware in the loop test-bed is implemented to test analyse the volts per hertz, simple back up overcurrent, and overvoltage and under voltage protection schemes. The HIL test bed was implemented using real time digital simulator and SEL 700G IED. The Hardware-in-the-Loop simulation results for over excitation conditions, overcurrent fault events, over and under voltage conditions of a generator is presented.

Keywords: Generator Over-excitation system, Volts per hertz, overvoltage, under voltage, overcurrent, and Hardware-in-the-Loop simulations.

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- The CPUT Library management and staff for their support and willing to provide me with the information needed for this study.
- All My CSAEMS colleagues for their support.

DEDICATION

This thesis is dedicated to my father Nnditsheni Justice Rathogwa and my entire family. Further dedication goes to my fiancée Rolivhuwa Masiagwala.

TABLE OF CONTENTS

Contents

LIST OF FIGURES

LIST OF TABLES

GLOSSERY

Term	Definitions
AcSELerator Architect	Configuring message publications and subscription requires software for substation communications networks utilizing the IEC 61850 MMS and GOOSE protocols.
AcSELerator-Quickset	SEL device configuration, commissioning, and management software for power system protection, control, metering, and monitoring experts.
Algorithm	A step-by-step instruction for using a computer to solve an problem.
Current Transformer	A mechanism for converting current from one magnitude to another.
DIgSILENT software	A software for modelling, analysing, and simulating power systems for use in industrial, transmission, and generation systems.
Ethernet	A protocol for participating of frame-based computer networking technologies to a local area network.
HIL	A method for testing control systems is called hardware-in-the-loop simulation.
GOOSE	The IEC 61850 component used for high-speed control messaging. IEC 61850 GOOSE automatically broadcasts messages onto the network for use by other devices that include status, controls, and measured values. IEC61850 GOOSE transmits messages several times, increasing the chance that other devices will catch them.
Human Machine Interface	A software program that displays information to a user or operator about the status of a process and accepts and applies the operator's control commands.

IEC61850 standard The ability of intelligent electronic devices (IEDs) for electrical substation automation systems to communicate with one another is a standard for vendor/manufacturer engineering setup.

IED A device used in the electric power sector to characterize microprocessor-based power system controllers for items like digital relays, circuit breakers, transformers, and capacitor banks.

Interoperability Ability of two or more IEDs to exchange information and utilise that information for proper performance of defined functions, regardless of the vendor.

Logical Node (LN) The smallest component of a function that communicates with another function and represents a function inside a physical device.

Merging Unit (MU) a device for communicating onto the process bus sampled measurements from transducers like CTs, VTs, and digital I/O.

MMS An international standard addressing messaging systems for exchanging supervisory control information and real-time process data between hardware and/or software applications.

Numerical Relay a relay that can collect instantaneous voltage and/or current samples and use a mathematical algorithm to process them.

Omicron CMC 356 tool and universal test set for relay commissioning.

Protection system System that comprises tools to safeguard human and equipment's from harm caused by mechanical or electrical failures, or by specific power system conditions.

RSCAD In order to do real-time digital simulations, real-time digital simulators (RTDS) hardware must be interfaced with power system simulation software.

SCADA a system for controlling processes that enables a system administrator to monitor and manage operations distributed over multiple remote sites.

TCP/IP The conceptual framework and group of communications protocols that are utilized on the internet and other similar computer networks are found at the internet protocol site.

NOMENCLATURE

A/D	Analogue to digital
ACSI	Abstract Communication Service Interface
ATP	Alternative Transient Program
AVR	Automatic Voltage Regulator
CSAEMS	Centre for Substation Automation and Energy Management Systems
CT	Current Transformer
CU	Central Unit
DGPS	Digital Generator Protection System
ECS	Excitation Control System
EMTP	Electromagnetic Transients Program
EPRI	Electric Power Research Institute
FCR	Field current Regulator
FPGA	Field Programmable Gate Array
GOOSE	Generic-Oriented-Object-System-Event
GSSE	Generic Substation Status Event
GTAO	Gigabit Transceiver Analogue Output Card
GTFPI	Inter-Rack Communication Card
HIL	Hardware-in-the-Loop
ICD	IED capability description
IEC	International Electro technical Commission
IEDs	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronics Engineers
IP	Inter-networking Protocol
LAN	Local Area Network
LD	Logical Device
LN	Logical Nodes
MMI	Man Machine Interface
MMS	Manufacturing Message Specification
MU	Merging unit
OEL	Over excitation Limiters
PRI	Protection Inverse Time
RTDS	Real-Time Digital Simulator
SAS	Substation Automation System
SCADA	Supervisory Control and Data Acquisition
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SEL	Schweitzer Engineering Laboratories

SG	Synchronous Generator
SSD	Substation Specific Description
SV	Sample value
UCA	Utility Communications Architecture
V/Hz	Volts per hertz
VT	Voltage Transformer

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Generators are a common source of energy in Industrial and commercial power systems. These generators supply all or part of the total energy required, or they provide emergency power in the event of a failure of the normal source of energy. Generator application can be classified as single isolated generators, multiple isolated generators, and large industrial generators(Institute of Electrical and Electronics Engineers. *et al.*, 1986). These generators represent a unique class of power network equipment because failures are extremely rare, but when they do occur they can be very destructive and very costly. Therefore, protective relaying must be provided against out of range operation not normally found in other types of equipment such as over-voltage, under-voltage, over-excitation, over frequency, under-frequency or speed range(Halpin, 2001). The protective relaying to be provided should have the following requirements:

- Speed: it should operate as fast as possible to minimise the damage on the equipment.
- Selectivity: it should be able to clear minimum number of segments
- Sensibility: it should be able to measure of the minimum input required to operate the protection device.
- Reliability: it should only trip when required
- Security: it should not trip when it is not required
- Simplicity: it should be able to minimise protection equipment and circuitry
- Redundancy: it should duplicate locally or remotely

For acceptable levels of thermal losses and dielectric strains, the magnetic cores of generators should operate at or below rated flux densities. In generators, the magnetic flux is inversely proportional to the running frequency and directly proportional to the applied voltage. When the voltage to frequency (V/Hz) ratio applied to the equipment's terminals reaches 105 percent (generator base), the generator will become overexcited. Overvoltage and the saturation of the generator's magnetic core may arise from exceeding these volts/hertz (V/Hz) ratios, and stray flux may be induced in non-laminated components that are not intended to carry flux. In the generator laminations, high flux may also result in excessive eddy currents and voltages between the laminations. This could result in the generator overheating severely and ultimately insulation failure. The generator's field current may also be too high (Power and Society, 2005).

The testing of the generator over excitation system's volts/hertz protection scheme is the main focus of this thesis. Generator and transformer over excitation protection can be provided by a volts-per-hertz element (24). When the volts-hertz ratio is too high, when the generator output voltage is high, or during startup, when the frequency is below normal, generator over-excitation methods protect the generator and unit transformer (Blackburn JL and Domin JT, 2006). The backup overcurrent, over, and under-voltage protection mechanism of a generator is also taken into account by the thesis.

This chapter explains the importance of generators in power systems. This chapter also covers the 1.2 Awareness of the problem, 1.3 Problem statement, 1.4 Research aims and objectives, 1.5 Hypothesis, 1.6 Motivation of the research, 1.7 Assumptions, 1.8 Research methodologies, 1.9 Thesis breakdown structure and 1.10 Conclusion.

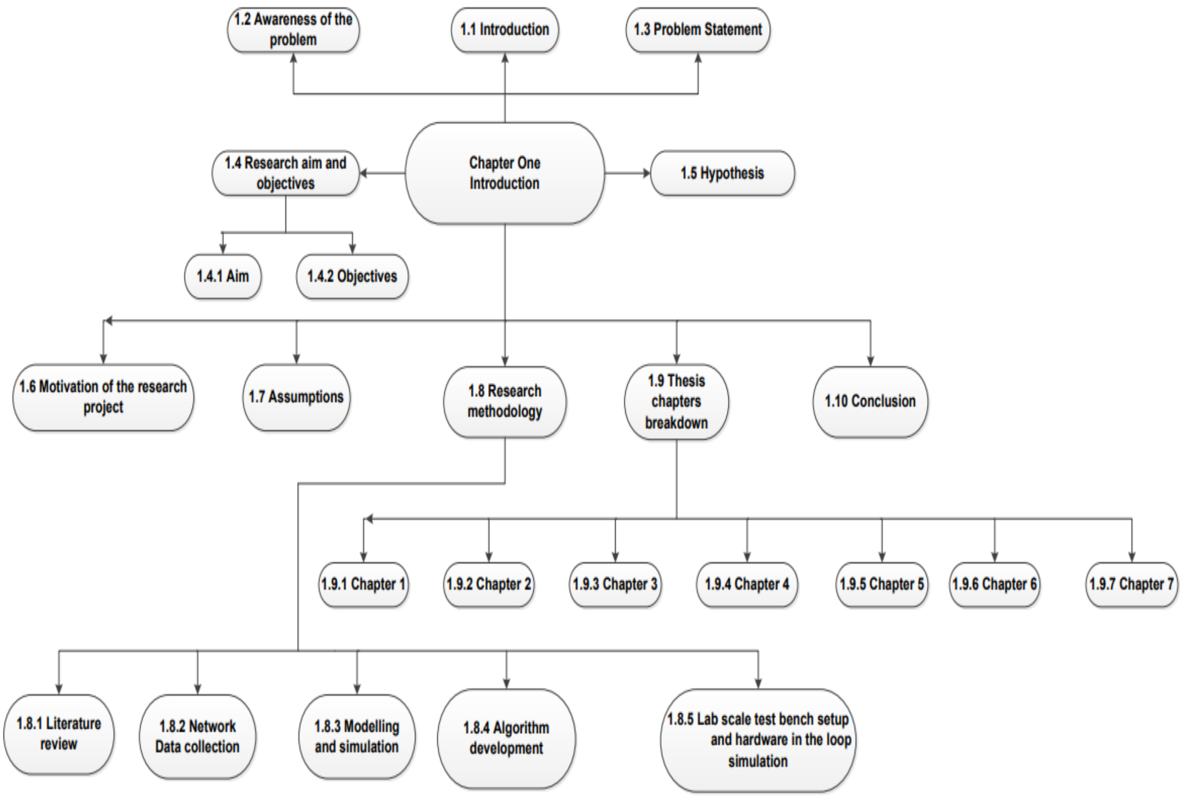

Figure 1.0: Summary of the content covered in chapter one

1.2 Awareness of the problem

In many applications, generators in a power plant are essential components for consistent production and supply of electricity. A power system's stability is greatly impacted by the generator protection system. When operating at reduced frequencies or when there is a significant loss of load, the generator in the power producing station may be subjected to over excitation during start-up and shutdown, which could result in both overvoltage and overspeed. Small overvoltages cause substantial exciting currents in transformers when operating normally around the knee of the iron saturation curve, and high flux densities and strange flux patterns in generators when operating normally. These may result in serious and significant harm (Blackburn JL and Domin JT, 2006).

Once the generator is attached to the system, there is very little chance of abrupt damage brought on by over-excitation. In any case, it is crucial that V/Hz protection is set up and configured properly (I. Kerszenbaum and G. Klempner, 2008). Power plant equipment can get damaged in a matter of seconds due to excessive variations in frequency and voltage, which also produce thermal and dielectric strains. Additionally, total load rejection that still leaves transmission lines linked to a producing station may result in over-excitation. The V/Hz may approach 125 percent in this situation. The over-excitation will typically be decreased to safe limits in a matter of seconds after the excitation control is in use (Power and Society, 2005)

Protective engineers often make cautious adjustments to ANSI 24 function on protection systems due to the potential effects of prolonged over-excitation (Kharel et al., 2010). The volts per hertz protection strategy features a component that detects over excitation circumstances to prevent malfunction caused on by overexcitation of a generator.
In order to test the volts per hertz, backup overcurrent, overvoltage, and undervoltage protection methods, this research thesis created a lab scale test bench setup and Hardware in the Loop (HIL) Simulation using Real Time Digital Simulators (RTDS) and SEL 700G relay.

1.3 Problem statement

A power system's stability is greatly impacted by the generator protection system. It has recently become necessary to think about upgrading the existing protective devices due to a rise in power demand and their aging. As a result, the testing of various generator protection mechanisms and generator disturbance circumstances are the main topics of this research.

Generator over excitation occurs when the magnetic core of the generator is saturated. When this occurs, stray flux is induced in non-laminated components, resulting in overheating of the generator. The generator shutdown with the automatic voltage regulator left in service; sudden load rejection with the automatic voltage regulator out of service; and manual excitation adjustment during start-up with faulty metering. In order to test volts per hertz relay for generator over-excitation circumstances, in this project work a test bench setup is established, hardware-in-the-loop simulation is conducted.

1.4 Research Aim and objectives

1.4.1 Aim

- The goal of this project research is to implement a volts-per-hertz protection method for a generator over excitation system and validate the volts-per-hertz protection function using hardware-in-the-loop simulation.
- Additionally, hardware test beds for a generator's over- and under-voltage protection functional testing is implemented.

1.4.2 Objectives

The following are the main objectives of the research:

- To conduct a literature review on generator over excitation system and its volts/hertz protection scheme.
- To conduct a literature review on backup overcurrent, overvoltage and under voltage systems of a generator
- To conduct a literature review on Hardware-in-the-Loop (HIL) simulation using Real-Time Digital Simulator (RTDS) and protection devices such as Intelligent Electronics Devices (IEDs).
- To model the power system network in Dig silent software environment.
- To investigate the volts/hertz generator over excitation system in Dig silent simulation using SEL700G relay model.
- To model the power system in RSCAD simulation environment and HIL to be conducted to investigate the volts/hertz generator over excitation system.
- To develop an algorithm and logic diagram for volts/hertz protection scheme for generator over excitation system.
- To investigate backup overcurrent, overvoltage and under voltage conditions of a generator on DigSILENT simulation environment using SEL700G relay model.
- To implement a lab scale test bench setup in the Centre for Substation Automation and Energy Management Systems (CSAEMS) laboratory, the power system modelled in RSCAD environment and hardware in the loop simulation is conducted to analyse the volts/hertz, overcurrent, over and under voltage protection schemes of a generator system using RDTS and SEL700G IED, and Omicron CMC356 test injection devices.

- To implement hardware-in-the-loop simulation and testing of a volts/hertz, back up overcurrent, over and under voltage protection schemes for a generator system.

1.5 Hypothesis

This research project will prove that:

- By strictly implementing hardwired application for generator over excitation system.
- By simply testing volts per hertz, protection scheme for generator over excitation system can be possibly controlled
- Overcurrent protection scheme can be used as a backup protection of a generator.
- By testing over- and under-voltage protection schemes, the over and under-voltage conditions can be mitigated.

1.6 Motivation of the research project

- This research tests volts per hertz protection scheme to protect the generator from over-excitation.
- The investigation of the Volts/Hertz and over-excitation limiters' activation when a generator is subjected to severe over-excitation conditions is presented in this study.
- This research tests overcurrent, over and under voltage protection scheme to generator from internal system disturbances.
- This research presents a lab scale test that is implemented in a real-time digital simulation environment to perform investigations of a generator system's protective features.

1.7 Assumptions

The following assumptions were made for this research thesis:

- The system network used was focusing on the generation system
- Volts /hertz protection scheme is applied for over excitation
- SEL 700 detects over excitation, back up overcurrent, over and under voltage
- Simulation test results conducted using RTDS are more realistic representation of generator over excitation protection scheme.
- Hardwired-based communication is much slower than GOOSE communication.

1.8 Research Methodology

These following research methods are applied in the process of development of the research project:

1.8.1 Literature review

The literature review has been conducted which looks at the generator over-excitation system, volts per her protection scheme, HIL as well as IEC 61850 for power utilities. Several methods available were identified for Generator over excitation protection such as volts per hertz protection scheme and over-excitation limiters. The literature review which looks at overcurrent, over and under voltage protection schemes of a generator system is also conducted.

1.8.2 Network Data collection

The IEEE 9 bus network system is used as a case study in this research work. The data of the IEEE 9 bus system are given from Table 4.1 to Table 4.5 in chapter 4 of this thesis. A thorough simulation is conducted in DIgSILENT and RTDS environments in order to collect the data pertaining to generator over-excitation conditions and generator protection schemes.

1.8.3 Modelling and Simulation

The simulation study and protection settings are conducted using Dig SILENT Power Factory and RTDS software in order to determine minimum requirements and network behaviour.

Quickset AcSELerator is used for the protection configuration and Omicron test universe software is used for the test injection device configuration.

1.8.4 Algorithm development

An algorithm and logic diagram is developed for volts per hertz protection scheme for generator over excitation as well as for over and under voltage conditions.

1.8.5 Lab scale Test Bench Setup and Hardware-in-the-loop simulation

Implementation of a lab scale test bench setup, the power system model in RSCAD environment and hard ware in the loop simulation will be conducted to configure the settings of the volts/hertz, backup overcurrent, over and under voltage protection schemes for generator system using RDTS and SEL700G relay. Omicron amplifier CMS356 and Omicron CMC356 test injection devices in the Centre for Substation Automation and Energy Management Systems (CSAEMS) laboratory are used as test injection device in the lab scale protection functional testing. AcSELerator Quickset software is used for SEL relay configurations.

1.9 Thesis chapter breakdown

1.9.1 Chapter 1

Introduction to the research project, Awareness of the problem, Problem statement, research objectives, hypothesis, and motivation of the project, assumptions and research methodology are discussed.

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1.9.2 Chapter 2

This chapter covers the literature reviews conducted on generator over excitation system and its volts per hertz protection scheme, overcurrent, over and under voltage protections scheme, hardware in the loop simulation using real time digital simulator and protection devices.

1.9.3 Chapter 3

This chapter covers theories on generator over excitation, volts per hertz, overcurrent, over and under voltage protection schemes.

1.9.4 Chapter 4

Modelling and configuration of power system diagram network single line equipment on Dig SILENT Power Factory is presented in this chapter. This chapter also investigated the current differential and overcurrent schemes in Dig silent simulation environment using Dig SILENT SEL 700G relay model.

1.9.5 Chapter 5

This chapter covers hardware in the loop simulation of the volts/hertz, backup overcurrent, over and under voltage protection schemes for generator system using RDTS, SEL700G relay and Omicron amplifier CMS356.

1.9.6 Chapter 6

This chapter covers modelling of the power system network on RSCAD simulation environment. The implementation hardware-in-the-loop simulation will be conducted to test volts per hertz protection scheme for generator over-excitation system.

1.9.7 Chapter 7

This chapter discussed the findings, deliverables, application of results, and the future field of research.

1.10 Conclusion

This chapter introduces the research project. This chapter also states the problem statement, aims and objectives, research delimitation and research methodologies of the research project together. The breakdown of the chapters is also provided.

The next chapter provides literature review on over-excitation, overcurrent, over and under-voltage conditions of a generator and their volts per hertz, overcurrent, over and under voltage protection schemes. The next chapter also provides literature review on protection Hardware-in-the-loop (HIL) simulation using Real Time Digital Simulations (RDTS).

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Generators are a special class of power network equipment, according to (Leonard L. Grigsby, 2007), and they are exceedingly complex since errors can be very costly and destructive even when they do occur. The removal of a generator in the event of a serious malfunction is also a primary, if not an obligatory need. For the majority of utilities, generating integrity must be kept by preventing incorrect tripping. The author further emphasized the need for protection against out-of-range operations that are typically not encountered with other kinds of equipment, such as overvoltage, overexcitation, and restricted frequency or speed ranges.

Numerous aberrant circumstances that do not exist with other system components must be taken into account in order to preserve generators. Equipment should have automatic protection against all dangerous situations when it is left unattended. It could be desirable to sound an alarm on an abnormal condition in installations with an attendant present rather than turn off the generator. Depending on the goals to be met, different generator protection strategies will be used (Institute of Electrical and Electronics Engineers. et al., 1986).

The investigation is described in the literature review together with the hardware-in-the-loop simulation utilizing a real-time digital simulator, the generator over excitation system and its volts per hertz protection scheme.

The literature review's first section looks into a generator's over-excitation, backup overcurrent, over, and under current conditions, as well as each of their corresponding protection schemes. A brief summary of all the flaws that lead to over excitation, overvoltage, and under voltage circumstances in a generator is provided by the study. The hardware-in-the-loop simulation employing a real-time digital simulator and IEDs is provided in the review's last part. Reviewing HIL simulations and testing of the volts per hertz, over- and under-voltage protection methods of a generator system are given special consideration.

This chapter provides a literature review on generator protection used in power system. It presents and analyse various technique methods utilized to improve generator protection. 2.2 provides the literature review overview, in 2.3 over excitation conditions and volts per hertz protection scheme of a generator are explained, 2.4 cover overvoltage conditions of a generator system, 2.5 under voltage conditions of a generator system is covered, in 2.6 Review overview of volts per hertz, over and under voltage protection schemes is presented, in 2.7 The review of the existing papers on volts per hertz, over and under voltage protection schemes is presented and analysed, 2.8 cover hardware in the loop simulations using RTDS and IEDs, 2.9 presents the review of the existing papers on HIL, RTDS and IEDs for a generator system and gives conclusion in 2.10 as shown in Figure 2.0.

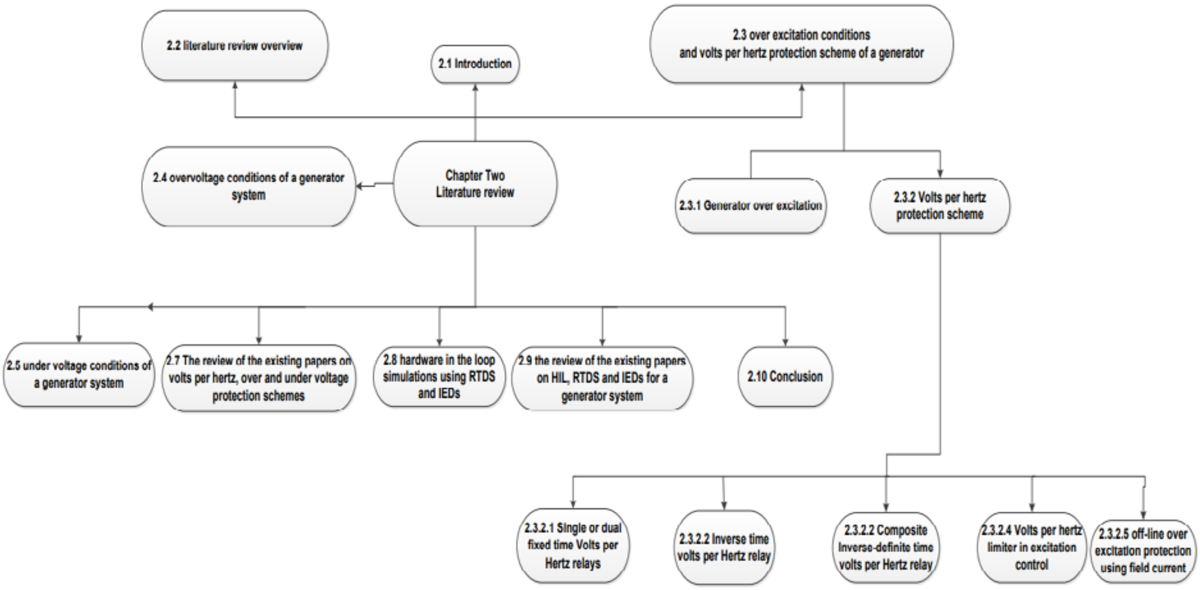


Figure 2.0: Summary of the content covered in chapter two

2.2 Literature review overview

As part of the review process, this literature review takes into account about 84 research papers from journals, standard publications, text books, and relay manuals. A graph showing the quantity of published research articles on generator protection is shown in Figure 2.1.

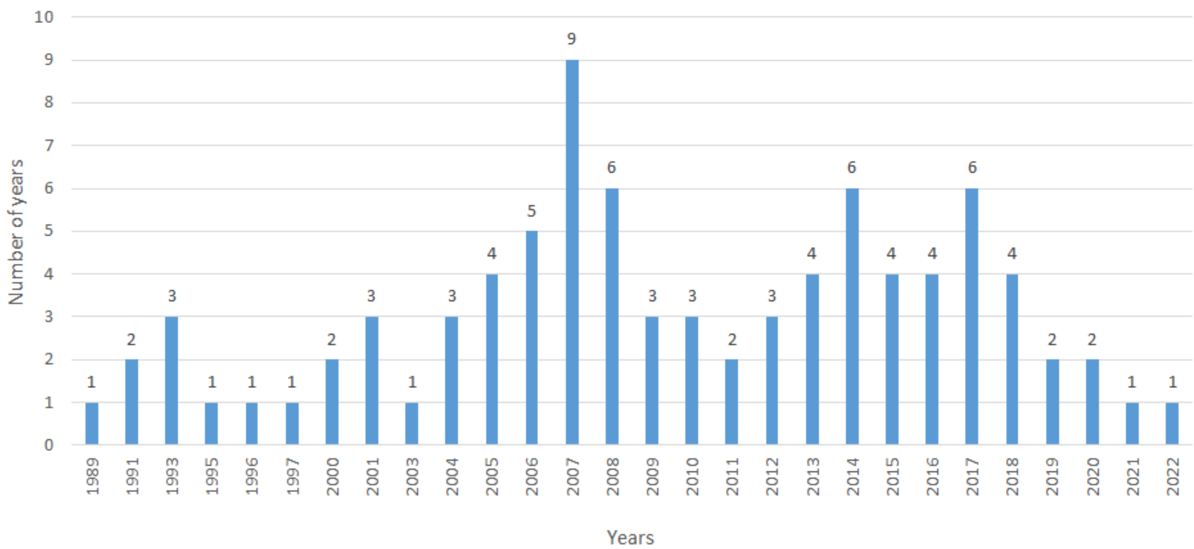


Figure 2.1: Publication reviewed per year

2.3 Over excitation condition and volts per hertz protection scheme of a generator

A generator's magnetic core becomes saturated, which leads to over excitation or over fluxing circumstances (SEL Manual, 2018). Due to the fact that these components are not made to transmit flux, heat or dielectric damage can happen very quickly. (Leonard L. Grigsby, 2007), making it one of these deviations that requires a monitoring and protection plan. Protection devices, according to (Won and Hyeon, 2012), increase the stability of the power system and prevent harm to the various facilities by rapidly and accurately identifying and fixing faults whenever they arise in the power system. The recent rapid development of protection algorithms and semiconductor technology has hastened the digitization of protection relays.

2.3.1 Generator over excitation

Operation of the unit under regulator control at decreased frequencies during start-up and shutdown is one of the major contributors to excessive V/Hz on generators and transformers. Additionally, complete load rejection that still leaves transmission lines connected to a generating station may result in over excitation(Power and Society, 2005). One of the key protection components that play a significant part in the Digital Generator Protection System (DGPS) is the over-excitation relaying algorithm described by (Won and Hyeon, 2012). The author first briefly discusses the fundamentals of over-excitation, adopts the DFT-based gain compensation technique for frequency measurement, and then presents the over-excitation prevention scheme.

2.3.2 Volts per hertz protection scheme

It was suggested by (Blackburn JL and Domin JT, 2006) that whenever the field excitation current, at rated output, is more than that needed at no-load, it is crucial to reduce the excitation in proportion to a reduction in load. Additionally, the author noted that since generator voltage is inversely proportional to frequency and magnetic flux, over-voltage protection should have a constant pickup as a function of the ratio of voltage to frequency, preferably using ANSI code 24 elements of the volts per hertz protection. A volt per hertz element identifies a generator's overexcitation state (SEL Manual, 2018). There are a number of ways to stop an overexcitation syndrome.

2.3.2.1 Single or dual fixed time Volts per Hertz relays

Volts per hertz relays are used configuration with the relay is typically set to 1.1pu of the rated voltage with a 0 to 6s time delay. To match the generator's volts per hertz capabilities, the dual fixed time protection uses relays that operate at stage two of volts per hertz. As shown in Figure 2.2, the stage 1 is set at 1.1 pu of volts per hertz with a time delay of 45 to 60 s, and the 2nd stage is set at a higher volts per hertz of 1.18pu with a time delay of 2 to 6 s.

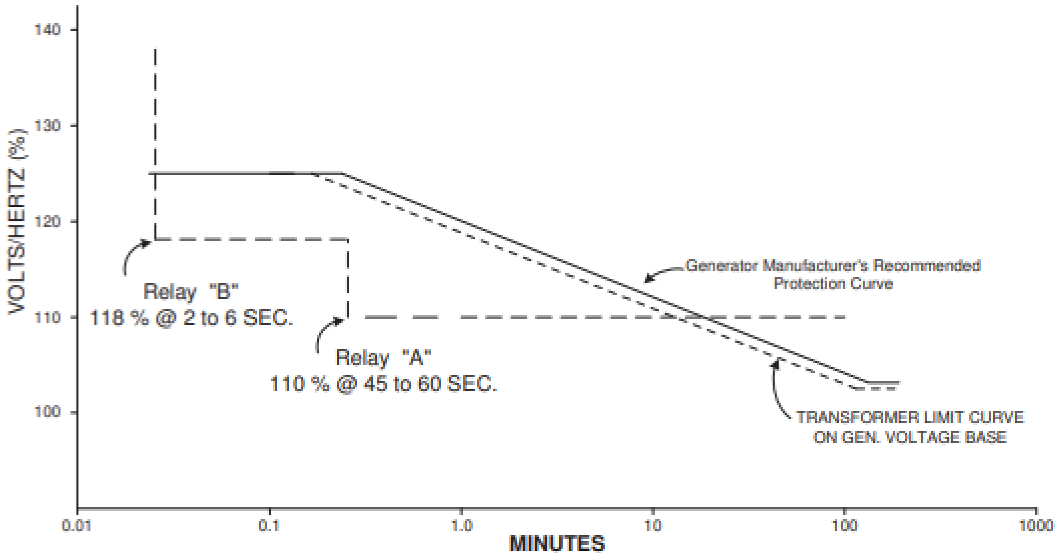


Figure 2.2: Setting for dual fixed time V/Hz relays (Power and Society, 2005).

2.3.2.2 Inverse time volts per Hertz relay

The inverse volts per hertz relay can be used to protect generator from excessive volts per hertz level. The minimum operating level in V/Hz and the delay time are usually set to closely match the combined V/Hz characteristic of the generator.

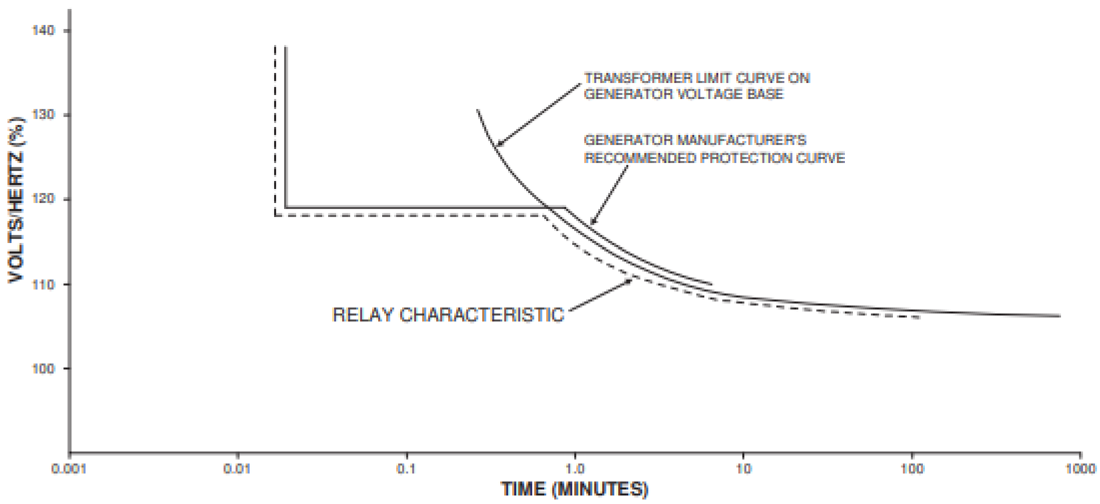


Figure 2.3: Setting for inverse-define time volts per hertz relay (Power and Society, 2005).

2.3.2.3 Composite Inverse-definite time volts per Hertz relay

This version of volts per hertz relay has combination of both inverse and definite time characteristics as shown in Figure 2.3. This unit may be connected to trip or alarm and extend the ability of the relay characteristic to match the V/Hz characteristic of a generator-transformer combination.

2.3.2.4 Volts per hertz limiter in excitation control

The limiter will limit the output of the machine to a set maximum V/Hz no matter what the speed of the unit. This limiter functions only in the automatic control mode. To provide protection when the unit is under manual control, the limiter may have a relay signal output that will activate any additional protective circuits to trip the generator field. The relay circuit is functional whether the excitation control is in or out of service.

2.3.2.5 Off-line over excitation protection using field current

This type of protection is applied when the generator is operating offline. The rated voltage is achieved by field current at no load.at no load the magnetic flux density is directly proportional to rated voltage.an increase if the machine rated voltage goes beyond the threshold value of 1.05pu ,it may results in excessive flux and heating in the stator core area. To avoid this, a dc relay is installed to monitor the machine field current.

2.4 Overvoltage conditions of a generator system

Overvoltage of a generator will occur when there is a sudden loss of load in the grid or when the Automatic Voltage Regulator (AVR) fails to operate. Also the increase of a generator speed due to various reasons will cause overvoltage in a generator. Generators are usually designed to operate continuously at a maximum voltage of 105% of its rated voltage, while delivering rated power at rated frequency. Sustained overvoltage above permissible limit may produce over fluxing (due to high V/Hz) and excessive electrical stress on the insulation system (Power and Society, 2005).
Usually automatic voltage regulator controls overvoltage conditions of a generator that may be caused by the recurrence events such as islanding; however, depending on the effects of overvoltage, AVR can be defective and fails to restore the voltage to normal conditions. For this reason, to ensure system reliability and avoid major failures, the overvoltage protection function (ANSI 59) must be coordinated with the AVR (Baracho *et al.*, 2021).

2.5 Under voltage conditions of a generator system

The generator will be subjected to under-voltage conditions when more loads are connected on to grid system or generator speed is reduced due to other recurrence events. Typically, the generators are designed to operate at a minimum voltage of 95% of its rated voltage. Operation below 95% may result in undesirable effects such as reduction in stability limit and import of excessive reactive power from the grid (Das, 2018). Similarly to overvoltage conditions, AVR controls generator voltage but may fail to restores the normal conditions if the effects of under voltage conditions are extreme and complex. For this reason, to ensure system reliability and avoid major failures, the overvoltage protection function (ANSI 27) of a generator must be deployed with the AVR to clear under voltage conditions.

2.6 Review overview of volts per hertz, over and under voltage protection schemes

An investigation of the activation of a synchronous generator's volts/hertz and over-excitation limiters was presented by (Piardi et al., 2013). The synchronous generator may operate with a field current that is greater than its nominal value under specific conditions, such as voltage sags or system islanding, according to the author. However, to protect the generator structure, particularly the field winding, from eddy current and overheating, volts per hertz limiters or over excitation limiters must be added to the excitation system, as shown in Figure 2.4.

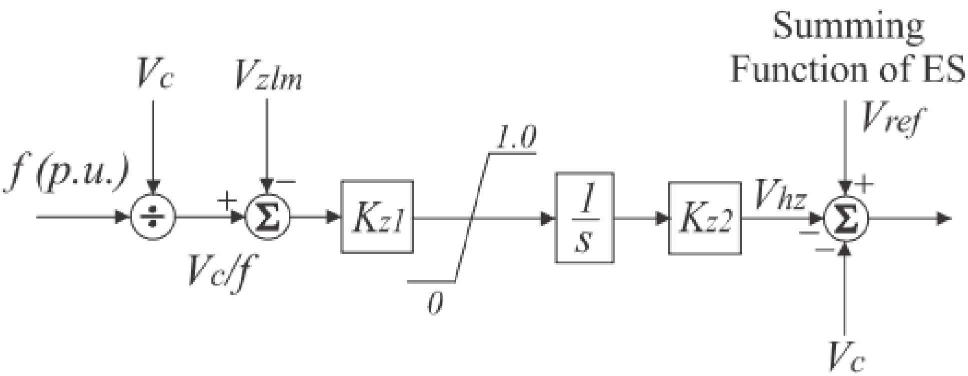


Figure 2.4: Dynamic Model of an Over-excitation Limiter(Piardi *et al.*, 2013)

The results of a study on the coordination tuning of a generator's V/Hz limit and over-excitation prevention were provided by Liu and Song (2014). According to the author, over-excitation prevention should not activate before the V/Hz limit function. In the event that the V/Hz limit is unable to sufficiently control the flux rise, over-excitation protection will kick in to safeguard the generator.

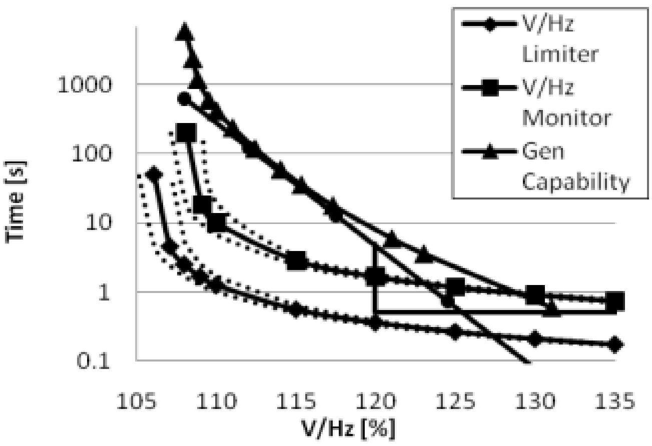


Figure 2.5: V/Hz Limiter, generator capability and protection settings(Kharel *et al.*, 2010)

The challenges in synchronizing the settings for the over-excitation limiters and monitors on generator automated voltage regulators (AVR) and the volts per hertz protective relay were summarized in (Kharel et al., 2010). The author also warns that exceeding the generator's V/Hz limitation may result in the device suffering irreparable harm in circumstances where volts per hertz limiters and protective settings were inappropriate for a particular machine.

An example of V/Hz setup for a real application is shown in Figure 2.5. The synchronous machine capabilities are demonstrated against the AVR limiter, monitor, and 24 protection settings.

A paper on improving the voltage stability of power networks using recent developments in excitation limiters was presented by (Shimomura et al., 2001). The author discovered that an over-excitation limiter allows a generator to supply reactive power up to its maximum limitation, improving voltage stability of a power system by allowing the full range of a generator's reactive power supplying ability to be utilized. It also prevents the generator field winding from overheating.

(Alves and Aur, 2010) update the theories surrounding over-excitation relaying in synchronous generators for hydro power plants and how it works in conjunction with the automatic voltage regulator's V/Hz limiter as well as the ANSI 24 protection mechanism. By adjusting the maximum permitted generator voltage set point in accordance with the actual frequency, the author claims that the V/Hz limiter of an AVR is used to prevent the operation of the electrical equipment in a power plant (generator, step-up transformer, auxiliary transformers, and systems) in a condition of excessive flux.

The author therefore presented his conclusions as follows:

- To prevent both damage to electrical equipment and inappropriate tripping, AVRV/Hzlimiter and the over-excitation must coordinate. To do this, equipment capability curves must be accessible and placed on a single basis together with the planned AVR V/Hz limiter and relay characteristic curve restrictions.

- The generator voltage should be able to reach its rated maximum value with the AVR V/Hz limiter settings in place. To prevent the unit from being tripped inadvertently, a security margin from the overexcitationprotection limit should be imposed. At least 2% less than the initial ANSI 24 relay pick up is a suggested value.
- It is necessary to adopt the restriction of the equipment that is the most restricting when setting up an overexcitation safeguard. Additionally, it is favored to permit It is necessary to adopt the restriction of the equipment that is the most restricting when setting up an overexcitation protection. To maintain at least 2% of the most restriction while allowing measurements errors and practical value is a security factor.
- The unit's operational flexibility and customer or system operator requests would also have an impact on the modifications. In this instance, the relay selection could limit or expand the available alternatives for the setting.

All large generators will now have V/Hz limiters, according to (Group and Committee, 1995). Though settings as low as 1.05 per unit have been seen, the committee stated that these limiters are normally adjusted to maintain a voltage to frequency ratio of 1.1 per unit. When this happens, overvoltage limiters, V/Hz relays, and V/Hz limiters commonly used in conjunction with each other interact with each other. These devices are often configured in a way that the most stringent limiting device always operates first, followed by the other limiter. Unless the limiters malfunction and damage to the generator is about to occur, the relays do not turn on.

(Murdoch *et al.*, 2000) described was the V/hz limiter's test procedure. According to the author, over-excitation limiters in the GE EX2000 implementation are always open loop during normal operation, so it's crucial to coordinate any testing of the V/Hz limiter with unit protection methods. Frequency response techniques can be used to test the loops' small signal dynamics in a very secure and reliable way.

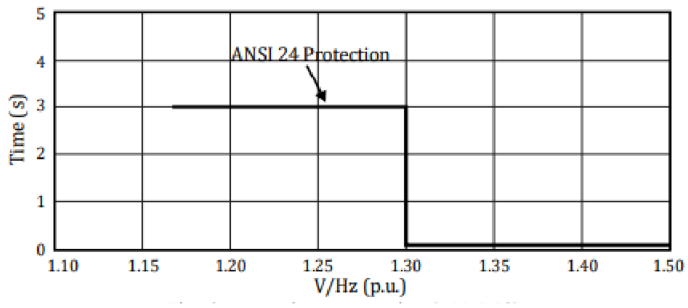


Figure 2.6: Overvoltage protection (ANSI 59)(Baracho et al., 2021)

(Baracho *et al.*, 2021) performed a test-bed for protection Studies of synchronous generators and it's Interaction with V/Hz Limiter, and over excitation, Overvoltage, and under frequency protections. The author applied the methodology to test the overvoltage protection element (59) for Synchronous Generator (SG). The author also presented the results of the relay s response in Figure 2.6. Figure 2.6 also shows the settings for the ANSI 59 protection used in the test's case study. In this instance, the first stage pickup of the 59 protection is set at 1.17pu with a fixed time of 3 seconds. At 1.30pu, the second stage begins with a defined time of 0.3 seconds.

(Torres, Jacome, and Henville, 2008) outlines a methodology for setting overvoltage relays while taking into account the overvoltage protection as a system protection rather than a local protection. He outlined that the following considerations should be made when determining the pickup and delay parameters of an overvoltage relay:

- Effect of Ferranti
- Reset ratio of the measuring device (depending on the type of relay used)
- Coordinating with the equipment's capability and system voltage control

In their article "Designed and Implementation of high speed FPGA for under and Over Voltage Relay," (Venkateshmurthy and Nataraj, 2017) offered a system that will be created based on the field programmable array for over and under voltage protection relay.

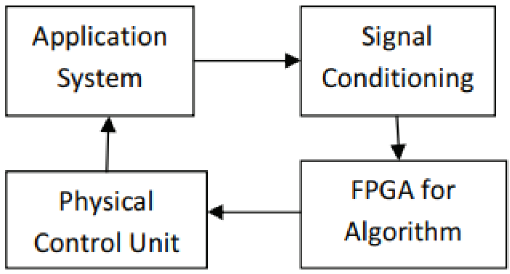


Figure 2.7: Top Level Block diagram for FPGA based control system (Venkateshmurthy and Nataraj, 2017).

The signal conditioning system is connected to the application unit or system that requires over and under voltage protection schemes in order to generate the necessary digital signal for Field Programmable Gate Array (FPGA) processing, as can be observed from the block diagram in Figure 2.7.

(Tsimtsios, Patsidis, and Nikolaidis, 2020) established an under voltage protection mechanism that meets with the most recent low-voltage-ride-through regulations for distributed generators connected to distribution networks. The simulation findings revealed to the author that the safety function allows for low voltage rides past voltage level criteria while preventing generator units from overly energizing the network.

In order to prevent important loads from tripping due to voltage sags, (Chen et al., 2008) proposed the design of under voltage relay settings for an industrial plant with cogeneration units. The influence of voltage sag on the important loads can be reduced, the author found, by turning on the under voltage relay in time to isolate the subsystem for islanding operation.

An under and over voltage relay, which is a component of an electric power system intended for constant voltage operation, was used and certain research were provided in (Sengül, Oztürk, and Yörükeren, 2003). The authors advise making sure that the relay does not work when there are brief voltage depressions to reduce the likelihood of an unintended trip.

2.7 The Review of the existing papers on volts per hertz, over and under voltage protection schemes

The review of the existing papers was carried out using the following criteria.

- Aim of the paper
- Method of protection
- Hardware or software used
- Findings

Table 2.1: Analysis of various papers on generator system

Paper	Aim	Method of protection	Used software/hardware	Findings
(A.B Piardi and J.R Pesente ,2013)	To assess over-excitation limiters and volts per hertz under an unbalanced load.	Volts per hertz limiters and over excitation limiters	Automatic Transient Program	Results show that the unbalance condition, linked to improper voltage transducer specification, may significantly affect the activation of these limiters.
(P.C Won and B.W Hyeon 2011)	Relaying for over-excitation to protect digital generators.	Volts per hertz relay and excitation limiters	Electro-Magnetic Transient Program	A gain compensation technique based on DFT and over-excitation was used.
(G liu and W Song 2014)	For the security of digital generators, use over-excitation relaying.	Over excitation protection (volts per hertz)	Generator excitation regulators	Both the over-excitation protection with definite time and the over-excitation protection with inverse time are coordinated with the V/Hz limit.
(C.W Park and W.H Ban ,2012)	To study over excitation algorithm	Over excitation protection	Automatic Transient Program and Electro-Magnetic Transient Program	In the event that inverse characteristics were applied, simulation results that obtain the fastest trip were successfully completed.
(Murdoch *et al.*, 2000)	During system events, to make sure the generator runs in the overexcited zone	Over-Excitation Limiters protective limiters	Automatic Voltage Regulator and Protection Inverse Time (PRIT) module.	New excitation system was adopted.
(M.Shimomura and Y. Xia, 2001)	Utilizing new advance over excitation limiters to increase the voltage stability of the power system	Advance Over-Excitation Limiters	D-AVR	The development of an advanced over excitation limiter (OEL) allows the generator to generate reactive power up to its maximum capacity while also protecting the field winding of the generator from overheating.
(A.P Kharel and MIET,2010)	To review generation system over flux limiters and protection	Volts per Hertz limiters(24)relay	ATP	In order to increase overall system reliability, standards for the coordination of generator excitation control and protection have been devised.
(E.F Alves and M. Aurelio de souza,2010)	To evaluate synchronous generator over excitation relaying for hydro power plants	Volts per hertz protection and Over-Excitation Limiters	Automatic Voltage Regulator	The capability of the relevant equipment and potential relay settings were taken into account when proposing new settings for the ANSI 24 relaying.

(A Murdoch and R.W Delmerico,2000)	Excitation system protective limiters	Over-Excitation Limiters Volts per Hertz limiters	Field Current Regulator	The limiter algorithm design has demonstrated that we may work toward the objective of having quick, stable limiters while maximizing the use of the entire spectrum of permissible operation.
(IEEE Task force ,1995)	To recommend models for over excitation limit device	Over Voltage Limiters, Volts per Hertz limiters Over-Excitation Limiters	Volts per Hertz limiter model Over-Excitation Limiters Model	Large-scale system stability analyses based on actual excitation system components have been produced.
(C.A Allen and R.F Martinez ,2000)	To verify test results of a new digital excitation system	Volts per hertz limiters	Test were conducted in Carolina plant in one of their generator	Results show how the excitation system performs dynamically.
(Baracho *et al.*, 2021)	Analyze how the Volts/Hertz limiter, over excitation, overvoltage, and under frequency safeguards of the synchronous generator interact with one another	over excitation protection (ANSI 24), overvoltage protection (ANSI 59), synchronous generator, under frequency protection (ANSI 81U), Volts/Hz limiter	RSCAD	Specifically in the applications of power utilities and industries, the coordination and selectivity of the control and protection systems of large generators can be increased.
(Torres, Jacome and Henville, 2008)	To configure Overvoltage relays treating the overvoltage protection as a system protection more than a local protection.	Overvoltage relay	Simulation program	The suggested method reduces transient overvoltage conditions
(Venkateshmurthy and Nataraj, 2017)	To create and implement an under and over voltage relay using a high-speed FPGA.	Overvoltage and under voltage relay	FPGA	By offering them effective and increased protection against over/under voltage loss, the suggested FPGA-based system will be offering a final answer to the current power system-based application.
(Tsimtsios, Patsidis and Nikolaidis, 2020)	To implement an under voltage safety feature for connected distribution networks' distributed generators	Under voltage protective function	MATLAB/Simulink	The protective function, however, prevents the DG unit from overly electrifying the network and gives flexibility to satisfy the LVRT criteria.
(Chen *et al.*, 2008)	To avoid essential loads from tripping due to voltage sag in an industrial plant with cogeneration units, under voltage relay settings must be designed.	Under voltage relay	Matlab	The impact of voltage sag on the important loads can be reduced by turning on the under voltage relay in time to isolate the subsystem for islanding operation.
(Sengül, Oztürk and Yörükeren, 2003)	To derive the characteristic curves	Under and over voltage relay(ABB)	Artificial neural networks	Modeling the system with an artificial neural network

	and model of an under/overvoltage relay using neural networks			system is simple and effective.
(Amreiz, Janbey and Darwish, 2022)	to study the operation of over voltage relay using High Voltage Transmission Line Analyzer	Overcurrent and overvoltage relay	HVAC transmission line emulator	Simulation results shows that the addition of over-voltage relay protected the transmission lines from faults

2.8 Hardware in the loop simulation using RTDS and IEDs

Control systems needed to operate complicated equipment and systems are developed and tested using a technique called hardware-in-the-loop (HIL) simulation. The physical component of a machine or system is replaced by a simulation with HIL simulation (Kleijn, 2014). The use of hardware-in-the-loop (HIL) simulation in the domains of power electronics and power systems is expanding rapidly. With HIL simulations, an innovative device' prototype can be tested repeatedly, safely, and affordably in a virtual environment under a variety of realistic situations. (2008) Ren, Steurer, and Baldwin

The practical applications of the simulator for the various stages of power system design, testing, and implementation were outlined in (Forsyth, Maguire, and Kuffel, 2004). The Real Time Digital Simulator (RTDS), according to the authors, enables developers to precisely and effectively mimic electrical power systems and their ideas for enhancing them. The real-time RTDS Simulator enables testing of physical protection and control equipment in addition to power system modeling. He came to the conclusion that real-time digital simulation is a relatively new technology that combines the continuous real-time responsiveness of old analogue models with the adaptability and precision of modem computer simulation techniques.

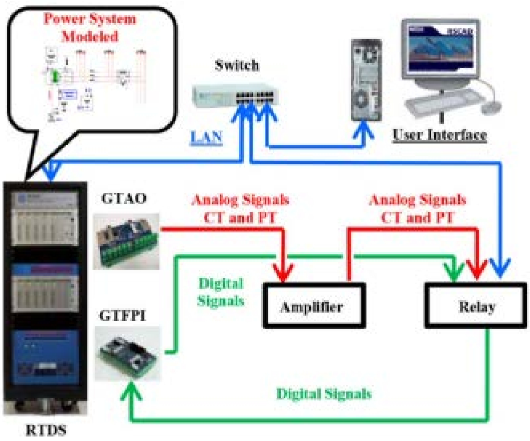


Figure 2.8: Hardware in the loop in the RTDS(Coelho *et al.*, 2015)

As shown in Figure 2.8, HIL tests with a physical numeric relay in a closed loop are used to assess the synchronization between the protective functions and the AVR limiters. As an illustration The power system transducers CTs and PTs (current and potential transformers) typically create secondary voltage and current signals, which are simulated in RSCAD and delivered to RTDS digital-to-analog (D/A) converters. These signals are taken out for the relay using the GTAO card (Analogue Output Card). Then, to accurately replicate the simulated PT and CT signals to the relay, these low-level signals (10 volts alternating current) are delivered to an amplifier

(3x250V - 3x25A). The relay responds to the secondary signals produced by the simulated system as a result. In the event of a fault, the relay trips the simulated circuit breakers in the RSCAD-modeled power system, stopping the fault's propagation. Through digital-input ports enabled by the GTFPI card (Front Panel Interface Card), trip signals from the relay are interfaced to the RTDS (Coelho, Silveira and Baracho, 2018).

To ensure the reliability of superconducting power applications, (Higashikawa et al., 2016) suggested employing hardware-in-the-loop (HIL) simulation as a technique to get around the difficulty of revealing fault conditions in actual power systems. The author claims that by using a small-scale superconducting device and accounting for its real-time reaction, we may simulate the behavior of a real-scale power system using real-time digital simulators and superconducting hardware (RTDS).

2.9 Review overview simulation using HIL Simulation for a generator system

A paper on a model for testing and modeling some synchronous generator protection features, with a focus on how they work in conjunction with the AVR excitation limiters, is presented by Coelho, Silveira, and Baracho (2018). For this, the analysis of such protective functions and the excitation limiters of the excitation system model are added to the generator test system built in a Real-Time Digital Simulator (RTDS). In order to test and evaluate several protection schemes, including ANSI 21 (generator backup distance protection), ANSI 24 (volts per hertz protection), ANSI 27 (under voltage protection), ANSI 59 (overvoltage protection), and ANSI 81, the authors then implemented a hardware-in-the-loop (HIL) using a commercial generator (under frequency and over frequency protection)

In a report that the author delivered, (F. Krutemela, 1993) covered the test results of a combined start-up and excitation control unit for gas and steam power using hardware in the loop simulation. The coupling algorithm used by the author was Newton-Raphson iteration, and the HIL test results largely indicate that the application software for the open and closed loop control functions is error-free and reliable.

(Almas, Vanfretti, and Vanfretti, 2014) provided the procedures and findings for the HIL and RT simulations of the excitation control system experimental performance evaluation. The ability of ABB's unit control 1020 excitation control system to control voltage as well as improve performance was also evaluated by the writers.

(Adewole and Tzoneva, 2015) published a paper on proposed generator-derived VS indices that were evaluated using an RSCAD-modeled 39-bus benchmark test system. The Real-Time Digital Simulator and a lab-scale test bed, real-time hardware-in-the-loop simulations (RTDS) methods were utilized by the authors. One case study taken into consideration was the combination of load rise, long-term dynamics of transformer ULTC action, and the operation of generator Over Excitation Limiters (OELs). Different operating situations were simulated utilizing the lab-scale test bed.

(Paulo, Goldemberg, and Pellini, 2006) used a real-time digital simulator to test hydro-generator static excitation systems using a hardware-in-the-loop methodology. For testing, troubleshooting, and pre-commissioning generator excitation systems, the real-time simulator is a helpful tool. For low power applications, (Karthikeyan et al., 2011) developed a hybrid, open-loop exciter for the induction generator driven by a wind turbine. This hybrid exciter automatically adjusts to variations in the generator's load or rotor speed while keeping the voltage and frequency at the load terminals almost constant.

The study to assess the Loss-of-Excitation (LOE) protection of synchronous generators using a Real Time Digital Simulator was produced by (Coelho et al., 2015). (RTDS). A numerical relay is used in the simulation's Hardware-In-The-Loop testing to gauge the under-excited generator's response.

In order to provide a test-bed for protection studies of synchronous generators and their interactions with V/Hz limiters, as well as overexcitation, overvoltage, and underfrequency protective functions, (Baracho et al., 2021) used hardware in the loop and real-time digital simulation. (2014) M.E. Iranian Static exciter systems (SES) can receive real-time digital and analog signals from the implemented HIL simulator, which also simulates the mechanical and electrical parts in a closed-loop.

2.10 The Review of the existing papers on HIL, RTDS and IEDs for a generator system

The review of the existing papers was carried out using the following criteria.

- Aim of the paper
- Method of protection
- Hardware or software used
- Findings

Table 2.2: Review overview of HIL and RTDS simulation using IEDs

Paper	Aim	Method used	protection	Used software/hardware	findings
(Coelho, Silveira and Baracho, 2018)	ANSI 21, 24, 27, 40, 59, and 81 protection methods will be tested and evaluated in a lab setting by using a (HIL) simulation during under-excited and overexcited events	Hardware in the loop simulation	Volts per hertz relay Over frequency relay	Real-time Digital Simulator, RSCAD	By properly protecting the machine with its limiters and corresponding protective features, the power system's security was increased and it was prevented from being destroyed.
(Almas, Vanfretti and Vanfretti, 2014)	Real-time hardware-in-the-loop simulation of an excitation control system will be used.	Hardware In the loop	ABB	Mat lab /Simulink	Inter-area oscillations are adequately dampened by the Real Time-HIL results.
(Adewole and Tzoneva, 2015	To evaluate the suggested VS indices under a range of plausible contingency scenarios, including higher system loads,	Hardware in the loop	generator Over Excitation Limiters	RTDS RSCAD and DIGsilent power factory	The VS indices are helpful when creating System Integrity Protection Schemes (SIPS), which can maintain the grid's integrity during shocks and parametric changes, preventing system blackouts.
(F. Krutemela, 1993)	To test a combined start-up and excitation control unit using a digital real-time simulator	open and closed loop control function	Siemens	test simulator	Essentially error-free, stable application software for the open and closed loop control function is the end result of this hardware-in-the-loop test.
(Soundararajan and Verma, 1991)	To perfom Real-Time Test for Microcomputer Based Digital Differential Relaying for Generator Protection	Hardware in the loop simulation.	Differential Relaying for Generator Protection	Real-time Digital Simulator	A successful digital differential relaying system based on a 16-bit microprocessor was created to protect generator windings.
(Karthikeyan *et al.*, 2011)	To study A wind turbine-driven induction generator with a hybrid, open-loop exciter for low power applications.	Open loop exciter	Excitation limiters	Mat lab	Results from simulations and laboratory tests show that the dynamic reactive power compensation of the generator is inherent in the proposed open-loop system

(M.E. Iranian, 2014)	To provide static exciter systems (SES) with real-time digital and analog signals and to simulate the mechanical and electrical parts in a closed-loop	Hardware-in-the-loop Closed loop	IED device Alstom (P847	Real time subsystem	Engineers can study the dynamic performance of static exciters and investigate their inherent constraints and features in a safe environment thanks to the HIL simulator.
(Paulo, Goldemberg and Pellini, 2006)	To design a hardware-in-the-loop real-time digital simulator for evaluating hydro-generator static excitation systems	Hardware in the loop simulation	Over excitation limiters, under excitation limiters	Real time simulators	A useful tool for testing, troubleshooting, and pre-commissioning generator excitation systems is the real-time simulator that was created.
(Coelho *et al.*, 2014)	Employing a real-time digital simulator to assess synchronous generators' Loss-of-Excitation (LOE) protection (RTDS)	Hardware-in-the-loop	Over excited limiters and under excited limiters	Real time digital simulators	In addition to examining the dynamics of the power system, the research analyzes real-time performance of a real protection device utilizing Hardware-In-The-Loop testing techniques.
(Naveen and Jena, 2020)	To find optimal settings of directional overcurrent relays by minimizing operating times of both primary and backup relays.	HIL	Directional overcurrent relays	Real time digital simulator	simulation and hardware results show that the proposed scheme has ability to mitigate miscoordination of DOCRs and provides adequate protection to microgrid in all operating state
(Baracho *et al.*, 2022)	To co-ordinate studies between Volts/Hertz limiter with over-excitation, overvoltage, and under-frequency protections of synchronous generators.	Hardware-in-the-loop	Volts/Hertz limiter with over-excitation, overvoltage, and under-frequency protections	Real Time digital simulator	Different scenario were simulated using HIL and RTDS and the simulation results were presented

2.11 Conclusion

The literature review analyses the various method used for generator protection. Digital algorithms for generator protection schemes in terms of speed, stability, security and dependability have placed a considerable burden and responsibility among protection. This chapter focused on methods and techniques used in existing paper tackle generator disturbances conditions such as over excitation, overvoltage and under voltage. The review also focuses Hardware-in-the-loop simulation using Real Time Digital Simulator (RTDS). Various scenarios have been developed by various researchers and those scenarios are evaluated. The research review on a simple back up overcurrent protection scheme of a generator is not active enough, This project has been reported on the development of Volts per hertz protection algorithms that prevent it from over-excitation condition of a generator.

Chapter three presents the theatrical aspect of generator protection schemes.

CHAPTER THREE

THEORECAL ASPECT OF GENERATOR PROTECTION SCHEME

3.1 Introduction

Generators are frequently the most vital electrical apparatus in any power plant. Actually, these generators form a unique class of power network equipment which are quite expensive. Given the prohibited cost of replacing them, the generator prominent cost goes into giving the greatest degree of protection inclusion. The importance of these protection system is to reduce the likelihood of physical harm to the equipment resulted from a fault in any part of the system, or from abnormal operation of the equipment (i.e. over-voltage, over and under-frequency, under-voltage, etc.). (I. Kerszenbaum and G. Klempner, 2008)

In addition , a very fast and reliable protection scheme must be given to activities that are too far to be reached that are usually not in other types of equipment i.e. Over-voltage, over-excitation, under-frequency or speed range, etc. (Halpin, 2001) The generator protection function should cut off the protected device before broad harm or damage occurs.

This chapter discusses a generator theory of the power system network. Additionally, it includes brief explanations of the current generator protection systems' functionality. In 3.2, various generator protection schemes method is explained and 3.3 give the conclusion of the chapter as presented in Figure 3.0.

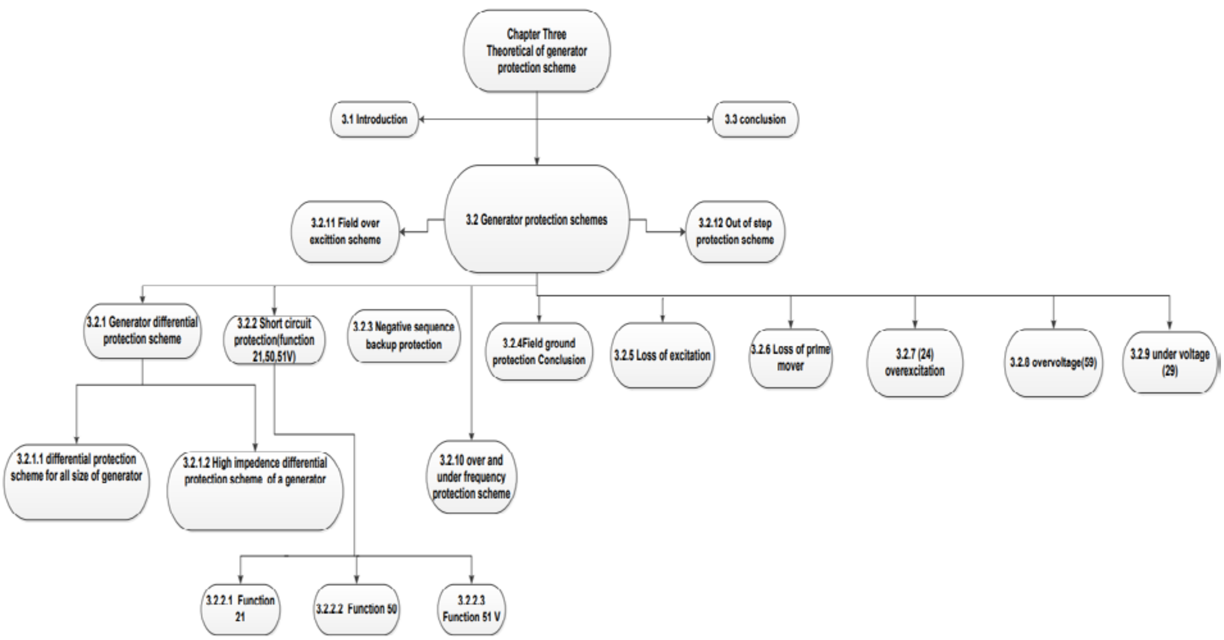


Figure 3.0: the summary of the content covered in chapter three

3.2 Generator Protection schemes

Traditionally, generators were monitored by utilizing electro-mechanical and static component relays. Currently, protection of generator units as well as replacements of out-dated component relays is performed using newly advance multifunction numerical generator devices.

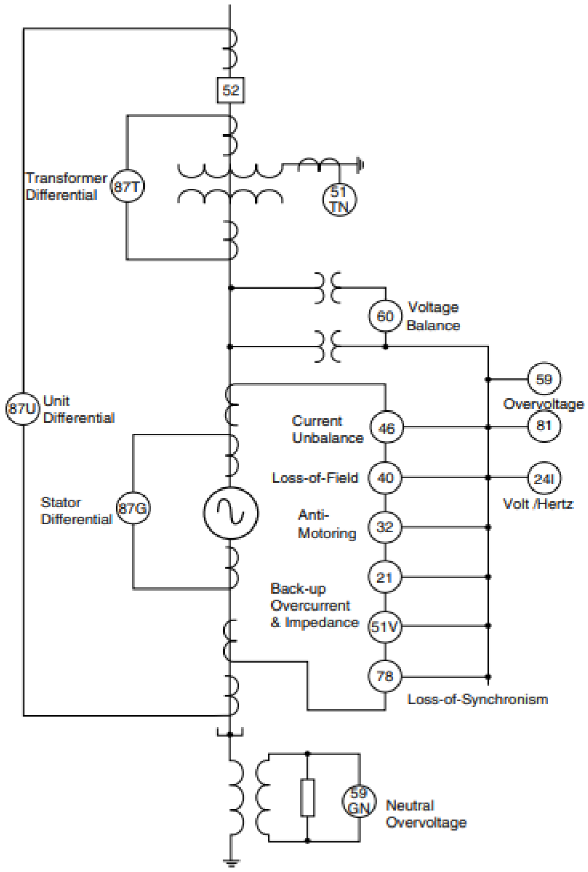


Figure 3.1: Generator protection scheme(Leonard L. Grigsby, 2007)

There are various protection scheme designed for generators. Figure 3.1 above illustrates a single line diagram of one numerical generator multifunction relay with numerous protection functions. The next section provides brief description of the most commonly utilized protection functions of a generator.

3.2.1 Generator differential protection scheme (87)

The protective function's (87) core basic structure consists of comparing two normally equal flows of current from the same phase. The current discrepancies at the ends of the protected zone generate the fault current as shown in Figure 3.2 (Prévé, 2006) if the current entering the protected zone is not equal to the current exiting this zone. Differential protection schemes can be applied in a variety of ways.

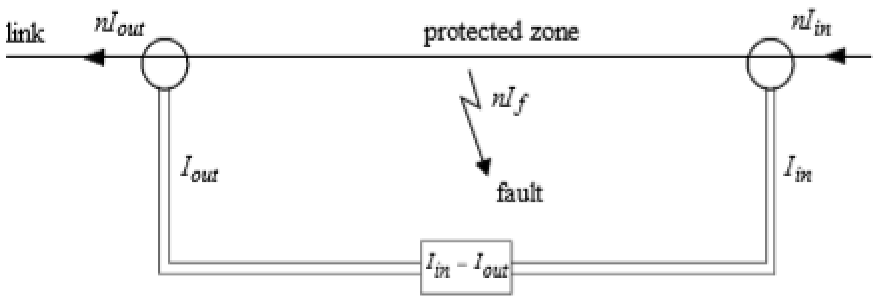


Figure 3.2: A Typical differential protection scheme diagram(Prévé, 2006)

3.2.1.1 Differential protection for all size of generator

This method is broadly utilised to give a high-speed and very responsive protection to the generator. The differential protective devices are connected to two sets of Current Transformers (CT); one set in the neutral leads, the other in the line side generators with associated breakers, the line-side current transformers are normally connected to the circuit breaker. This method is highly recommended to allow the utilization of differential protective devices with very low percentage characteristics.(Blackburn JL and Domin JT, 2006).

Figure 3.3 illustrates the typical differential protection scheme connection for a star connected generator. This method is likewise utilized for winding protection.

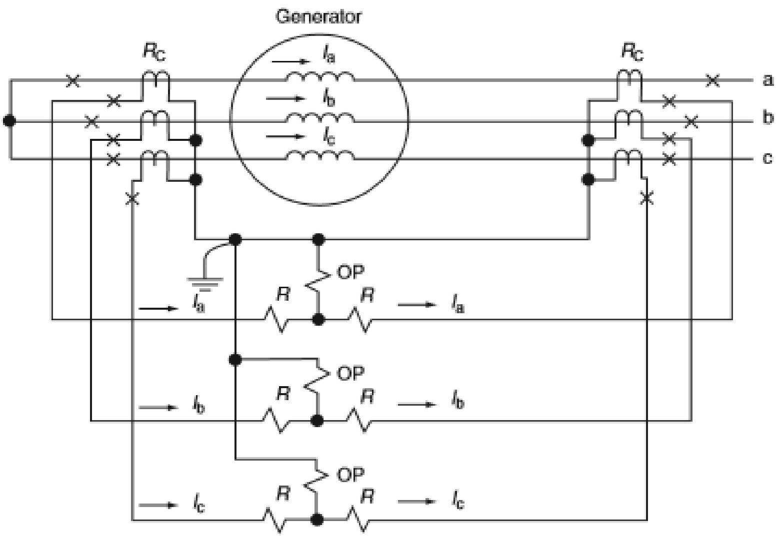


Figure 3.3: A typical differential scheme connection(Blackburn JL and Domin JT, 2006)

3.2.1.2 High impedance differential protection scheme of generator.

This method can be put in application as an alternative to the current-differential type. In this methodology, protective devices are connected between phase and neutral leads of the paralleled current transformers. For external faults, the voltage across the relay will be relatively small due to the current that flows between the low current transformers whereas for the internal faults the fault currents must flow past exciting branch and high-impedance function of each current transformer, so that the current transformers are saturated for most faults, generating high voltage to operate the relay(Blackburn JL and Domin JT, 2006).

3.2.2 Short-Circuit Protection (Functions 21, 50, 51V,)

Figure 3.3 present a typical system backup protection. These functions must provide protection for both phase faults and ground faults. These devices are utilised to secure generator resistant to short-circuits that are either inside or outside the generator or alternator windings(I. Kerszenbaum and G. Klempner, 2008)

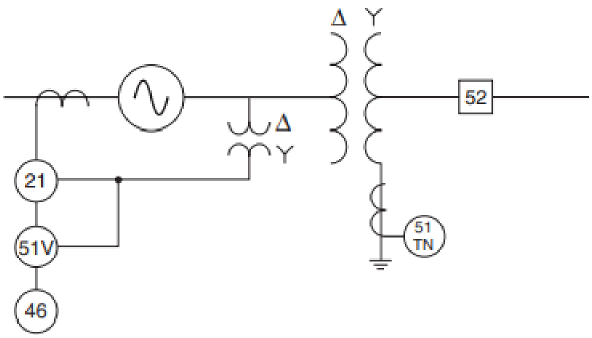


Figure 3.3: Backup protection basic scheme(Leonard L. Grigsby, 2007)

3.2.2.1 21V function

The phase distance back up protection (21) is usually found on large generators to provide phase to phase as well as three phase fault protection. In this method of protection Zone 1 of function 21 is configured with generator impedance with additional 50% of the generator winding impedance, with no appreciable time delay. Zone 2 is configured to give lengthy time delay for breaker failure backup protection (Das, 2018).

3.2.2.2 51V function

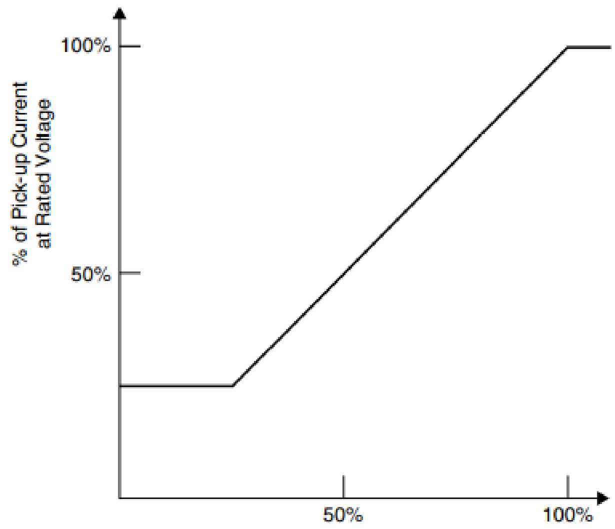


Figure 3.4: Voltage restraint overcurrent relay(Leonard L. Grigsby, 2007)

The backup protection of the generator is guaranteed by voltage-controlled (51C) and voltage-restrained protection (51V) systems. According to Figure 3.4, the voltage restraint overcurrent element will have its pick-up current decreased in a proportional manner to the voltage reduction, and the voltage controlled overcurrent relay will block the overcurrent element unless the voltage drops below a certain value (Leonard L. Grigsby, 2007). If a system fault has not been resolved by any other functions after an appropriate amount of time has passed, it disconnects the unit from the system. This method of protection likewise ensures the system parts against excessive harm and keeps generator and its auxiliaries from surpassing their thermal constraint. However this method should be coordinated in a way that it cannot usually operate because generator's other protective functions should take care of faults (Das, 2018).

3.2.2.3 Time Overcurrent function

This protection is used detect single-phase, two-phase or three-phase over-currents. The protective function will operate when one, two or three of the currents exceeded pick-up current. This protection can be time delayed and in this case will only be activated if the current monitored rises above the setting threshold for a period of time at least equal to the time delay selected. This delay can be an independent (definite) time or inverse time delays (Preve C, 2006).

3.2.3 Negative-Sequence Current Backup Protection

Negative-sequence protection scheme has been utilized for quite some years. Traditionally, the system was using electro-mechanical relays to protect the generator against negative sequence during unbalance loading conditions as well as system faults which were later replaced by newly advance multifunction numerical relays. These relays provide a very rapid clearance in the presence of current faults(Ibrahim, 2011).

3.2.4 Field-Ground Protection (64)

This method of protection scheme is applied to monitor the generator against earth faults occurring in various locations in a generator. These earth faults can generate a current that is high enough to cause severe harm on the rotor and other components of generator such as exciter. These protection schemes make use of voltage divider across exciter and a sensitive DC type relay across the bridge and ground. This arrangement is very important because whenever there is a ground fault in the field of exciter, a voltage appears across the relay to produce the operation.

3.2.5 Loss of excitation (40)

The generator will be subjected to loss of excitation under the following conditions:(Leonard L. Grigsby, 2007)

- The real power of the generator will remain nearly constant for the following seconds after the field supply is cut off. The generator output voltage gradually decreases as the excitation voltage diminishes. The current increases about at the same rate as the voltage decreases to make up for it.

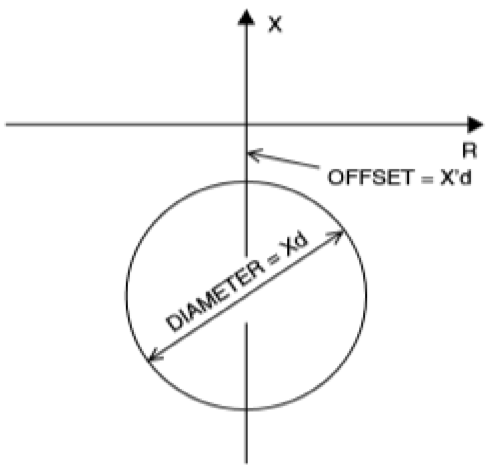


Figure 3.5: A typical mho relay characteristics (Leonard L. Grigsby, 2007)

- The generator will then start to absorb increasingly negative reactive power as it becomes underexcited.

- The generator positive sequence impedance as measured at its terminals will enter the impedance plane in the second quadrant because the generator voltage over current ratio gets lower and smaller as the phase current overtakes the phase voltage.

However, a generator's loss of excitation is detected and prevented by the Loss of Excitation (40) Protection Scheme. As shown in Figure 3.5, this protective mechanism used the mho offset relay approach to monitor the generator against loss of excitations. This technique uses the voltages and currents at the generator terminals and is often coupled to a time relay.

3.2.6 Loss of prime mover (32)

This method of protection scheme is put into application whenever the prime mover supply is detached while the generator is connected to power network, the power system will drive the unit as asynchronous motor. This is very critical for steam and hydro units since it can lead to over-heating and potential harm to the turbine and turbine blades. Therefore this method provides a very sensitive relay to respond to this kind of situation.

3.2.7 (24) Over-excitation Protection

There are various situations that can develop into over-excitation conditions in generators. One of the major causes of over-excitation is operation at reduced voltage under regulator control at reduced frequencies during start-up or shutdown. And whenever this happens, the ratio of volts per hertz can be easily exceeded resulting in possible damage.

Furthermore generators must not be liable to over-voltage with the exception of short or transient excursions. With usual activity near the knee of core saturation curve, the extreme flux densities as well as abnormal flux patterns are generated inside the generators due to little over-voltages resulted from large amount exciting currents. These can cause extreme and broad harm. The field excitation current, at rated output, is higher than that required at no-load, so it is essential to decrease the excitation correspondingly as load is reduced. Regularly, this is practiced by the managing system(Blackburn JL and Domin JT, 2006).

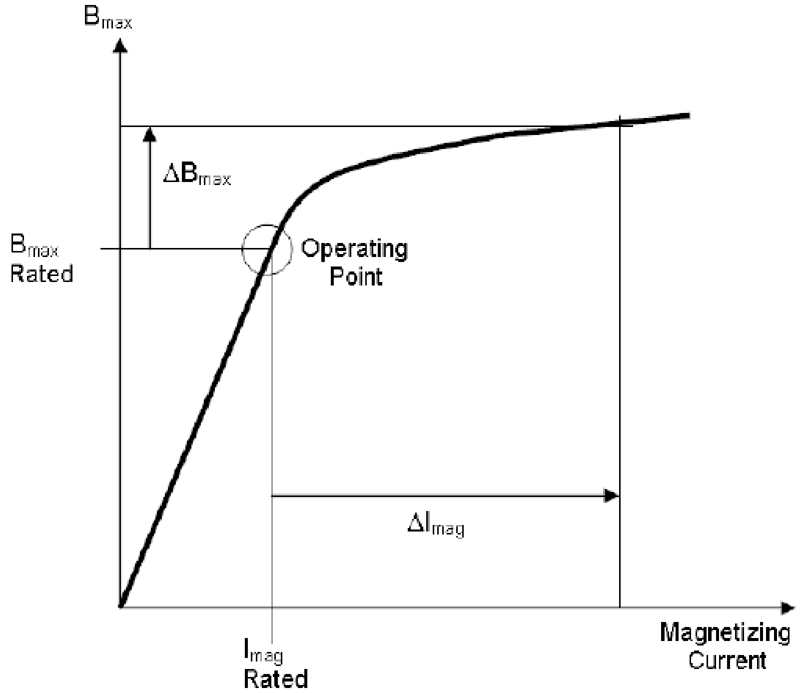


Figure 3.6: A typical saturated curve (I. Kerszenbaum and G. Klempner, 2008)

At the point when over-excitation condition takes place, the generator core becomes saturated beyond its designation, this causes stray fluxes to be generated in the non-laminated parts resulting in dielectric and thermal damage in generator. In generators the operating point of voltage at a rated frequency and flux should always be below the knee of saturation point as appears in figure 3.6 (I. Kerszenbaum and G. Klempner, 2008).

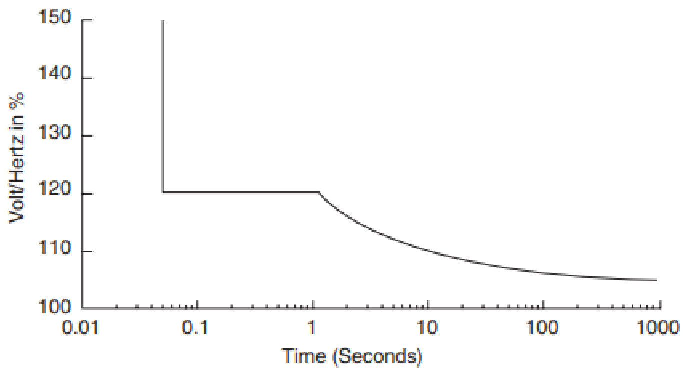


Figure 3.7: Combined definite and inverse characteristics(Leonard L. Grigsby, 2007)

Volts per hertz (24) can provide generator over-excitation protection. Figure 3.7 present the combined definite and inverse characteristics curve of volts per hertz protection scheme. The generator protection relays offer the following types of characteristics for the volts-per-hertz protection element:

- Determined-time function.
- Definite time characteristic with two levels.

- Inverse time feature.
- Definite-time and inverse-time properties combined.

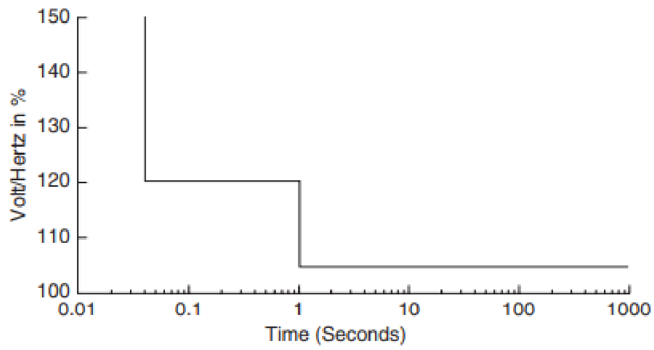


Figure 3.8: Dual level characteristics(Leonard L. Grigsby, 2007)

Figure 3.8 depicts a typical dual definite-time feature. The ability to sense voltage magnitude and frequency over a wide variety of frequencies is one of the main requirements for a ANSI 24 element volts per hertz relay.

3.2.8 Over-voltage (59)

Figure 3.9 shows a typical overvoltage and under voltage protection scheme of a generator.

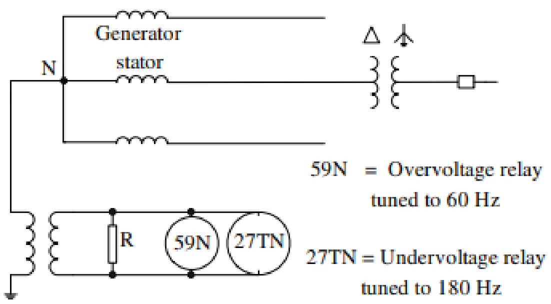


Figure 3.9: Over and under voltage protection scheme(Ibrahim, 2011)

Over-voltage protection scheme of a generator is put in application to monitor over-voltage resulted from sudden loss of load.(59) function also monitors over-voltages due to excessive exciting current during operations in close to the knee saturation curve. Over-voltage relays are likewise utilized used as backup to function 24 during typical operation of the machine (I. Kerszenbaum and G. Klempner, 2008).

3.2.9 Under-voltage (27)

Generators will be subjected to an under voltage conditions when there is a network overload, the faulty operation of a transformer tap changer and a short circuit. Under-voltage protection scheme of generators is utilized to monitor the operations of voltage regulators, the voltages prior the switch overs of the sources as well as monitoring the overload. The foundation principle if this method is to be activated whenever the voltage drops below threshold value.

3.2.10 Over- and Under- Frequency Protection scheme

Comparing the network frequency to a minimum and maximum threshold frequency is the fundamental basis of this technique of security methods. If the phase-to-phase voltage falls below a set threshold, the protection is disengaged. C. Preve (2006)

Over-frequency is typically the consequence of an abrupt loss offload. Over-frequency can likewise happen because of failure in generator controls or as consequence of islanding. Over-frequency operation because of excessive power in an island will not cause over-heating except if rated power and about 1.05pu voltage are surpassed.(Blackburn and Domin, 2006) Under- and over-frequency relays are installed to give backup for generator controls in case of off-frequency activities or operations due to their failures. A typical cause of off-frequency operation is boundless system unsettling influences during which different line trip-outs take place. Under and over-frequency protection will allow: (Preve C, 2006)

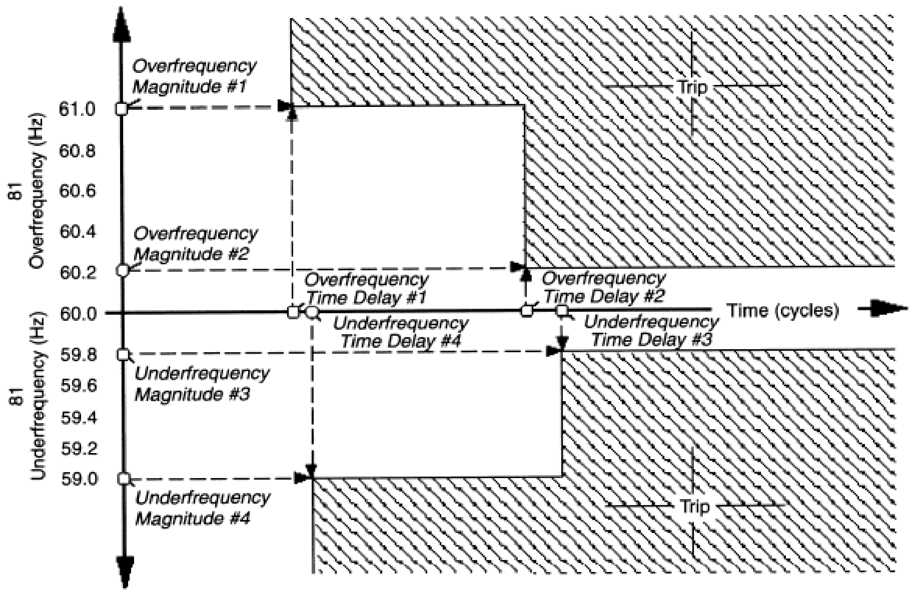


Figure 3.10: Basic over and under frequency region of operation and protective settings(I. Kerszenbaum and G. Klempner, 2008)

- In the event of an overload, the loads will be reduced by cutting the power to non-priority users.
- To solve issues with the computers' stability, the network will be split into multiple smaller networks.
- Micro-plants without synchronous control will be disconnected.

The settings of this protective relaying should be typically co-ordinated with most load shedding schemes however this ought to be examined dependent upon the situation. Figure 3.10 shows an example of over and under frequency operating ranges and protective device settings

3.2.11 Field Over-excitation protection scheme

This method of protection scheme makes use of Over- and Under-Excitation Limiters (OEL and UEL). Field over excitation is caused by small voltages that give rise to voltage controllers to support exciter voltages to high values. These limiters are arranged with inverse and fixed time characteristics. The configuration settings for these limiters ought to shield the field from harm while taking into account full utilization of wanted field capacity. OEL must be coordinated with over exaction protection scheme before it can be put into application.

3.2.12 Out of step protection scheme

The loss of synchronization can have disastrous effects in generator, with conditions such as out of step resulting in the loss of synchronisation. Traditionally the out of step condition was avoided by making use of the blockage within the transmission system , in the modern era, the numerical function distance relay detect out of step of a generator. The protective function will monitor all the system disturbances in the network. (I. Kerszenbaum and G. Klempner, 2008)

3.3 Conclusion

This chapter included a theoretical review of the various generator safety techniques, including differential protection for generators, volts per hertz, over- and under-voltage, over- and under-frequency, negative-sequence backup, field over-excitation, and out-of-step generator protection. The Implementation of differential and overcurrent protection methods using the DIgSILENT Power Factory simulation tool is covered in the following chapter.

CHAPTER FOUR

DIGSILENT IMPLEMENTATION OF DIFFENTIAL AND BACK UP OVERCURRENT PROTECTION SCHEMES FOR A GENERATOR

4.1 Introduction

Generator is one of the most critical and expensive equipment in the power system network. In fact, any fault in any part of a generator can results in severe harm to the equipment and can also results in loss of power system stability in power generation system. Therefore, protective devices that are very reliable and sensitive must be provided to monitor the generator against any system disturbances. One of the most detrimental system disturbances is internal and external faults of a generator. Generator must be cautiously monitored in order to operate safely during faults events. This condition can be detected by volts per hertz protection scheme (function 24).

Dig-Silent power factory software program is be used to conduct this simulation. The Power Factory database environment fully integrates all data for defining cases, scenarios, single line graphics, outputs, run conditions, calculation options, graphics, user defined models, etc… (DIgSILENT, 2020)

The generator current differential and overcurrent protection schemes are implemented using SEL-700 protection in the Dig-SILENT software environment. A model of the grid-network focusing on the generating system is adopted and its specifications are considered. Different types of faults are put into application in the grid-network so as to determine the configuration settings of the protective functions.

The case study involves an examination of the generator over-excitation system's overexcitation situation. Simulations of the over-excitation conditions are used to examine the effectiveness of the generator protective relaying system. As a case study, the IEEE 9-Bus Grid-network is used. The Western System Coordinating Council (WSCC) section of the system is represented by the IEEE 9-Bus test case as a comparable system with nine buses and three generators. Researchers employ IEEE sample systems to put their new ideas, developed novel algorithms and concepts into practice and test them using software tools.

This chapter presents the simulation and analysis of the current differential and overcurrent protection for the generator system. In 4.2 IEEE 9 bus system input data is presented, 4.3 analyse the load flow, 4.4 covers short circuit simulations, in 4.5, the differential protection function of a generator is analysed and the results are presented,4.6 covers overcurrent protection of a generator and 4.7 gives a conclusion as present in Figure 4.0.

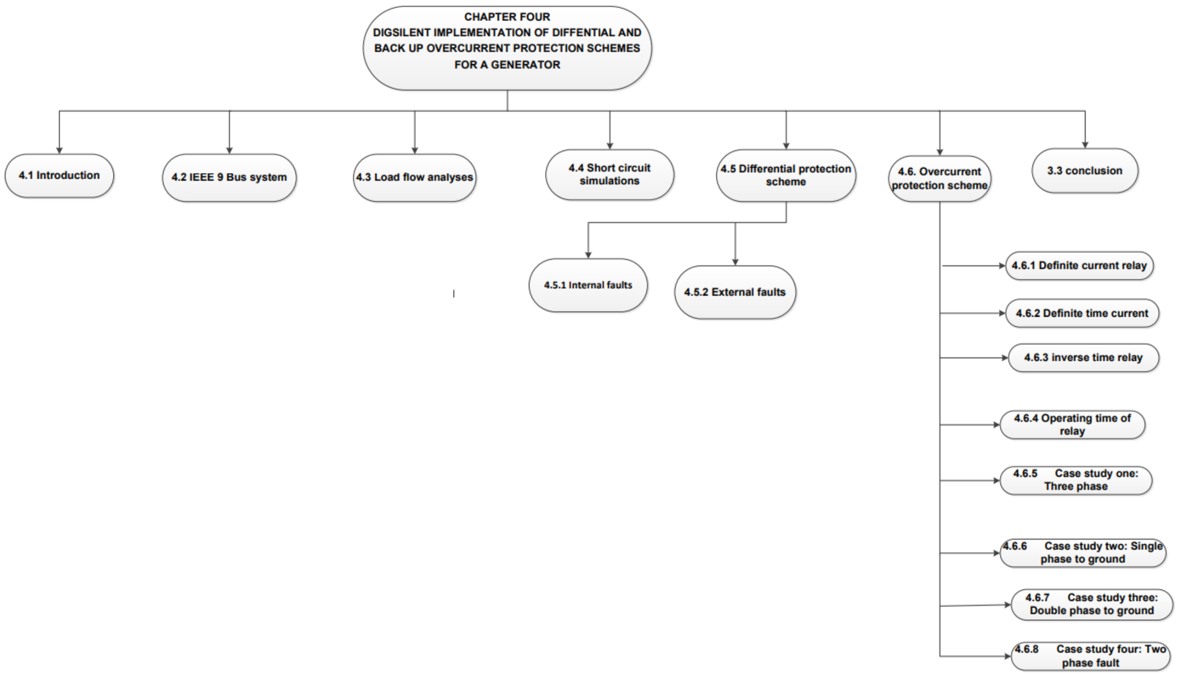


Figure 4.0: Summary of the content covered in Chapter four

Figure 4.1 presents one line diagram of the selected IEEE 9 Bus network. This technical note describes the details of the IEEE 9-bus system . The network is made up of 9 buses , 3 loads, 6 transmission lines, three two winding transformer (TF1 ,TF2 and TF3) and 3 generators as appear in Figure 4.1. the IEEE 9 Bus system single line diagram was modelled using DIgSILENT powerfactor simulation tool.

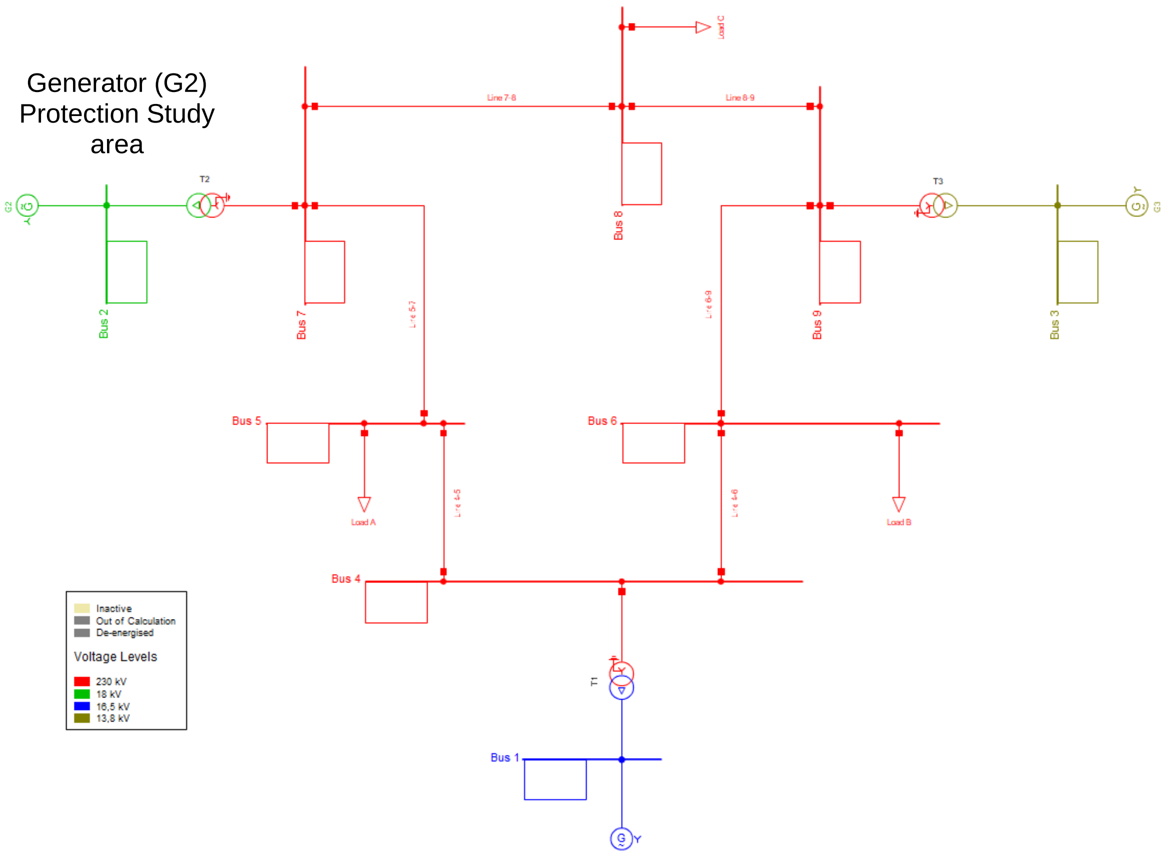


Figure 4.1: IEEE 9 Bus system single line diagram

4.2 IEEE 9 Bus system

This section provides the IEEE 9 bus system's input data. The bus voltage magnitudes are shown in Table 4.1 as rated and per unit values. In Table 4.3, the buses that include generators and loads are also included.

Table 4.1: Bus Data input of the selected grid network

Bus no	Rated voltage in (KV)	V (pu)	Angle (deg)
1	16.5	1.04	0
2	18	1.02	9.3
3	13.8	1.02	4.7
4	230	1.03	147.8
5	230	1.00	146
6	230	1.01	146.3
7	230	1.03	153.7
8	230	1.02	150.7
9	230	1.03	152

Table 4.2 provides transformer data of the IEEE 9 bus network.

Table 4.2: Transformer information Data input of the IEEE 9 bus network

Transformer	S MVA	I rated in kA	HV in KV	LV in KV	Sc. voltage uk in %	Sc. voltage uk0 in %	F in Hz	Vector group
1	250	1	230	16.5	14.4	3	60	Yn/D
2	200	1	230	18	12.5	3	60	Yn/D
3	150	1	230	13.8	8.78	3	60	Yn/D

Table 4.3 provides load demand data of the IEEE 9 bus network.

Table 4.3: Load information data of IEEE 9 bus network

Load	Active power in (MW)	Reactive power(Mvar)	Technology	location
A	125	50	3ph-phe	Bus 5
B	90	30	3ph-phe	Bus 6
C	100	35	3ph-phe	Bus 8

Table 4.4 provides transmission line data of the IEEE 9 bus network system.

Table 4.4: Transmission data of IEEE 9 bus network

Line Name	Vrated (kV)	Type of line	Conductor material	R Ω/km	X in Ω/km	Susceptance (μS/km)
Line 1	230	Overhead	Aluminium	5.29	44.965	332.7
Line 2	230	Overhead	Aluminium	16.928	85.169	578.45
Line 3	230	Overhead	Aluminium	4.4965	38.088	281.66
Line 4	230	Overhead	Aluminium	6.2951	53.3232	395.08
Line 5	230	Overhead	Aluminium	20.631	89.93	676.75
Line 6	230	Overhead	Aluminium	8.993	48.668	298.69

Table 4.5 provides generator data of the IEEE 9 bus network

Table 4.5: Generator data of IEEE 9 bus network

Generator	Bus type	P (MW)	Q(Mvar)	V(pu)	pf	Xd(pu	Xd in pu	S (MVA
1	slack	0	0	1.04	0.9	1.7	1.65	512
2	PV	163	6.7	1.025	0.85	1.7	1.62	270
3	PV	85	-10.9	1.025	0.85	1.22	1.16	125

4.3 Load flow analysis

Analysing the load flow of the system is the most important and fundamental technique to deal with examining issues in power system simulations. The steady operation state with node voltages and branch power flow in the power system is solved by load flow analysis based on a defined generating state and transmission network configuration. Without taking into account system transient processes, load flow analysis can give a power system that is operating in a balanced steady state. (2008) Wang, Song, and Irving

When simulating the current and power equations for the chosen network, the Newton-Raphson method is used to execute an AC load flow, balanced, positive sequence. Dig-SILENT Power Factory Software was used to run the simulations for the power system load flow, and the results are displayed in Table 4.7 for Main Incomer Maximum Demand. The findings of the entire load flow are displayed in Table 4.8 below. These outcomes offered an overview of the maximum apparent, real, and reactive powers that were used to determine whether the system voltages remained within specified bounds of +/- 10% as per IEEE/IEC standard during normal operating conditions and to determine whether the transformers and transmission lines are overloaded.

According to the IEEE standard voltage requirements, Table 4.6's voltage profile of the IEEE 9-bus system demonstrates that the predicted load flow results' voltage profile variation is within a +/-10% tolerance level (IEEE standard, 1994).

Table 4.6: Bus voltage load flow results of IEEE 9 bus network

Grid: Grid | System Stage: Grid | Study Case: Study Case | Annex: / 3

	rtd.V [kV]	Bus - voltage [p.u.]	[kV]	[deg]	Voltage - Deviation [%] (-10, -5, 0, +5, +10)
BUS 1	16,50	1,040	17,16	0,00	
BUS 2	18,00	1,025	18,45	9,28	
BUS 3	13,80	1,025	14,14	4,66	
BUS 4	230,00	1,026	235,93	147,78	
BUS 5	230,00	0,996	229,00	146,01	
BUS 6	230,00	1,013	232,91	146,31	
BUS 7	230,00	1,026	235,93	153,72	
BUS 8	230,00	1,016	233,66	150,73	
BUS 9	230,00	1,032	237,44	151,97	

Figure 4.2 shows the voltage profile of the IEEE 9-bus system. Limit. All the voltages are within the 10% tolerance limit of the IEEE standard

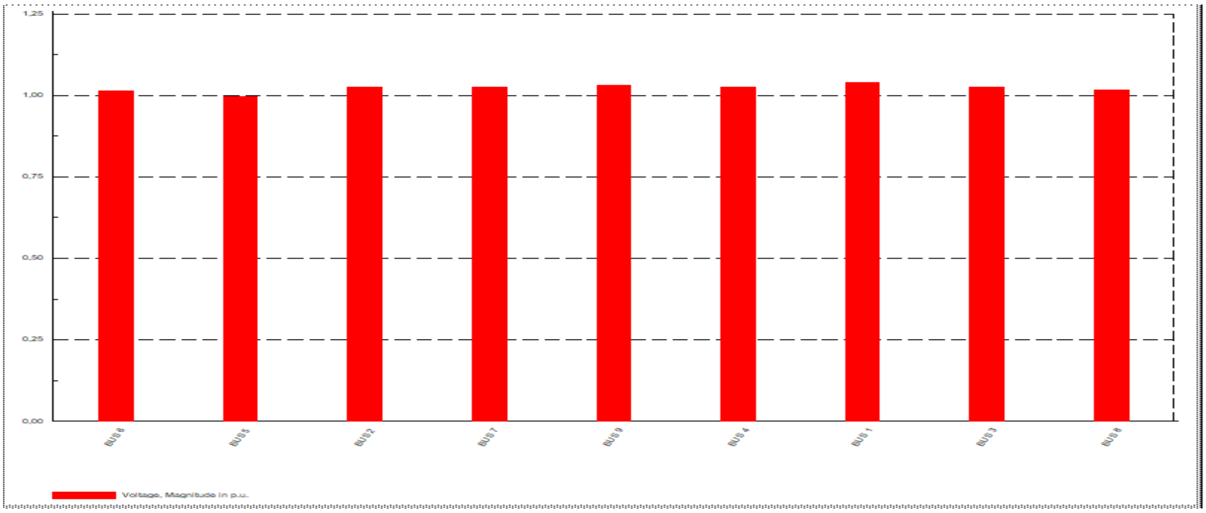


Figure 4.3: Typical voltage for the IEEE 9-Bus network

Table 4.7 shows the grid summary of the system i.e. apparent power, active and reactive power flow results of the system.

Table 4.7: Grid summary of IEEE 9 bus network

Grid: Grid	System Stage: Grid	Study Case: Study Case	Annex: / 1

Grid: Grid — Summary

No. of Substations	0	No. of Busbars	9	No. of Terminals	0	No. of Lines	6
No. of 2-w Trfs.	3	No. of 3-w Trfs.	0	No. of syn. Machines	3	No. of asyn.Machines	0
No. of Loads	3	No. of Shunts	0	No. of SVS	0		

Generation	=	319,64	MW	22,80	Mvar	320,45	MVA
External Infeed	=	0,00	MW	0,00	Mvar	0,00	MVA
Inter Grid Flow	=	0,00	MW	0,00	Mvar		
Load P(U)	=	315,00	MW	115,00	Mvar	335,34	MVA
Load P(Un)	=	315,00	MW	115,00	Mvar	335,34	MVA
Load P(Un-U)	=	0,00	MW	0,00	Mvar		
Motor Load	=	0,00	MW	0,00	Mvar	0,00	MVA
Grid Losses	=	4,64	MW	-92,20	Mvar		
Line Charging	=			-140,58	Mvar		
Compensation ind.	=			0,00	Mvar		
Compensation cap.	=			0,00	Mvar		
Installed Capacity	=	796,55	MW				
Spinning Reserve	=	0,00	MW				
Total Power Factor:							
Generation	=	1,00	[-]				
Load/Motor	=	0,94 / 0,00	[-]				

Table 4.8 presents the load flow results of the edge elements of network

The results analysis shows that the transmissions lines loading and the three transformers loading are within operating capabilities. The results also show that the loading of the generator is as well as their reactive outputs is also with the acceptable limits.

Table 4.8: load flow results of the edge element of IEEE 9 bus network

Grid: Grid	System Stage: Grid	Study Case: Study Case	Annex: / 1

Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power.-factor [-]	Current [kA]	Current [p.u.]
LOAD 1	Lod		BUS 5	125,000	50,000	0,93	0,339	1,004
LOAD 2	Lod		BUS 6	90,000	30,000	0,95	0,235	0,987
LOAD 3	Lod		BUS 8	100,000	35,000	0,94	0,262	0,984
G1	Sym	14,96	BUS 1	71,641	27,040	0,94	2,576	0,144
G2	Sym	60,42	BUS 2	163,000	6,642	1,00	5,105	0,589
G3	Sym	68,55	BUS 3	85,000	-10,879	0,99	3,498	0,669
Line 1	Lne	14,15	BUS 5	-40,680	-38,686	-0,72	0,142	0,142
			BUS 4	40,937	22,891	0,87	0,115	0,115
Line 2	Lne	21,45	BUS 7	86,620	-8,380	1,00	0,213	0,213
			BUS 5	-84,320	-11,314	-0,99	0,214	0,214
Line 3	Lne	18,94	BUS 7	76,380	-0,810	1,00	0,187	0,187
			BUS 8	-75,905	-10,692	-0,99	0,189	0,189
Line 4	Lne	8,46	BUS 8	-24,095	-24,308	-0,70	0,085	0,085
			BUS 9	24,183	3,098	0,99	0,059	0,059
Line 5	Lne	15,43	BUS 9	60,817	-18,073	0,96	0,154	0,154
			BUS 6	-59,463	-13,460	-0,98	0,151	0,151
Line 6	Lne	8,61	BUS 6	-30,537	-16,540	-0,88	0,086	0,086
			BUS 4	30,703	1,026	1,00	0,075	0,075
T1	Tr2	29,45	BUS 4	-71,641	-23,917	-0,95	0,185	0,295
			BUS 1	71,641	27,040	0,94	2,576	0,295
T2	Tr2	79,58	BUS 7	-163,000	9,190	-1,00	0,400	0,796
			BUS 2	163,000	6,642	1,00	5,105	0,796
T3	Tr2	55,74	BUS 9	-85,000	14,975	-0,98	0,210	0,557
			BUS 3	85,000	-10,879	0,99	3,498	0,557

Figure 4.4 shows the three phase voltages and currents at bus 2 of a generator during normal condition of the selected 2 bus network

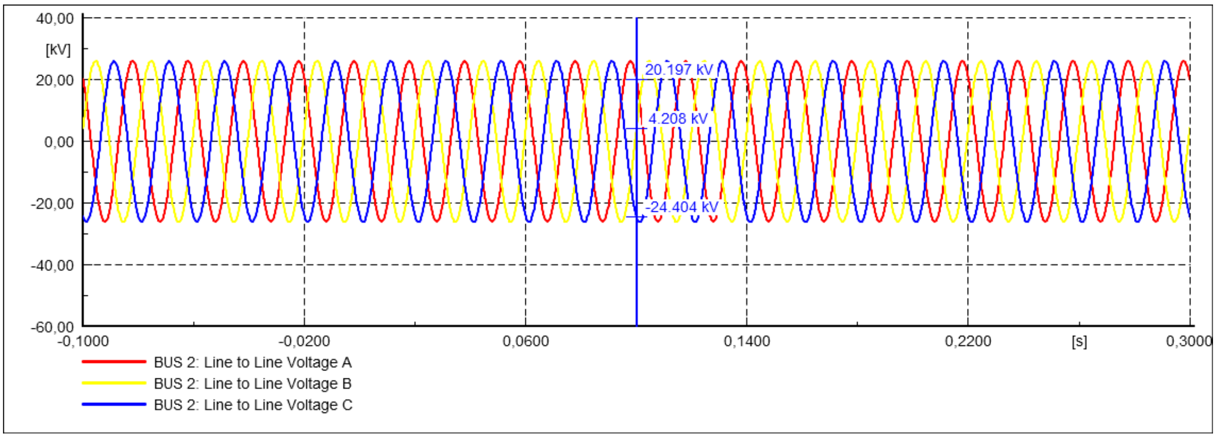


Figure 4.4: Three phase voltages at bus 2 of IEEE9-Bus system

4.4 Short Circuit Simulation

The significance of short circuit simulations in determining the rating of power equipment and the setting of protection devices is discussed in (Battistelli et al., 2008). Additionally, it frequently serves as a tool for determining the voltage profile of the network's buses and the electromagnetic compatibility of nearby circuits. There are five different kinds of short circuits.

- Short circuit in three phases
- only one line-to-ground short circuit
- Short circuit between lines
- Short circuit from two lines to the earth

The circuit diagram in Figure 4.5 below shows different types of faults and description of various short circuits.

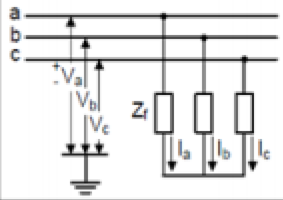
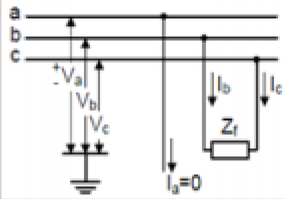
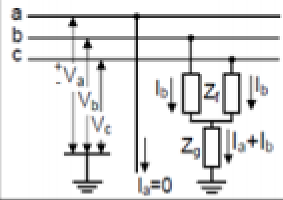
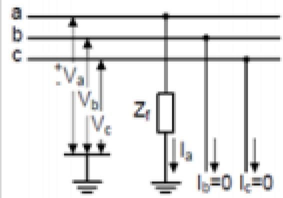
Fault	Circuit diagram of the fault point	Boundary conditions	Description
Three-phase SC		$I_a+I_b+I_c=0$ $V_a=Z_f I_a$ $V_b=Z_f I_b$ $V_c=Z_f I_c$	• Connection of all conductors with or without simultaneous contact to ground • Symmetrical loading of the three external conductors • Calculation on a single-phase basis
Line-to-line SC		$I_a=0$ $I_b=-I_c$ $V_b-V_c=Z_f I_b$	• Unsymmetrical loading • All voltage non-zero • SC current higher than in a three-phase SC near-to generator
Double line-to-ground SC		$I_a=0$ $V_b=(Z_f+Z_g)I_b+Z_g I_c$ $V_c=(Z_f+Z_g)I_c+Z_g I_b$	• The leakage current flowing to ground is a capacitive ground fault current
Single line-to-ground SC		$I_b=I_c=0$ $V_a=Z_f I_a$	• Very frequent occurrence in low voltage networks

Figure 4.5: Different types of short circuit in a three phase network(IEC International Standard 90909, 2001)

Both in steady-state and transient situations, a thorough short-circuit research is necessary. The software DIG-Silent power factory simulation is used to analyze the short circuit defects. This tool may coordinate protection equipment for system planning and set protection relays for system operations, among other things. Following completion of all network parameters, the Dig-SILENT simulation program is used to determine the necessary short circuit current values. The location of the short circuit and its specifications are chosen. The initial three phase short circuit current$I_k^{"}$, single phase to earth short circuit current $I_{kl}^{"}$, and the peak short circuit current I_p of the system operation are simulated and taken into consideration. The total of the AC symmetrical and DC decaying components is taken into account when calculating the initial short circuit current. The components for faults far from the generator and the components for faults closer to the generator are fundamentally different from one another. Using the IEC 60909 standard, the maximum and minimum short circuit current values are computed. The short circuit power is also taken into account when calculating the short circuit current for the fault levels $S_k^{"}$. The equations used are represented as follows:(IEC International Standard 90909, 2001)

$$I_k^{"} = \frac{cV_n}{\sqrt{3}Z_k} \quad (4.1)$$

$$I_{kl}^{"} = \frac{\sqrt{3}cV_n}{Z_{k(1)}+Z_{k(2)}+Z_{k(0)}} \quad (4.2)$$

$$k = 1.02 + 0.98e^{\frac{-3}{X/R}} \quad (4.3)$$

$$I_p = k \times \sqrt{2}I_k^{"} \quad (4.4)$$

$$S_k^{"} = \sqrt{3}I_k^{"}V_n \quad (4.5)$$

Where $I_k^{"}$ is the initial short circuit

I_p Is peak short circuit current

tk Is the constant factor

c is the voltage factor

V_n is the nominal voltage of the short circuit location

Z_k is the equivalent short-circuit impedance

$Z_{k(1)}$ is the equivalent positive sequence short-circuit impedance

$Z_{k(0)}$ is the equivalent zero sequence short-circuit impedance

$Z_{k(2)}$ is the equivalent negative sequence short-circuit impedance

R is the resistance of the network

X is the reactance of the network

The next section of this chapter presents the differential protection function for a generator using the Dig-silent power factory simulation software. Simulation results are studied for both normal and abnormal conditions.

4.5 Differential protection functions of a power generator.

The DIgSILENT power factory simulation software is utilized to investigate the differential protective function of a generator using SEL700G relay model with the capacity of 270MVA, 18KV generator. The IEEE 9 bus network is simulated in DIgSILENT environment and is shown in Figure 4.6 below

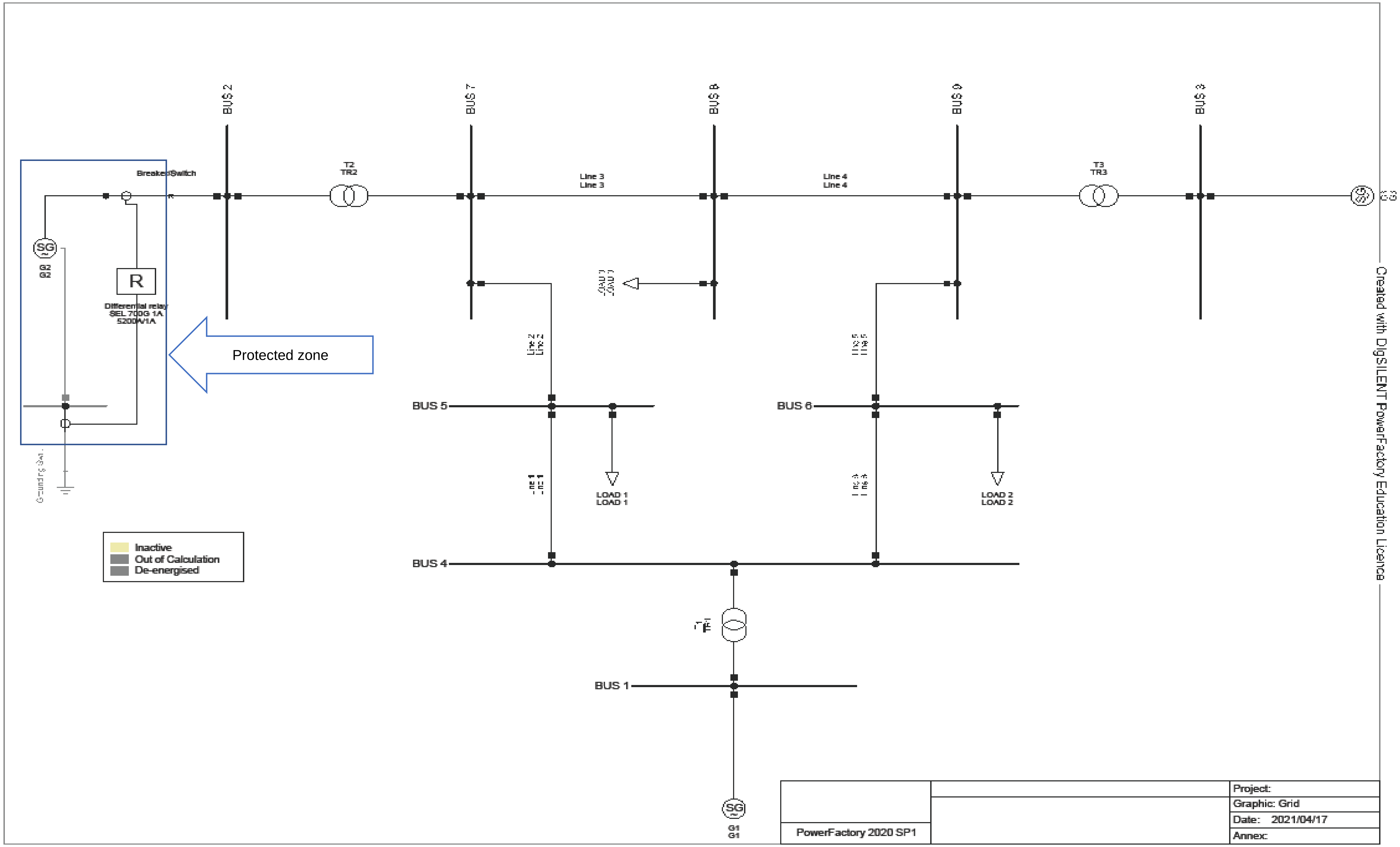


Figure 4.6: IEEE 9 Bus network in a DigSILENT simulation environment

For this application, the phase differential elements are implemented for differential protection studies. The relay also has phase inter-blocking feature for 2nd and 4th harmonic blocking which is common blocking that prevents all restrained elements from tripping if any blocking element is picked up. It also contains the fifth harmonic current that is utilized as an independent blocking. For harmonic restraint, the values of the second- and fourth-harmonic currents are summed, and that value is used in the relay characteristic, however for the purpose of this application, only the phase differential elements are implemented. The SEL700G differential relay model is connected on X-side terminal of generator (G2) and on neutral terminal of the generator as shown in Figure 4.8 above, Winding connections of the SEL700G relay model are compensated using two current transformer adapter elements and that is for winding X and for winding Y. Both current transformers are connected in the same voltage level of an 18 kV of a generator and have the same current transformer ratio. The parameter settings of the SEL700G relay model in the Dig silent power factory simulation environment is given in table 4.5 below

Table 4.9: Parameter setting of the SEL700G differential relay model in the DigSilent Power Factory environment

Description	Release Threshold	Res. 1st Slope Threshold	Restraint 2nd Slope Threshold	Res. 1st Slope	Res.t2nd Slope	UnrestraintDif. Threshold
Differential Setting Element	0.99p.u	0	1	35%	75%	8
Generator Tap Setting	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Max rated power
	1.67A	1.67 A	-	-	-	270MVA
Description	CT ratio	Nominal terminal line-line voltage		Current Transformer Connection		Vector group
X-side Ct Adapter	5200	18KV		Y		-
Y side Ct Adapter	5200	18KV		Y		0

Two matched Ct adapter are used to supply the SEL700G differential relay and are located at each end of the generator windings. Their accuracy parameters are set according to the IEC standards. The current transformers have three numbers of phases and phase technology is ABC. Their secondary connection is star. The voltage transformer is placed out of service for this application.

Table 4.10: Instrument Transformer settings of the differential protection scheme

Protection device	Location	Manufacturer	Model	CT	Slot	Ratio [pri.A/sec .A]
Relay model	Generator G2	Schweitzer	SEL700G	CTX @ X-Side	Ct x	5200/1
				CTY @Y-Side	Ct y	5200/1
				Ct in @ Neutral Terminal	Ct in	5200/1

A fault at Bus 2 is considered internal faults, whereas any fault applied outside the protected zone is considered through faults or external faults. For this application Bus 5 and Bus 7 are considered for external faults.

4.5.1 Internal faults

For this case study, the internal fault is applied inside the protected zone at bus 2 and results are analysed. The behaviour of the differential relay is investigated for four types of short circuit simulations namely:

- Short circuit in three phases
- short circuit from one phase to the ground
- Short circuit from two phases to the ground
- Circuit failure in two phases

This section discusses the generator internal faults case studies simulated results.

Table 4.11: Internal faults case studies on dig silent simulation environment

Type of fault	Location of fault	Measured voltage and current at fault location
Short circuit in three phases	Internal fault at bus 2	Bus 2 voltage and current signals
Short circuit from one phase to the ground	Internal fault at bus 2	Current and voltage signals at Bus 2
Short circuit from two phases to the ground	Internal fault at Bus 2	Signals of voltage and current at Bus 2
Circuit failure in two phases	Internal fault at Bus 2	Signals for voltage and current at Bus 2

4.5.1.1 Three phase short circuit faults at Bus 2

This case study aims to analyse the performance of differential relay elements for a three phase short circuit fault on a generator. Three phase short circuit fault is applied on the applied at bus 2 of a generator terminal also referred as internal fault for differential protection scheme and the method utilized complete. The break out time is set at 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

The EMT simulation results are shown in figure 4.9 below. As it can be observed in figure 4.9 the three phase internal fault at Bus 2 generates a short circuit current of 122.923 kA. The terminal voltage drops to the magnitude of 0 V.

Table 4.7 shows the results performance of differential relay when the three phase internal fault was applied. It is observed that the relay tripping time response is 0.170 seconds.

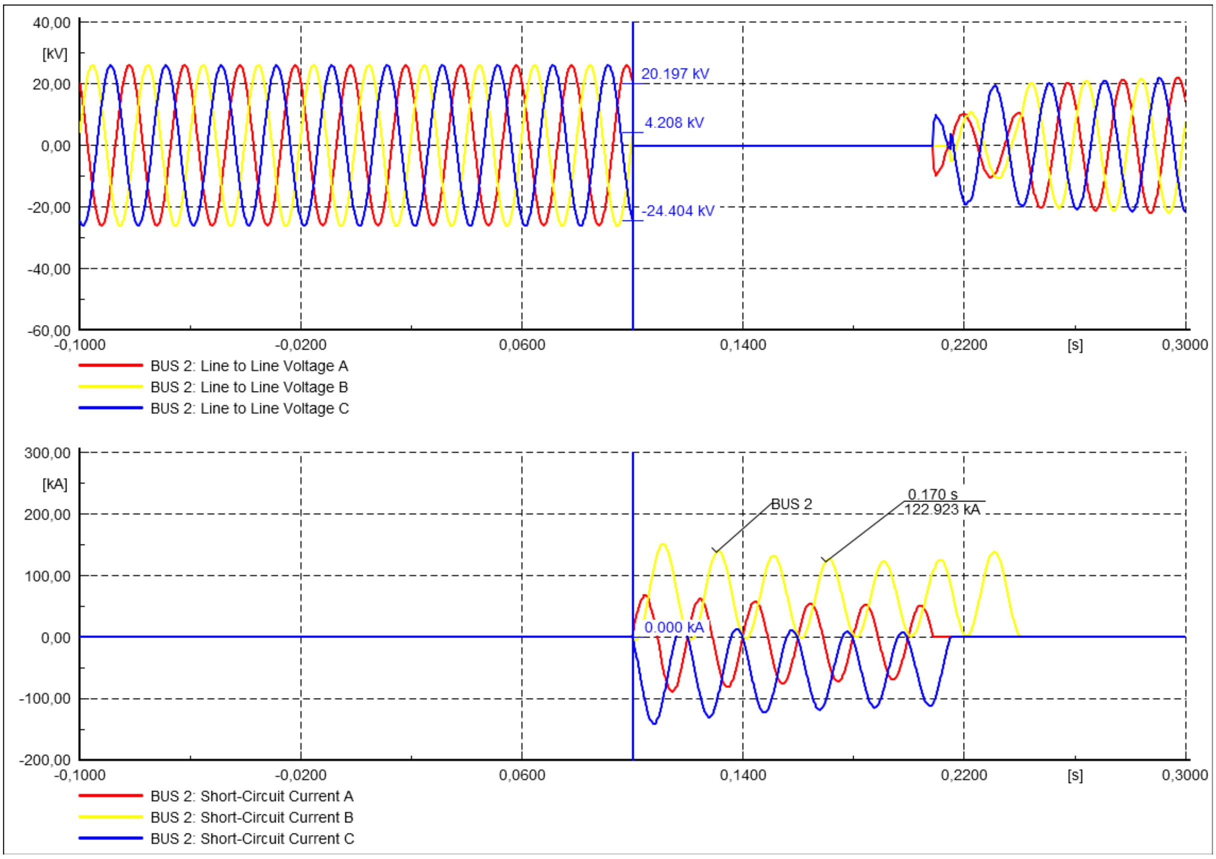


Figure 4.7: Voltage and current Plots for 3ph internal fault at Bus 2

Table 4.11: SEL 700G relay response to three phase internal fault

```
-------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                              |
| Short-Circuit Calculation / Method : complete                              3-Phase Short-Circuit    / Max. Short-Circuit Currents |
-------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                 | Fault Impedance                     |                                          |
|    Break Time                   0,10 s |     Resistance, Rf          0,00 Ohm |                                          |
|    Fault Clearing Time (Ith)    0,20 s |     Reactance, Xf           0,00 Ohm |                                          |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid          | Study Case: Study Case              | Annex:                / 1  |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Differential relay               Relay Type : SEL 700G 1A                                                                    |
|   Ct X  : CT X                   Location   : Busbar       : N Terminal       /              Ratio        : 5200A/1A       |
|                                                Branch       : G2                              Connection   : Y              |
|                                                             :                                                               |
|   Ct Y  : CT Y                   Location   : Busbar       : Y terminal       /              Ratio        : 5200A/1A       |
|                                                Branch       : G2                              Connection   : Y              |
|                                                             :                                                               |
|   Ct In : Ct in                  Location   : Busbar       : N Terminal       /              Ratio        : 5200A/1A       |
|                                                Branch       : Grounding Switch                Phase 1      : N              |
|                                                             :                                                               |
|   OutputLogic Output Logic                                                        yout             :     0,025 s          |
|     Breaker           Cubicle       Branch               Busbar               / Substation       Fault Clearing Time       |
|      Switch            Cub_1         G2                    N Terminal          /                           0,025 s          |
-------------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.8 below shows the current comparison differential plot for three phase internal fault at Bus 2. It is observed that the differential relay trips at 0.025s. It is observed that the fault generates the differential currents of 44.882kA.

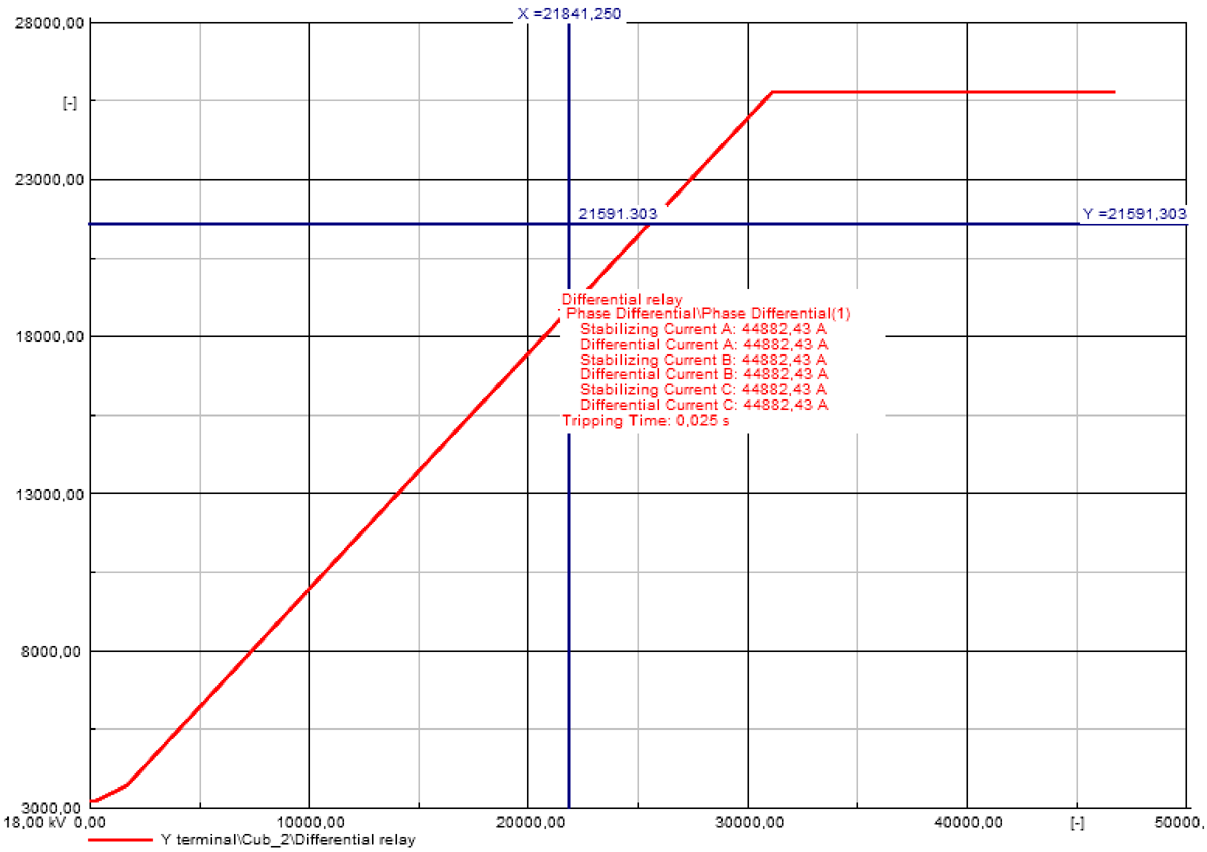


Figure 4.8: Current comparison differential plots for three phase internal fault

4.5.1.2 Single phase to ground short circuit faults at Bus 2

This case study aims to analyse the performance of differential relay elements for a single phase to ground short circuit fault on a generator. The single phase to ground faults is applied at Bus 2 on the phase side of a generator at the break out time of 0.1 seconds and is cleared at 0.15 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in Figure 4.9, the single phase to ground internal fault at bus 2 generates a short circuit current of 71.679kA. The terminal voltage of phase B and phase C drops to the magnitude of 13.588 kV.

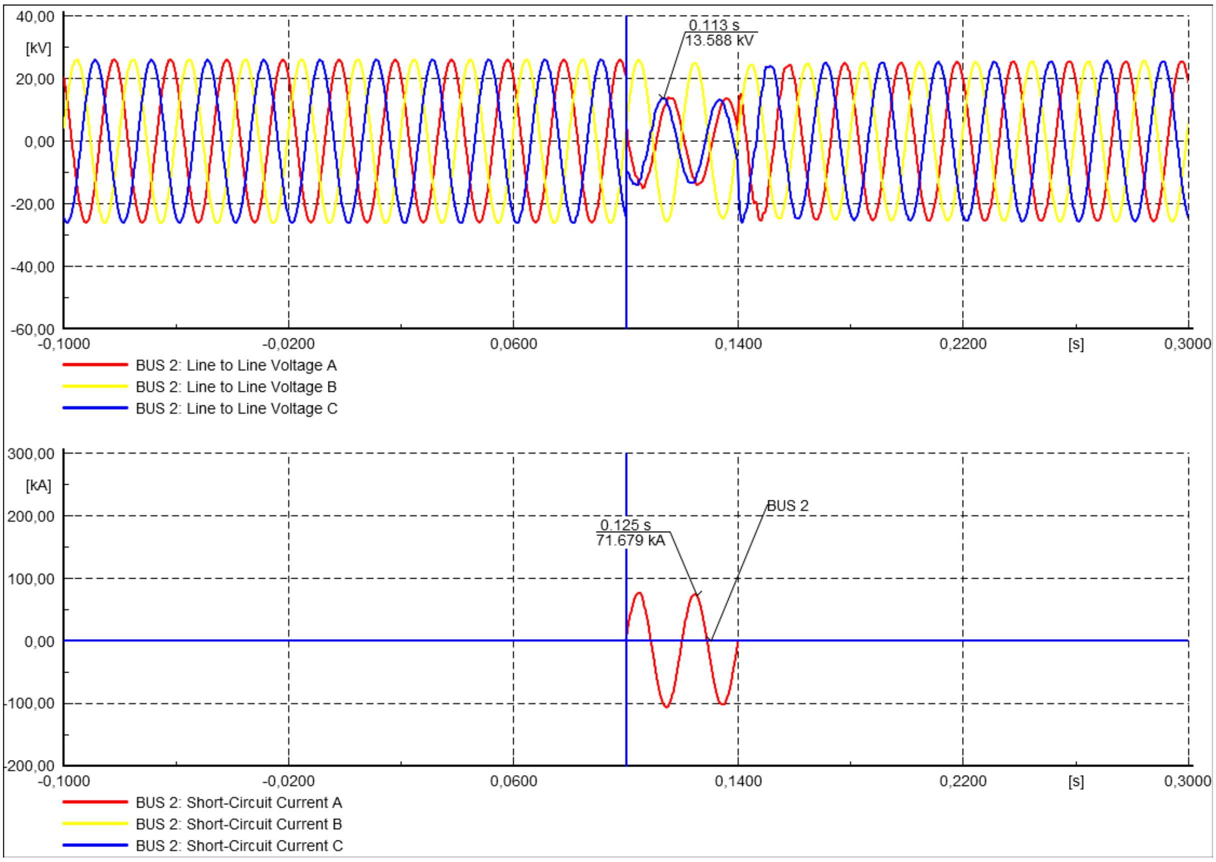


Figure 4.9: Voltage and current Plots for single phase to ground at Bus 2

Table 4.12 shows the results performance of differential relay when the single phase to ground internal fault was applied. It is observed that the relay tripping time response is 0.025 seconds. The tripping time of the relay is highlighted by blue colour as shown in table 4.12 below.

Table 4.12: SEL 700G relay response single phase to ground internal fault

```
-------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                               |
| Short-Circuit Calculation / Method : complete                                      Single Phase to Ground   / Max. Short-Circuit Currents |
-------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                     | Fault Impedance                    |                                            |
|    Break Time                    0,10 s |    Resistance, Rf          0,00 Ohm |                                            |
|    Fault Clearing Time (Ith)     0,20 s |    Reactance, Xf           0,00 Ohm |                                            |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                 System Stage: Grid             | Study Case: Study Case              | Annex:                / 1  |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Differential relay                  Relay Type : SEL 700G 1A                                                                   |
|   Ct X   : CT X                      Location   : Busbar      : N Terminal          /              Ratio       : 5200A/1A     |
|                                                  Branch      : G2                                   Connection  : Y            |
|                                                              :                                                                 |
|   Ct Y   : CT Y                      Location   : Busbar      : Y terminal          /              Ratio       : 5200A/1A     |
|                                                  Branch      : G2                                   Connection  : Y            |
|                                                              :                                                                 |
|   Ct In : Ct in                      Location   : Busbar      : N Terminal          /              Ratio       : 5200A/1A     |
|                                                  Branch      : Grounding Switch                     Phase 1     : N            |
|                                                              :                                                                 |
|   OutputLogic Output Logic                                                          yout            :          0,025 s        |
|     Breaker            Cubicle       Branch                  Busbar               / Substation       Fault Clearing Time        |
|      Switch             Cub_1        G2                       N Terminal         /                             0,025 s        |
-------------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.10 below shows the current comparison differential plot for single to ground phase internal fault at Bus 2. It is observed that the differential relay trips at 0.025s. It generated the differential currents of 55.802 kA and 9.616 kA for phase A and phase B respectively.

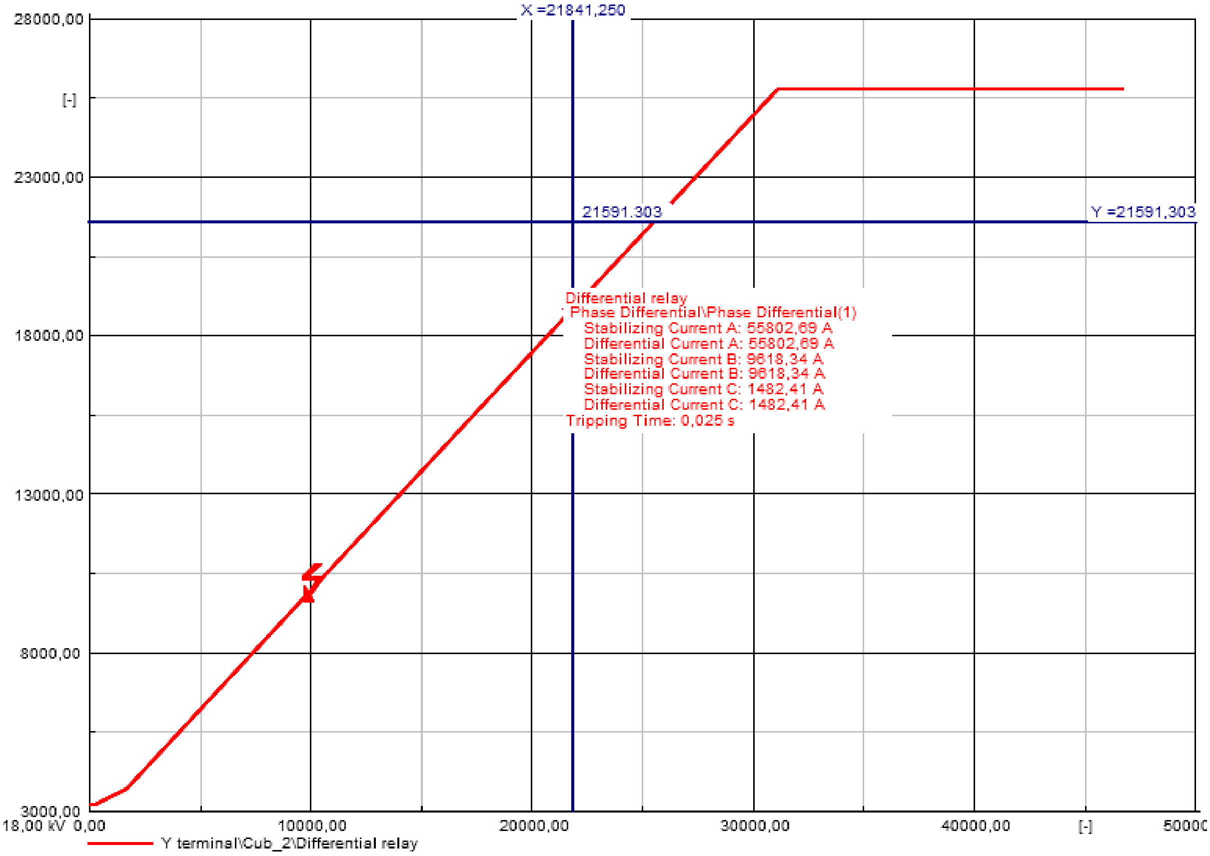


Figure 4.10: Current comparison differential plots for single phase to ground internal fault

4.5.1.3 Two phase short circuit internal fault

This case study aims to analyse the performance of differential relay elements for a two phase short circuit internal fault on a generator. The single phase to ground faults is applied at Bus 2 on the phase side of a generator at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in Figure 4.11 the two phase internal fault at Bus 2 generates a short circuit current of 102.750kA. The terminal voltage of red phase drops to the magnitude of 0 V.

Table 4.13 shows the results performance of differential relay when the two phase internal fault was applied. It is observed that the relay tripping time response is 0.025 seconds.

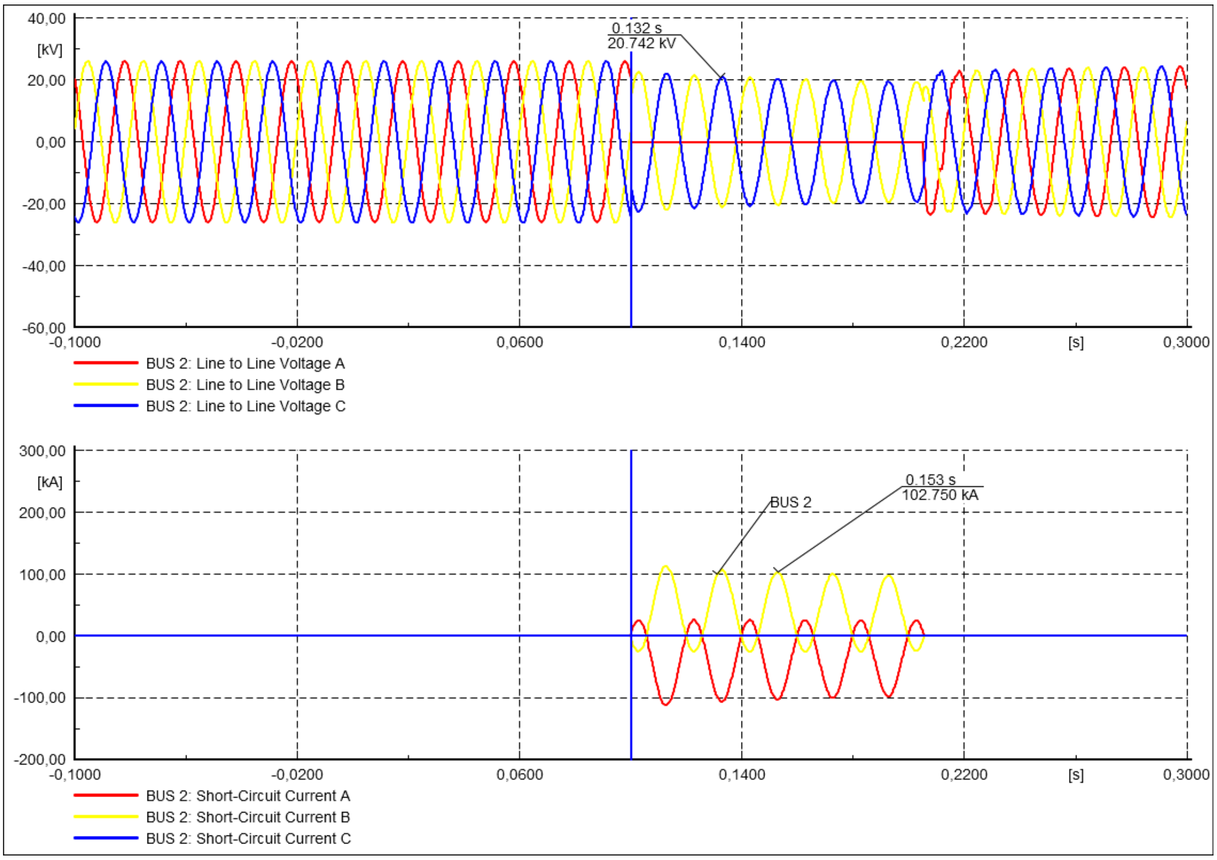


Figure 4.11: Voltage and current Plots for two phase internal fault

Table 4.13: SEL 700G relay response two phase internal fault

```
--------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                                |
| Short-Circuit Calculation / Method : complete                          2-Phase Short-Circuit     / Max. Short-Circuit Currents |
--------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                  | Fault Impedance                 |                                                  |
|    Break Time                 0,10 s |      Resistance, Rf          0,00 Ohm |                                                  |
|    Fault Clearing Time (Ith)  0,20 s |      Reactance, Xf           0,00 Ohm |                                                  |
--------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid           | Study Case: Study Case              | Annex:                  / 1  |
--------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------
| Differential relay               Relay Type : SEL 700G 1A                                                                     |
|   Ct X  : CT X                   Location   : Busbar        : N Terminal        /               Ratio        : 5200A/1A     |
|                                                Branch        : G2                                Connection   : Y            |
|                                                              :                                                              |
|   Ct Y  : CT Y                   Location   : Busbar        : Y terminal        /               Ratio        : 5200A/1A     |
|                                                Branch        : G2                                Connection   : Y            |
|                                                              :                                                              |
|   Ct In : Ct in                  Location   : Busbar        : N Terminal        /               Ratio        : 5200A/1A     |
|                                                Branch        : Grounding Switch                  Phase 1      : N            |
|                                                              :                                                              |
|   OutputLogic Output Logic                                                         yout         :      0,025 s              |
|     Breaker            Cubicle       Branch                   Busbar            / Substation      Fault Clearing Time        |
|      Switch             Cub_1         G2                       N Terminal        /                        0,025 s            |
--------------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.12 below shows the current comparison differential plot for two phase internal fault at Bus 2. It is observed that the differential relay trips at 0.025s.it generated the differential currents of 36.349 kA and 41.393 kA for phase A and phase C respectively.

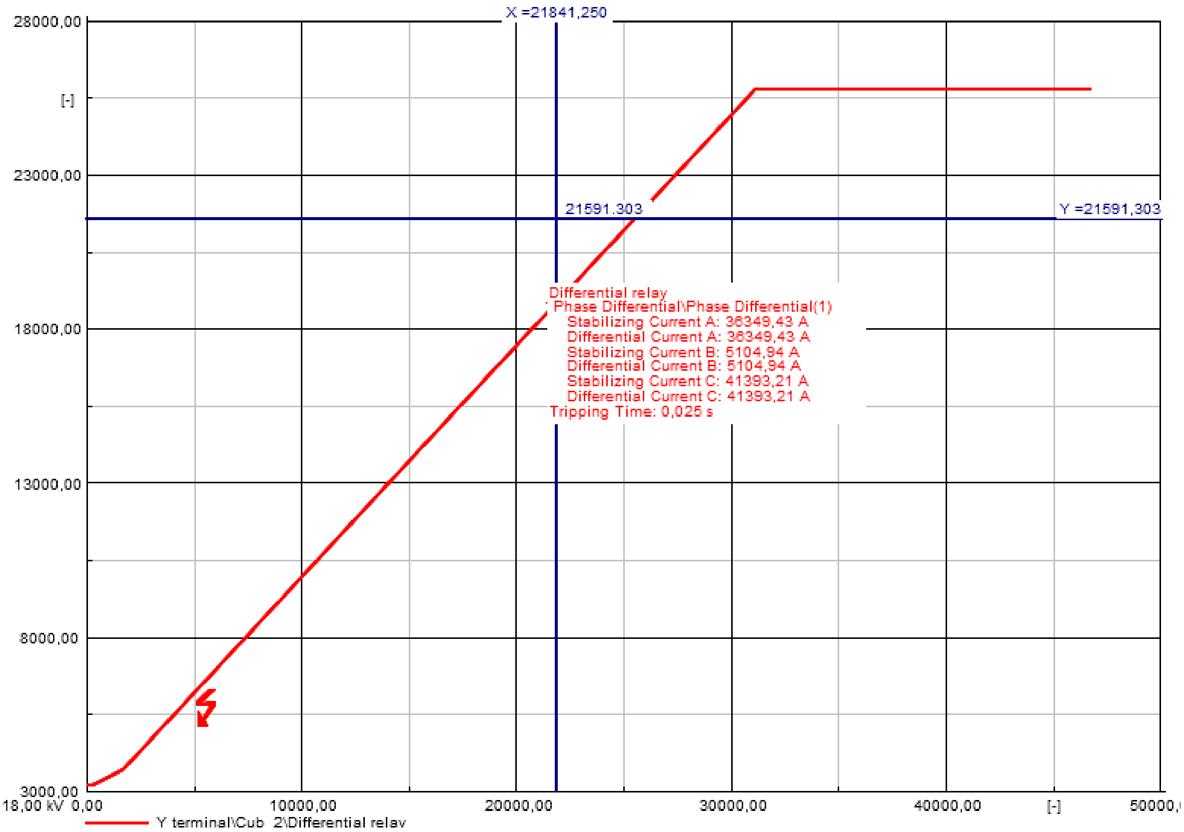


Figure 4.12: Current comparison differential plots for two phase internal fault

4.5.1.4 Two phase to ground short circuit internal fault

This case study aims to analyse the performance of differential relay elements for a two-phase to ground short circuit internal fault on a generator. The double phase to ground faults is applied at Bus 2 on the phase side of a generator at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in Figure 4.13 the two-phase to ground internal fault at Bus 2 generates a short circuit current of 154.292kA. The terminal voltage of yellow and blue have the magnitude of 11.062kV.

Table 4.14 shows the results performance of differential relay when the two-phase to ground internal fault was applied. It is observed that the relay tripping time response is 0.025 seconds.

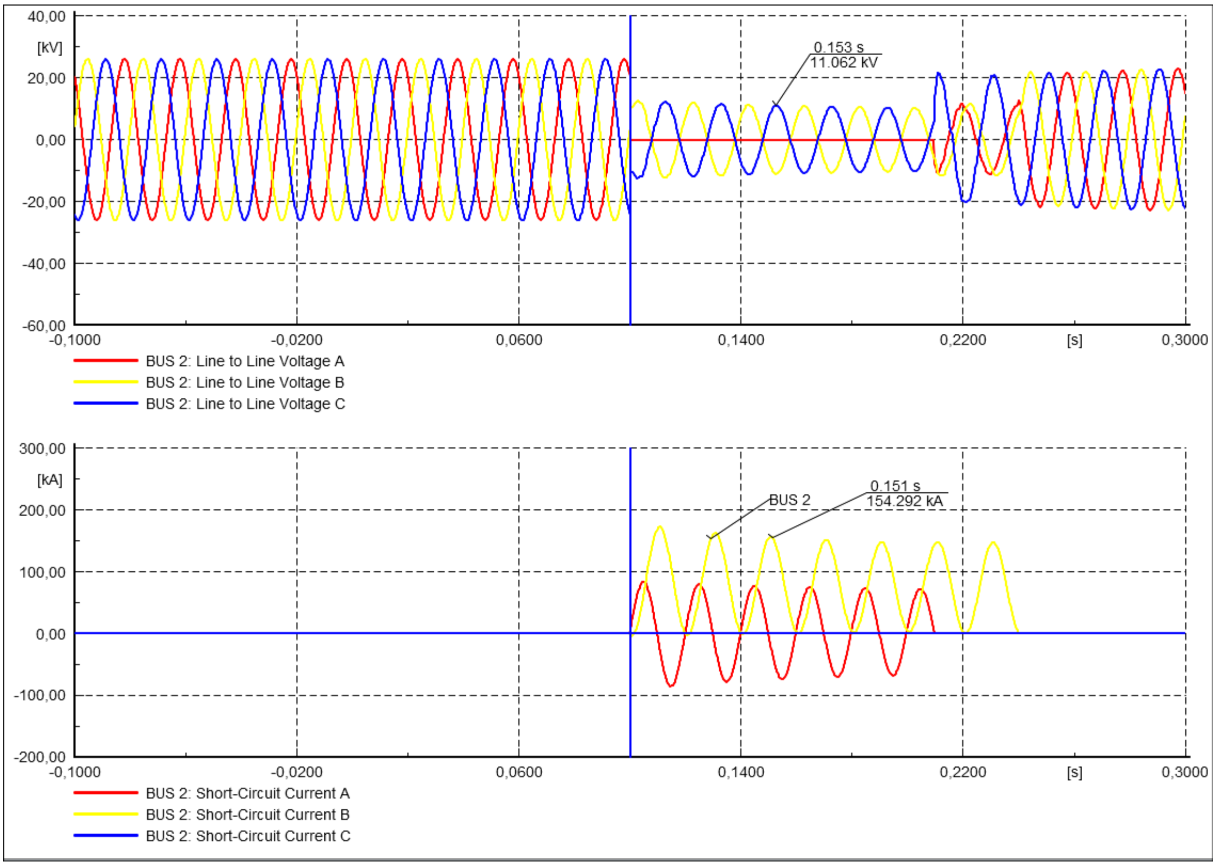


Figure 4.13: Voltage and current Plots for two-phase to ground internal fault

Table 4.14: SEL 700G relay response two phase to ground internal fault

```
-----------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                           |
| Short-Circuit Calculation / Method : complete                            2-Phase to Ground       / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                 | Fault Impedance                          |                                        |
|    Break Time                 0,10 s |     Resistance, Rf            0,00 Ohm |                                        |
|    Fault Clearing Time (Ith)  0,20 s |     Reactance, Xf             0,00 Ohm |                                        |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid           | Study Case: Study Case              | Annex:                  / 1  |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Differential relay               Relay Type : SEL 700G 1A                                                                    |
|   Ct X  : CT X                   Location   : Busbar      : N Terminal        /                 Ratio        : 5200A/1A     |
|                                                Branch      : G2                                    Connection   : Y            |
|                                                            :                                                                |
|   Ct Y  : CT Y                   Location   : Busbar      : Y terminal        /                 Ratio        : 5200A/1A     |
|                                                Branch      : G2                                    Connection   : Y            |
|                                                            :                                                                |
|   Ct In : Ct in                  Location   : Busbar      : N Terminal        /                 Ratio        : 5200A/1A     |
|                                                Branch      : Grounding Switch                      Phase 1      : N            |
|                                                            :                                                                |
|   OutputLogic Output Logic                                                         yout              :   0,025 s           |
|     Breaker           Cubicle      Branch              Busbar                / Substation       Fault Clearing Time         |
|      Switch            Cub_1        G2                   N Terminal           /                            0,025 s         |
-----------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.14 below shows the current comparison differential plot for two-phase to ground internal fault at Bus 2. It is observed that the differential relay trips at 0.025s. It generates the differential and stabilizing currents of 53.154 kA, 6.999 kA and 51.430 kA for phase A, phase B and phase C respectively. The relay in this case study trips for all three phase windings since the differential currents generated are lower than that of restraining current.

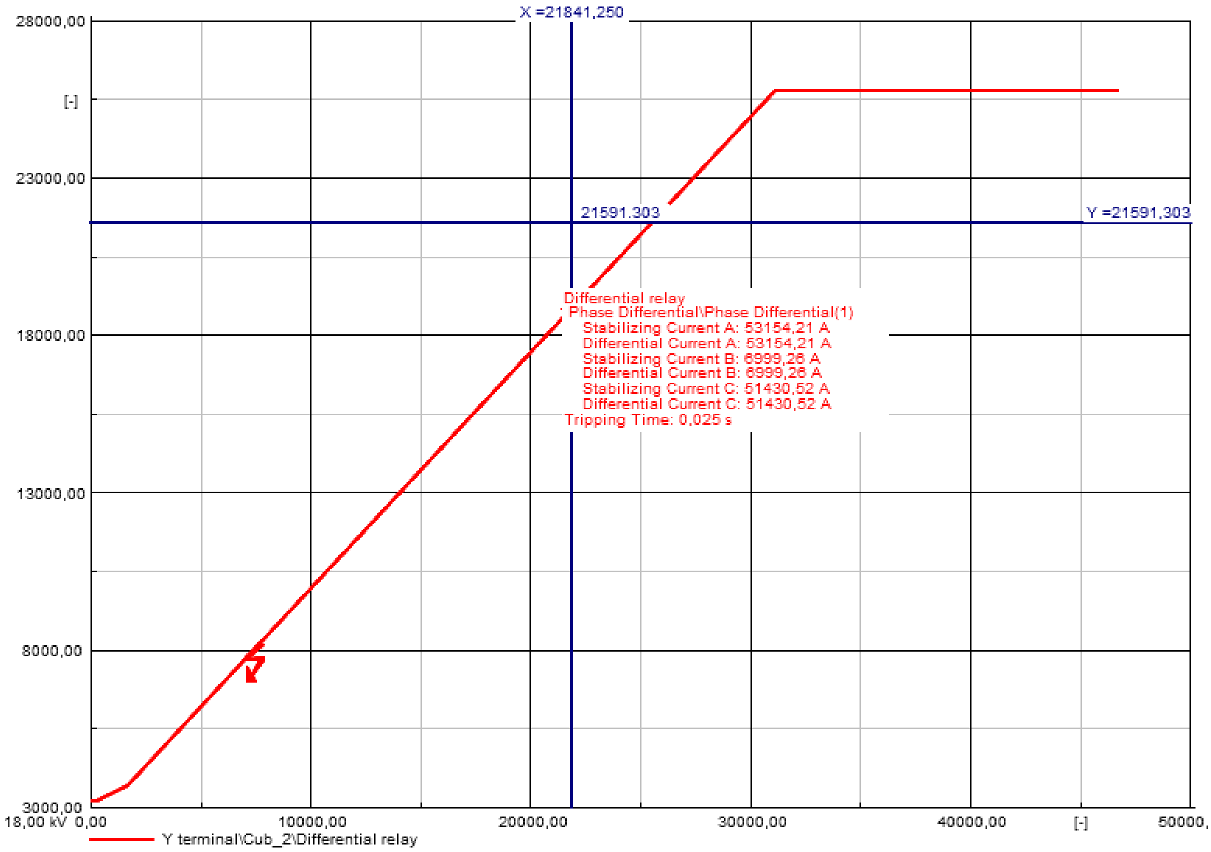


Figure 4.14: Current comparison differential plots for two-phase to ground internal fault

4.5.2 External faults

Any faults that occur outside the protected zone are called external faults or through faults. The fundamental of differential protection scheme on external faults states that any fault occurring or existing outside the protected zone should not operate the differential relay. For this case study, the fault is applied outside the protected zone at Bus 7 and results are analysed. The behaviour of the differential relay is investigated for four types of short circuit simulations namely:

- Three phase short circuit
- Single phase-to-ground short circuit
- Double phase-to-ground short circuit
- Two phase short circuit

This section discusses the generator External faults case studies simulated results

4.5.2.1 Three phase short circuit external fault

This case study aims to analyse the performance of differential relay elements for a three phase short circuit fault on a generator. Three phase short circuit fault is applied at bus 7 of the network also referred as external fault for differential protection scheme and the method utilized is complete. The break out time is set at 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

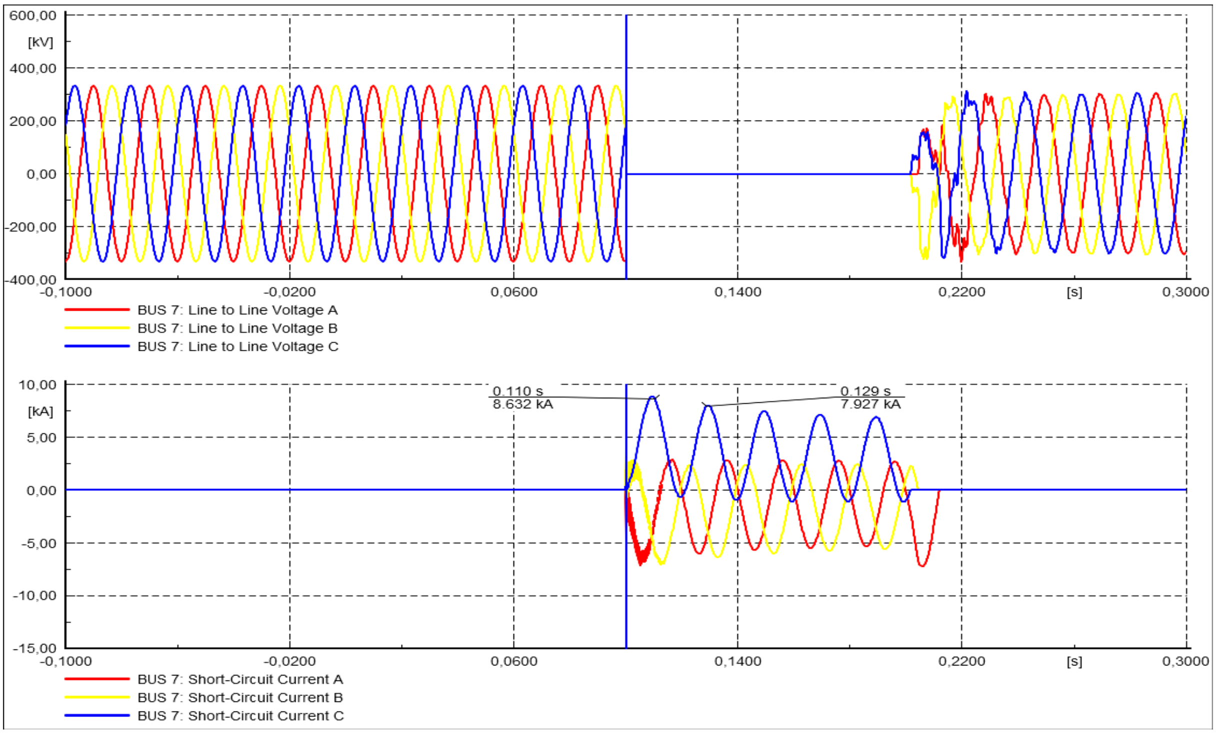


Figure 4.15: Voltage and current Plots for 3ph external fault at Bus 7

The EMT simulation results are shown in Figure 4.15. As it can be observed in Figure 4.17 the three phase external fault at bus 7 generates a short circuit current of 8.632kA. The terminal voltage drops to the magnitude of 0 V

Table 4.15: SEL 700G relay response to three phase external fault

```
-----------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                                  |
| Short-Circuit Calculation / Method : complete                              3-Phase Short-Circuit    / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                    | Fault Impedance                        |                                            |
|    Break Time                     0,10 s  |    Resistance, Rf              0,00 Ohm |                                            |
|    Fault Clearing Time (Ith)      0,20 s  |    Reactance, Xf               0,00 Ohm |                                            |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid            | Study Case: Study Case                | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Differential relay                 Relay Type : SEL 700G 1A                                                                      |
|   Ct X   : CT X                    Location   : Busbar       : N Terminal           /             Ratio       : 5200A/1A        |
|                                                 Branch       : G2                                  Connection  : Y               |
|                                                              :                                                                  |
|   Ct Y   : CT Y                    Location   : Busbar       : Y terminal           /             Ratio       : 5200A/1A        |
|                                                 Branch       : G2                                  Connection  : Y               |
|                                                              :                                                                  |
|   Ct In  : Ct in                   Location   : Busbar       : N Terminal           /             Ratio       : 5200A/1A        |
|                                                 Branch       : Grounding Switch                    Phase 1     : a               |
|                                                              :                                                                  |
|   OutputLogic OutputLogic                                                          yout              :  9999,999 s             |
|     Breaker            Cubicle       Branch                   Busbar              / Substation      Fault Clearing Time         |
|      Switch             Cub_1        G2                        N Terminal         /                          9999,999 s         |
-----------------------------------------------------------------------------------------------------------------------------------
```

Table 4.15 shows the results performance of differential relay when the three phase external fault was applied. It is observed that the relay tripping time response is 9999.99 seconds, this means that the relay did not trip for the external fault applied.

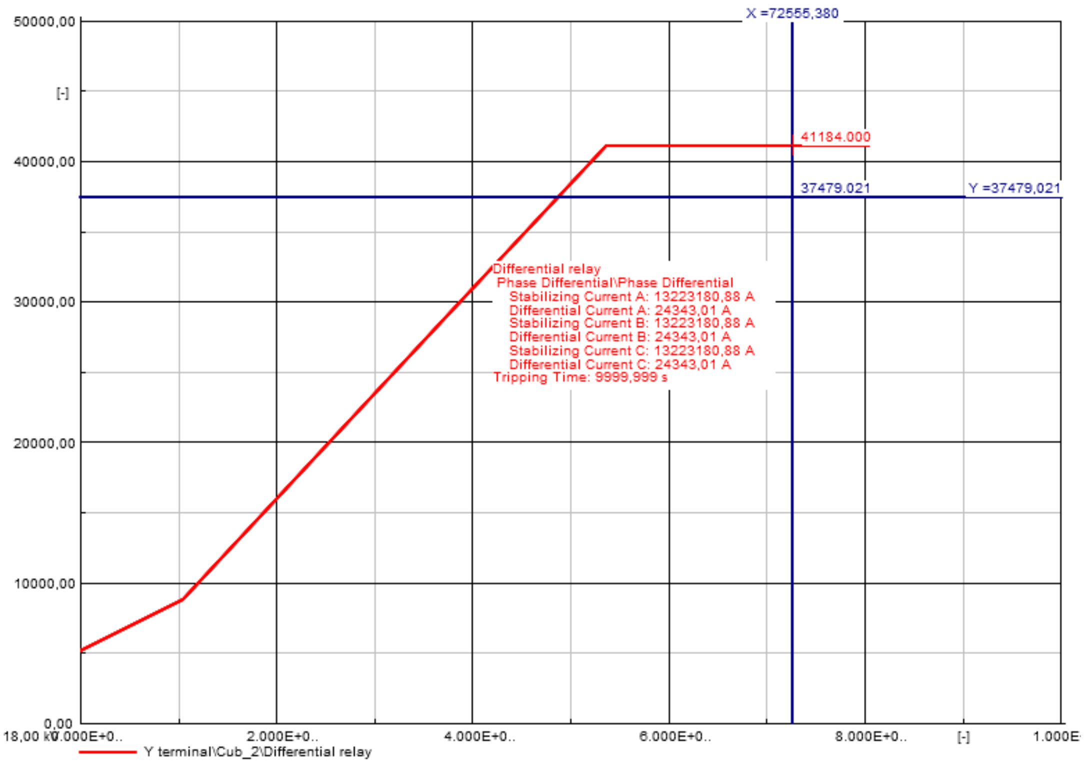


Figure 4.16: Current comparison differential plots for three phase external fault.

The Figure 4.16 shows the current comparison differential plot for three phase external fault at bus 7. It is observed that the differential relay trip response time is 9999.99s. This means that the relay did not response to the external applied fault.

4.5.2.2 Single phase to ground short circuit faults

This case study aims to analyse the performance of differential relay elements for a single phase to ground short circuit fault outside the generator. The single phase to ground fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in figure 4.17, the single phase to ground external fault at bus 7 generates a short circuit current of 4.198kA. The terminal voltage of phase B and phase C rises to the magnitude of 142.736 kV.

Table 4.16 shows the results performance of differential relay when the single phase to ground external fault is applied. It is observed that the relay tripping time response is 9999.99 seconds, this means that the relay did not trip for the external fault applied.

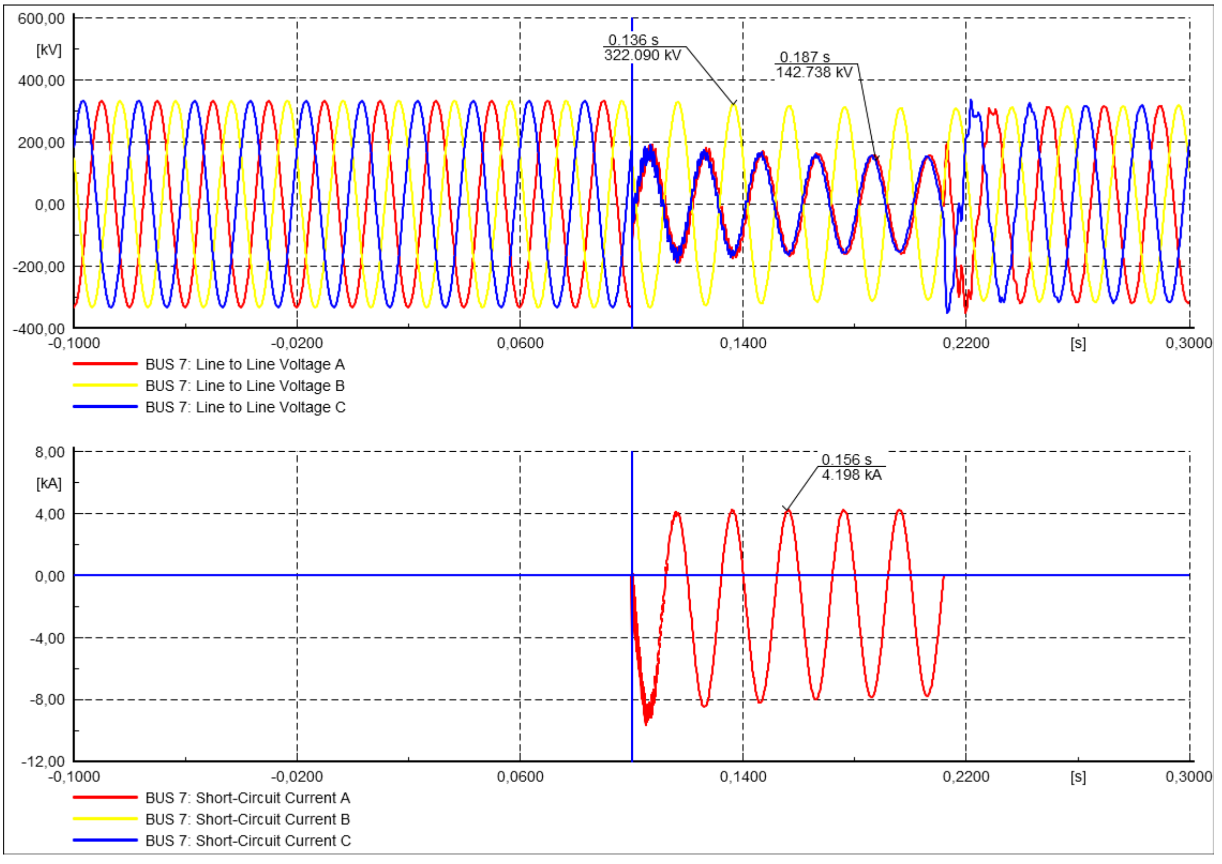


Figure 4.17: Voltage and current Plots for single phase to ground fault at Bus 7

Table 4.16: SEL 700G relay response to single phase to ground external fault

```
---------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                                  |
| Short-Circuit Calculation / Method : complete                                   Single Phase to Ground   / Max. Short-Circuit Currents |
---------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                    | Fault Impedance                   |                                              |
|     Break Time                  0,10 s |     Resistance, Rf          0,00 Ohm |                                              |
|     Fault Clearing Time (Ith)   0,20 s |     Reactance, Xf           0,00 Ohm |                                              |
---------------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid           | Study Case: Study Case              | Annex:                  / 1  |
---------------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------------
| Differential relay                Relay Type : SEL 700G 1A                                                                       |
|   Ct X   : CT X                   Location   : Busbar    : N Terminal          /                Ratio       : 5200A/1A    |
|                                                Branch    : G2                                      Connection  : Y           |
|                                                          :                                                                  |
|   Ct Y   : CT Y                   Location   : Busbar    : Y terminal          /                Ratio       : 5200A/1A    |
|                                                Branch    : G2                                      Connection  : Y           |
|                                                          :                                                                  |
|   Ct In : Ct in                   Location   : Busbar    : N Terminal          /                Ratio       : 5200A/1A    |
|                                                Branch    : Grounding Switch                        Phase 1     : a           |
|                                                          :                                                                  |
|   OutputLogic OutputLogic                                                            yout          :  9999,999 s            |
|     Breaker              Cubicle       Branch                  Busbar              / Substation      Fault Clearing Time      |
|      Switch              Cub_1          G2                      N Terminal          /                        9999,999 s      |
---------------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.18 below shows the current comparison differential plot for single phase to ground external fault at bus 7. It is observed that the differential relay trip response time is 9999.99s. This means that the relay did not response to the external applied fault.

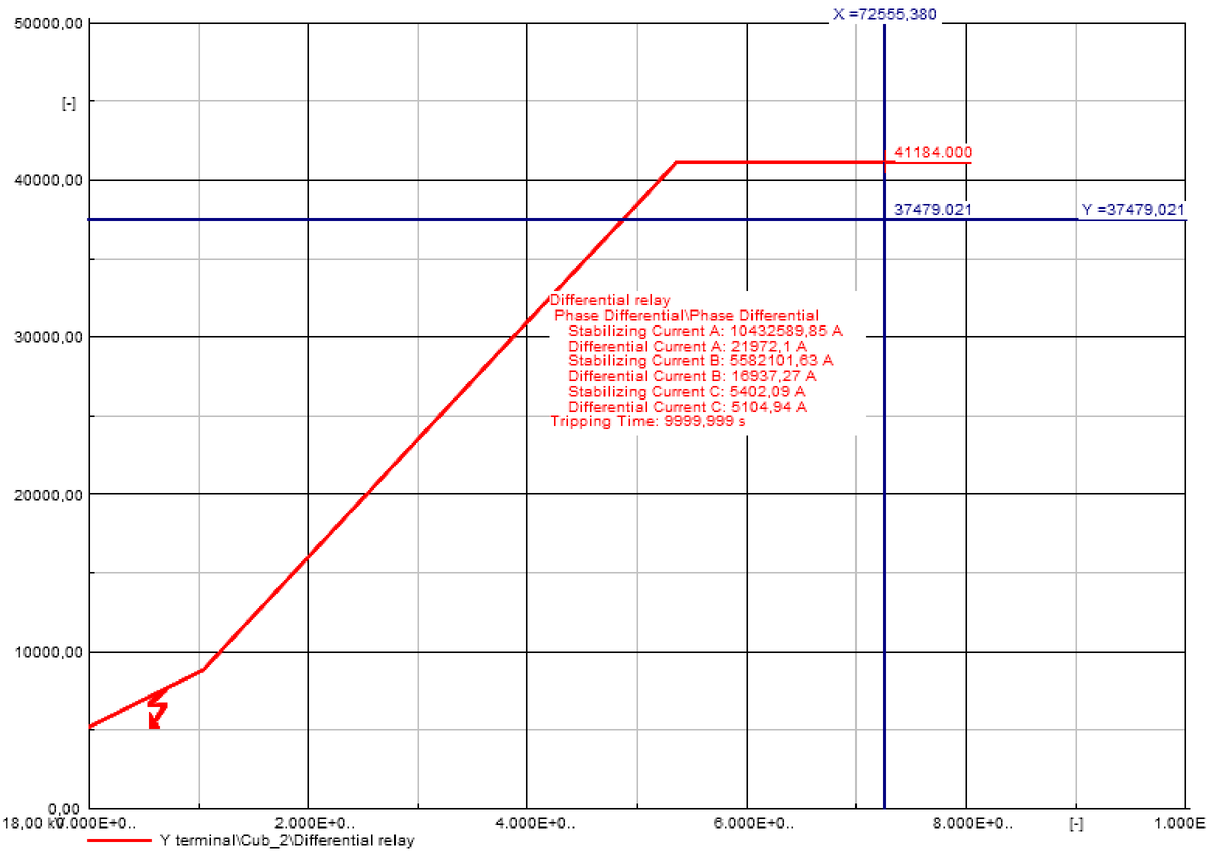


Figure 4.18: Current comparison differential plots for single phase to ground external fault.

4.5.2.3 Two phase short circuit external fault

This case study aims to analyse the performance of differential relay elements for a two-phase short circuit external fault. The two-phase fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in figure 4.19, the two-phase external fault at bus 7 generates a short circuit current of 4.070kA. The terminal voltage of phase B and phase C drops to the magnitude of 276.980 kV.

Table 4.17 shows the results performance of differential relay when the single phase to ground external fault is applied. It is observed that the relay tripping time response is 9999.99 seconds, this means that the relay did not trip for the external fault applied

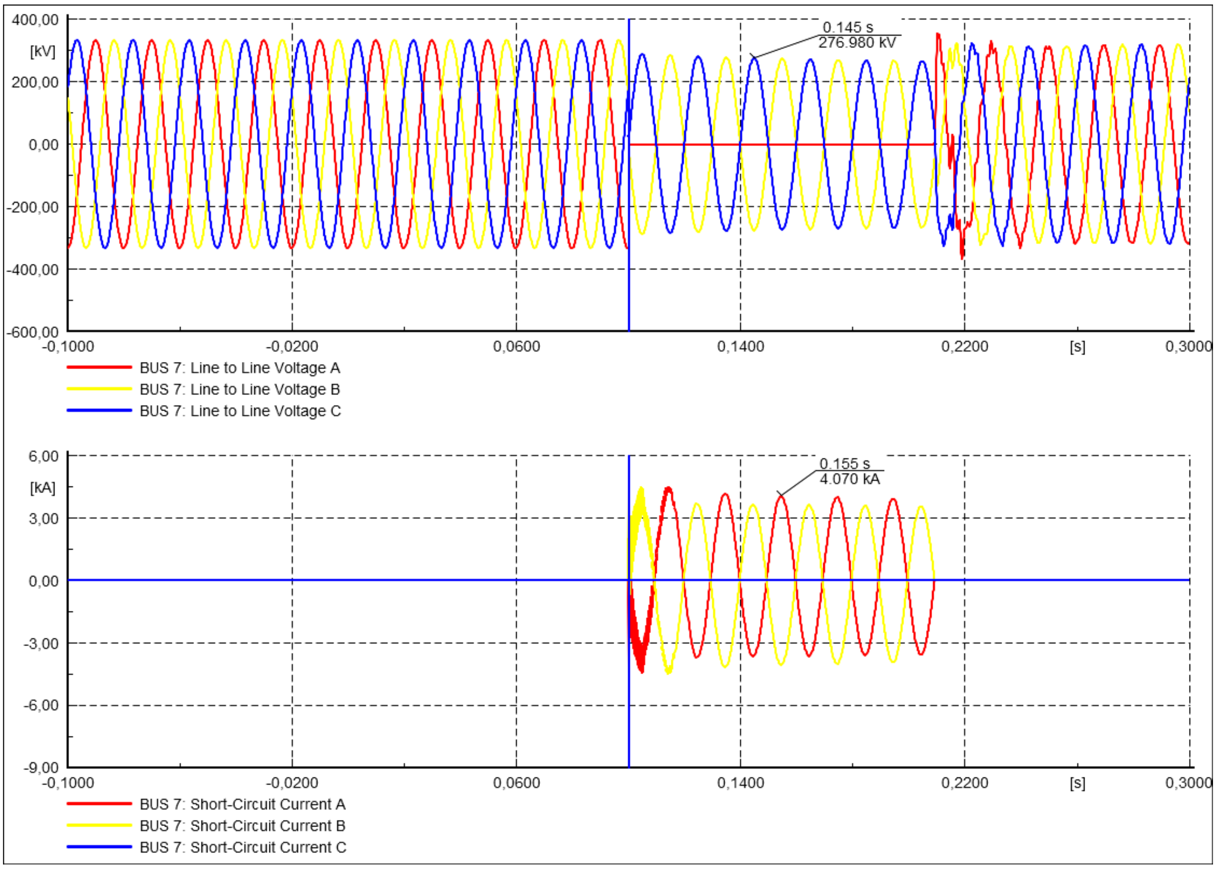


Figure 4.19: Voltage and current Plots for two phase external fault at Bus 7

Table 4.17: SEL 700G relay response to two-phase external fault

```
-----------------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                                  |
| Short-Circuit Calculation / Method : complete                                    2-Phase Short-Circuit    / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                    | Fault Impedance                          |                                         |
|    Break Time                  0,10 s |      Resistance, Rf              0,00 Ohm |                                         |
|    Fault Clearing Time (Ith)   0,20 s |      Reactance, Xf               0,00 Ohm |                                         |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                    System Stage: Grid             | Study Case: Study Case                  | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Differential relay                 Relay Type : SEL 700G 1A                                                                      |
|   Ct X   : CT X                    Location   : Busbar        : N Terminal          /               Ratio       : 5200A/1A     |
|                                                Branch        : G2                                   Connection  : Y            |
|                                                              :                                                                   |
|   Ct Y   : CT Y                    Location   : Busbar        : Y terminal          /               Ratio       : 5200A/1A     |
|                                                Branch        : G2                                   Connection  : Y            |
|                                                              :                                                                   |
|   Ct In : Ct in                    Location   : Busbar        : N Terminal          /               Ratio       : 5200A/1A     |
|                                                Branch        : Grounding Switch                     Phase 1     : a            |
|                                                              :                                                                   |
|   OutputLogic OutputLogic                                                           yout                :  9999,999 s          |
|     Breaker           Cubicle       Branch                  Busbar              / Substation      Fault Clearing Time          |
|      Switch            Cub_1        G2                       N Terminal          /                          9999,999 s          |
-----------------------------------------------------------------------------------------------------------------------------------
```

Figure 4.20 below shows the current comparison differential plot for two-phase external fault at bus 7. It is observed that the differential relay trip response time is 9999.99s. This means that the relay did not response to the external applied fault.

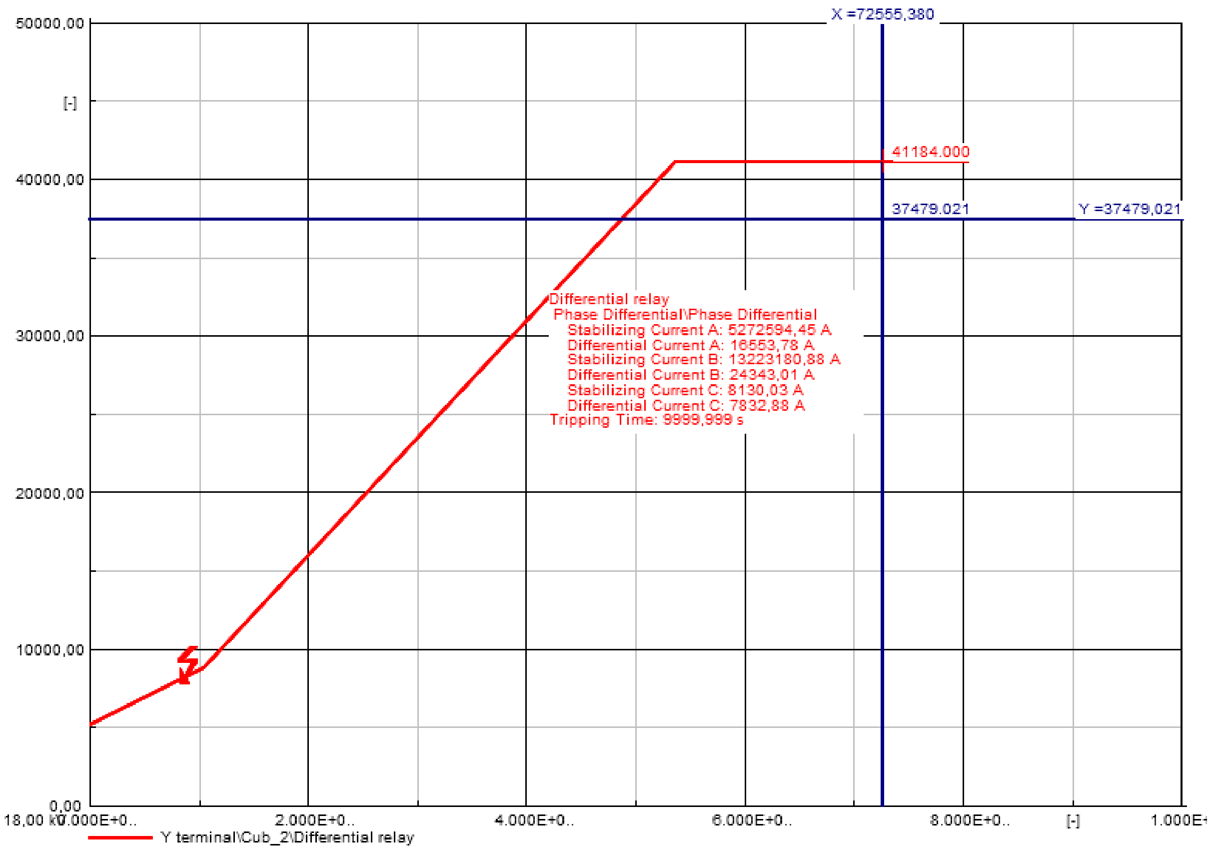


Figure 4.20: Current comparison differential plots for two-phase external fault

4.5.2.4 Two phase to ground short circuit external fault

This case study aims to analyse the performance of differential relay elements for a two-phase to ground short circuit external fault. The two-phase to ground fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

As it can be observed in figure 4.21, the two-phase to ground external fault at bus 7 generates a short circuit current of 2.101kA. The terminal voltage of phase B and phase C drops to the magnitude of 66.906 kV.

Table 4.18 shows the results performance of differential relay when the two-phase to ground external fault is applied. It is observed that the relay tripping time response is 9999.99 seconds, this means that the relay did not trip for the external fault applied.

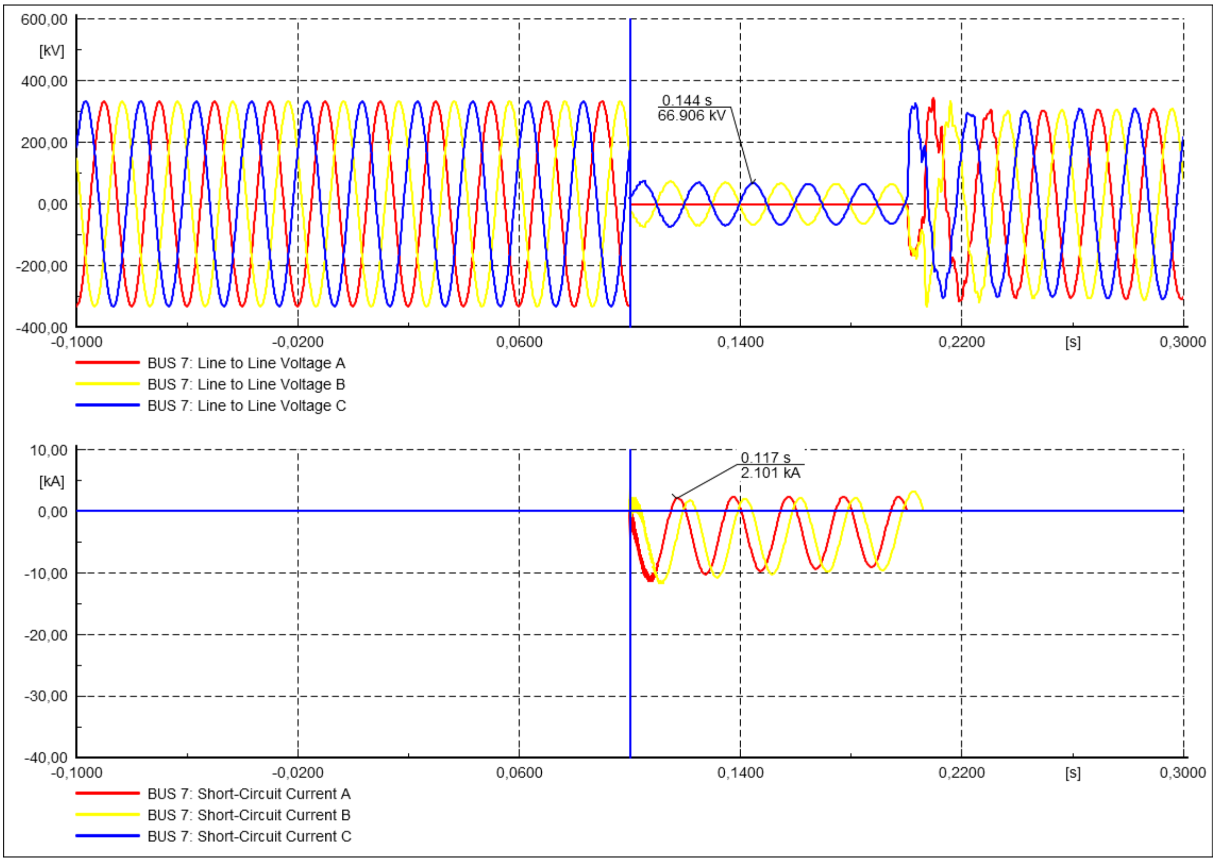


Figure 4.21: Voltage and current Plots for two-phase to ground external fault

Table 4.18: SEL 700G relay response to two-phase to ground external fault

```
-----------------------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                                           |
| Short-Circuit Calculation / Method : complete                        2-Phase to Ground        / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                  | Fault Impedance                  |                                            |
|    Break Time                  0,10 s |    Resistance, Rf           0,00 Ohm |                                            |
|    Fault Clearing Time (Ith)   0,20 s |    Reactance, Xf            0,00 Ohm |                                            |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid             | Study Case: Study Case                | Annex:           / 1  |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Differential relay               Relay Type : SEL 700G 1A                                                                 |
|   Ct X  : CT X                   Location   : Busbar      : N Terminal        /            Ratio      : 5200A/1A        |
|                                               Branch      : G2                              Connection  : Y               |
|                                                           :                                                               |
|   Ct Y  : CT Y                   Location   : Busbar      : Y terminal        /            Ratio      : 5200A/1A        |
|                                               Branch      : G2                              Connection  : Y               |
|                                                           :                                                               |
|   Ct In : Ct in                  Location   : Busbar      : N Terminal        /            Ratio      : 5200A/1A        |
|                                               Branch      : Grounding Switch                Phase 1     : a               |
|                                                           :                                                               |
|   OutputLogic OutputLogic                                                   yout               :  9999,999 s          |
|     Breaker            Cubicle       Branch                Busbar            / Substation       Fault Clearing Time     |
|      Switch             Cub_1        G2                     N Terminal       /                         9999,999 s      |
-----------------------------------------------------------------------------------------------------------------------------
```

The Figure 4.22 below shows the current comparison differential plot for two-phase to ground external fault at bus 7. It is observed that the differential relay trip response time is 9999.99s. This means that the relay did not response to the external applied fault.

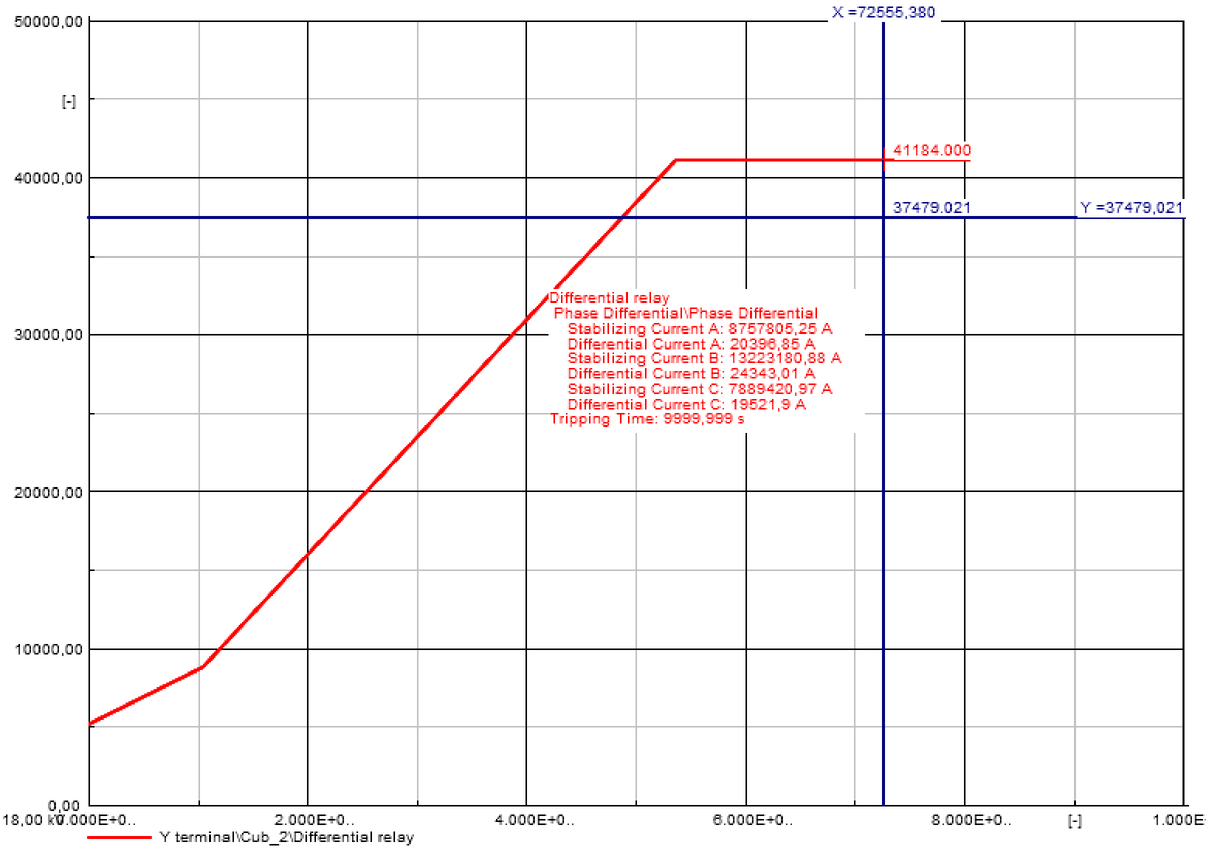


Figure 4.22: Current comparison differential plots for two-phase to ground external fault

In conclusion, the phase differential elements are implemented for dual slope angles. The settings for SEL700G relay model and its instrument transformer settings are described. The relay tripping time is verified for both internal and external events using the current comparison differential plot. The next section of this chapter presents the backup overcurrent protection scheme for a generator using the Dig-silent power factory simulation software. Simulation results are studied for both normal and abnormal conditions.

4.6 Overcurrent protection functions of a power generator.

The SEL700G relay model is used to evaluate the backup overcurrent protection system of a generator using the Dig SILENT power factory simulation program. At Bus 7, the relay is put into use. Overcurrent relays can be divided into three groups based on how the relay operates:

1. Instantaneous Overcurrent Relay
2. Define Time Overcurrent Relay
3. Inverse Time Overcurrent Relay (IDMT Relay)
    - Moderately Inverse
    - Very Inverse Time
    - Extremely Inverse
    - Directional overcurrent Relay

4.6.1 Definite Current relays

These kinds of relay start working instantly when the level of current exceed specific level. The configuration is made so that the relay will function for a low current value at the substation farthest from the source and that the operating currents of the relay grow gradually at each substation as one move closer to the source.

4.6.2 Definite Time relays

This kind of relay enables the configuration to be changed to accommodate various current levels by employing various operating times. The parameters can be changed such that the breaker closest to the fault trips in the shortest amount of time, followed by the other breakers trip in sequence with increasing time delays, moving back toward the source.

4.6.3 Inverse Time relays

As demonstrated by the characteristic curves above, the key characteristic of these relays is that they operate in a time that is inversely proportional to the fault current. They have a benefit over definite-time relays in that extremely high currents can be handled with substantially shorter tripping times without jeopardizing the protective selectivity.

4.6.4 Operating time of relay defined by IEC 60255 and IEEE C37.112

The same methods are performed for the subsequent upstream relay until the settings of the uppermost relay are determined. The operation time as specified by IEEE C37.112 and IEC 60255 is:

$$t = \frac{k(\beta)}{(\frac{I}{I_s})^{\alpha} - 1} + L$$

Where:

t Relay operating time in seconds

k Time dial or time multiplier setting

I Fault current level in secondary amperes

I_s Tap or pickup current selected

L Constant

α Slope constant

β Slope constant

Table 4.19 shows constant values of the parameters for curves defined by IEEE and IEC standards.

Table 4.19: IEEE and IEC constants for standard, overcurrent relays

IDMT curve description	Standard	α	β	L
Moderately inverse	IEEE	0.02	0.0515	0.114
Very inverse	IEEE	2	19.61	0.491
Extremely inverse	IEEE	2	28.2	0.1217
Inverse	US-CO8	2	5.95	0.18
Short-time inverse	US-CO2	0.02	0.02394	0.01694
Standard inverse	IEC	0.02	0.14	
Very inverse	IEC	1	13.5	
Extremely inverse	IEC	2	80.0	
Long-time inverse	IEC	1	120	

Table 4.20 show the overcurrent settings of SEL 700g relay model for phase element (50) to be investigated. Table 4.21 provides the current transformer data.

Table 4.20: Overcurrent settings on SEL700G relay model

Phase Elements Active	Name	Tripping Characteristics	I Pick-up	Time	Reset ratio	Direction
Yes	50PX1P	IEC Definite Time	1.2 Iref	0.01	0.95	none

Table 4.19: Instrument Transformer settings of the overcurrent protection scheme

Protection device	Location	Branch	Manufacturer	Model	CT	Slot	Ratio
Relay model	Bus 7	-	Schweitzer	SEL700G	CTX	Ct	600/1
					CoreCT	Ct	600/1

In this case study, the backup overcurrent relay's behaviour is examined for four different short circuit simulations, including:

- Three phase short circuit at Bus 7
- Single phase-to-ground short circuit at Bus 7
- Double phase-to-ground short circuit at Bus 7
- Two phase short circuit at Bus 7

4.6.5 Case study one: Three phase fault at bus 7

This case study aims to investigate the performance of backup overcurrent relay elements for a three phase short circuit fault at Bus 7. It should be considered that the differential relay was out of service when this case was conducted. The reason for this was to observe how the backup protections relay would perform if the main function which in this case was differential protection scheme was to fail to clear the fault.

The three-phase fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

The EMT simulation results are shown in figure 4.25 below. As it can be observed in Figure 4.23, the three phase fault was introduced at 0.1 seconds and it generated a short circuit current of 8.803kA, simultaneously the voltage of the three phases dropped to zero Volt until the fault was cleared at 0.2 seconds.

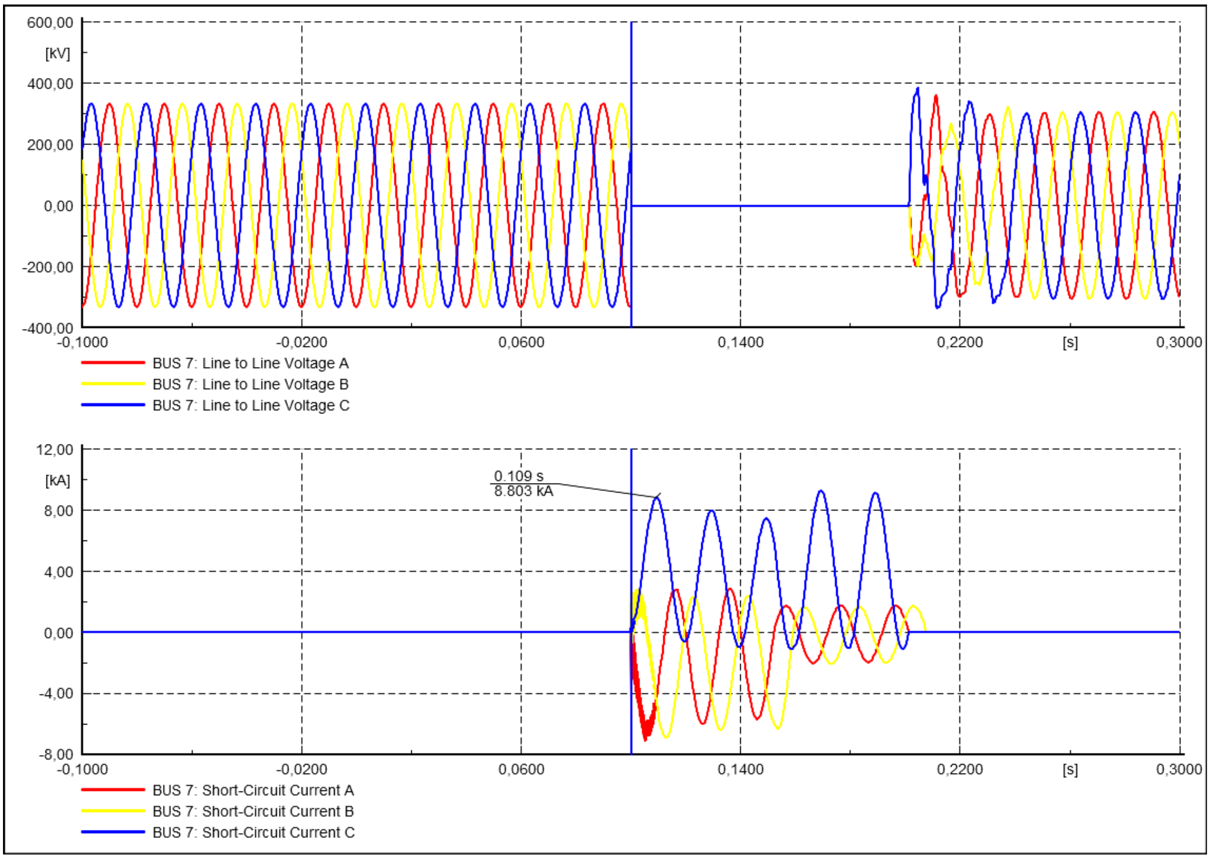


Figure 4.23: Voltage and Current signals for three phase fault at Bus 7

The Table 4.20 shows the results performance of overcurrent relay when the three phase fault is applied. It is observed that the relay tripping time response is 0.030s.

Table 4.20:SEL700G Overcurrent relay response to three phase fault

```
-----------------------------------------------------------------------------------------------------------------
| Relays Detailed                                                                                               |
| Short-Circuit Calculation / Method : complete                        3-Phase Short-Circuit    / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                 | Fault Impedance                 |                                  |
|    Break Time                 0,10 s |     Resistance, Rf            0,00 Ohm |                                  |
|    Fault Clearing Time (Ith)  0,20 s |     Reactance, Xf             0,00 Ohm |                                  |
-----------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------
| Grid: Grid                 System Stage: Grid          | Study Case: Study Case              | Annex:          / 1 |
-----------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------
| Back up overcurrent Relay        Relay Type : SEL 700G 1A                                                      |
|   Ct X  : CT1                    Location   : Busbar       : BUS 7             /          Ratio        : 600A/1A |
|                                               Branch       : T2                            Connection   : Y       |
|                                                            :                                                     |
|   Ct Y  : CT1                    Location   : Busbar       : BUS 7             /          Ratio        : 600A/1A |
|                                               Branch       : T2                            Connection   : Y       |
|                                                            :                                                     |
|   Ct In : CT1                    Location   : Busbar       : BUS 7             /          Ratio        : 600A/1A |
|                                               Branch       : T2                            Connection   : Y       |
|                                                            :                                                     |
|   OutputLogic Output Logic                                                      yout         :      0,030 s    |
|     Breaker              Cubicle       Branch              Busbar           / Substation   Fault Clearing Time   |
|      Switch               Cub_1         T2                  BUS 7            /                     0,030 s     |
```

Figure 4.24 below shows SEL700G relay time-overcurrent curve for three phase fault, it is used to analyse the response of back up overcurrent relay. The curve consist of phase element tripping times of three phase fault.it generated a fault of 1.905kA.it can be observe that the three phase fault triggered the phase element (50PX1P) of the relay. The definite time overcurrent element (50PX1P) clears at the fault at 0.030s.

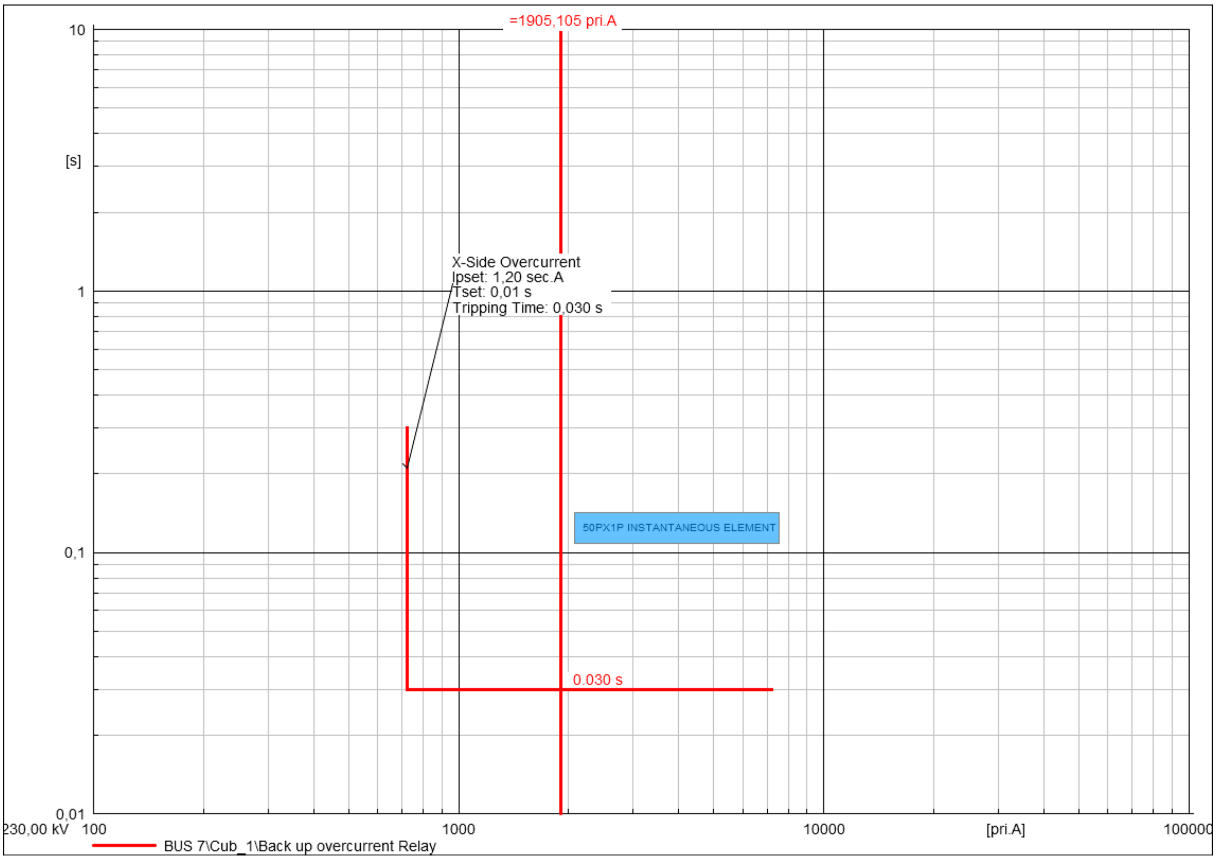


Figure 4.24: Time overcurrent curve for SEL700G relay response to three phase fault

4.6.6 Case study two: Single phase to ground fault at bus 7

This case study aims to investigate the performance of backup overcurrent relay elements for a single phase to ground short circuit fault at Bus 7.Technically, the main function should clears the fault but for this case it was out of service. Single phase to ground fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

The EMT simulation results are shown in figure 4.25 below. As it can be observed in Figure 4.25, the single phase to ground fault was introduced at 0.1 seconds and it generated a short circuit current of 3.865kA, simultaneously the voltage of the red and blue phases dropped to 166.236kV until the fault was cleared at 0.2 seconds.

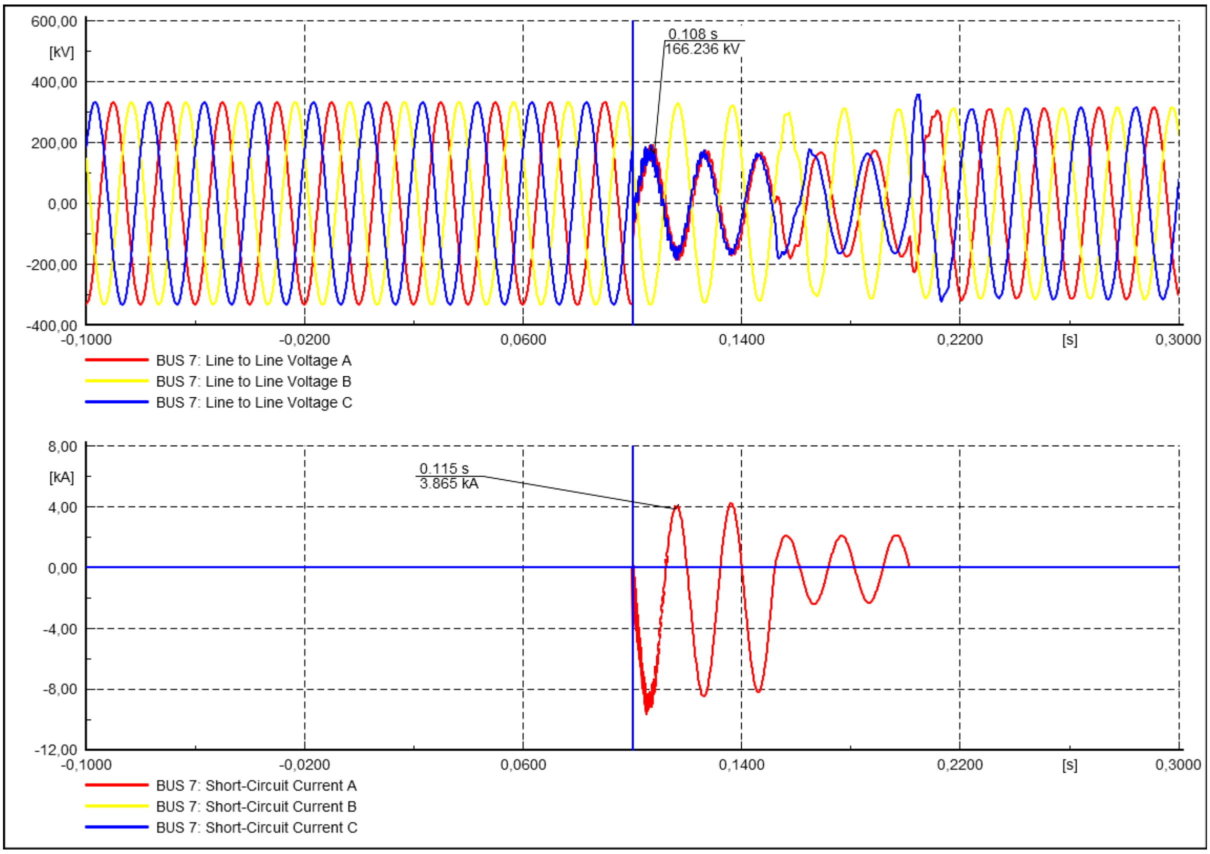


Figure 4.25: Voltage and Current signals for a single phase to ground fault at Bus 7

Figure 4.26 below shows SEL700G relay time-overcurrent curve for single phase to ground fault, it is used to analyse the response of back up overcurrent relay. The curve consist of phase and residual elements tripping times of single phase to ground fault.it can be observe that the single phase fault triggered both the phase and ground elements of the relay. The single phase to ground fault generated a fault current 3.103kA. The definite time overcurrent phase element (50PX1P) clears at 0.030s

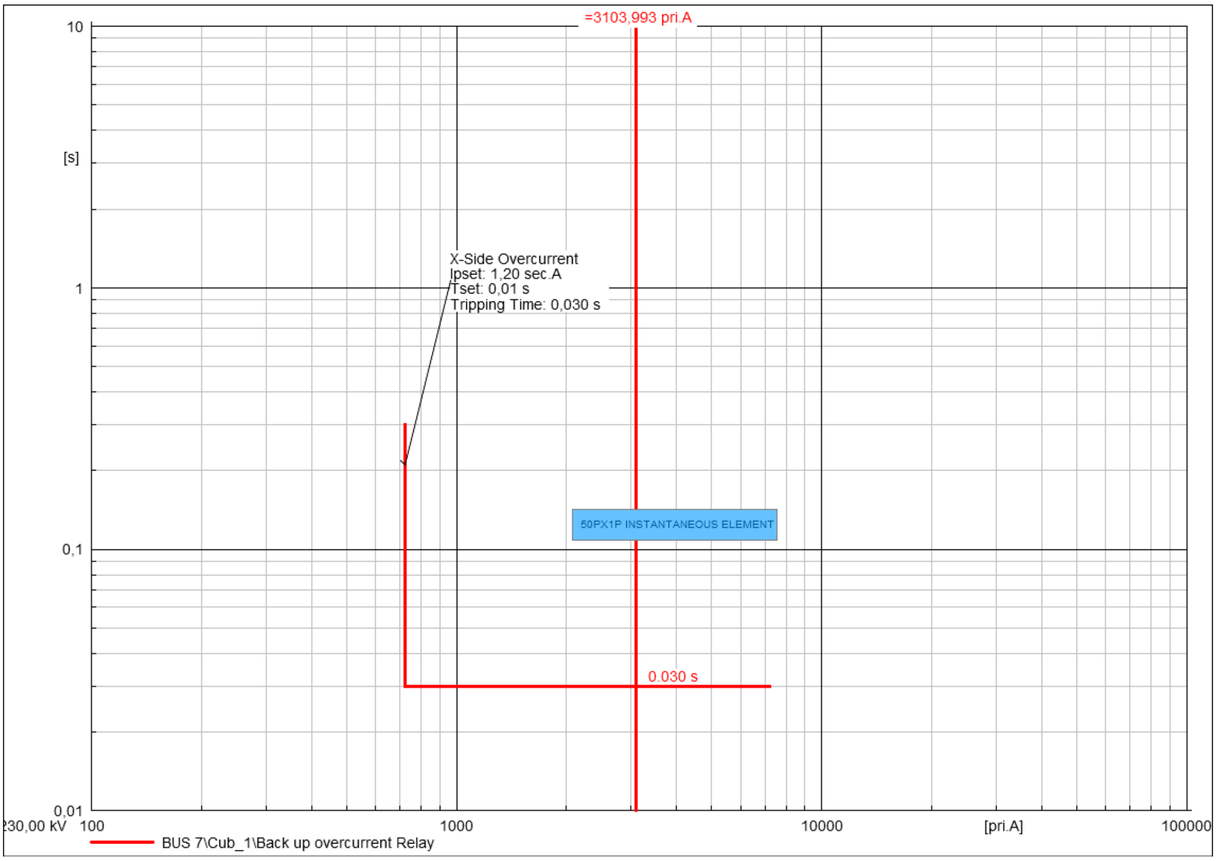


Figure 4.26: Time overcurrent curve for SEL700G relay response for single phase to ground fault.

4.6.7 Case study three: Double phase to ground fault at bus 7

This case study aims to investigate the performance of backup overcurrent relay elements for a double phase to ground short circuit fault at Bus 7.it should be noted that the main function should clear the fault but anyhow, for this case it was out of service to observe how the backup protections relay would perform if the main function which in this case was differential protection scheme was to fail to clear the fault.

Double phase to ground fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds.

The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds. The EMT simulation results are shown in figure 4.27 below. As it can be observed in Figure 4.27, the double phase to ground fault was introduced at 0.1 seconds and it generated a short circuit current of 1.329kA, simultaneously the voltage of the yellow and blue phases dropped to 150.057kV until the fault was cleared at 0.2 seconds.

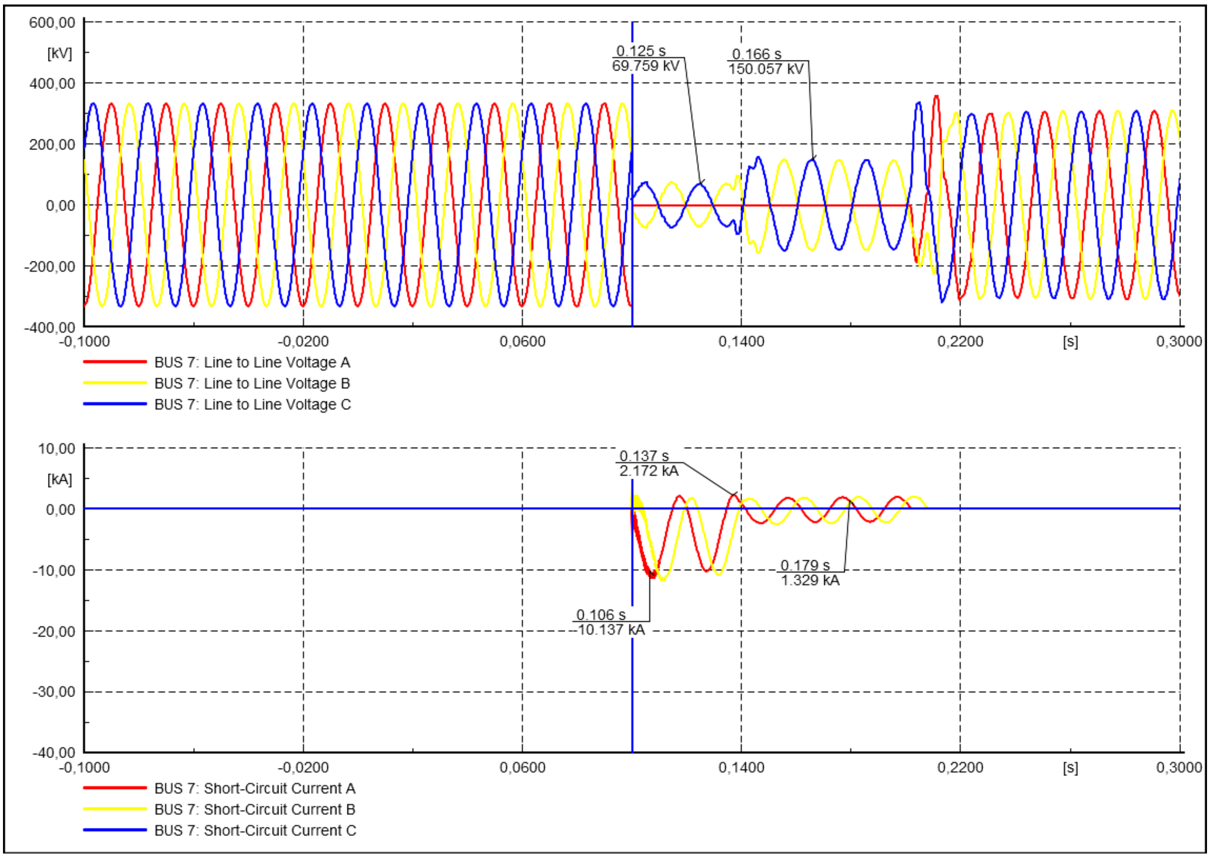


Figure 4.27: Voltage and Current signals for double phase to ground fault at Bus 7

Figure 4.28 provides phase elements of SEL700G overcurrent response. It can be observed that relay picks up the double phase to ground fault. When the double phase to ground fault was applied, it generated a fault current 3.640kA. The definite time overcurrent phase element (50PX1P) clears the fault at 0.030s as presented in Figure 4.28.

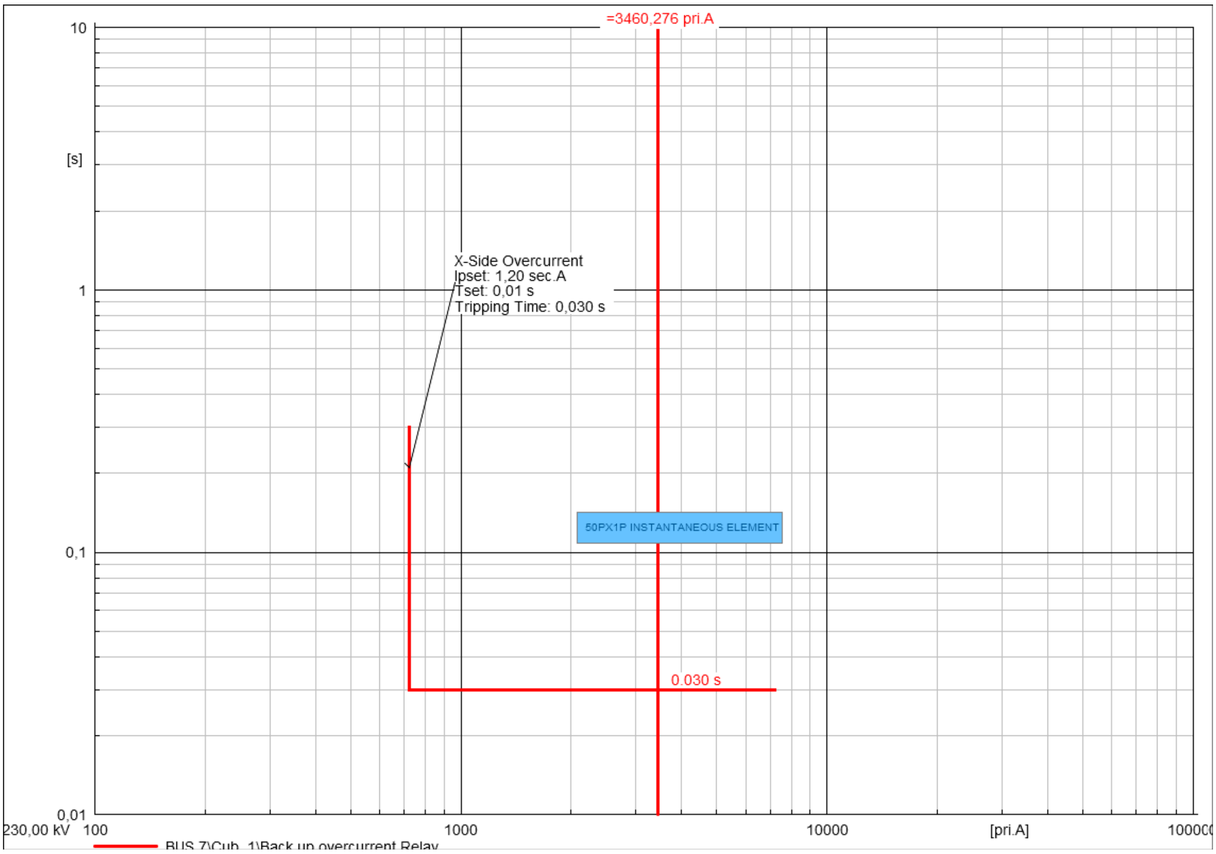


Figure 4.28: Time overcurrent curve for SEL700G relay response for double phase to ground fault.

4.6.8 Case study four: Two phase fault at bus 7

This case study aims to investigate the performance of backup overcurrent relay elements for a two short circuit fault at Bus 7.it should be noted that the main function should clear the fault but anyhow, for this case it was out of service to observe how the backup protections relay would perform if the main function which in this case was differential protection scheme was to fail to clear the fault. Double phase to ground fault is applied at bus 7 at the break out time of 0.1 seconds and is cleared at 0.2 seconds. The total Electro-Magnetic Transient (EMT) simulation time is set at 0.3 seconds.

The EMT simulation results are shown in figure 4.29 below. As it can be observed in Figure 4.29, two phase fault was introduced at 0.1 seconds and it generated a short circuit current of 4.382kA for the first 0.4s after the fault was introduced and eventually dropped to 1.639kA for the reminder of faulty period, simultaneously the voltages of the yellow and blue phases dropped until the fault was cleared at 0.2s.

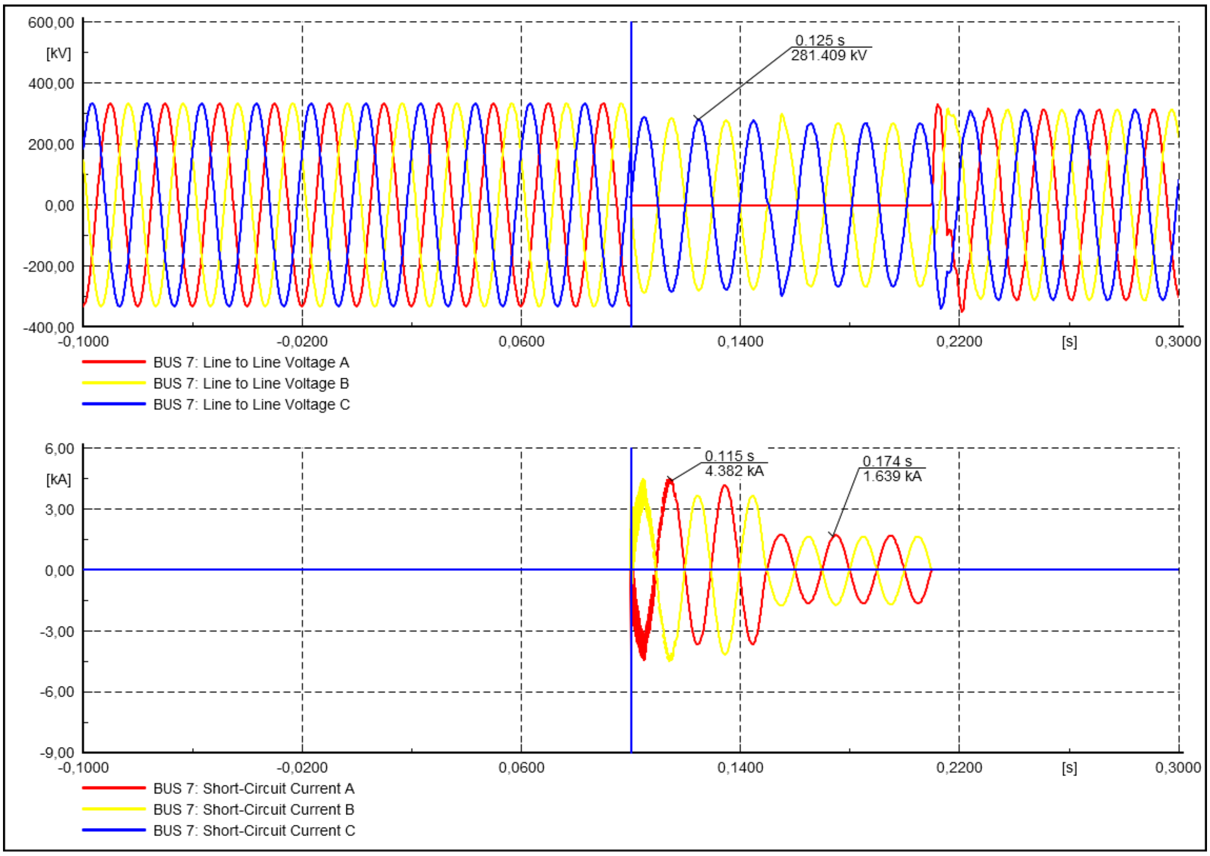


Figure 4.29: Voltage and Current signals for double phase to ground fault at Bus 7

Figure 4.30 presents the response of phase element of SEL700G overcurrent response. It can be observe that the two phase fault triggered only the phase elements of the relay. When the two phase fault was introduced, it generated a fault current 1.847kA. The definite time overcurrent phase element (50PX1P) clears at 0.030s

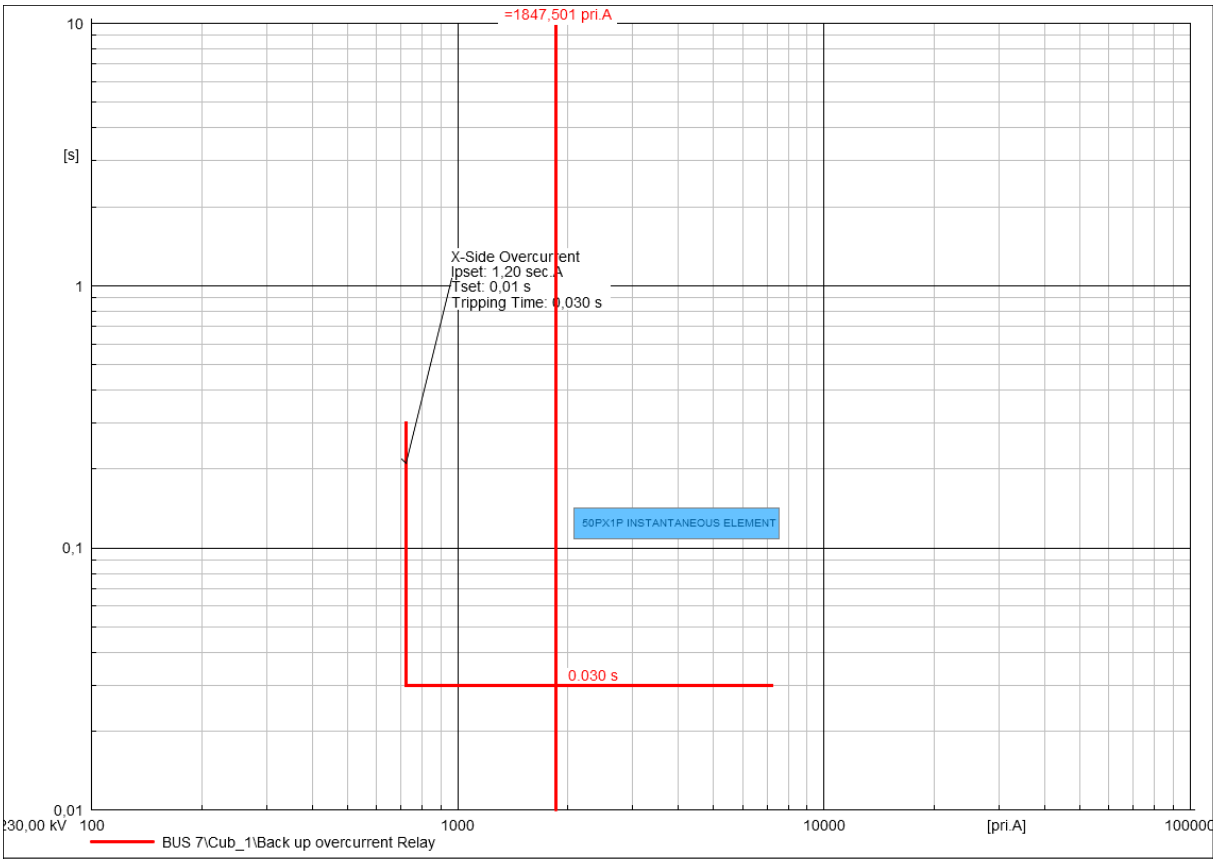


Figure 4.30: Time overcurrent curve for SEL700G relay response for two phase fault

4.7 Conclusion

In conclusion, this chapter has described the implementation of the differential and overcurrent protection schemes of a generator in a DIgSILENT power factory simulation environment. The IEEE 9 Bus system was used to simulate both the generator differential protection and backup overcurrent protection schemes on DIgSILENT simulation environment. Simulation results were studied and analysed for load flow calculations. The phase differential elements are implemented for dual slope angles. The settings for SEL700G relay model for differential protection scheme and its instrument transformer settings are described. The relay tripping time is verified for both internal and external events using the current comparison differential plot. This chapter also provide the implementation of back up overcurrent protection for generator using SEL 700G in a DIgSILENT simulation environment. Simulation results are studied for both normal and abnormal conditions. The next chapter provides the lab scale test bench setup to test volts per hertz, overcurrent, over and under voltage protection schemes for a generator.

CHAPTER FIVE
IMPLEMENTATION OF THE LAB SCALE TEST BENCH TO TEST VOLTS PER HERTZ, A BACK UP OVERCURRENT, OVER AND UNDER VOLTAGE PROTECTION SCHEMES FOR A GENERATOR

5.1 Introduction

Protective relaying plays a vital in power system protection. When a fault develops in the power system, protection devices increase the stability of the power system and prevent harm to the various facilities by rapidly and accurately identifying and correcting the fault (Won and Hyeon, 2012). For system disturbances in a generator, many protective strategies are used.

This chapter provides the lab scale test bench setup to test volts per hertz, the overcurrent, over and under voltage protection schemes for a generator. The SEL 700G relay only utilises the X-side of a generator for all four generator protection schemes. The 24 volts per hertz relay configuration settings which include the dual level V/Hz characteristics, simple inverse time characteristics as well as the composite inverse. The overcurrent relay configuration settings which include the definite time (50) characteristics are used as the backup protection of a generator.

This chapter provides the lab scale test bench setup to test volts per hertz, the overcurrent, over and under voltage protection schemes for a generator.in 5.2 the SEL 700G volts per hertz protection setting is presented, 5.3 present the overcurrent protection settings, 5.4 the SEL 700G over and under voltage protection settings of a generator is presented and 5.5 provides conclusion as presented in Figure 5.0..

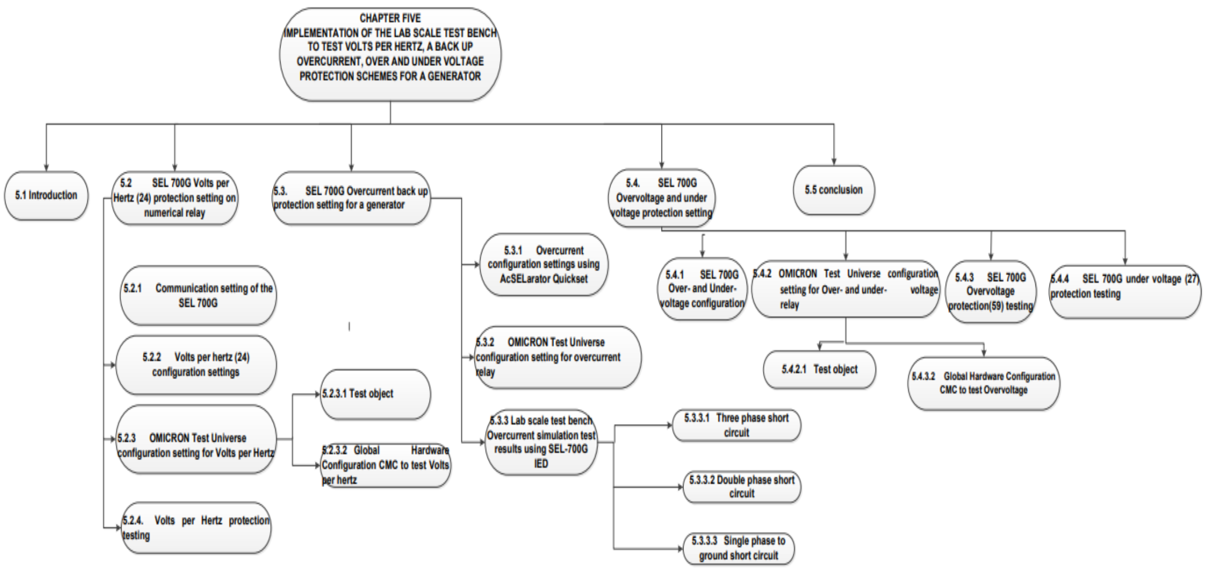


Figure 5.0: The summary of the content found in chapter five

The next sections provide the implementation lab scale test bench set up for volts per hertz, back up overcurrent, over voltage and under voltage protection scheme using SEL 700G IED relay.

5.2 SEL 700G Volts per Hertz (24) protection setting on numerical relay

This section provides the lab scale test bench setup for the 24 Volts per Hertz,. The protection elements are tested utilizing the CMC 356 Omicron test injection device. The volt per hertz lab scale test bench set up is shown in Figure 5.1. It has the generator intelligent electronic device (SEL 700G) protection elements, OMICRON test set (CMC 356) and a personal computer with the relay configuration tools (AcSELarator Quickset and test universe software). The Ruggedcom Ethernet switch (RSG 2288) connects to SEL 700G IED relay, personal computer and OMICRON CMC 356 test set for communication purposes using static IP network as shown in Figure 5.1.

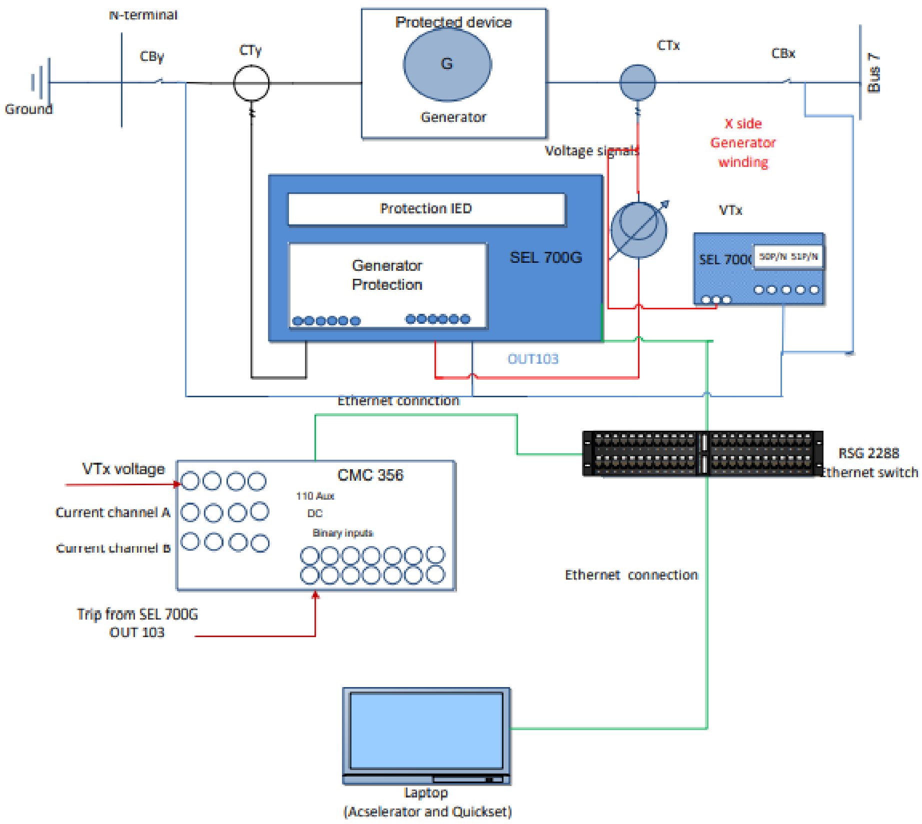


Figure 5.1: Volts per hertz (24) lab-scale test bench setup

The OMICRON test injection device is used to inject the voltage and frequency signals from a generator's x side into the voltage channel of the SEL 700G. Circuit breakers are attached to a generator's two ends (CBy and CBx). The voltage and frequency signals from the Y side of the generator are not taken into account in this lab scale test bench arrangement because the relay only uses the x side of a generator. The trip signal of the circuit breaker is expressed using binary signal attached to the output port (OUT103) of the SEL 700G. As shown in Figure 5.1, the binary input of the trip signal is subsequently mapped to that of the OMICRON test injection device.

5.2.1 Communication setting of the SEL 700G relay

AcSELerator Quickset is software that can be used to configure, commission, and administer SEL devices for power system monitoring, control, and metering. Relay serial ports are used by AcSELarator Quickset to communicate with the SEL relays.

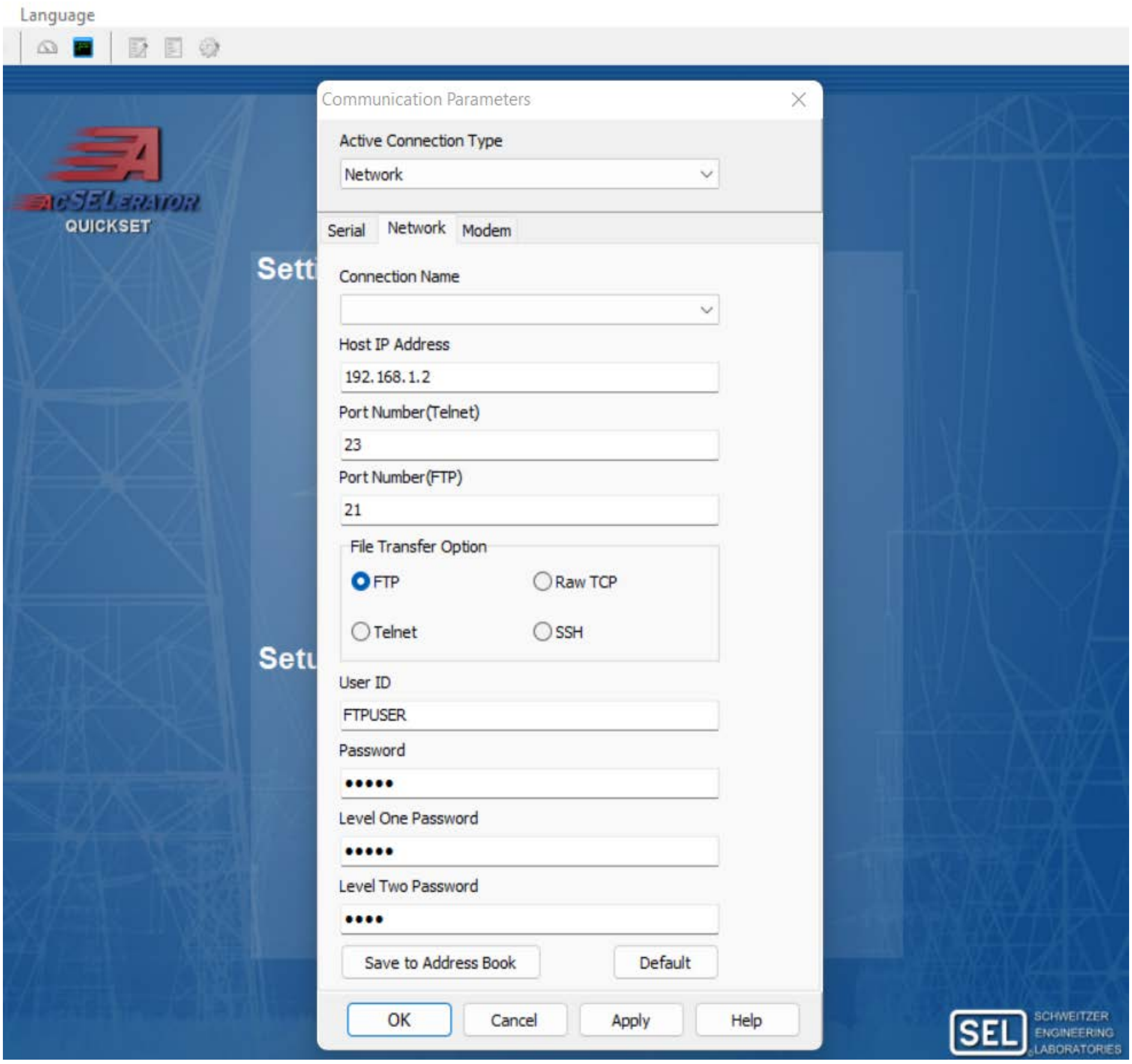


Figure 5.2: SEL 700G communication parameter setting on AcSELarator

The Figure 5.2 shows the communication parameters setting of SEL 700G. The IP address domain used in the communication must correspond with that of SEL 700G relay as well as with that of personal computer.

5.2.2 Volts per hertz (24) configuration settings using AcSELarator Quickset

This section outlines the volts per hertz (24) configuration settings using quickset. The volts per hertz(24) has three characteristics curve namely: dual level definite time volts per hertz characteristics(DD), simple time universe characteristics(I) and composite definite/universe time characteristics(ID). Table 5.1 provides the volts per hertz protection parameters of the three characteristics respectively. The table 5.1 also provides the voltage transformer settings and the overall generator data.

Table 5.1: Generator and volts per hertz protection setting data input

Parameter Name	Parameter Value	Description
Frequency	60Hz	Nominal system frequency
Generator Data	270MVA	Rated power
	13.8 kV	Rated voltage of the generator
VT data	230000 V/110 V	VT ratio of the x side of a generator
Dual level definite time volts per hertz characteristics(DD)	24D1P= 105%	Level 1 volts/hertz element as an over-excitation alarm
	24D1D=1s	Time delay of 1.0 second to allow time for correction of an over excitation condition prior to an alarm.
	24D2P1=110%	Dual-level definite-time level1 pickup
	24D2T1=45s	Dual-level definite-time level1 time delay
	24D2P2=120%	Dual-level definite-time level 2 pickup
	24D2T2=4s	Dual-level definite-time level 2 time delay
Simple time universe characteristics(I)	24IP=106%	Level 2 Inverse time pick up
	24IC=0.5	Level 2 Inverse Time Curve
	24ITD=4s	Level 2 Inverse Time factor
composite definite/universe time characteristics(ID)	24IP=106%	Level 2 Inverse time pick up
	24ITD=4	Level 2 Inverse Time Curve

	24D2P2=118%	Dual-level definite-time level 2 pickup
	24D2D2=3s	Dual-level definite-time level 2 time delay

The Table 5.2 below provides the current and voltage transformer ratio of the X side of a generator. The phase current transformer ratio is set at 600/1 and the voltage ratio is set 230kV/110V.

Table 5.2: Instrument transformer ratio

Abbreviation (Relay Word Bit)	Description of relay word bit	value
CTRN	Neutral Current Transformer Ratio	600
PTRS	Synchronising Voltage Potential Transformer ratio	2091
CTRX	X Side Phase Current Transformer ratio	600
PTRX	X Side Potential Transformer Ratio	2091
CTRY	Y Side Phase Current Transformer Ratio	600
PTRY	Y Side Potential Transformer ratio	2091

The Figure 5.3 below provides the general settings of SEL 700G volts per hertz relay which includes the nominal system frequency of 60Hz and the volts per hertz fault SELogic equation.

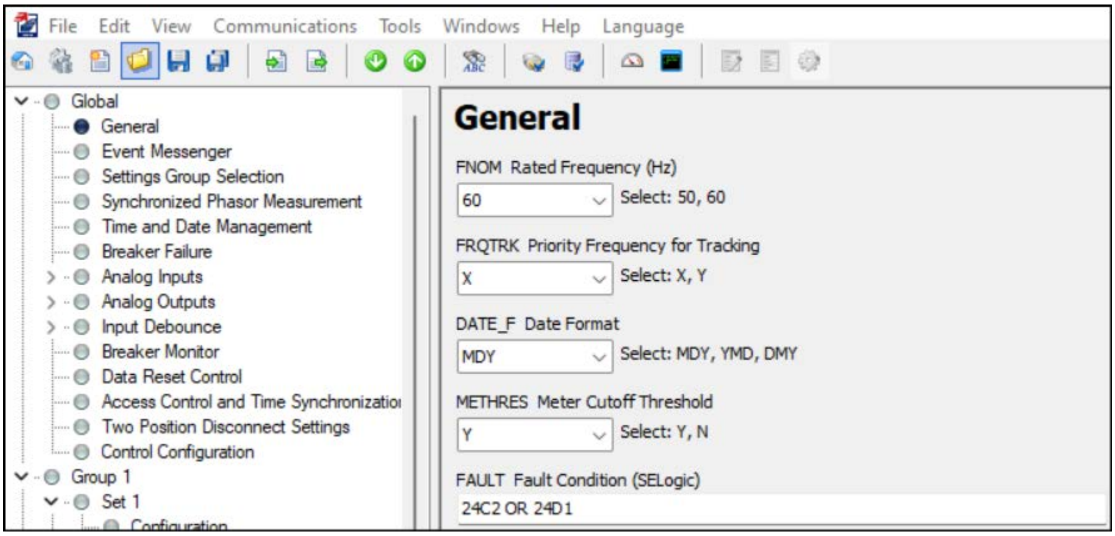


Figure 5.3: General setting of SEL700G IED on AcSELarator Quickset

The Table 5.3 provides the machine nominal Line to Line voltage of 230kV as well as nominal generator current of 1 amps. The nominal frequency of the machine is 60 Hz.

Table 5.3: Generator nominal Voltage, current and frequency

Abbreviation Relay Word Bit	Description of relay word bit	value
INOM	Nominal Generator Current(A)	1
VNOM_Y	Y Side Nominal L-L Voltage(kV)	230
VNOM_X	X Side Nominal L-L Voltage(kV)	230
FNOM	X Side Nominal Frequency(Hz)	60

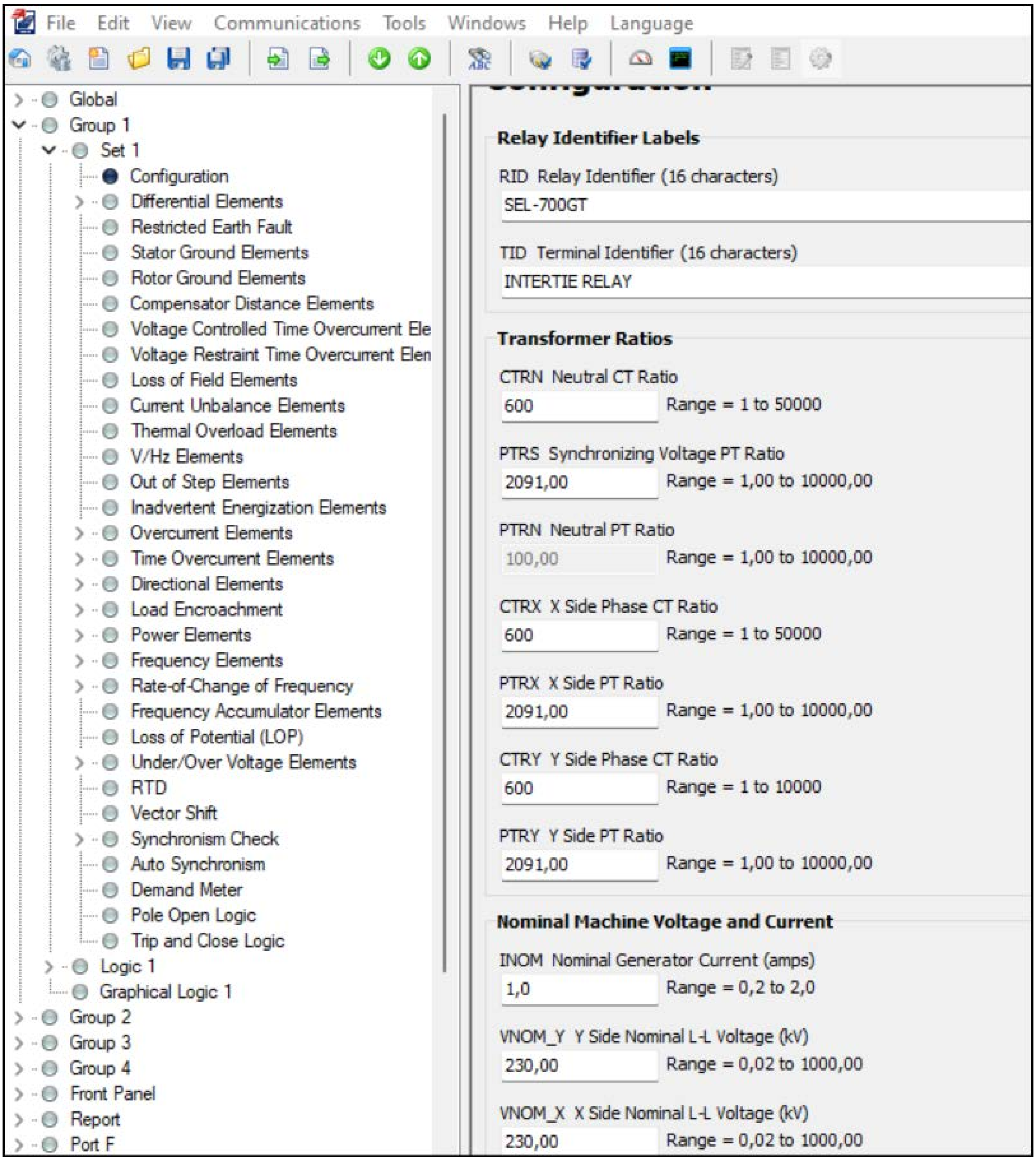


Figure 5.4: Instrument transformer ratio and nominal machine settings

Figure 5.4 offers the instruments configuration on quickset AcSELarator software application. It connects to the appropriate X side of a generator and has a current transformer ratio of 600 and a potential transformer ratio of 2091. It should be noted that all current transformers and potential voltage on a generator's Y side are not taken into account for this case study because the volt per hertz relay determines the actual V/Hz level by using the highest phase-to-phase voltage and the X-side frequency.

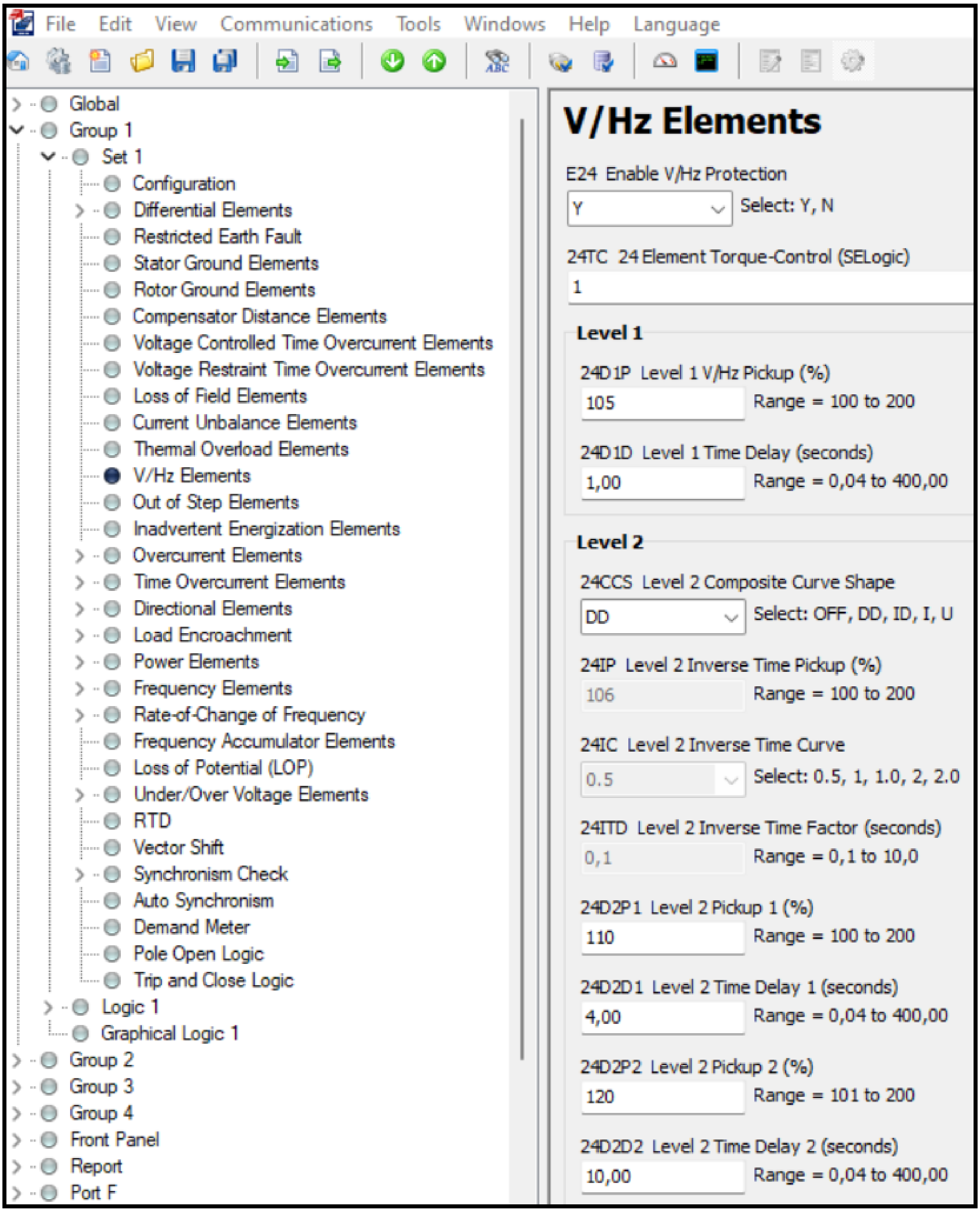


Figure 5.5: Volts per hertz configuration setting (24CCS=DD) in AcSELarator Quickset

The configuration setting for the 24 level 2 composite curve shape (24CCS=DD) is shown in Figure 5.5 below. As shown in Figure 5.5, the dual-level definite-time level 1 (24D2P1) and level 2 (24D2P2) pick up are set at 110 % at 4 seconds and 120 % at 10 seconds respectively. The level 1 volts per hertz element (24D1P), which serves as an over excitation alert, is set to 105 %

In the configuration settings for the SEL 700G's 24 level 2 composite curve shape (24CCS=ID), shown in Figure 5.6 below, the level 2 inverse time pick up (24IP) is set to 106 % with a 0.1-second time delay, and the dual-level definite-time level 2 pickup (24D2P2) is set to 120 % with a 10-seconds delay.

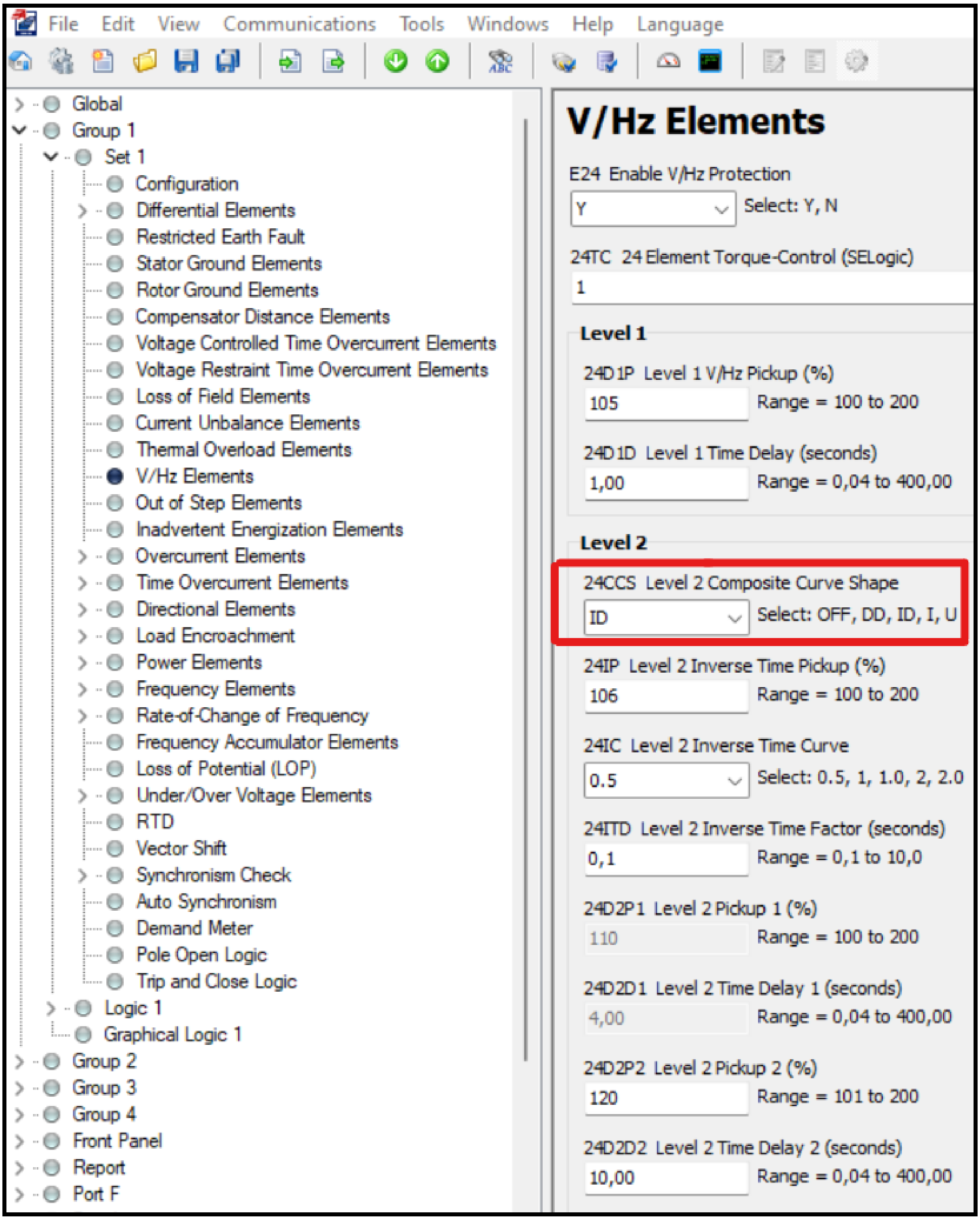


Figure 5.6: Volts per hertz configuration setting (24CSS=ID) in AcSELarator Quickset

Figure 5.7 below depicts the configuration settings for the SEL 700G's 24 level 2 composite curve shapes (24CCS=I), including the level 2 inverse time pick up (24IP) set at 106 percent with a 4 second time delay and a 0.5 degree curve selection.

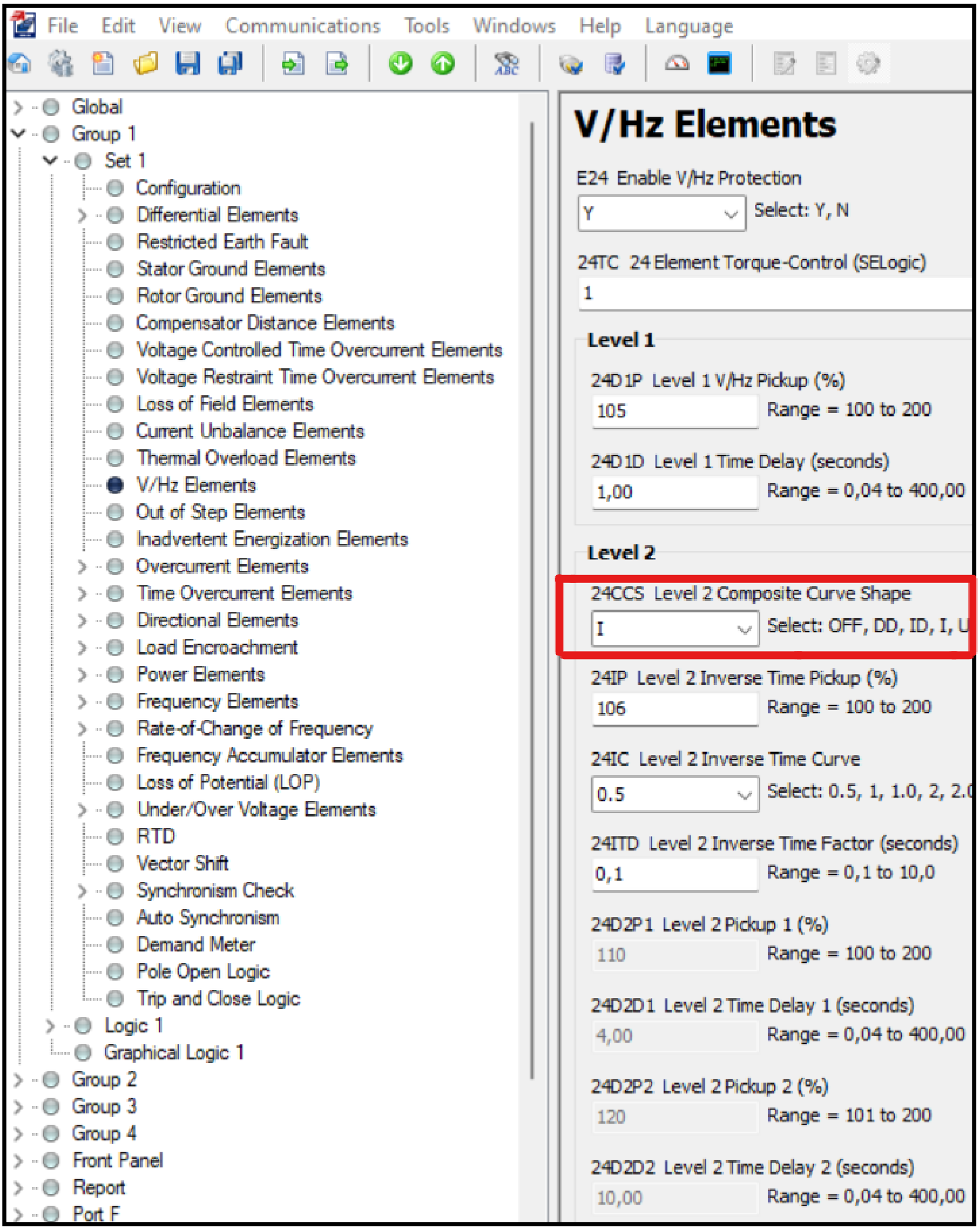


Figure 5.7: Volts per hertz configuration setting (24CCS=I) in AcSELarator Quickset

The trip and close logic settings for the SEL 700G contacts in slot A, which contain the relay word bits (24C2T OR 24DT1 OR TR1) that are set up to trip the field breaker and the generator's breaker X, are shown in Figure 5.7.

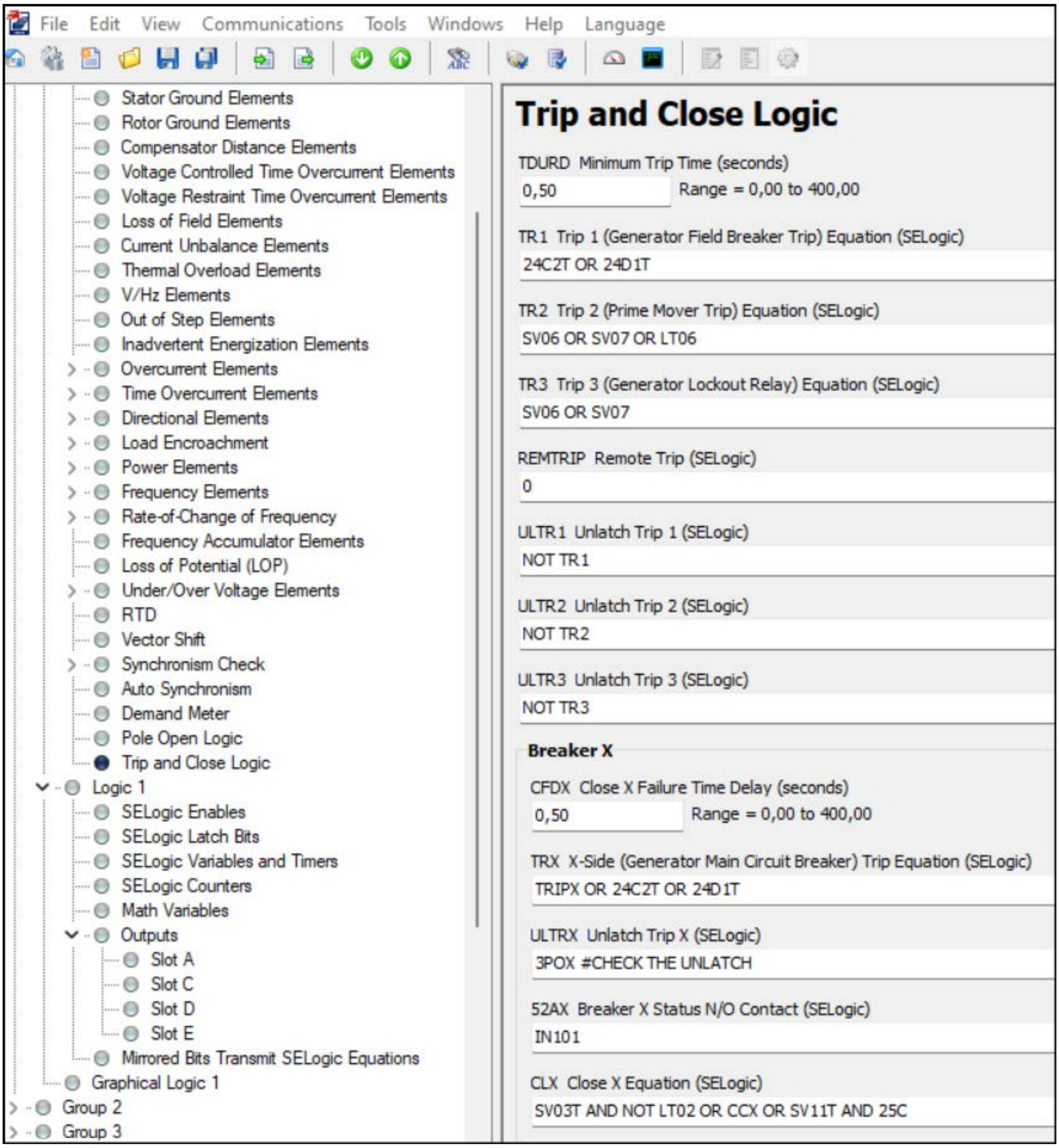


Figure 5.8: Trip and close logic configuration setting for V/Hz elements

Table 5.4 provides the Relay Word Bit utilized to implement the generator volts per hertz (24) protection scheme.

Table 5.4: Relay Word Bit of the generator volte per hertz protection relay

Abbreviation Relay Word Bits	Description of the relay word bits
24C2	Level 2 Volts/Hertz composite element pick up
24C2T	Level 2 Volts/Hertz composite element timed out
24CR	Level 2 Volts/Hertz element fully reset
24D1	Level 1 Volts/Hertz definite-time element pick up
24D1T	Level 1 Volts/Hertz definite-time element timed out

TRIP	Trip logic output
TRIPX	X side (Generator main circuit) breaker trip
TRX	Trip X SELogic equation
TRIP 1	Generator field breaker trip
TR1	Trip 1 SELogic equation
TR2	Trip 2 SELogic equation
TR3	Trip 3 SELogic equation
OUT103	Control equation for contact output OUT103
ER	Event report

The logic diagram for the volts/hertz elements is shown in Figure 5.9. The relay asserts the 24D1 Relay Word bit and activates the 24D1D timers if the torque control 24TC SELOGIC control equation is valid and the volts/hertz value exceeds the 24D1P setting. The relay asserts the 24D1T Relay Word bit if the condition persists for 24D1D seconds. This is typically used as an over-excitation alarm (SEL Relay Manual, 2018)

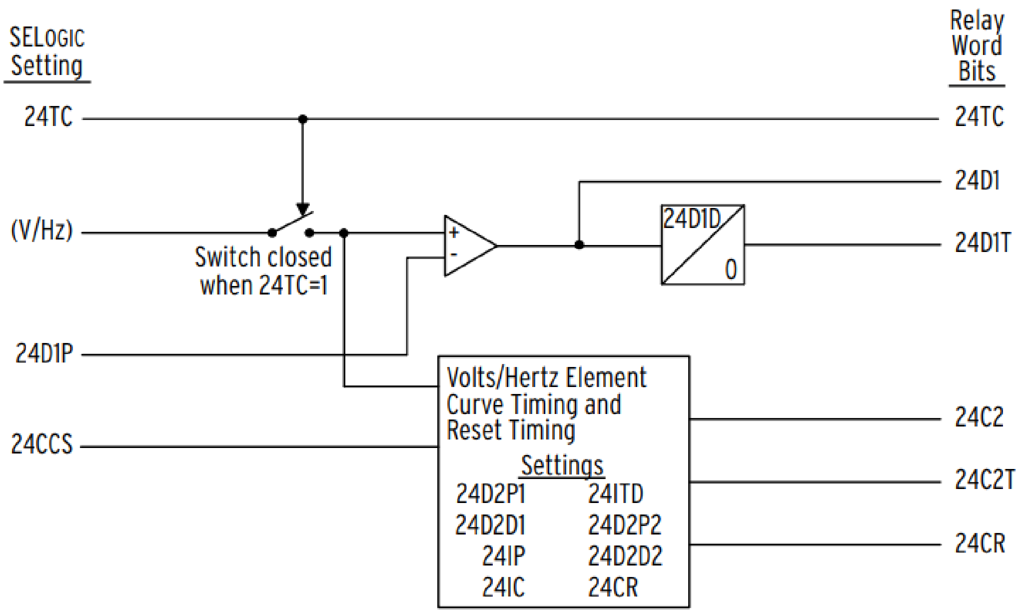


Figure 5.9: Volts per hertz trip logic (SEL Relay Manual, 2018)

5.2.3 OMICRON Test Universe configuration setting for Volts per Hertz

A software program called OMICRON Test Universe was created as an engineering tool for utilities and manufacturers to use in testing protection and measurement equipment. Modern hardware and user-friendly Windows-based software make up this system, which offers complete flexibility and adaptability to various testing applications. A variety of function-oriented test modules are also included. Volts per hertz configuration settings are provided in this section of OMICRON Test Universe (24).

5.2.3.1 Test object

This test item defines the relay settings. To accomplish this, start a fresh test document and double-click the test object as shown in Figure 5.9.

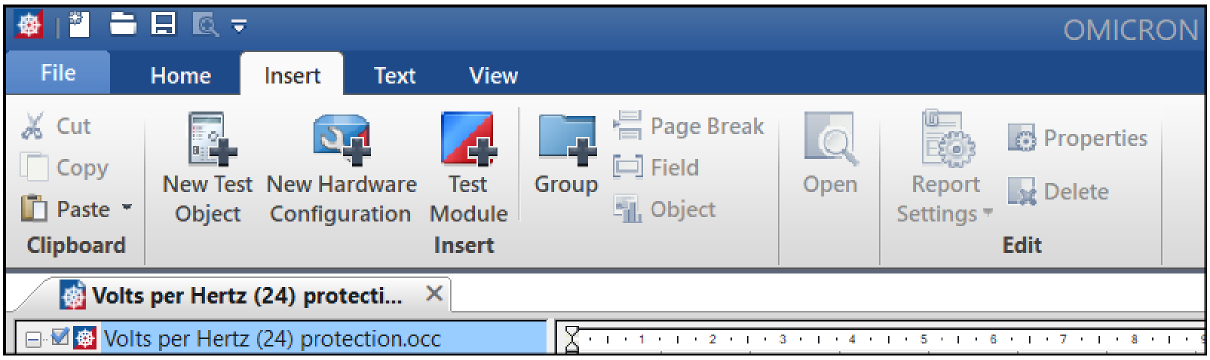


Figure 5.10: Defining the Test Object for SEL 700G on Test Universe software

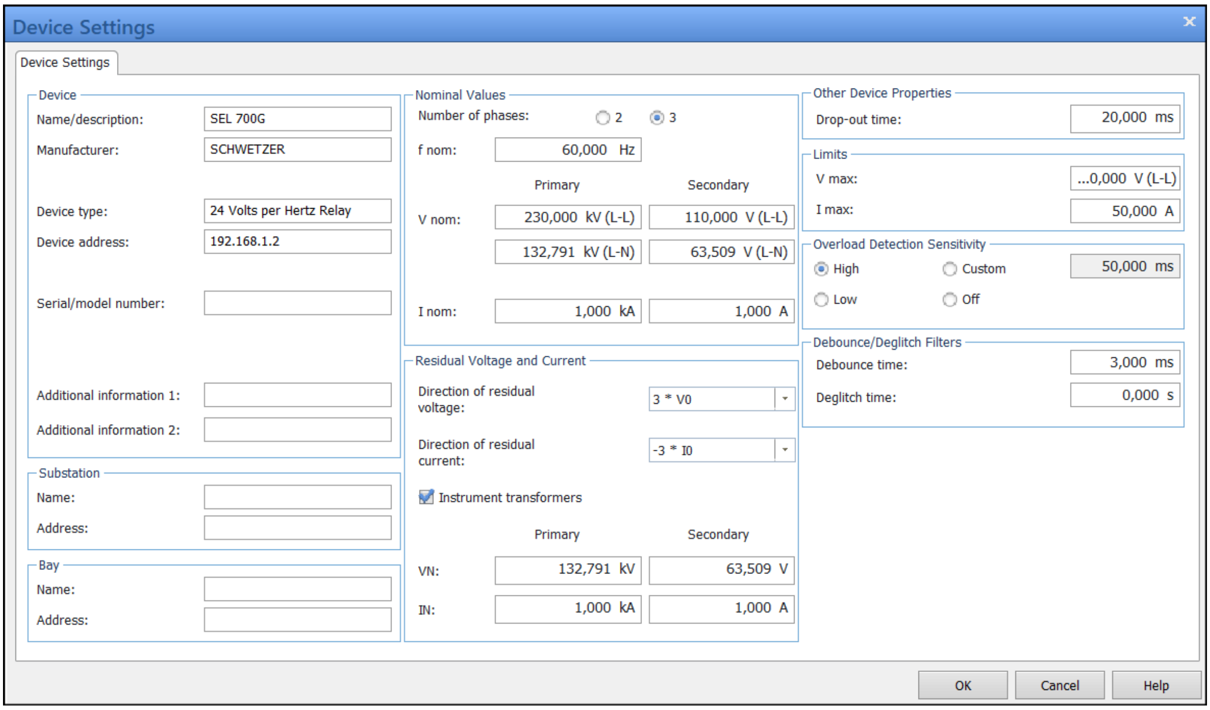


Figure 5.11: SEL700 Device settings on test universe

The Figure 5.11 provides the device settings which include the detail description of the protection relay .The relay settings (e.g. Substation, relay address, or current transformer and voltage transformer parameters) are entered into the RIO function Device. As provided in Figure 5.10, the values of primary and secondary voltages of the potential transformer are 230kV and 110V respectively. The nominal frequency of the generator is 60 Hz.

5.2.3.2 Global Hardware Configuration CMC to test Volts per hertz

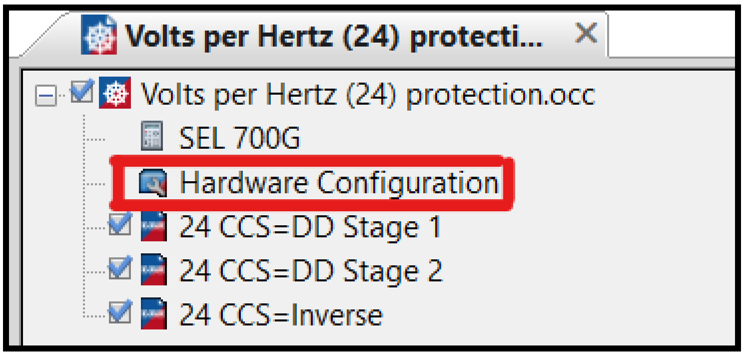


Figure 5.12: Global Hardware Configuration CMC to test Volts per hertz

The hardware configuration is defined according to the relay connection. This is done by double clicking on the hardware configuration entry in the OCC file as illustrated in Figure 5.12.

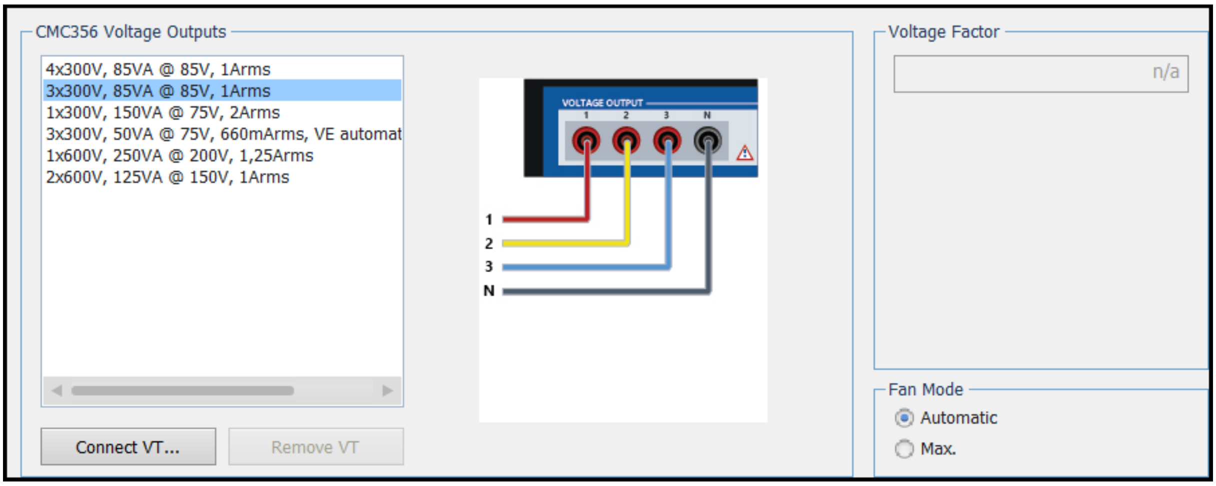


Figure 5.13: Output configuration of volts per hertz protection

Figure 5.13 shows the output configuration of volts per hertz protection scheme. The analogue outputs as well as the binary inputs and binary outputs are activated individually in the local Hardware Configuration of the specific test module. The volts per hertz protection scheme needs one set of voltage input which is provided by the voltage channel of the Omicron test set .The Voltage output was configured in the analogue output as presented in Figure 5.14 and the current outputs are not used for this study case.

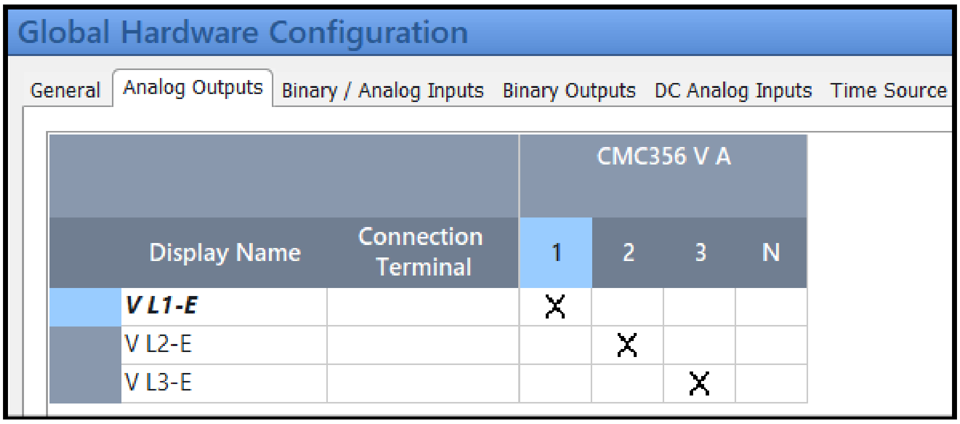


Figure 5.14: Analogue output of the volts per hertz relay

The command inputs can be connected using any Binary Input from (BI1) to Binary Input 10(BI10).The trip command is connected to binary input 1 as shown in Figure 5.15. The start command is optional; hence in this case it was not connected to any binary input. For wet contacts the nominal voltages of the binary inputs have to be adapted to the voltage of the circuit breaker trip command.

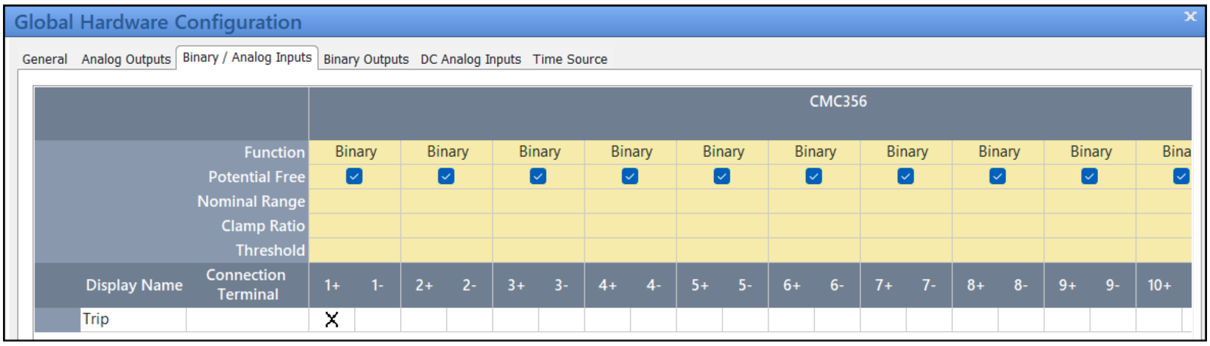


Figure 5.15: The trip signal of the volts per hertz protection scheme

5.2.4. Volts per Hertz protection testing

State Sequencer enables a CMC test set to deliver a defined sequence of states to a test object in real time. With automatic assessment, this can be used to calculate trip times or other time measurements. Each generator's amplitude, frequency, and phase can be adjusted by the State Sequencer for each individual state. The responses of the test object are time-dependently measured, recorded, and either automatically or manually analyzed after testing. The progression of the series can be controlled by specifying trigger circumstances. These events can be classified according to state persistence, test object reaction, or manual control. (Instructions for OMICRON, 2022) The State Sequence Test Module is used to test the protection against voltage per hertz.

For this case study, the behaviour of the 24 Volts per hertz relay is investigated for its three characteristics namely:

- Dual level Definite time characteristics volts per hertz relay stage 1
- Inverse time characteristics volts per hertz relay
- Combination of inverse-definite volts per hertz relay

5.2.4.1 Dual level definite time characteristics volts per hertz relay

This case study aims to analyse the performance of volts per hertz elements for Dual level definite time characteristics (DD) on the X-side of a generator. The volt per hertz relays are set at 110% and 120%for stage 1 and stage 2 respectively as shown in Figure 5.5.the values of volts per hertz to be injected are calculated using equation 5.1 below

When level of over excitation exceeded by 110%

$$\frac{V}{Hz} = \frac{V}{f} \tag{5.1}$$

$$= \frac{110}{60} \times 110\%$$

$$= 2.02\ Per\ Unit$$

The frequency to be injected is then calculated using the nominal voltage and Volts per hertz per unit value at 110%.

$$\frac{V}{Hz} = 2.02\ pu$$

$$f = \frac{110}{2.02}$$

$$f = 54.55Hz$$

The voltage to be injected using the frequency method is then calculated

$$\frac{V}{Hz} = 2.02\ pu$$

$$V = 2.02 \times 60$$

$$V = 121.2V$$

$$V = \frac{121.2}{\sqrt{3}}$$

$$= 69.97V$$

Therefore the fault state values to be injected for dual definite characteristics stage 1 is 69.97V at a frequency of 54.55Hz.Note that the nominal state utilises the generator nominal (RMS) values of the frequency and voltage.

Figure 5.16 provides nominal state and fault state values of dual definite settings for stage 1.

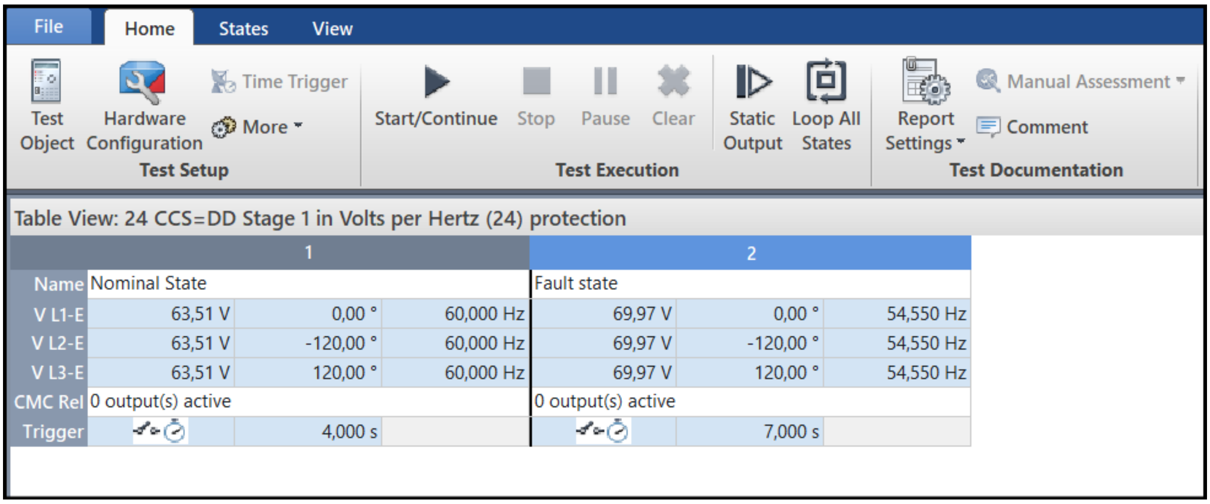


Figure 5.16: Nominal state and faults state values for DD stage 1

The detailed view of the fault condition is illustrated in Figure 5.17 below. It shows the values of voltages and frequencies to be injected.

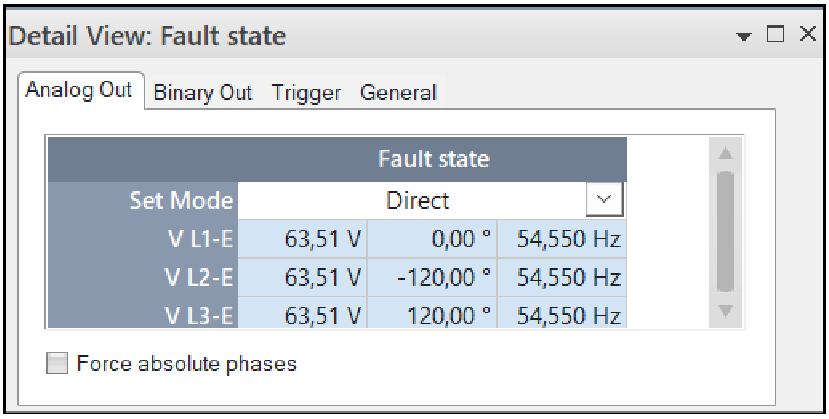


Figure 5.17: The detailed view of the fault condition for DD stage 1

The trip time of the relay is calculated using equation 5.2 below

$$T = \frac{0.003 \times K}{\{\frac{\frac{V}{Hz}}{100} - 1\}} \qquad (5.2)$$

Where T is the trip time of the relay in seconds

K is the time dial of the relay

V/Hz is the Over excitation value in percentage

Therefore

$$T = \frac{0.003 \times 45}{\{\frac{110}{100} - 1\}}$$

$$T = 13.5s$$

The binary trigger condition is set at Trip X and the time out is of the relay is set at 16s to allow some time reaction of the relay as shown in Figure 5.18 below.

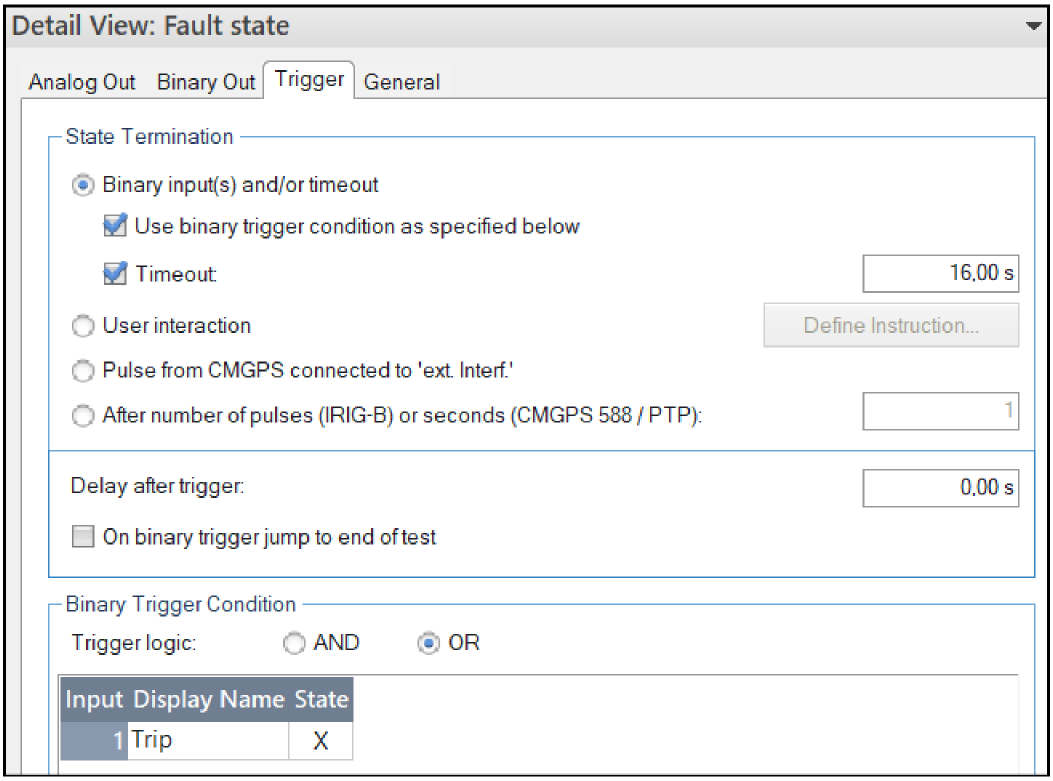


Figure 5.18: The state termination for DD stage 1

The Figure 5.19 shows the event file report of Dual Level Time characteristics Volts per Hertz Protection scheme.it is observed that the relay picked up the generator 24 volts per hertz alarm and execute trip signal after the volts per hertz value exceeded the threshold value.

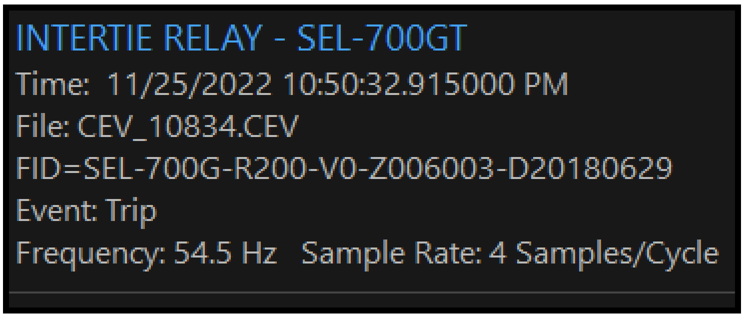


Figure 5.19: DD Event report file on Synchro event wave

The results of the dual level definite time characteristics relay are analysed using the AcSELerator Synchro event wave tool. The tool provides phase to phase voltages of 191.828 kV. The 24D1T element clear the over-excitation at 0.082s and TRX element trip the generator X breaker at 0.087 seconds, suppose if 24D1T fail to clear the fault as shown in Figure 5.20.

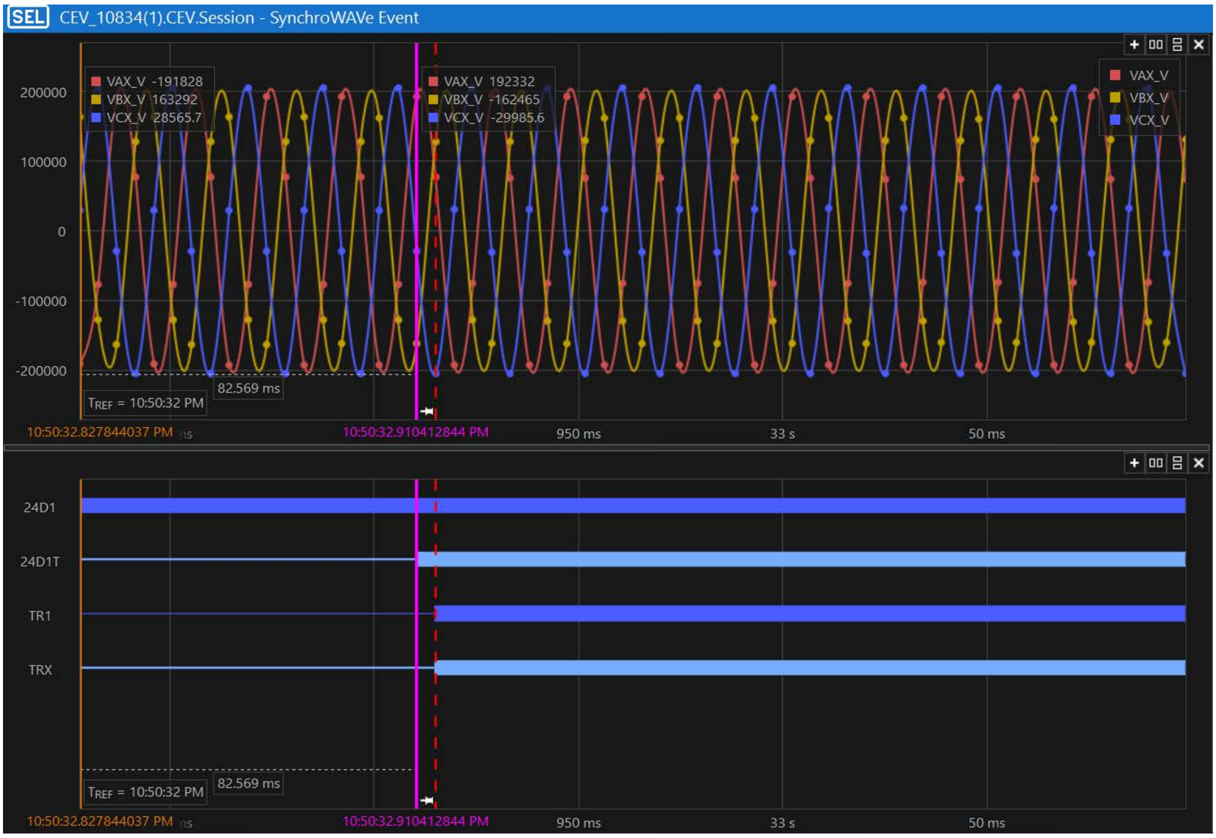


Figure 5.20: Phase to phase voltage and digital signals of the SEL 700G IED at V/Hz level 110%

When the volts per hertz value is exceeded by 120%

$$\frac{V}{Hz} = \frac{V}{f} \tag{5.3}$$

$$= \frac{110}{60} \times 120\%$$

$$= 2.2 \; Per \; Unit$$

The frequency to be injected is then calculated using the nominal voltage and Volts per hertz per unit value at 120%.

$$\frac{V}{Hz} \quad = 2.2 \; pu$$

$$f \quad = \frac{110}{2.2}$$

$$f \quad = 50Hz$$

The voltage to be injected is then calculated using the frequency method

$$\frac{V}{Hz} = 2.2\,pu$$

$$V = 2.2 \times 60$$

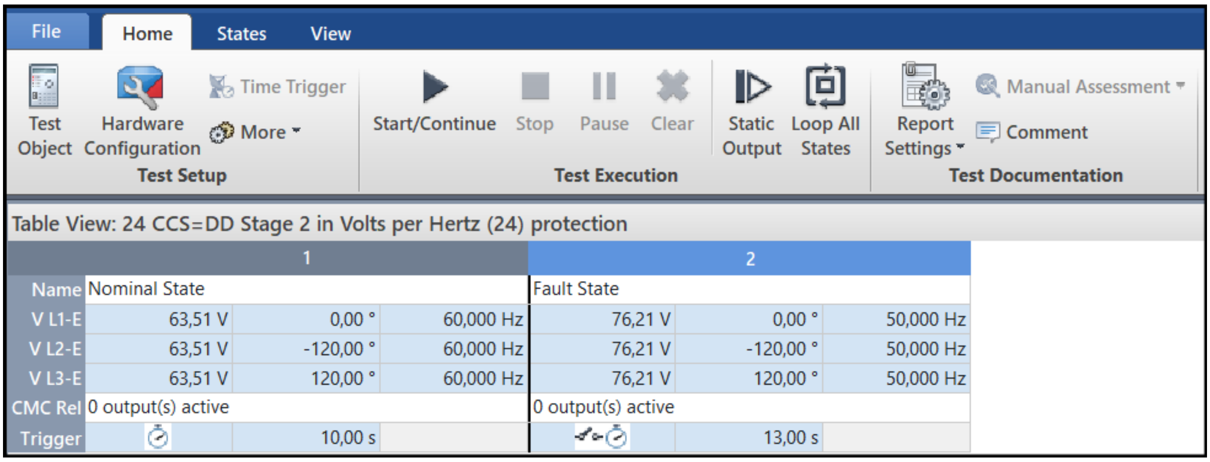
$$V = 130V$$

$$V = \frac{130}{\sqrt{3}}$$

$$= 76.21V$$

Therefore, the voltage and frequency values to be injected for dual definite characteristics stage 2 are 76.21V at a frequency of 50Hz. It should be noted that the nominal state utilises the generator nominal (RMS) values of the frequency and voltage

Figure 5.21 provides the nominal state and fault state values for dual definite level 2 settings. The trigger time is set at 3s.



	1			2		
Name	Nominal State			Fault State		
V L1-E	63,51 V	0,00 °	60,000 Hz	76,21 V	0,00 °	50,000 Hz
V L2-E	63,51 V	-120,00 °	60,000 Hz	76,21 V	-120,00 °	50,000 Hz
V L3-E	63,51 V	120,00 °	60,000 Hz	76,21 V	120,00 °	50,000 Hz
CMC Rel	0 output(s) active			0 output(s) active		
Trigger		10,00 s			13,00 s	

Figure 5.21: Nominal state and faults state values for DD stage 2

Figure 5.22 presented the behaviour of voltage signals and relay when the threshold value was exceeded. The results of the dual level definite time characteristics relay are analysed using the AcSELerator Synchro event wave tool. The AcSELerator Synchro event wave tool provides phase to phase voltages of 191.828 kV The 24D1T composite element clear the issue a trip after 0.090s, the TRX and TR1 elements of the generator breaker and field breaker issue the trip at 0.095s, suppose if 24D1T fail to clear the fault as shown in Figure 5.22.

Figure 5.22: Phase to phase voltages and trip signals of the SEL 700G at V/Hz level of 120%

5.2.4.2 Inverse time characteristics volts per hertz relay

This case study aims to analyse the performance of volts per hertz elements for inverse time characteristics (I) on the X-side of a generator. As provided in figure 5.6, the pickup value for the inverse time element is set at 106%. The values of volts per hertz to be injected are calculated as follows

$$\frac{V}{Hz} = \frac{V}{f} \tag{5.4}$$

$$= \frac{110}{60} \times 106\%$$

$$= 1.94\ Per\ Unit$$

The frequency to be injected is then calculated using the nominal voltage and Volts per hertz per unit value is 106%.

$$\frac{V}{Hz} = 1.94pu$$

$$f = \frac{110}{1.94}$$

$$f \quad = 56.70Hz$$

The voltage to be injected is then calculated using the frequency method

$$\frac{V}{Hz} \quad = 1.96\ pu$$

$$V \quad = 1.94 \times 60$$

$$V \quad = 116.4V$$

$$V \quad = \frac{116.4}{\sqrt{3}}$$

$$= 67.20V$$

Therefore, the voltage and frequency values to be injected for inverse time characteristics are 67.20V at a frequency of 56.70Hz. It should be noted that the nominal state utilises the generator nominal (RMS) values of the frequency and voltage.

Figure 5.23 provides the nominal state and fault state values for inverse time characteristics settings. The trigger time is set at 3s.

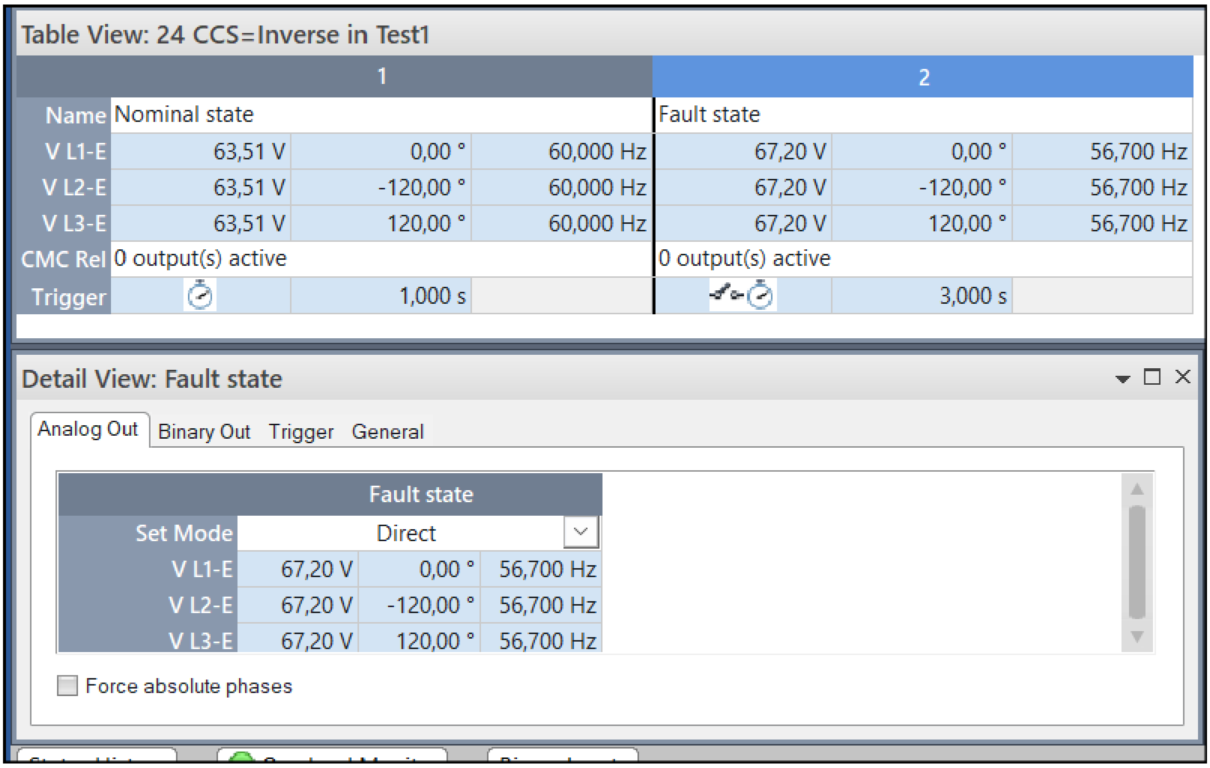


Figure 5.23: Nominal state and faults state values for inverse time characteristics

Figure 5.24 presented the behaviour of voltage signals and relay when the threshold value was exceeded. The 24C2T composite element of the inverse characteristics clear the over excitation condition at 0.0790s. The TRX and TR1 elements of the generator field and X breaker issues the trip at 0.085 seconds, supposedly 24C2T fail to clear the overexcitation as shown in Figure 5.24.

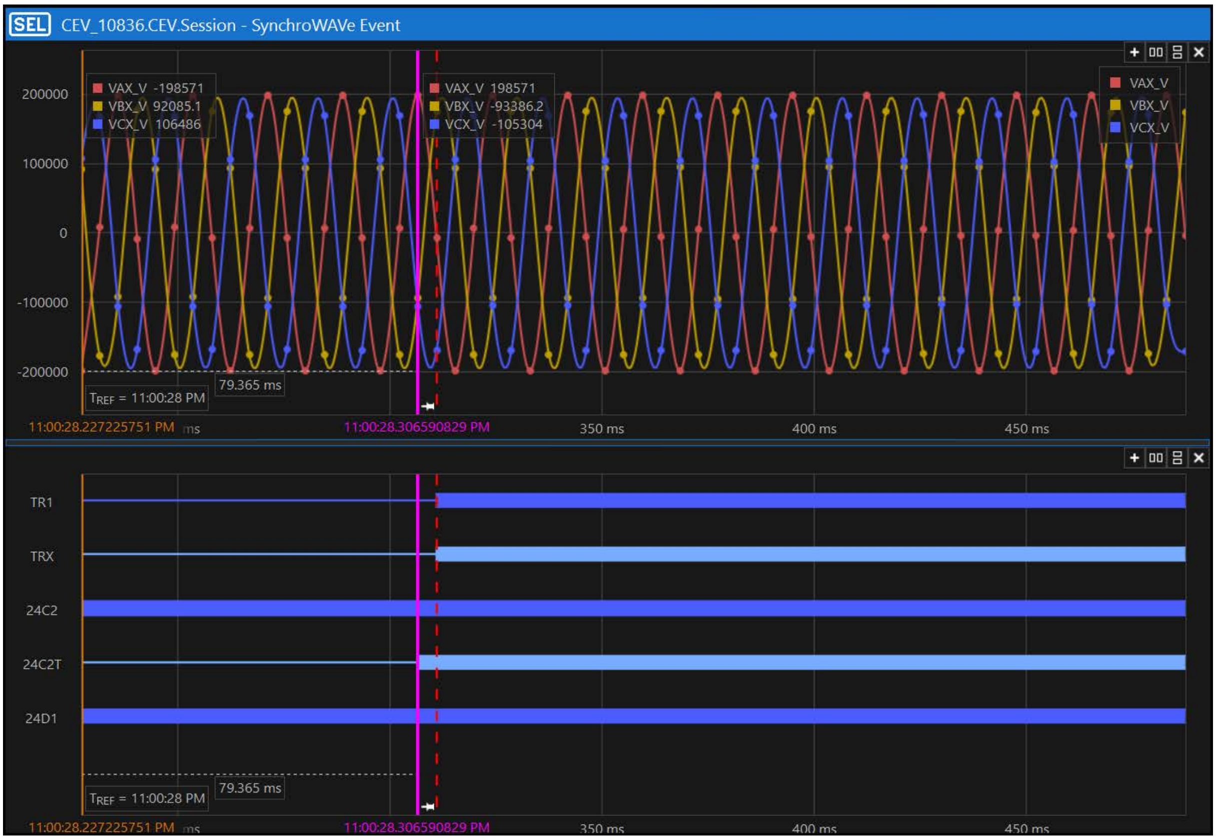


Figure 5.24: Phase to phase voltages, frequency and trip signals of the SEL 700G IED inverse time characteristics

5.3. SEL 700G Overcurrent back up protection setting for a generator

SEL 700G relay has an overcurrent function that serves as backup protection for a generator. This section provides the configuration settings of the SEL700G overcurrent backup relay Quickset acSELarator software and its lab scale test bench setup. The protection elements are tested utilizing the CMC 356 Omicron test injection device. The backup overcurrent relay lab scale test bench set up is shown in Figure 5.1. The simulation results are also provided and analysed in this section.

5.3.1 Overcurrent configuration settings using AcSELarator Quickset

The Figure 5.25 below shows the general settings of SEL 700G overcurrent relay which includes the nominal system frequency of 60Hz and the fault condition SELogic equation.

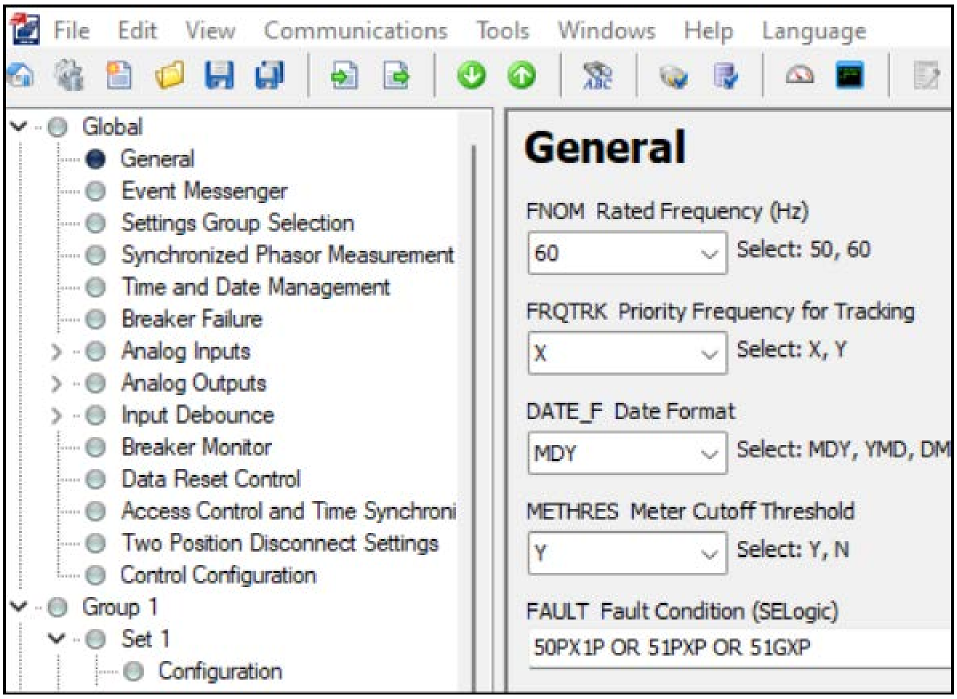


Figure 5.25: General settings of SEL 700G overcurrent relay

Table 5.5 provides the instrument transformer settings of SEL700G overcurrent relay. There are connected in the x side of a generator and valued at 600A.

Table 5.5: Current Transformer settings of SEL overcurrent relay

Abbreviation	Description	Value
CTRN	Neutral CT ratio	600
CTRX	X side CT phase ratio	600

Table 5.6 provides the Relay Word Bit utilized to implement the generator overcurrent protection scheme.

Table 5.6: Relay word bit of generator overcurrent relay

Abbreviation Relay Word Bits	Description of the relay word bits
50PX1P	X side definite time overcurrent trip level(Amps)
50PX1D	X side definite time overcurrent time dial
50PX1TC	X side definite time overcurrent trip level(Amps)
51PXP	X side phase time overcurrent trip level
51PXC	X side phase TOC curve selection
51PXTD	X side phase time overcurrent time dial
51PXTC	X side phase time overcurrent torque control
51GXP	X side residual time overcurrent trip level (amps)
51GXC	X side residual TOC curve selection
51GXTD	X side residual time overcurrent time dial

51GXTC	X side residual time overcurrent torque control.

.

Figure 5.26 provides the SEL 700G tripping logic diagram for overcurrent elements. These equations are designed to operate when the SELOGIC control equation trip variable setting TRX is asserted and to unlatch when the SELOGIC control equation setting ULTRX is asserted. The relay logic allows the conditions that cause a trip and unlatch the trip and mapped to the output contact of the relay.

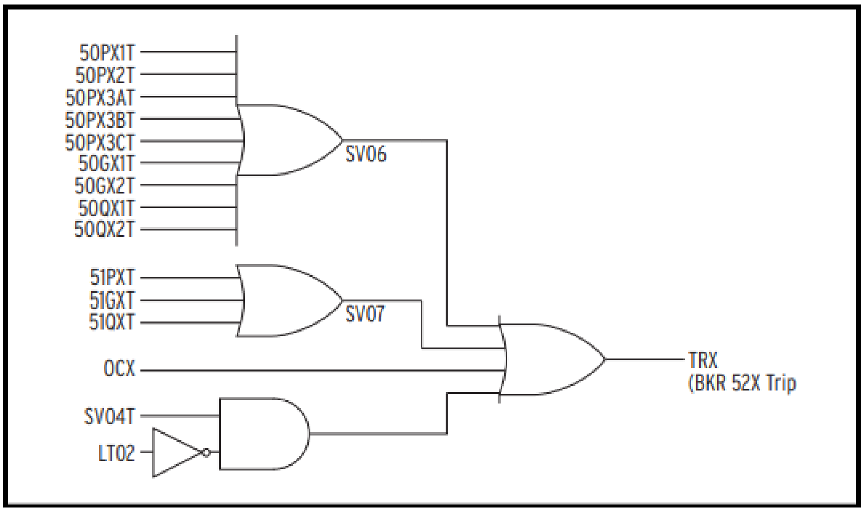


Figure 5.26: SEL 700G Trip logic Diagram(SEL Relay Manual, 2018)

5.3.2 OMICRON Test Universe configuration setting for overcurrent relay

The tests required for the non-directional overcurrent protection function are carried out using the Overcurrent test module. In this instance, the power transformer is protected as a backup by the non-directional overcurrent protection features. This section provides a definition of the Test Object settings and a description of the Hardware setup for non-directional overcurrent elements: The RIO function device, as shown in Figure 5.27, provides general relay settings such as relay type, relay ID, and substation information.

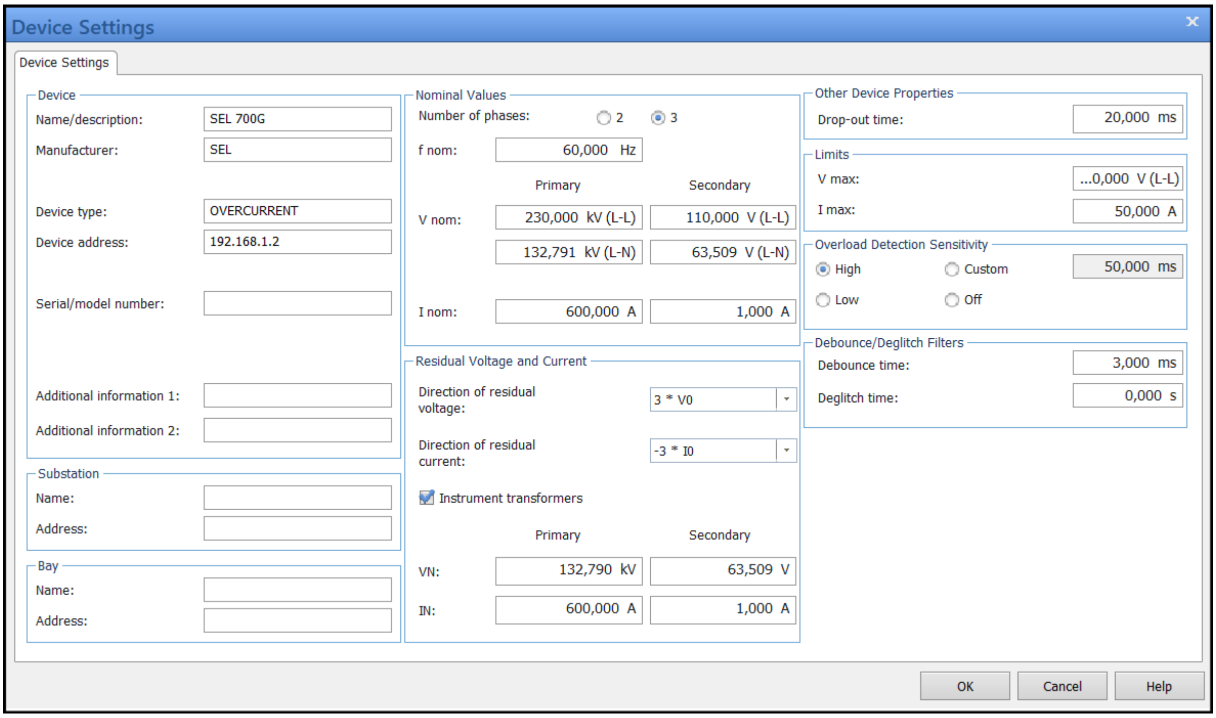


Figure 5.27: SEL 700G device setting in the Test Universe

5.3.2.1 Overcurrent relay parameters

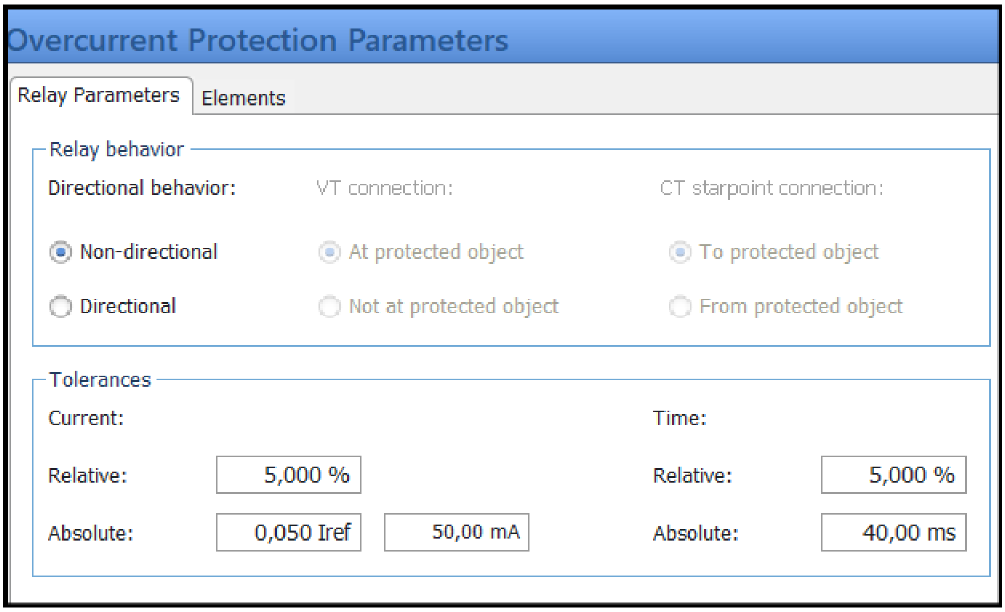


Figure 5.28: Overcurrent relay parameters

Figure 5.28 shows the overcurrent protection parameters. The description of the protection setting is given below:

- Non-directional overcurrent relay has to be activated for overcurrent protection setting.
- .The CT star point connection has to be set according to the connection of the secondary windings of the CT

5.3.2.2 Overcurrent relay elements

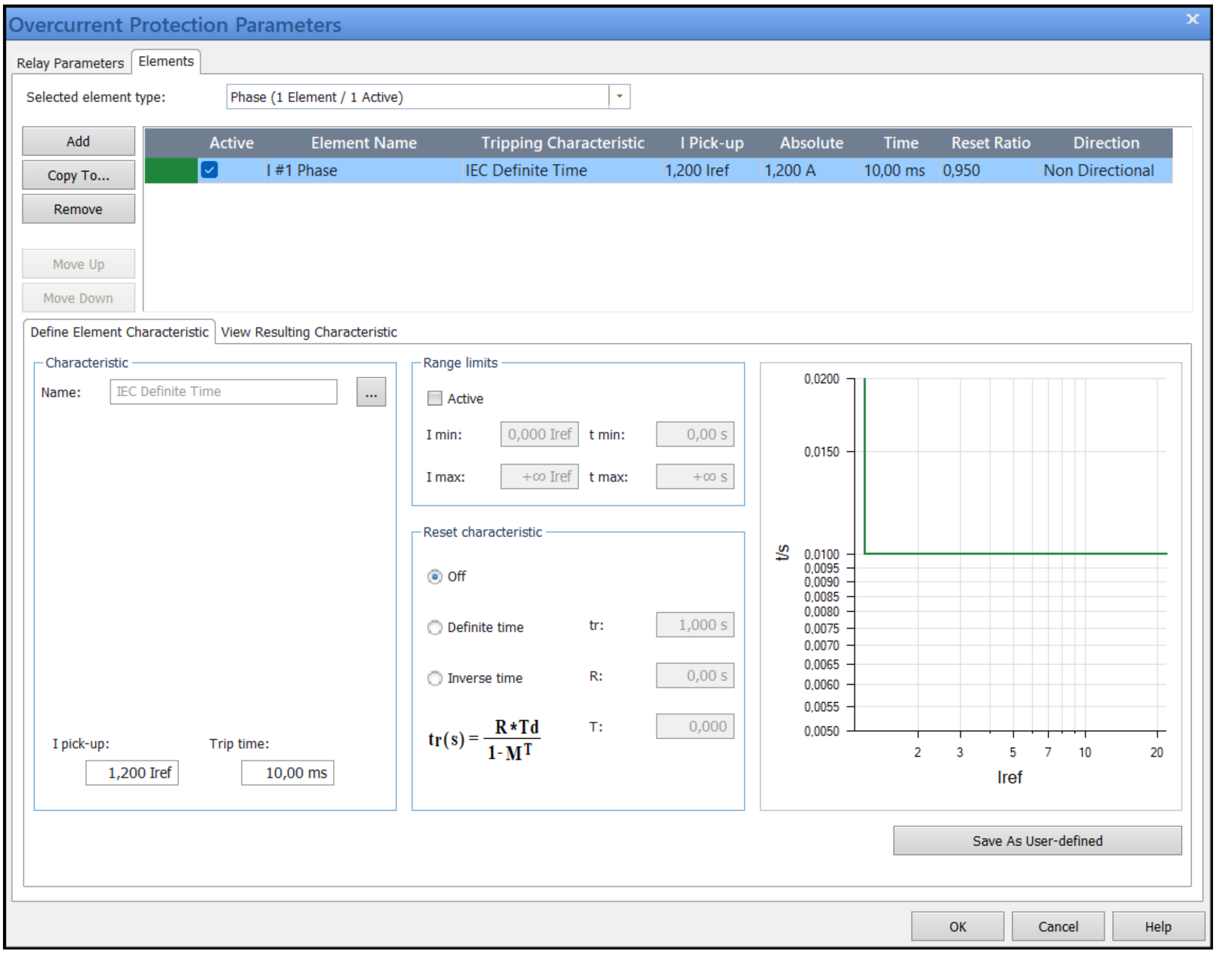


Figure 5.29: Overcurrent relay parameters

Figure 5.29 shows the overcurrent protection elements. The description of the protection setting in Figure 5.29 is given below:

- The Phase element is defined in the selected element type.
- The characteristic type selected id IEC Definite Time characteristic.
- The pickup current and index are at 1.2Iref and 10ms respectively.

Table 5.7 provide the configuration setting of the IEC Definite Time overcurrent characteristics of a phase element.

Table 5.7: IEC definite TOC phase element configuration

Active	Name	Tripping Characteristics	I-pickup	Time(s)	Reset Ratio	Direction
Yes	1#2 Phase	IEC Definite Time	1.2 Iref	0.01	0.95	Non Directional

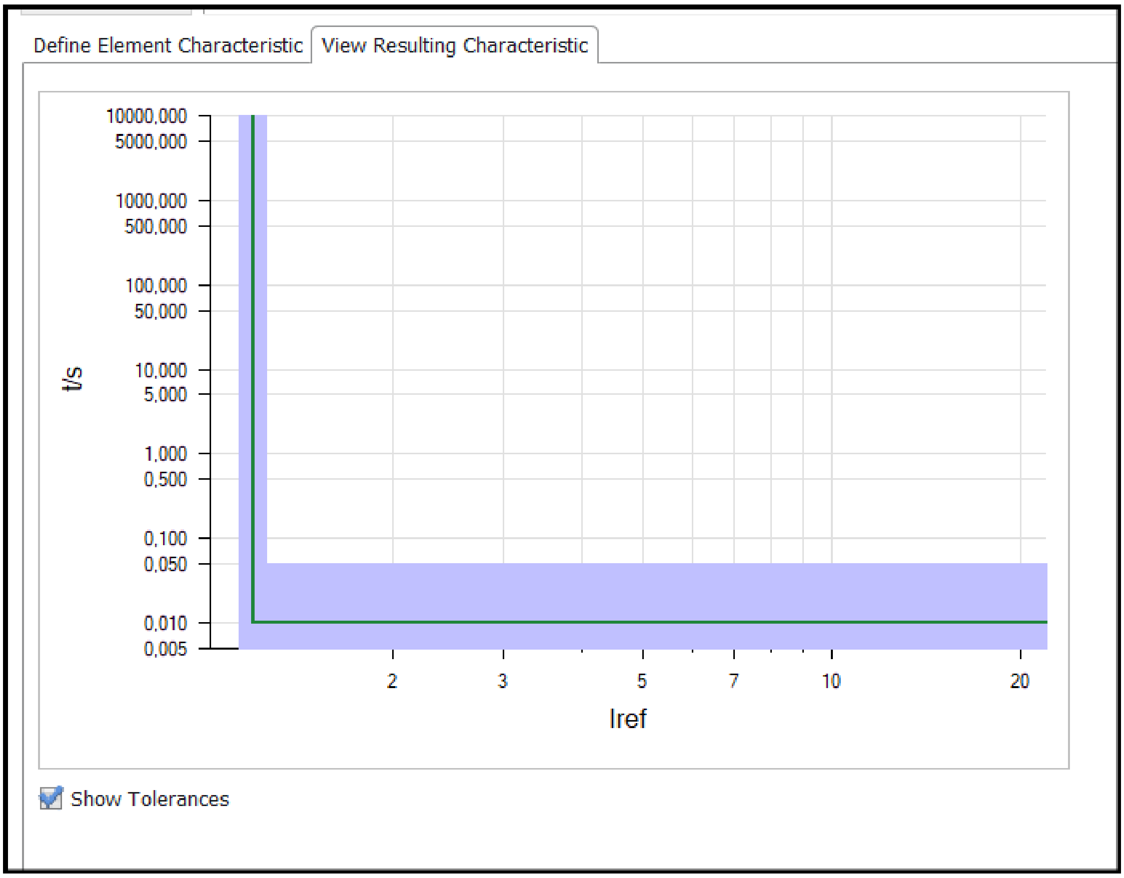


Figure 5.30: Phase overcurrent curve on Test Universe

Figure 5.30 shows the resulting phase overcurrent curve on the test universe

5.3.2.3 Hardware configuration setting of SEL700G overcurrent element in test universe

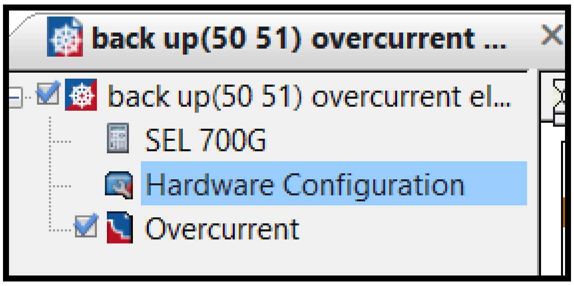


Figure 5.31: Global Hardware Configuration on Test Universe

Figure 5.31 illustrate the hard configuration of the overcurrent test module. The global Hardware Configuration is defined according to SEL700G relay connection. It can be started by double clicking the Hardware Configuration entry in the OCC file.

The voltage signals are not used in this case the current signals of the SEL 700G are mapped to the channel A of the Omicron CMC 256plus test injection device as shown in Figure 5.32.

The output configuration of the current channel A is set to a 1 A nominal secondary current as shown in Figure 5.32.

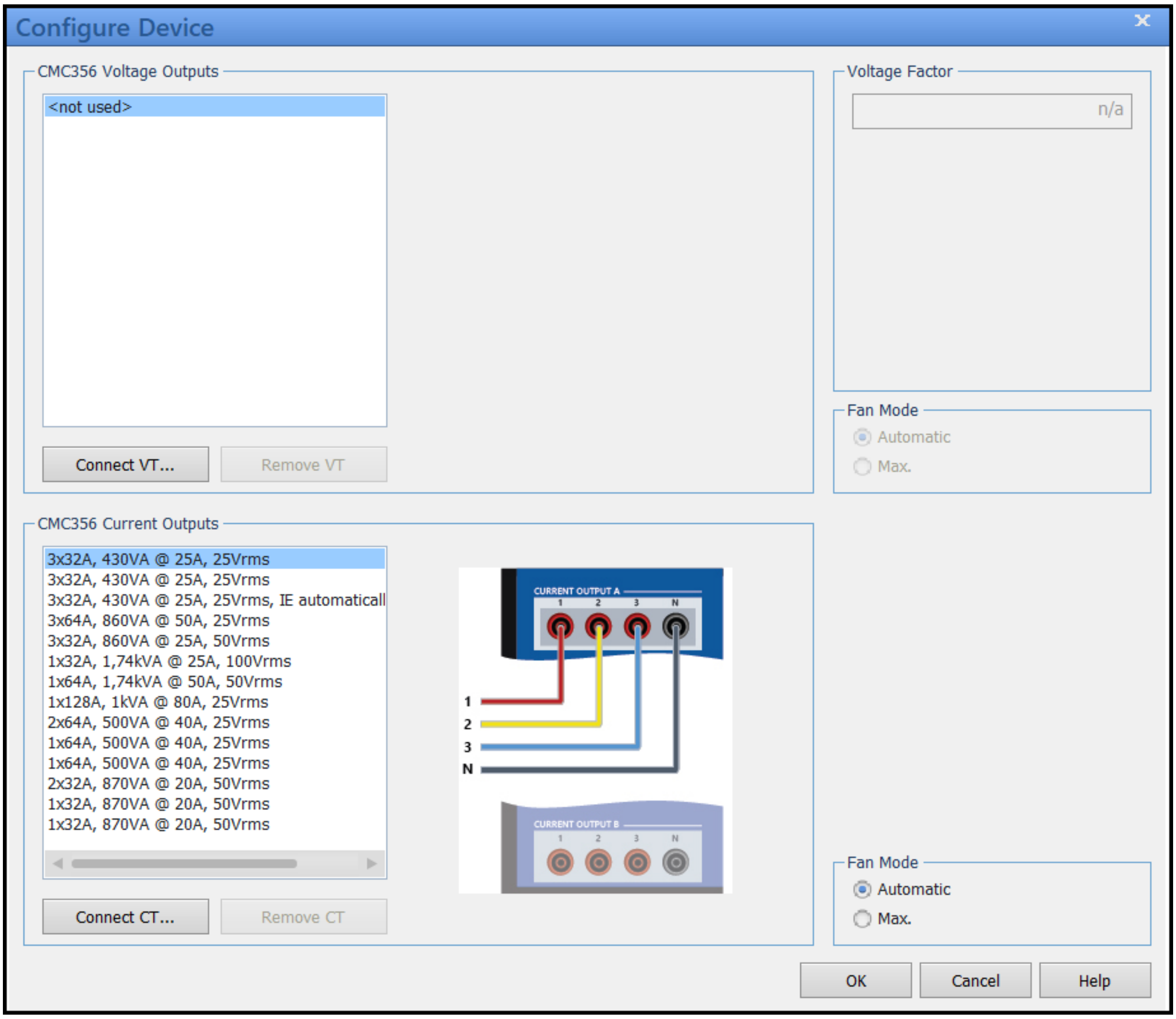


Figure 5.32: Current channel A output configuration settings of CMC 356 device

The current output was configured in the analogue output and as illustrated in Figure 5.33

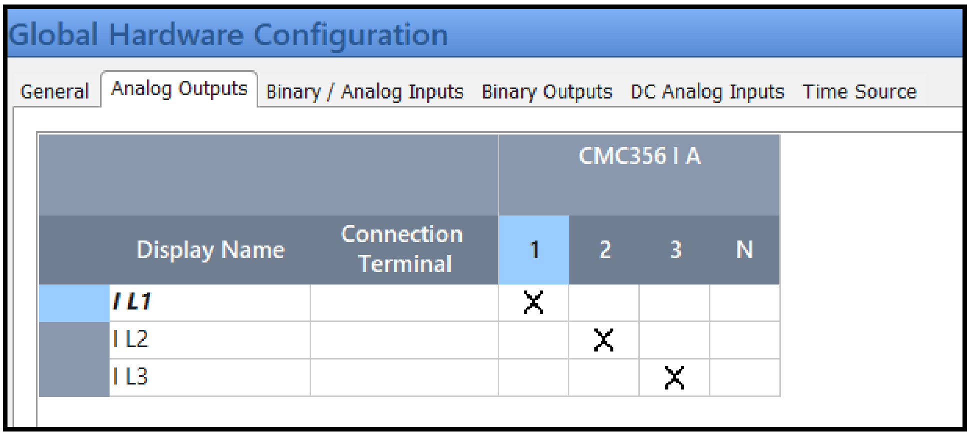


Figure 5.33: Analog output configuration settings of SEL 700G

The command inputs are connected using any Binary Input from (BI1) to Binary Input 10(BI10). for this case, the start command is mapped to the pickup current of the overcurrent element and it is connected to Binary input (BI1).The trip command is mapped to the trip element of the overcurrent relay and it is connected binary input 2 (BI2) as shown in Figure 5.34

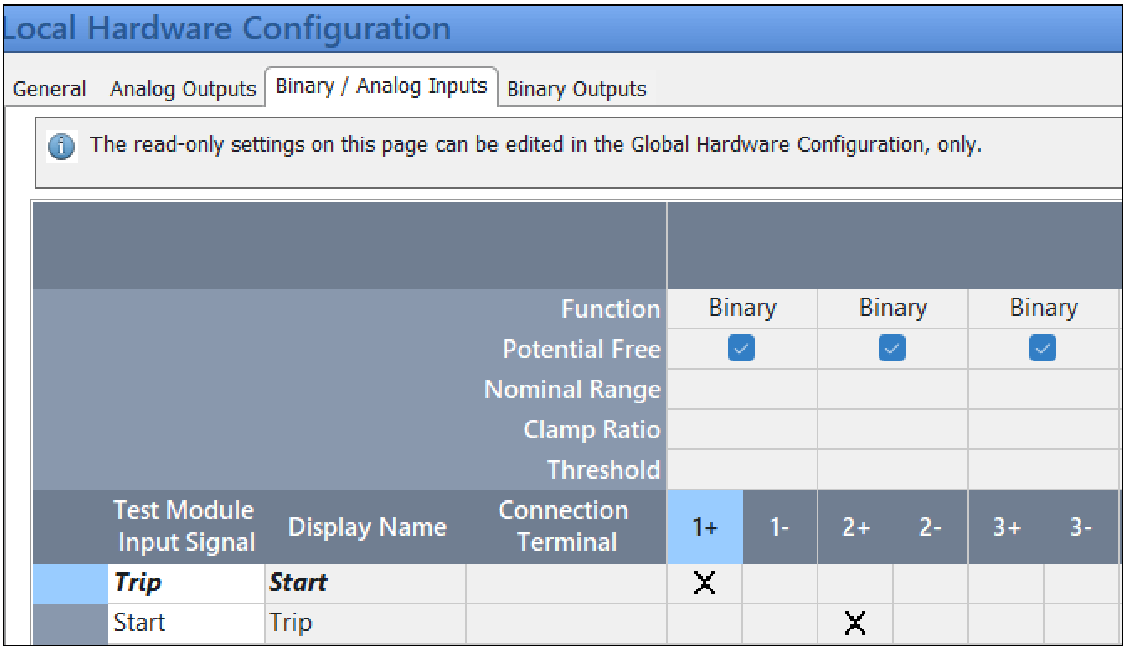


Figure 5.34: Binary inputs configuration settings of SEL 700G

5.3.3 Lab scale test bench Overcurrent simulation test results using SEL-700G IED

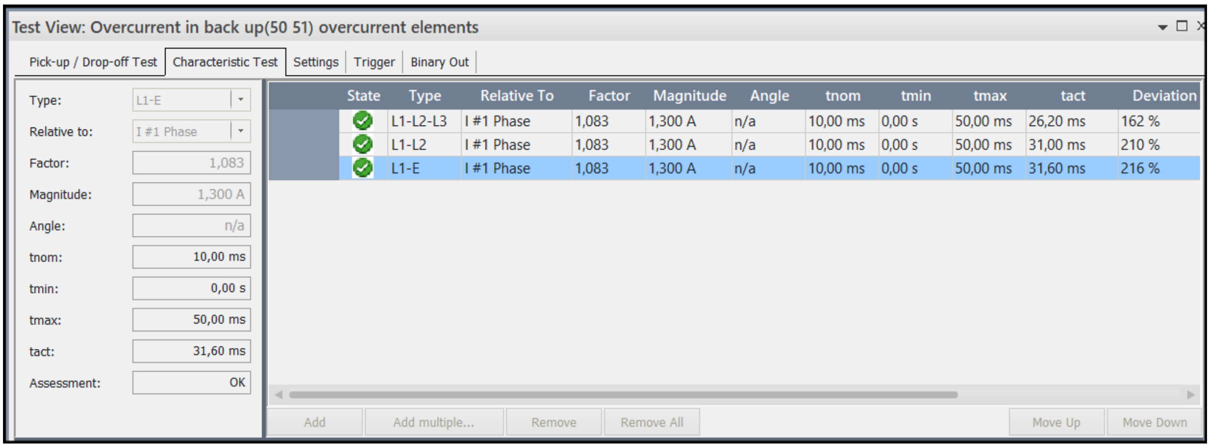


Figure 5.35: Trip time characteristics test tab

Figure 5.35 present the trip time characteristics test tab. The description of the characteristics test is as follow:

- The simulation tests conducted passed and were of three scenarios and which are, three phase fault, double phase fault and single phase.
- The Angle for direction is defined as non-directional.
- The tnom was set at 0.01s

5.3.3.1 Three phase short circuit simulation results

The results of the SEL 700G overcurrent relay is analysed AcSELerator Synchro wave tool which provides 1075Amps for three phase (L1-L2-L3) fault loop, and it is the same as the test universe simulation result. 50PX1P instantaneous element picks up the fault after 0.0167 seconds and 50PX1T element issues the trip signal at 0.0125 seconds after the pickup as shown in Figure 5.36. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0125 after the pick up

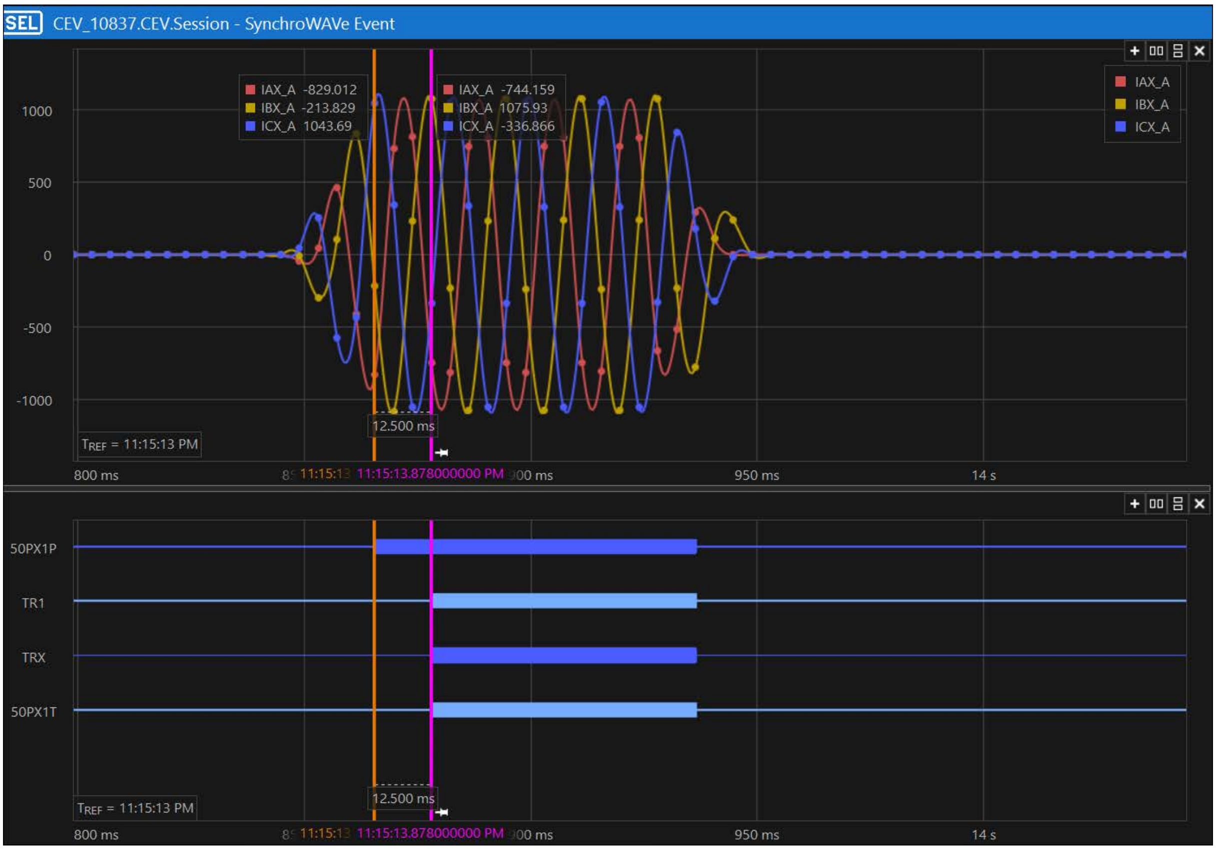


Figure 5.36: Three phase fault signals of SEL700G overcurrent relay

5.3.3.2 Double phase short circuit simulation results

The results of the SEL 700G overcurrent relay is analysed with AcSELerator Synchro wave tool which provides 1052 Amps for double phase (L1-L2) fault loop, and it is the same as the test universe simulation result. 50PX1P instantaneous element picks up the fault after 0.0191 seconds and 50PX1T element issues the trip signal at 0.0125 seconds after the pickup as shown in Figure 5.37. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0125 after the pick up

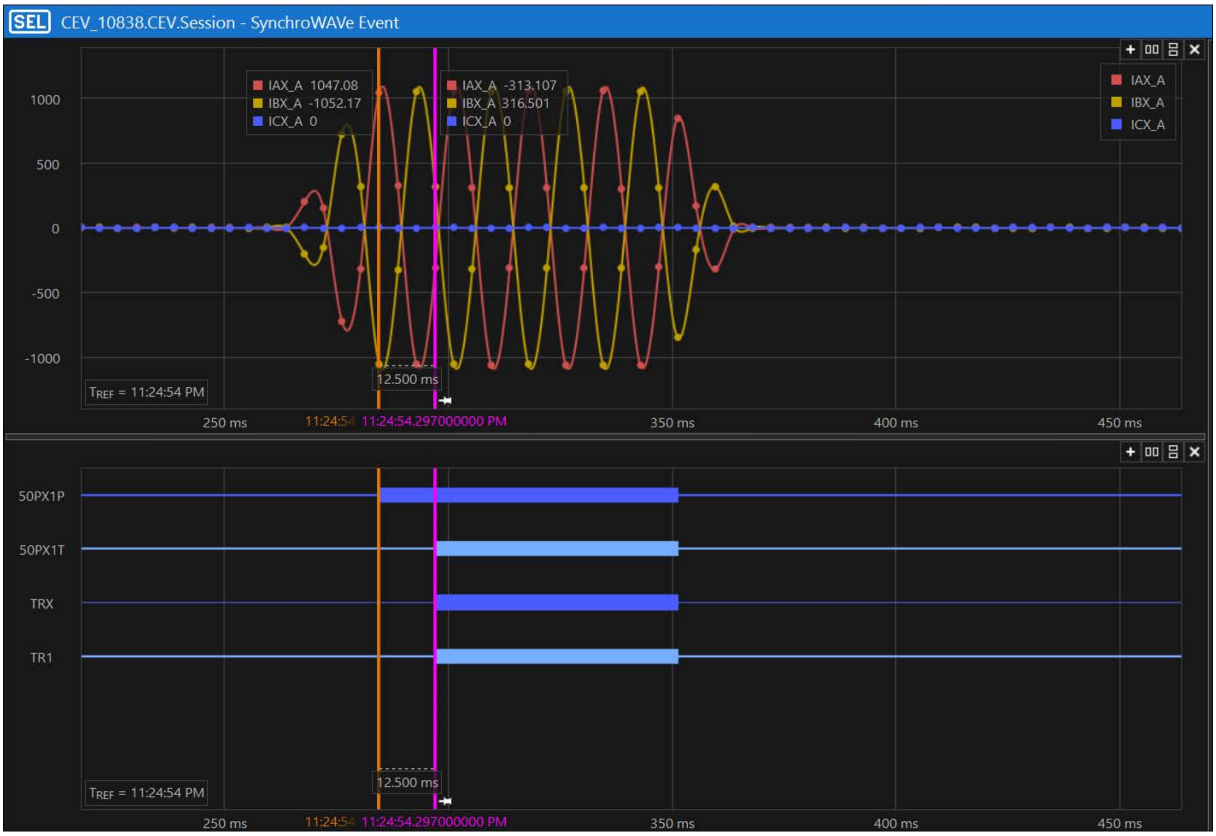


Figure 5.37: Double phase fault signals of SEL700G overcurrent relay

5.3.3.3 Single phase to ground short circuit simulation results

The results of the SEL 700G overcurrent relay is analysed with AcSELerator Synchro wave tool which provides 1033.51 Amps for a single phase to ground (L1-E) fault loop, and it is the same as the test universe simulation result. 50PX1P instantaneous element picks up the fault after 0.0191 seconds and 50PX1T element issues the trip signal at 0.0125 seconds after the pickup as shown in Figure 5.38. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0125 after the pickup.

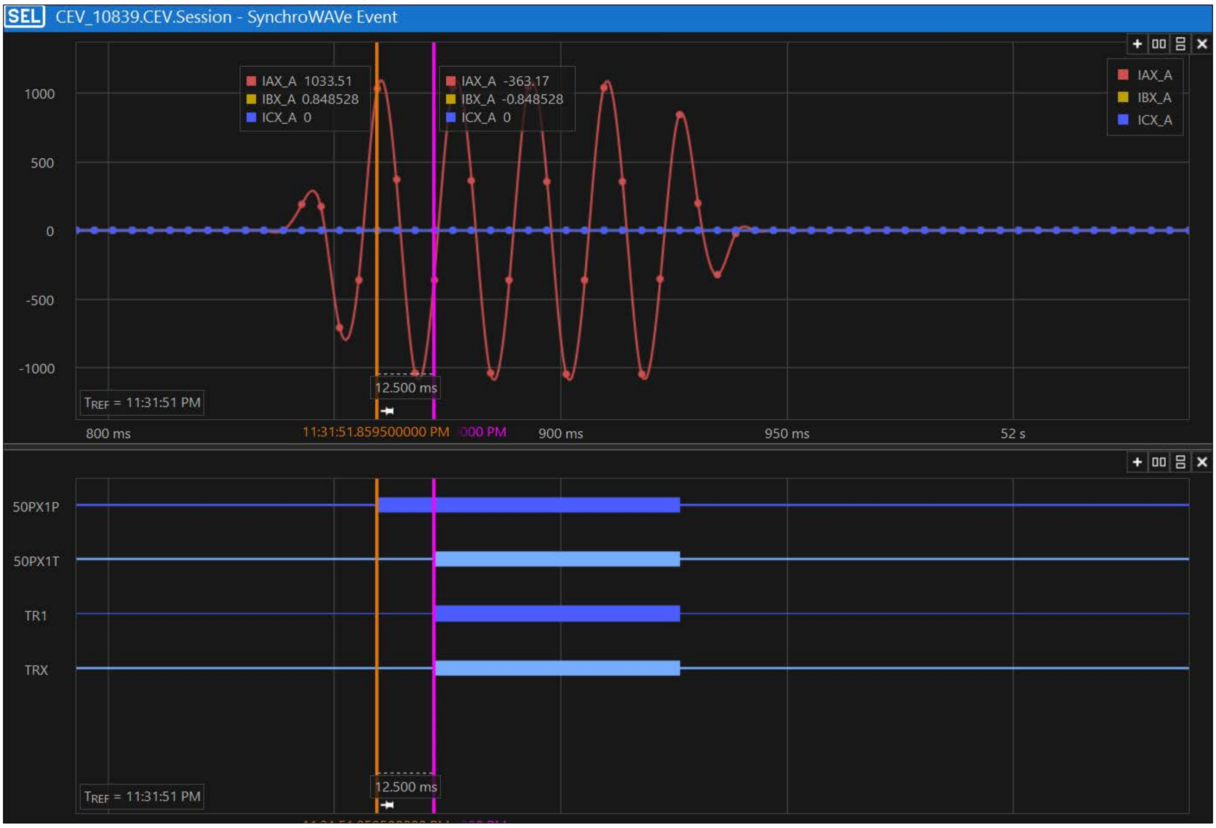


Figure 5.38: Single phase fault signals of SEL700G overcurrent relay

5.4. SEL 700G Overvoltage and under voltage protection setting for a generator

Generator will be subjected to overvoltage conditions when there is a sudden loss of load in the grid or when the automatic voltage regulator fails to operate. Also the increase of a generator speed due to various reasons will cause overvoltage in a generator. Generators are usually designed to operate continuously at a maximum voltage of 105% of its rated voltage, while delivering rated power at rated frequency. Sustained overvoltage above permissible limit may produce over fluxing (due to high V/Hz) and excessive electrical stress on the insulation system (Power and Society, 2005). On the contrary, the under-voltage conditions will occur when the speed is reduced or when more loads is connected on to grid system. Typically, the generators are designed to operate at a minimum voltage of 95% of its rated voltage. SEL 700G over voltage (59) and under voltage (27) functions detect and clear over- and under-voltage faults respectively.

The next sections provide the implementation of lab scale test bench set up for over-voltage and under-voltage protection scheme using SEL 700G IED relay to cater for over and under voltage conditions. The protection elements are tested utilizing the CMC 356 Omicron test injection device. The overvoltage lab scale test bench set up is shown in Figure 5.1. It has the generator intelligent electronic device (SEL 700G) protection elements, OMICRON test set (CMC 356) and a personal computer with the relay configuration tools (AcSELarator Quickset and test universe software). The Ruggedcom Ethernet switch (RSG 2288) connects to SEL 700G IED relay, personal computer and OMICRON CMC 356 test set for communication purposes using static IP network as shown in Figure 5.1.

5.4.1 SEL 700G Over- and Under-voltage configuration settings using Quickset AcSELerator software

This section outlines the Over- and under-voltage configuration settings using quickset AcSELarator. The SEL 700G IED protective relaying has both instantaneous unit and time delay with inverse characteristics, however for the purpose of this study; the test is performed on relay with instantaneous characteristics for stage 1 and stage 2 for both over-and under-voltage conditions. Note that the inverse characteristics relay was not considered for this test because the SEL 700G relay utilized does not support the inverse characteristics ,hence the test were conducted for instantaneous elements only.

Figure 5.39 provide the general settings of SEL 700G Over- and Under-voltage relay. The descriptions of general settings are given below:

- The nominal frequency of the system is 60 hertz
- The relay uses x side of a generator
- The fault SELogic equation is also provided for over and under voltage elements.

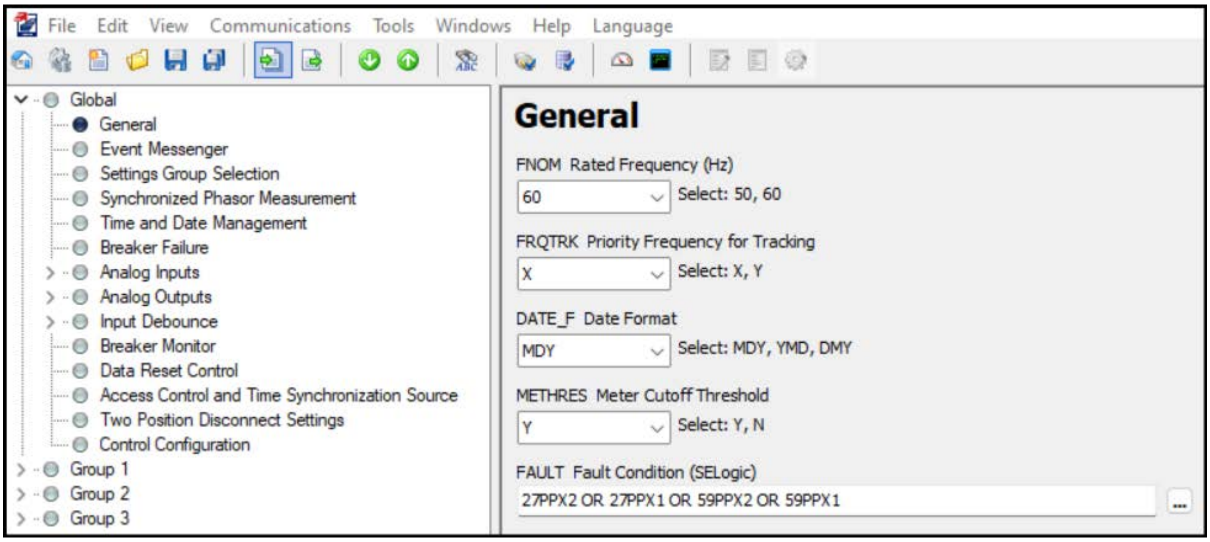


Figure 5.39: General setting of SEL 700G Over- and Under-voltage Protection relay

The table 5.8 provides the relay words bit of instantaneous characteristic for over- and under-voltage relay.

Table 5.8: Relay Word Bits of the generator overprotection protection relay

Abbreviation Relay Word Bits	Description of the relay word bits
59PX1P	Phase overvoltage pickup
59PX1D	Phase overvoltage trip delay
59PPX1P	Phase to phase overvoltage pickup
59PPX1D	Phase to phase overvoltage time dial
59PX2P	Phase overvoltage level 2 pickup
59PX2D	Phase overvoltage level 2 trip dial
59PPX2P	Phase to phase overvoltage level 2 pickup
59PPX2D	Phase to phase overvoltage level 2 pickup
27PX1P	Phase under-voltage pickup
27PX1D	Phase under-voltage trip delay
27PPX1P	Phase to phase under-voltage pickup
27PPX1D	Phase to phase under-voltage time dial
27PX2P	Phase under-voltage level 2 pickup
27PX2D	Phase under-voltage level 2 trip dial
27PPX2P	Phase to phase under-voltage level 2 pickup
27PPX2D	Phase to phase under-voltage level 2 pickup

Figure 5.40 provides the logic diagram of overvoltage instantaneous relay elements of generator Protection (59PPm1P and 59PPm2).the elements are compared to the maximum phase to phase voltage of a generator.

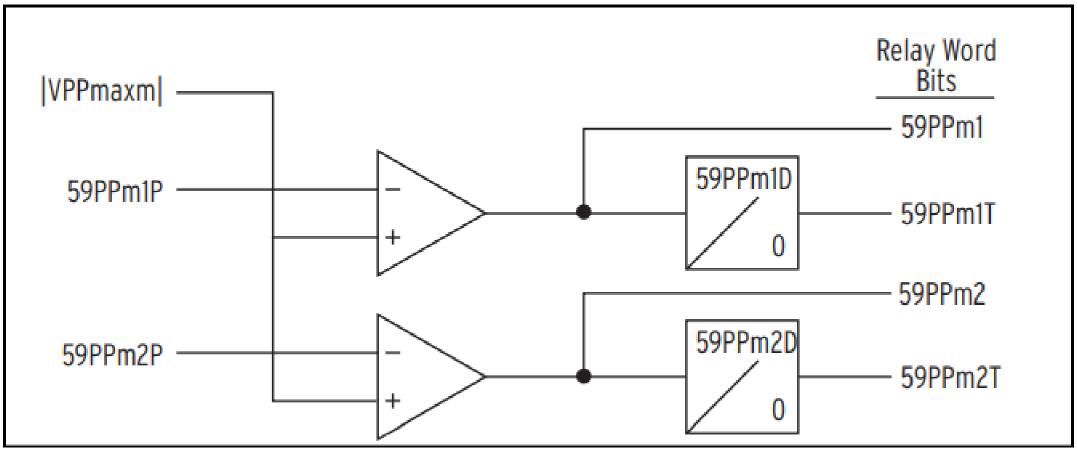


Figure 5.40: Overvoltage logic (SEL Relay Manual, 2018)

Figure 5.41 provides the logic diagram of under-voltage instantaneous relay elements of generator Protection (27PPm1 and 27PPm2).the elements are compared to the minimum phase to phase voltage of a generator respectively.

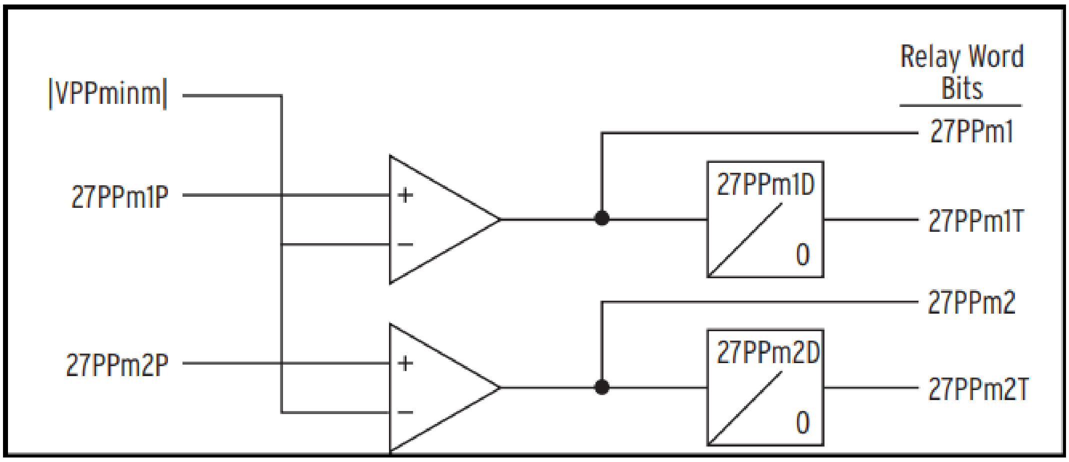


Figure 5.41: Under-voltage logic (SEL Relay Manual, 2018)

5.4.2 OMICRON Test Universe configuration setting for Over- and under-voltage relay

the over- and under-voltage relay uses state sequence to perfom test for instantaneous protection function. The test object settings and the hardware configaration settings are provided in this section.

*5.4.*2.1 Test object

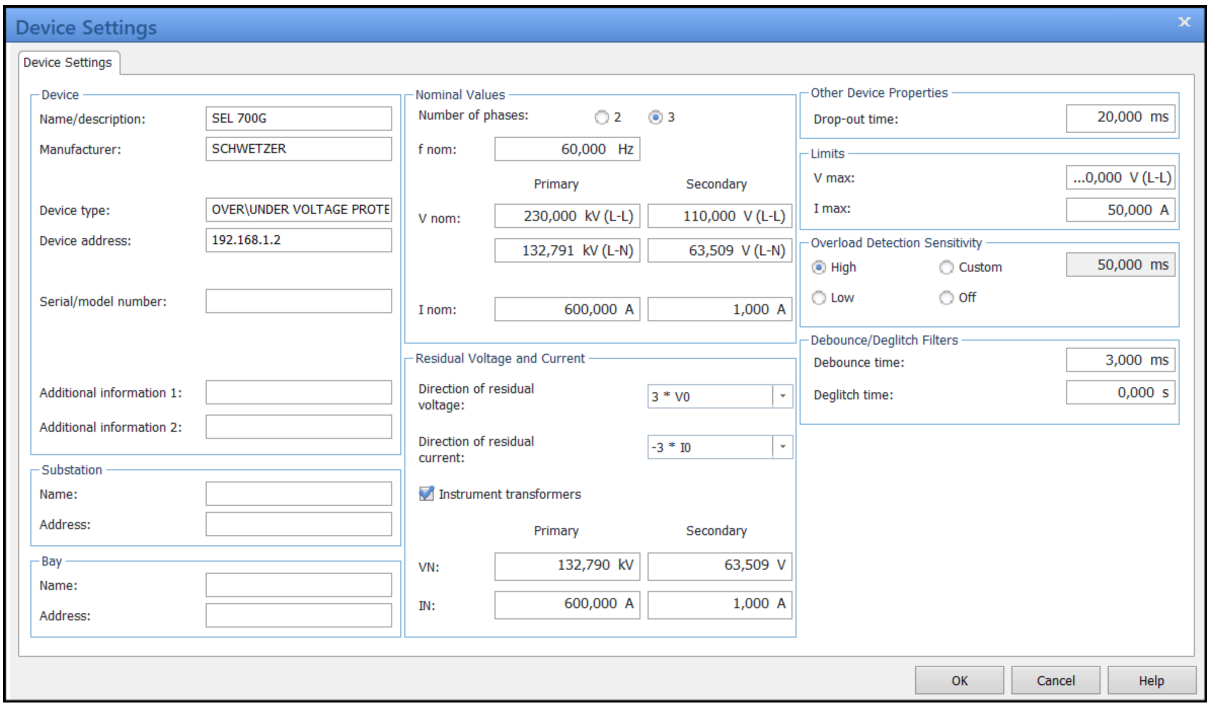


Figure 5.42: Test object settings of over- and under-voltage relay.

Figure 5.42 defines the test object settings of Over- and under-voltage relay. It provides the device settings which include the detail description of the protection relay. The relay settings (e.g. Substation, relay ID, or CT and VT parameters) are entered into the RIO function Device. As provided in Figure 5.10, the values of primary and secondary voltages of the potential transformer are 230kV and 110V respectively.

5.4.3.2 Global Hardware Configuration CMC to test Overvoltage

The hardware configuration is defined according to the relay connection. This is done by double clicking on the hardware configuration entry in the OCC file as illustrated in Figure 5.43.

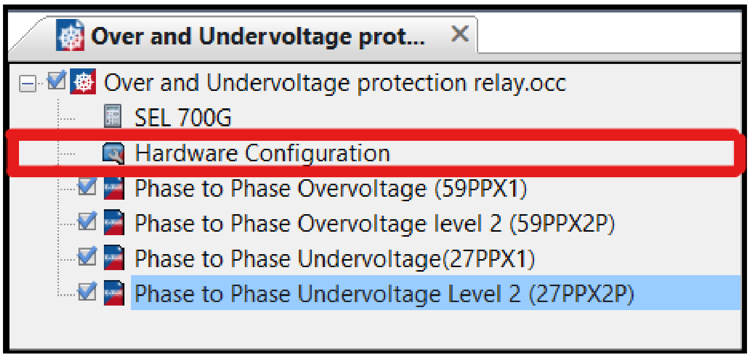


Figure 5.43: Global hardware configuration setting of over- and under-voltage relay

The Voltage output was configured in the analogue output and the current outputs are entered as not used as illustrated in Figure 5.44.

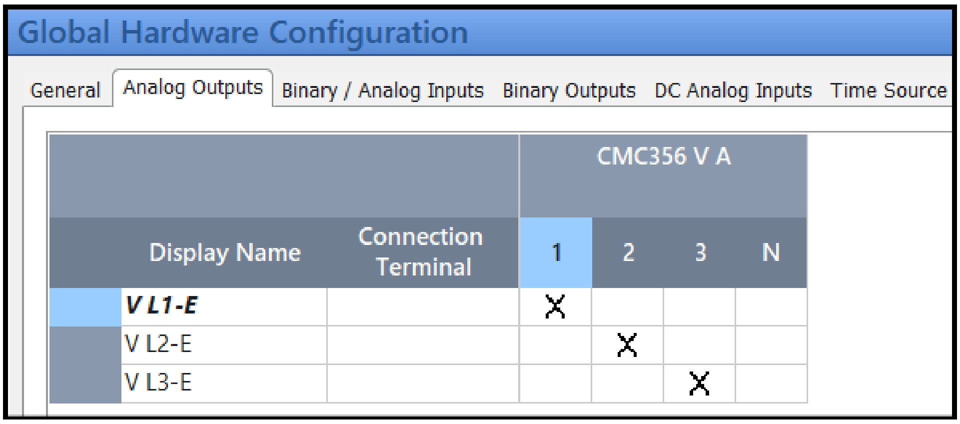


Figure 5.44: Analogue output of the over-and under-voltage relay

Figure 5.45 shows the output configuration of over-and under-voltage protection scheme. The analogue outputs as well as the binary inputs and binary outputs are activated individually in the local Hardware Configuration of the specific test module. The over- and under-voltage protection schemes need one set of voltage input which is provided by the voltage channel of the Omicron test set.

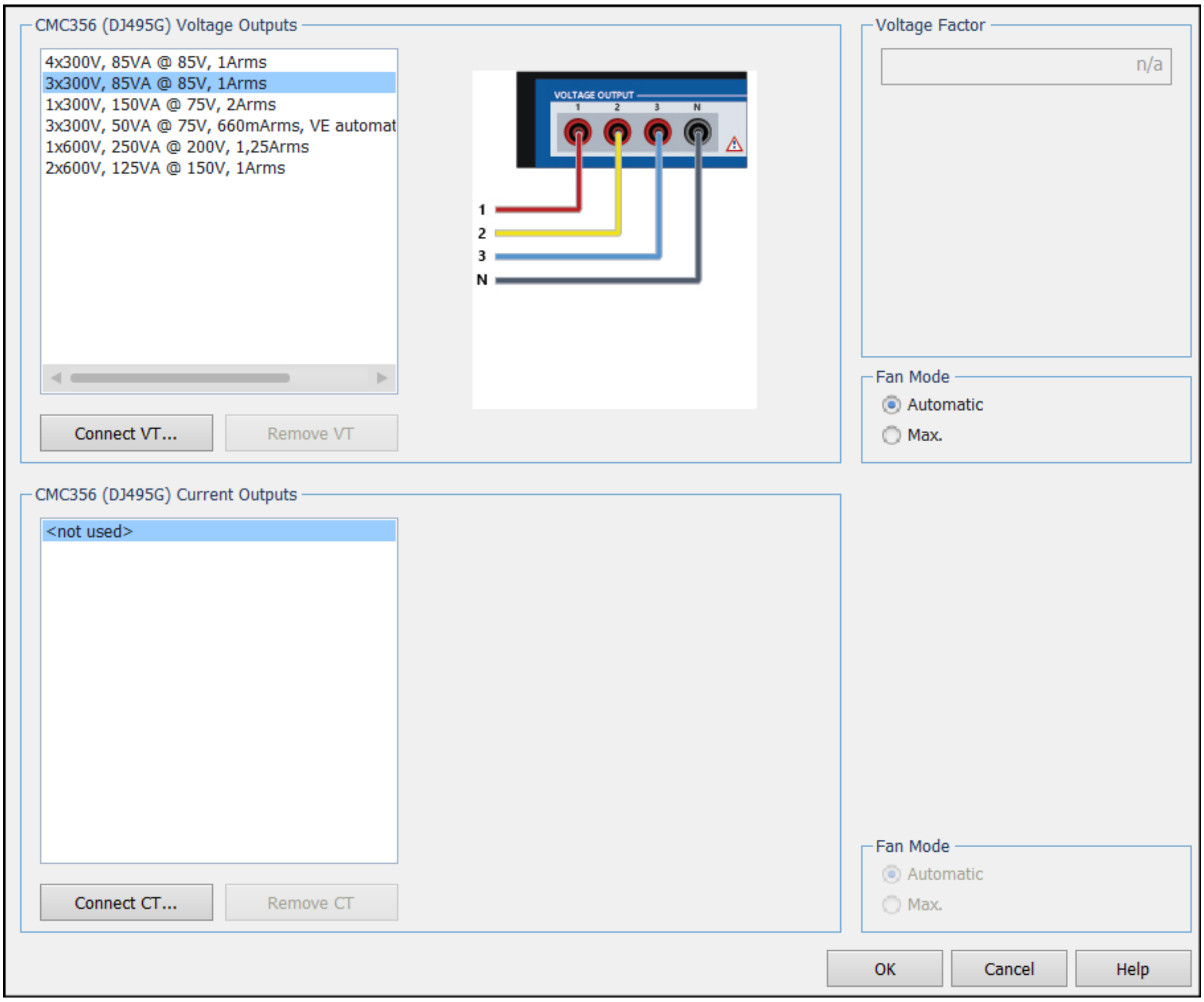


Figure 5.45: Output configuration of over- and under-voltage protection

The command inputs can be connected using any Binary Input from (BI1) to Binary Input 10(BI10).The trip command mapped to the trip element of over or under voltage relay and is then connected to binary input 1 as shown in Figure 5.46. For wet contacts the nominal voltages of the binary inputs have to be adapted to the voltage of the circuit breaker trip command.

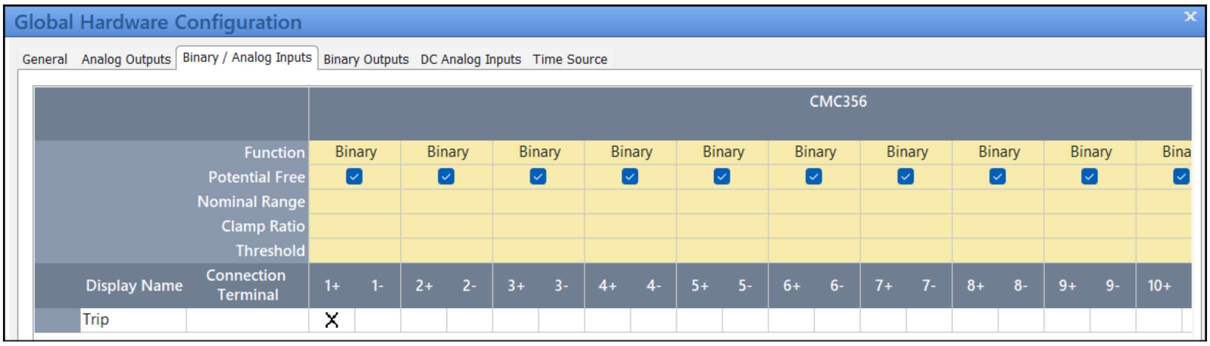


Figure 5.46: The trip signal of the over- and under-voltage protection scheme

5.4.3 SEL 700G Overvoltage protection (59) testing

The overvoltage protection is tested using State sequence test module. For this case study, the behaviour of the 59 overvoltage function is investigated with two stages of voltage pickup and definite time delay set points namely:

- Phase to phase overvoltage level one pickup (59PPX1P)
- Phase to phase overvoltage level two pickup (59PPX2P)

The first stage of pick up is set at 110 % of the generator rated voltage with definite time delay of 0.5s and the rated generator voltage is 110V. The level one pick is calculated as follows

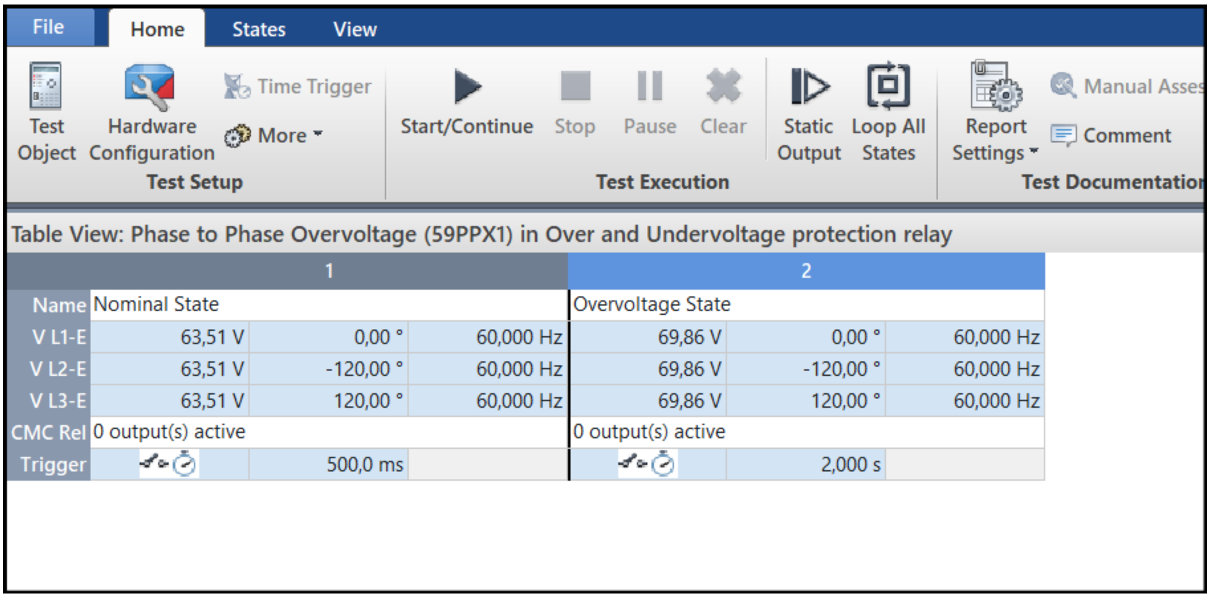
$$Vlowset = 110V \times 110\% \qquad (5.5)$$

$$Vlowset = 121V$$

It should be noted that the voltage to be injected must be phase to neutral hence,

$$VRn = \frac{121}{\sqrt{3}}$$

$$VRn = 69.86V$$



	1			2		
Name	Nominal State			Overvoltage State		
V L1-E	63,51 V	0,00 °	60,000 Hz	69,86 V	0,00 °	60,000 Hz
V L2-E	63,51 V	-120,00 °	60,000 Hz	69,86 V	-120,00 °	60,000 Hz
V L3-E	63,51 V	120,00 °	60,000 Hz	69,86 V	120,00 °	60,000 Hz
CMC Rel	0 output(s) active			0 output(s) active		
Trigger		500,0 ms			2,000 s	

Figure 5.47: Test view of overvoltage protection relay stage 1

Figure 5.47 provides detail and time signal views of the overvoltage relay element level 1 (59PPX1). It includes the nominal state and fault state values of overvoltage relay settings subjected to be injected to omicron test universe. The operating time of the relay is 6.5s.

Figure 5.47 provides the state termination of the relay. The binary trigger condition used is set as a trip and on state X as shown in Figure 5.48.

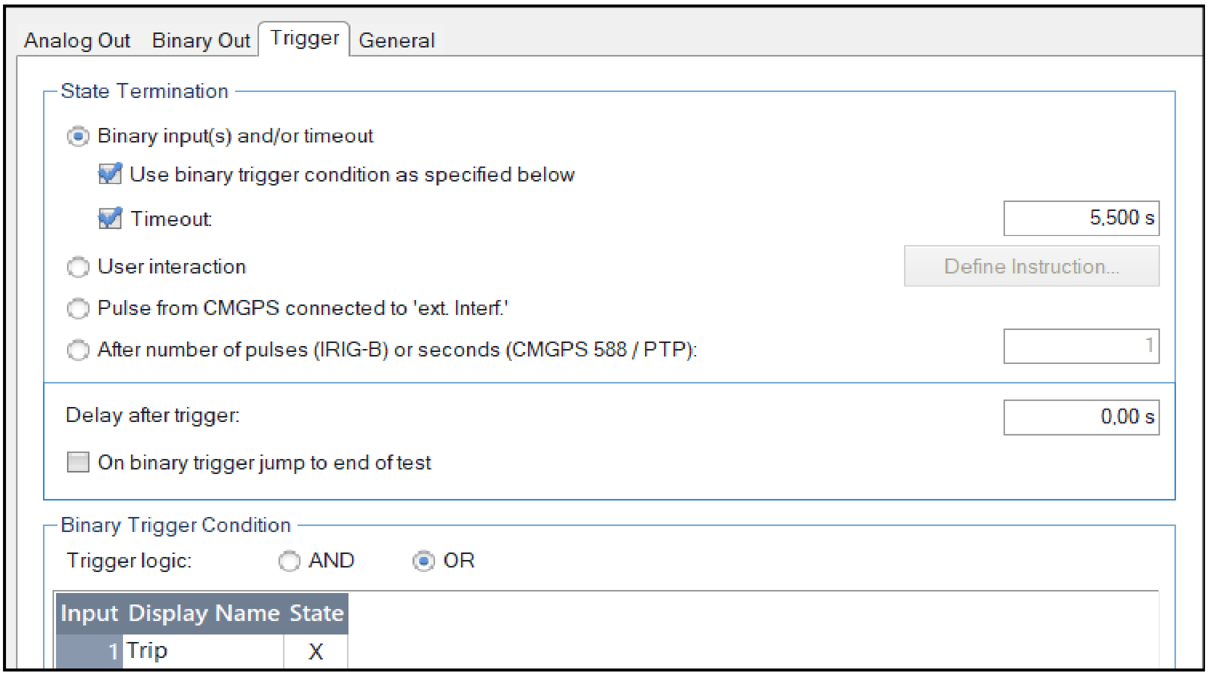


Figure 5.48: The state termination for over- and under-voltage relay

5.4.3.1 Lab scale test bench Overvoltage simulation test results using SEL-700G IED

This section discusses the lab scale overvoltage simulation results for stage 1 element (59PPX1) and stage 2 elements (59PPX2P2p). The results of the SEL 700G overvoltage relay are analysed AcSELerator Synchro wave tool. It presents the magnitudes of phase to phase (VABX, VBCX and VCAX) and the behaviour of relay s response when the level of voltage exceeds the threshold value.

i. 59PPX1P simulation results

AcSELerator Synchro wave tool provides a phase to phase voltage of 190.646kV and it is the same as the test universe simulation result. 59PPX1P instantaneous element picks up the overvoltage condition after at 0 seconds delay and 59PPX1T element issues the trip signal at 0.079 seconds after the pickup as shown in Figure 5.49. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.079 after the pick up

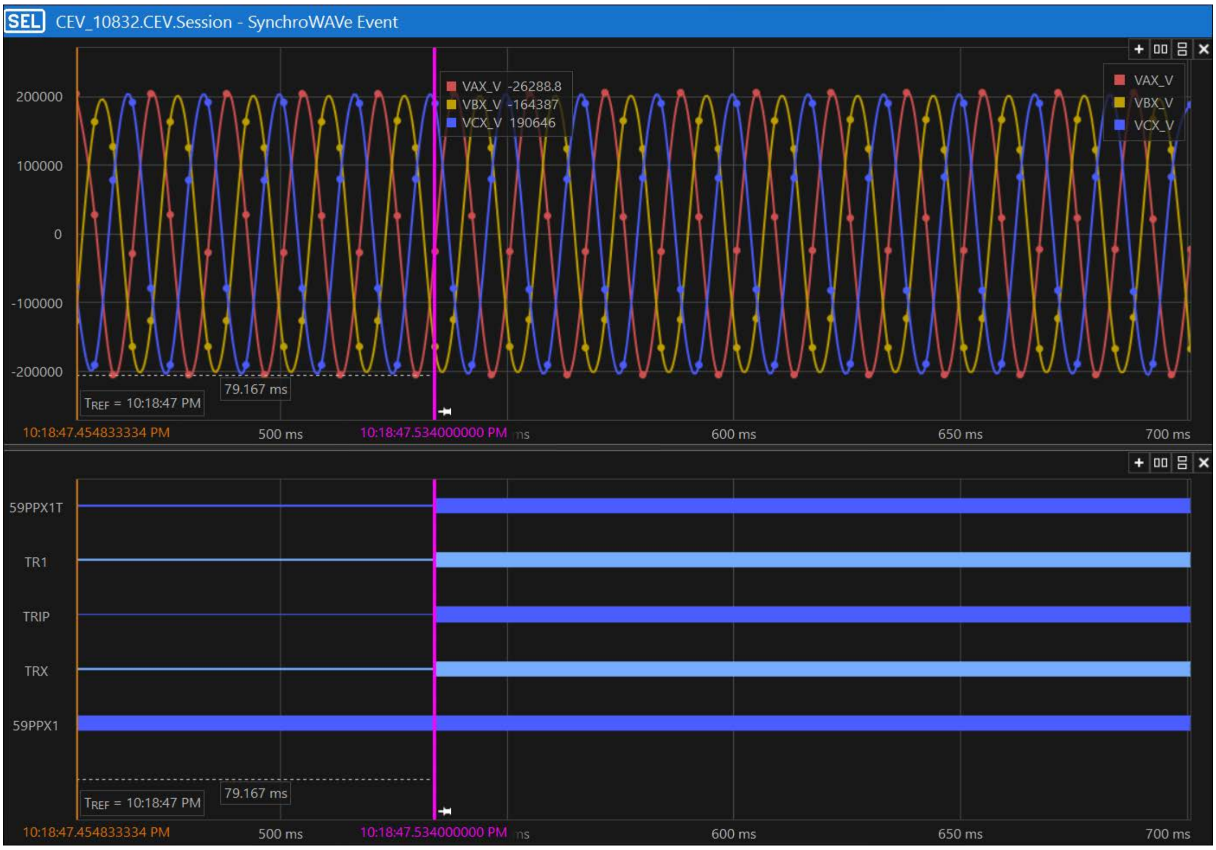


Figure 5.49: Phase to phase voltages and trip signals of the SEL 700G over voltages relay (5PPX1P).

The level 2 pickup is set at 120% of the rated generator voltage with definite time delay of 0.01.

$$Vlowset = 110V \times 120\% \tag{5.6}$$

$$Vlowset = 132V$$

$$VRn = 76.21$$

The voltage to be injected for level two pick up is 76.21V

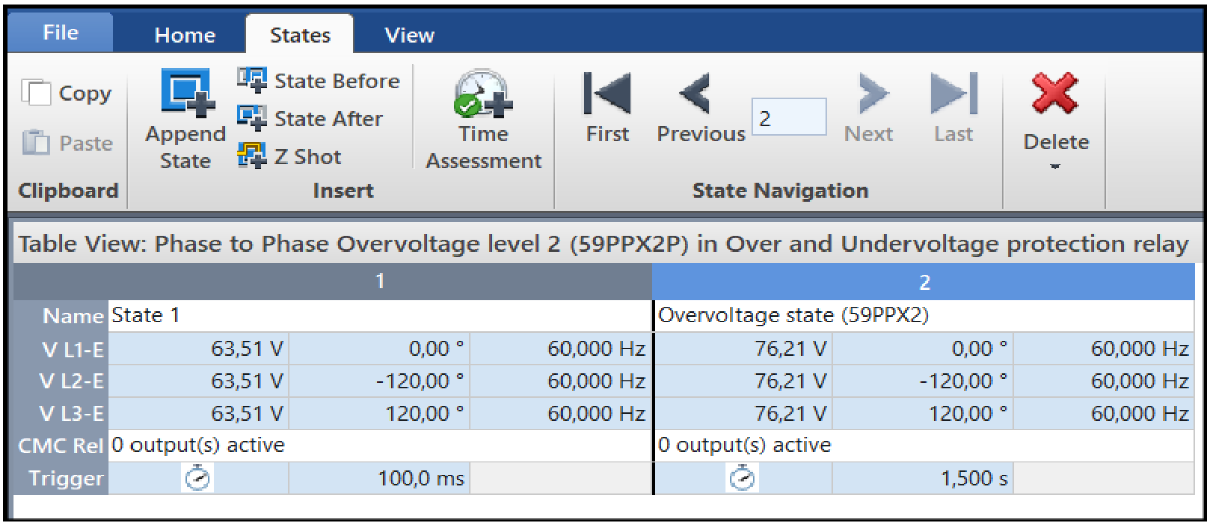


Table View: Phase to Phase Overvoltage level 2 (59PPX2P) in Over and Undervoltage protection relay

	1			2		
Name	State 1			Overvoltage state (59PPX2)		
V L1-E	63,51 V	0,00 °	60,000 Hz	76,21 V	0,00 °	60,000 Hz
V L2-E	63,51 V	-120,00 °	60,000 Hz	76,21 V	-120,00 °	60,000 Hz
V L3-E	63,51 V	120,00 °	60,000 Hz	76,21 V	120,00 °	60,000 Hz
CMC Rel	0 output(s) active			0 output(s) active		
Trigger		100,0 ms			1,500 s	

Figure 5.50: Test view of overvoltage protection relay stage 2

Figure 5.50 provides detail and time signal views of the overvoltage relay element level 1 (59PPX2P). It includes the nominal state and fault state values of overvoltage relay settings subjected to be injected to omicron test universe. The operating time of the relay is 1.5s.

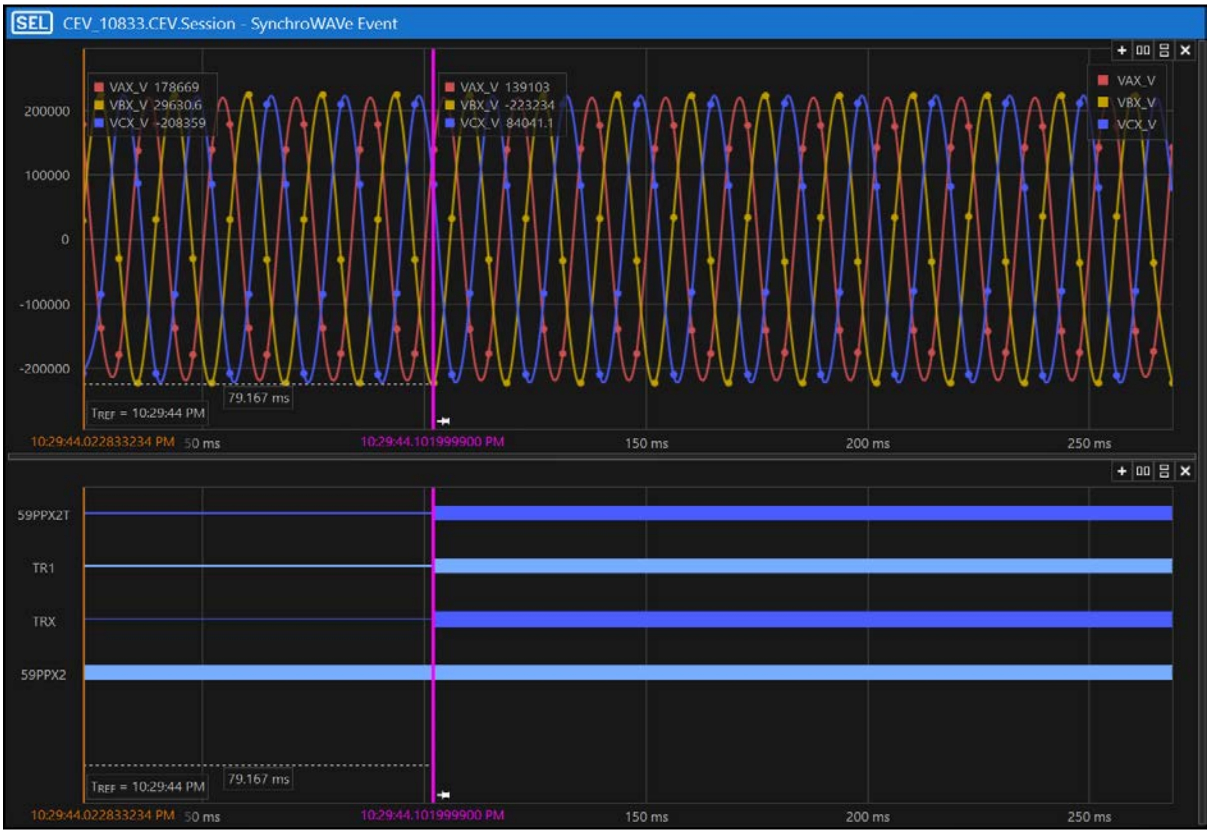


Figure 5.51: Phase to phase voltages and trip signals of the SEL 700G overvoltages relay (59PPX2P).

ii. 59PPX2P simulation results

This section discusses the lab scale overvoltage simulation results for stage 2 elements (59PPX2P). The results of the SEL 700G overvoltage relay are analysed AcSELerator Synchro wave tool. AcSELerator Synchro wave tool provides a phase to phase voltage of 223.234Kv and it is the same as the test universe simulation result. 59PPX2P instantaneous element picks up the overvoltage condition after at 0 seconds delay and 59PPX2T element issues the trip signal at 0.079 seconds after the pickup as shown in Figure 5.51. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.079 after the pickup.

5.4.4 SEL 700G under voltage (27) protection testing

The under voltage protection is tested using State sequence test module. For this case study, the behaviour of the 27 overvoltage function is investigated for two stages of voltage pickup and definite time delay set points namely:

- Phase to phase overvoltage level one pickup (27PPX1P)
- Phase to phase overvoltage level two pickup (27PPX2P)

The first stage of pick up is set at 95 % of the generator rated voltage with definite time delay of 1s and the rated generator voltage is 110V. The level one pick is calculated as follows

$$Vlowset = 110V \times 95\% \tag{5.7}$$

$$Vlowset = 104.45V$$

It should be noted that the voltage to be injected must be phase to neutral hence,

$$VRn = \frac{104.5}{\sqrt{3}}$$

$$VRn = 60.33\text{V}$$

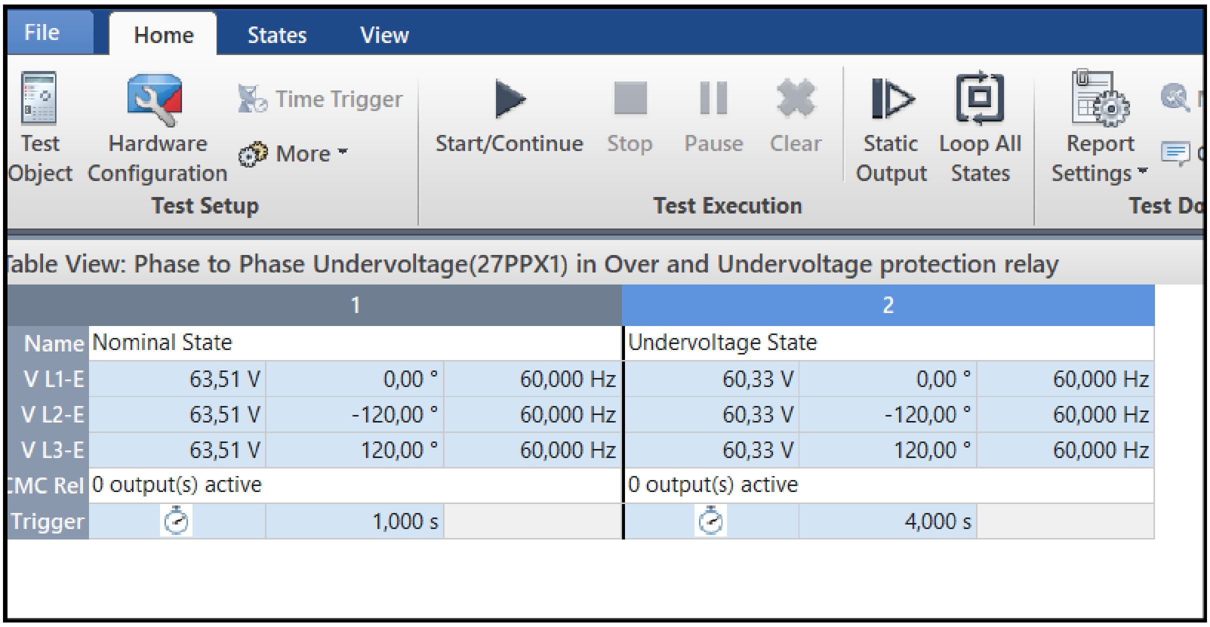


Figure 5.52: Test view of under voltage protection relay stage 1

Figure 5.52 provides detail and time signal views of the under voltage relay element level 1 (27PPX1P). It includes the nominal state and fault state values of overvoltage relay settings subjected to be injected to omicron test universe. The operating time of the relay is 4

5.4.4.1 Lab scale test bench Overvoltage simulation test results using SEL-700G IED

This section discusses the lab scale under voltage simulation results for stage 1 element (27PPX1) and stage 2 elements (27PPX2P2p). The results of the SEL 700G under voltage relay are analysed AcSELerator Synchro wave tool

i. 27PPX1P simulation results

The results of the SEL 700G under voltage relay are analysed AcSELerator Synchro wave tool. 27PPX1P instantaneous element picks up the under voltage condition immediately and 27PPX1T element issues the trip signal at 0.079 seconds after the pickup as shown in Figure 5.53. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.079 after the pickup.

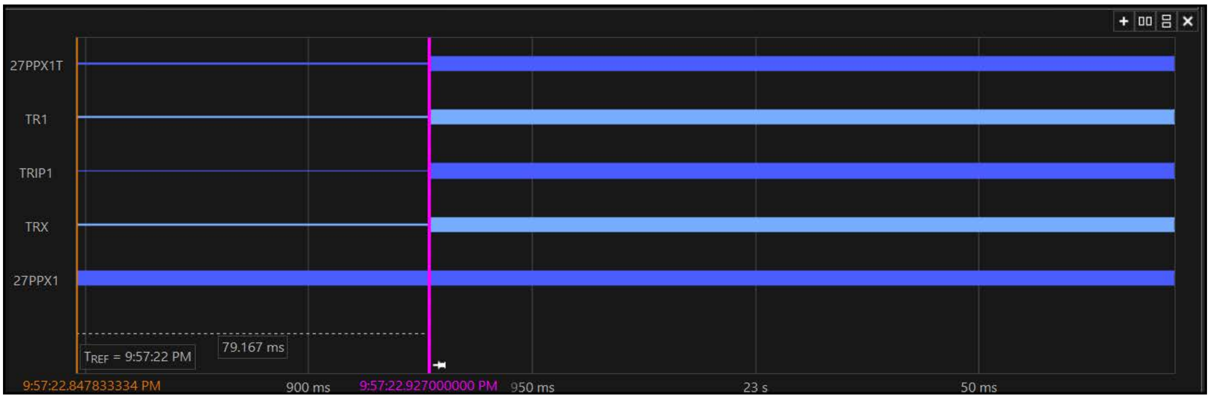


Figure 5.53: trip signals of the SEL 700G under voltages relay (27PPX1P).

The second stage of pick up is set at 90 % of the generator rated voltage with definite time delay of 0.5s and the rated generator voltage is 110V. The level one pick is calculated as follows

$$Vlowset = 110V \times 90\% \qquad (5.8)$$

$$Vlowset = 99V$$

It should be noted that the voltage to be injected must be phase to neutral hence,

$$VRn = \frac{99}{\sqrt{3}}$$

$$VRn = 57.16$$

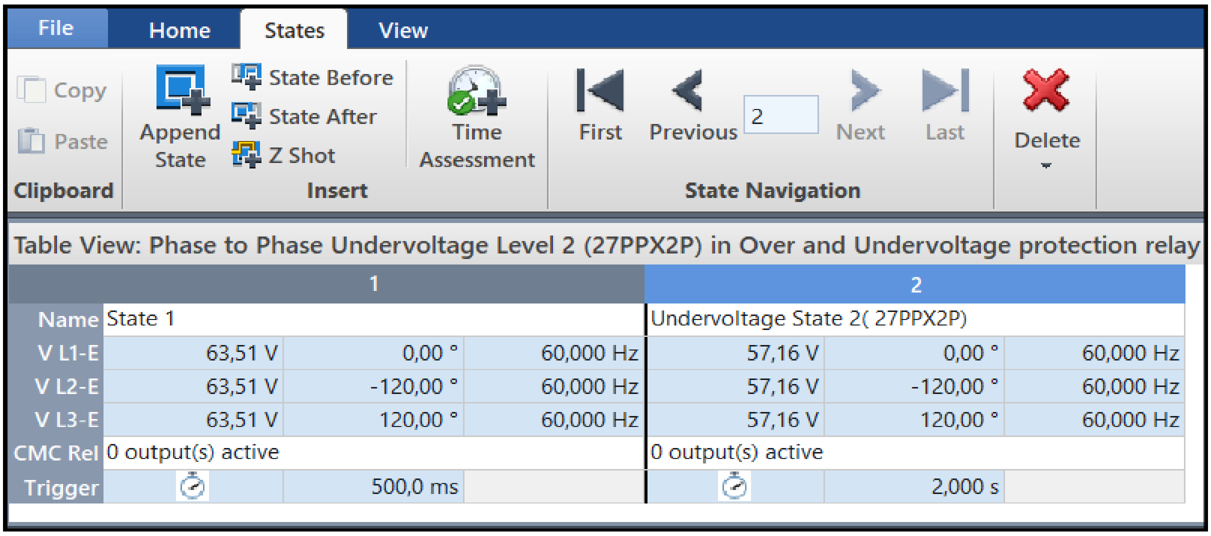


Figure 5.54: Test view of under voltage protection relay stage 2

Figure 5.54 provides detail and time signal views of the under voltage relay element level 2 (27PPX2P). It includes the nominal state and fault state values of overvoltage relay settings subjected to be injected to omicron test universe. The operating time of the relay is 2s.

ii. 27PPX2P simulation results

The results of the SEL 700G under voltage relay are analysed AcSELerator Synchro wave tool. 27PPX2P instantaneous element picks up the under voltage condition immediately and 27PPX2T element issues the trip signal at 0.0792 seconds after the pickup as shown in Figure 5.55. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0792 after the pickup.

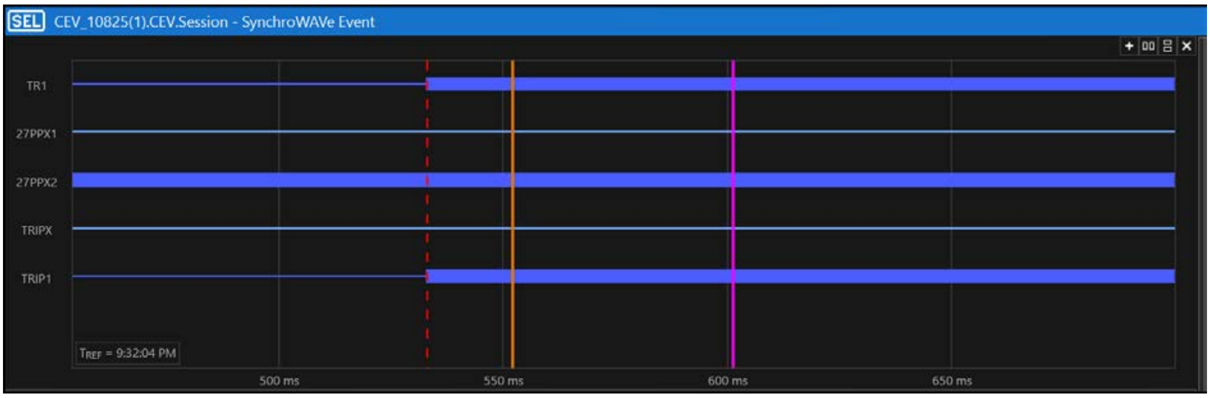


Figure 5.55: Trip signals of the SEL 700G under voltages relay (27PPX2P).

5.5 Conclusion

This chapter provided the configuration settings of volts per hertz, overcurrent, and overvoltage and under voltage protection schemes. The detailed description of the rest object settings and hardware configuration setting for all protection schemes test modules are provided.

The ANSI code (24) Volts per hertz function of SEL 700G was successfully tested for dual level definite time and inverse time characteristics.

A simple overcurrent generator backup protection SEL-700G performance was also successfully tested for three case studies:

- Three phase fault
- Single phase fault to ground fault

Over voltage and under voltage protection schemes response was successfully tested for the following elements and levels:

- 59PPX1P
- 27PPX1P

Chapter six discusses the implementation of hardware-in-the-loop simulation to test volts per hertz, overcurrent, and overvoltage and under voltage protection for generator disturbance conditions.

CHAPTER SIX

IMPLEMENTATION OF THE HARDWARE-IN-THE-LOOP SIMULATION TO TEST VOLTS PER HERTZ, A BACK UP OVERCURRENT, OVER AND UNDER VOLTAGE PROTECTION SCHEMES FOR A GENERATOR

6.1 Introduction

This chapter analyse the over-excitation, overcurrent, overvoltage and under voltage conditions using the hardwired application with data obtained in the Real Time Digital Simulator (RTDS). The hardware in the loop simulation tests were implemented for IEEE 9 bus system network modelled in the RSCAD simulation environment. Hardware in loop simulation tests were conducted using RTDS and SEL 700G IED. The following case studies were conducted:

- Case one analyse the generator over excitation conditions.
- Case two analyse the generator overcurrent conditions.
- Case three analyse generator overvoltage conditions.
- Case four analyse the generator under voltage conditions.

The physical SEL 700G IED is connected in closed loop configuration with RTDS. The SEL 700G relay is configured to trip the circuit breaker to avoid malfunction caused by over-excitation, overcurrent, and overvoltage and under voltage conditions

This chapter presents the modelling and simulation of IEEE 9-Bus system in RSCAD. The real time fault simulations on a generator were performed using RTDS in a closed loop configuration with a physical IED (SEL 700G). Finally, the results of the RSCAD runtime environment and event records simulation are examined. In 6.2 the IEEE 9 Bus system is presented in RSCAD, 6.3 cover the hardware in the loop simulation test-bed implementation for a generator protection schemes and 6.4 gives the conclusion as present in Figure 6.0

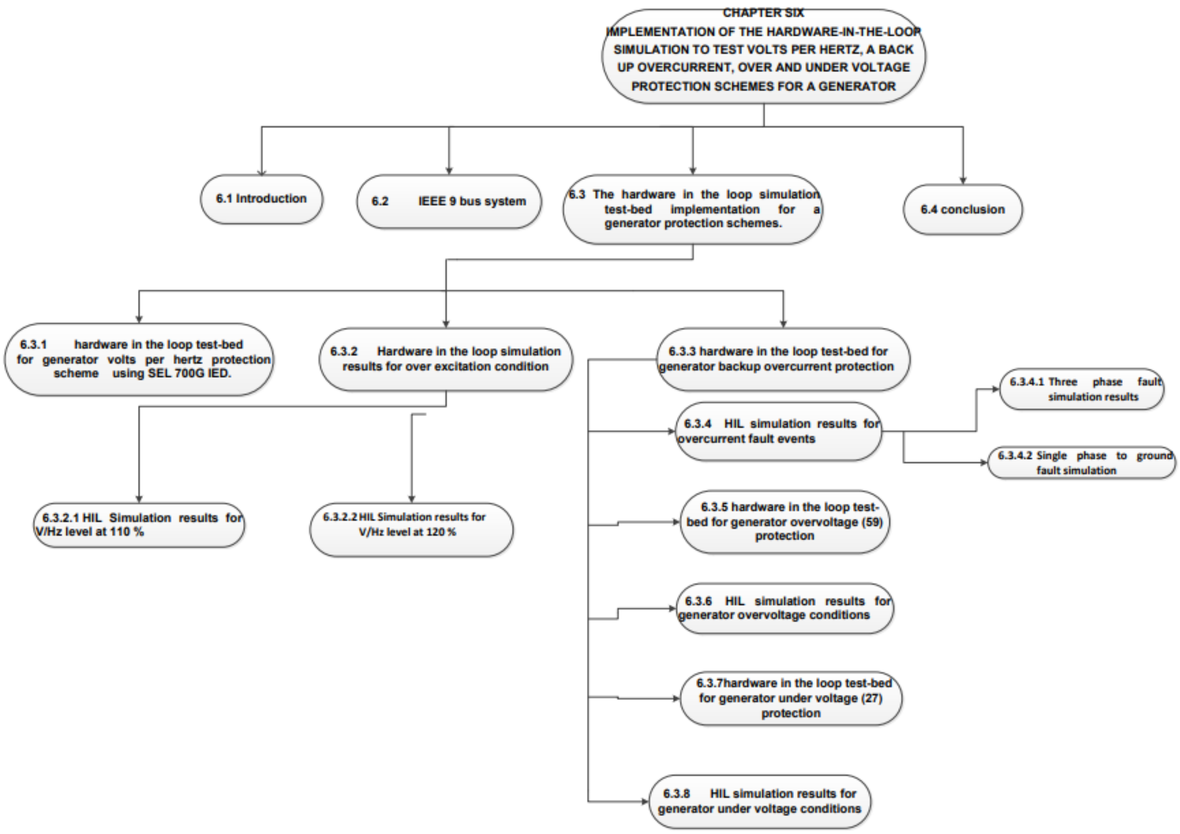


Figure 6.0: Summary of the content covered in Chapter six

6.2 IEEE 9-Bus system

The IEEE 9-Bus test case represents a portion of Western System Coordinating Council (WSCC) to an equivalent system with nine buses and three generators. IEEE systems are used by researchers to implement and test the innovative ideas and concepts using the power system simulation software tools.

The IEEE 9-Bus System network is made up of 9 buses, 3 loads, 6 transmission lines, three two winding transformer (TF1, TF2 and TF3) and 3 generators. The network is designed and modelled on the RSCAD software environment using data given in Tables 4.1 to 4.5.

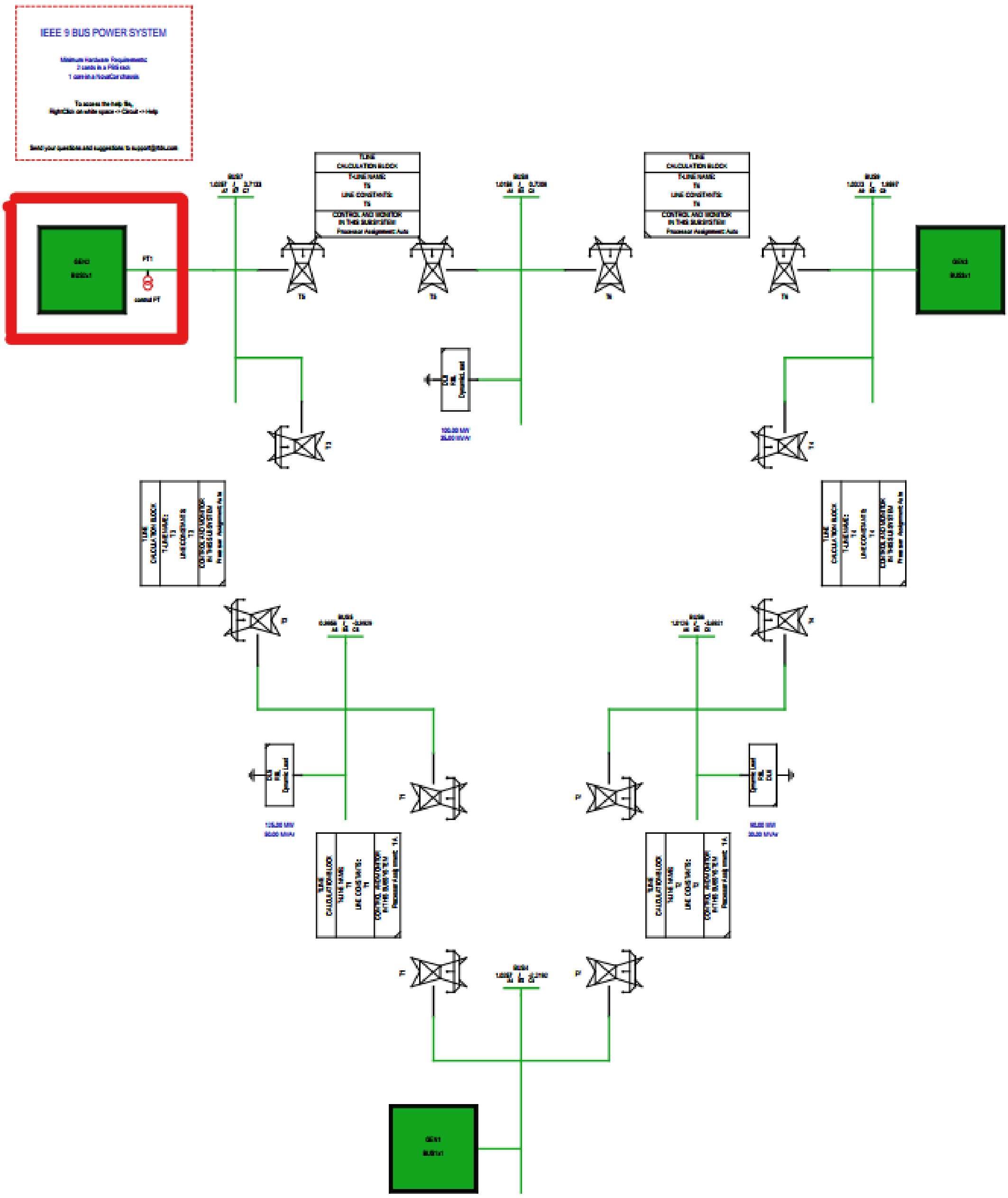


Figure 6.1: IEEE 9-Bus system on RSCAD Environment

Figure 6.1 provides one line diagram of the selected IEEE 9 Bus network. The highlighted part represents the generator protection study area. The full IEEE 9-Bus system can be found in Appendix A. Figure A.2.

6.3 The hardware in the loop simulation test-bed implementation for a generator protection schemes.

Control systems needed to operate complicated equipment and systems are developed and tested using a technique called hardware-in-the-loop (HIL) simulation. The physical component of a machine or system is replaced by a simulation with HIL simulation (Kleijn, 2014). Power electronics and power system fields use hardware-in-the-loop simulations more and more frequently.

This section provides the implementation hardware in the loop simulation using RTDS and SEL 700G IED for the following case studies:

- Case one analyse the generator over excitation conditions.
- Case two analyse the generator overcurrent conditions.
- Case three analyse generator overvoltage conditions.
- Case four analyse the generator under voltage conditions.

6.3.1 The implementation of hardware in the loop test-bed for generator volts per hertz protection scheme using SEL 700G IED.

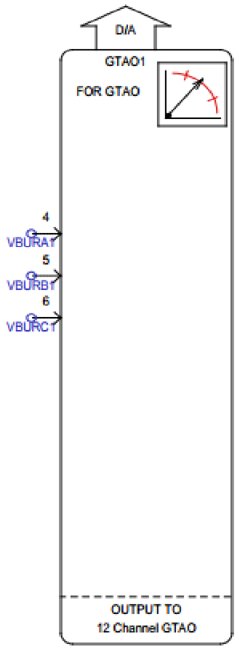


Figure 6.2: DAC component on RSCAD Environment

The RSCAD's digital to analogue converter component is utilized to transmit the voltage measured by the potential transformers to the protective relay equipment, as illustrated in Figure 6.2, which also shows the DAC with its voltage signals. The voltages of the Potential Transformer (PT1) are VBURA1, VBURB1, and VBURC1..

The input signals are sent to the GTAO High precision analogue output card by the Gigabit Transceiver Analogue Output (GTAO) component from RSCAD. The output range of the GTAO card's 12 16-bit channels is plus or minus 10 volts. The component converts the input signals, scales them to 16 bits, and delivers them to the GTAO card through the RTDS hardware's optical interface.

As shown in Figure 6.3, the interface block that RSCAD built allows connection between the SEL 700G and the RTDS GTAO interface card. The SEL700G relay receives the voltage signals (PT1) given by the real-time digital simulator. The physical SEL 700G relay's feedback connection to the Digital, I/O port of the RTDS's front panel is set up to provide trip signals, as seen in Figure 6.3. The SEL700G relay's generator terminal voltage signals are continuously tracked and updated. The SEL 700G external relay receives amplified digital voltage signals from the RTDS GTAO card. The PT1 voltage signals are amplified by the Omicron CMS 356 amplifiers to the SEL 700G generator terminal voltage, which emulate a real-time simulation environment.

The SEL-700G generator volts per hertz (24) relay is defined to provide trip signals for generator over-excitation conditions (i.e. when volts per hertz level exceeds generator terminal voltage limits) on a generator. The relay is configured using AcSELarator Quickset software tool.

As shown in Figure 6.3, the GTAO and CMS156 Omicron amplifiers transmit generator terminal voltage signals from real-time digital simulator simulation constantly to the generator SEL700G relay's. The SEL 700G relay is connected to the RTDS's generator terminal voltage signals via the back panel. When the amount of volts per hertz at Bus 7 of the highlighted Gen 2 as shown in Figure 6.1 exceeds the threshold value, the SEL 700G relay produces a trip signal based on its protection logic. According to Figure 6.3, the digital input port on the front panel of the RTDS hardware receives this trip signal from the SEL700G relay. The SEL700G relay hardware physically completes the loop by transmitting the trip signal through the cables attached to the front panel (digital input port) of the RTDS. Figure 6.3 depicts the hardware-in-the-loop test configuration for the SEL 700G generators over the excitation relay and the RTDS.

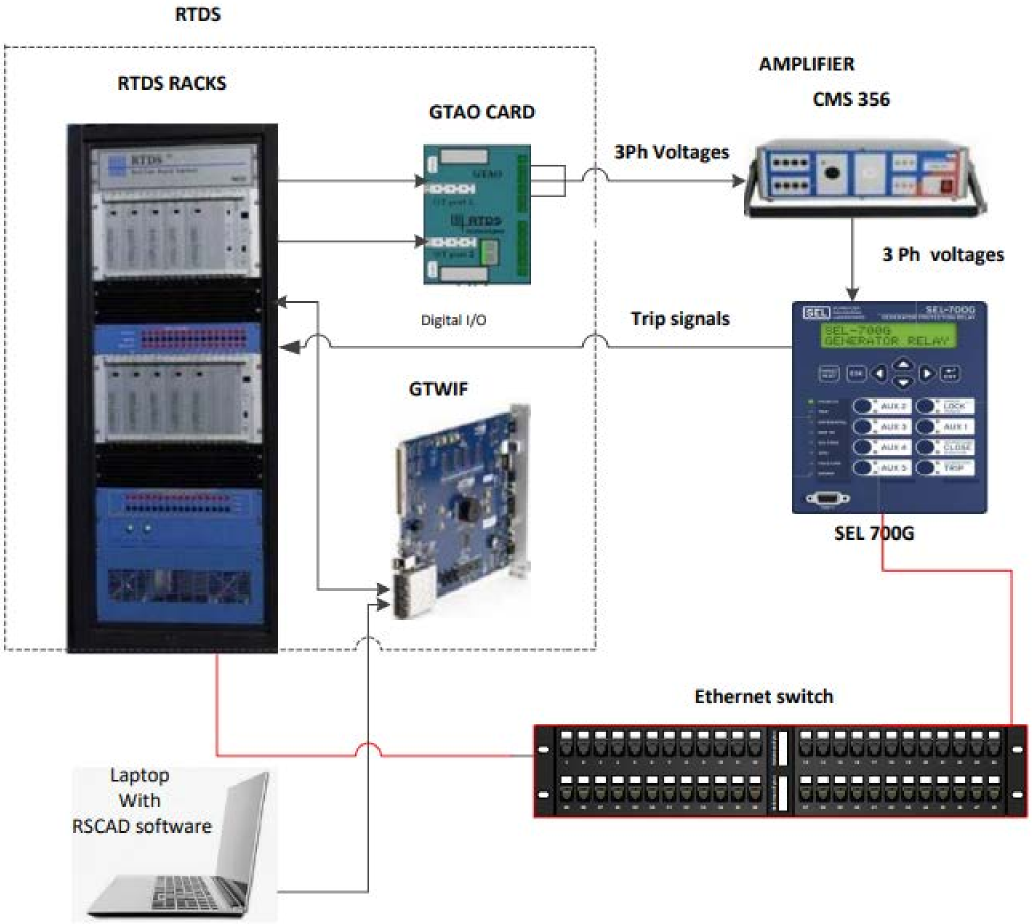


Figure 6.3: Hardware in the loop test bed for volts per hertz protection scheme

The GTWIF card is used to export the simulation results from the RTDS to the RSCAD Runtime environment. As shown in Figure 6.3, the GTAO card is connected to the CMS 356 Omicron amplifier, which converts 10V analogue voltage signals into the generator terminal voltage channels of the SEL700G relay.

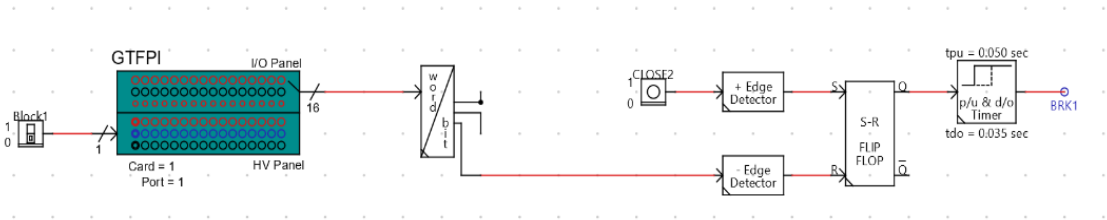


Figure 6.4: GTFI component for breaker control on RSCAD

In order to respond to digital signal interface through a digital I/O panel, the Gigabit Transceiver Front Panel Interface (GTFPI) component for breaker control was modelled in RSCAD and can be shown in Figure 6.4. 16 digital inputs are interfaced with using the digital I/O panel. The physical SEL700G relay to RTDS interface trip is done through the I/O panel.

6.3.2 Hardware in the loop simulation results for over excitation condition

The hardware in the loop simulations was conducted for dual level definite time characteristics volts per hertz and the generators over excitation conditions were studied. For this case study, the generator over excitation conditions were achieved by increasing the field current beyond generator volts per hertz restrictions in RSCAD runtime as shown in Figure 6.5. The field current was varied according to the two case scenarios:

- When the volts per hertz level exceeded by 110%
- And When the volts per hertz level exceeded by 120%

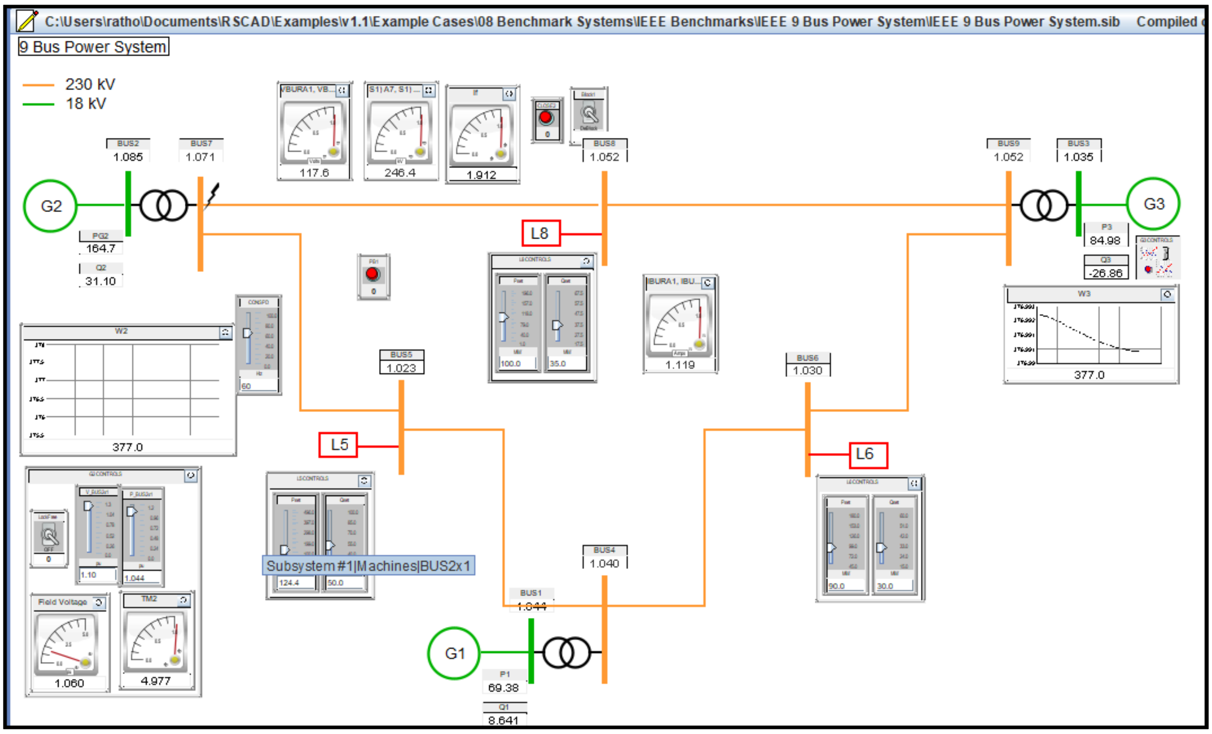


Figure 6.5: Volts per hertz protection on RSCAD runtime

6.3.2.1 HIL Simulation results for V/Hz level at 110 %

The hardwired results of the dual level definite time characteristics relay are analysed using the AcSELerator Synchro event wave tool .the AcSELerator Synchro wave tool provides a phase to phase voltage of 199.753kV and it is the same as the test universe simulation result. 24D1 dual level definite element picks up the over-excitation condition immediately after the field current was increased beyond110% of the limit and 24D1T element issues the trip signal at 0.075 seconds after the pickup as shown in Figure 6.6. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.079 seconds after the pickup.

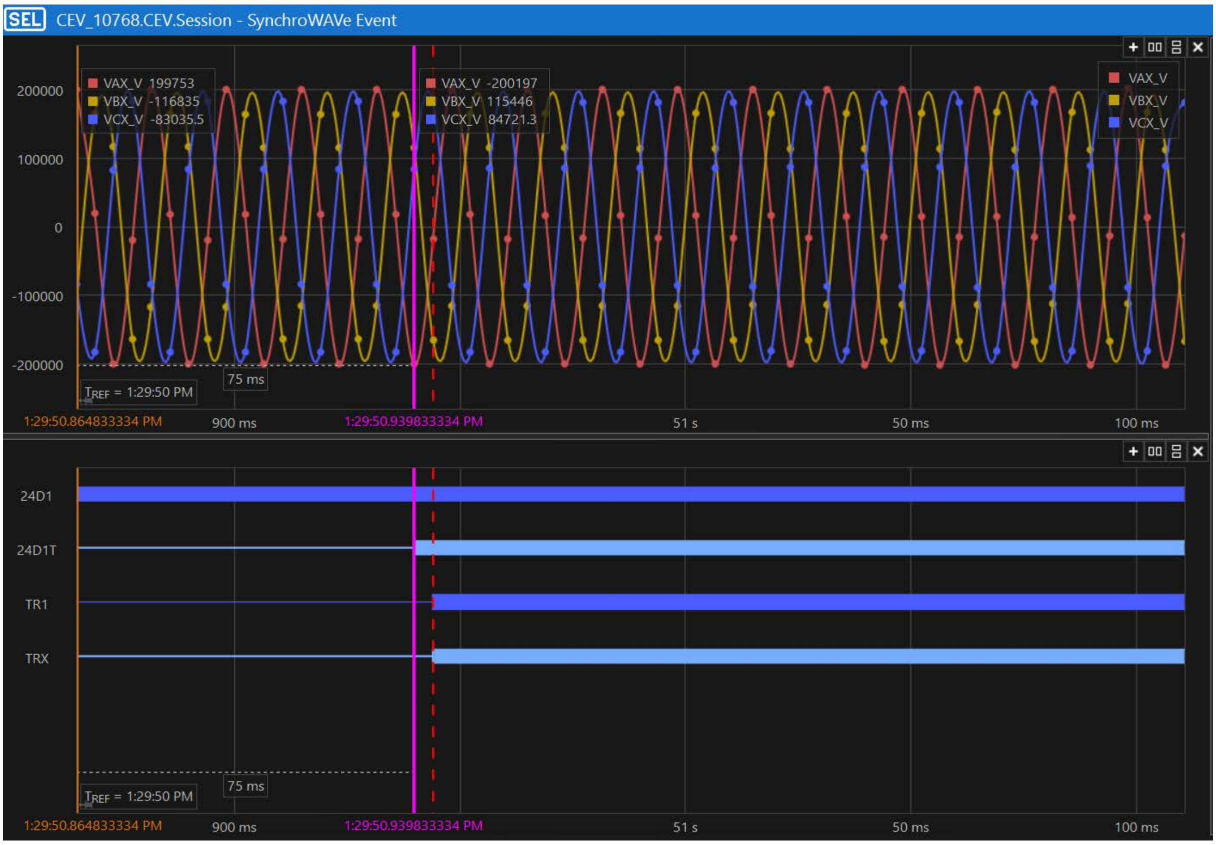


Figure 6.6: Phase to phase voltages and trip signals of the SEL 700G IED at V/Hz level of 110%

6.3.2.2 HIL Simulation results for V/Hz level at 120 %

The hardwired results of the dual level definite time characteristics relay are analysed using the AcSELerator Synchro event wave tool .the AcSELerator Synchro wave tool provides a phase to phase voltage of 206.229kV. 24D1 dual level definite element picks up the over-excitation condition immediately after the field current was increased beyond 120% of the limit and 24C2 composite element pick up the over excitation condition after 0.021 seconds. 24D1T element issues the trip signal at 0.075 seconds after the pickup. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.079 after the pickup.24C2T of the composite element trip issues a trip signal after 0.15 seconds, supposedly the 24D1T elements fails to clear the over-excitation condition of generator as shown in Figure 6.7.

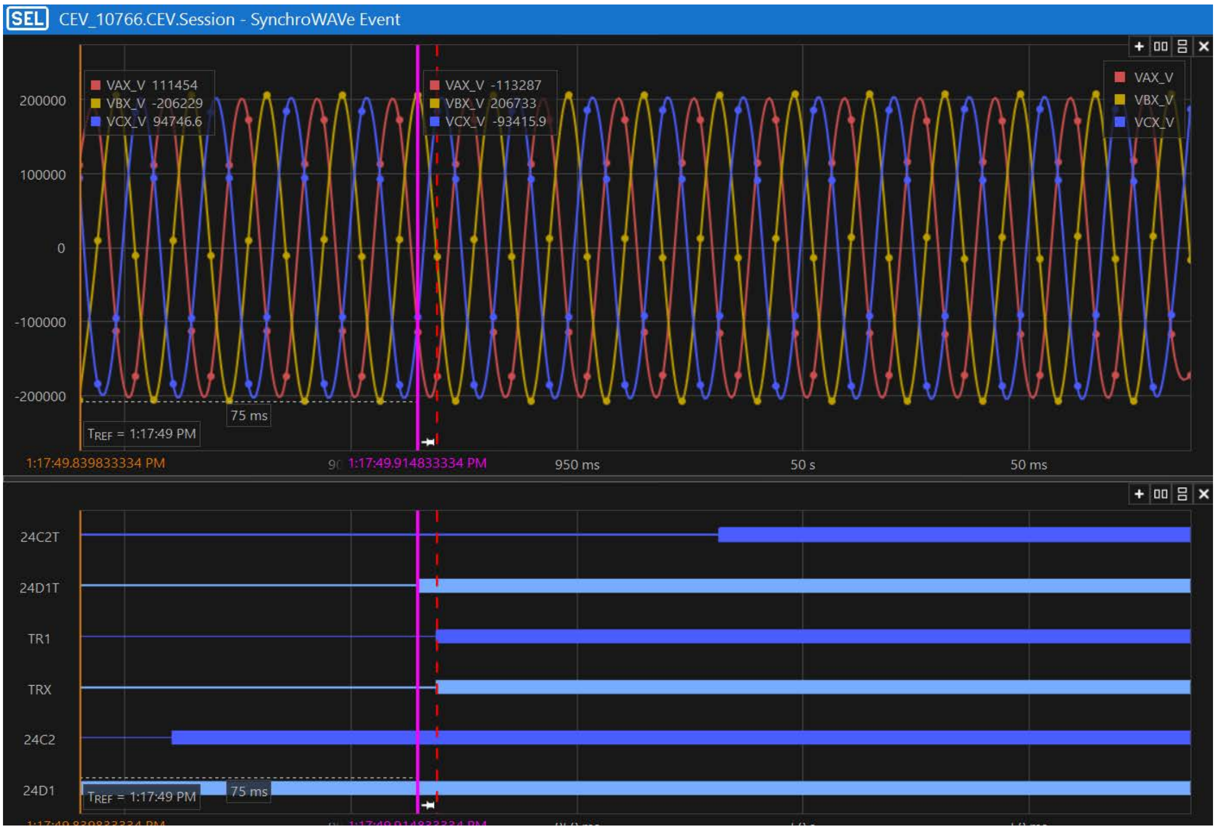


Figure 6.7: Phase to phase voltages and trip signals of the SEL 700G IED at V/Hz level of 120%

6.3.3 The implementation of hardware in the loop test-bed for generator backup overcurrent protection scheme using SEL 700G IED.

The test bed implementation of the generator back overcurrent protection system is provided in this section. Three phase fault, double phase fault, and single phase to ground fault tests are performed on the SEL 700G's overcurrent relay performance.

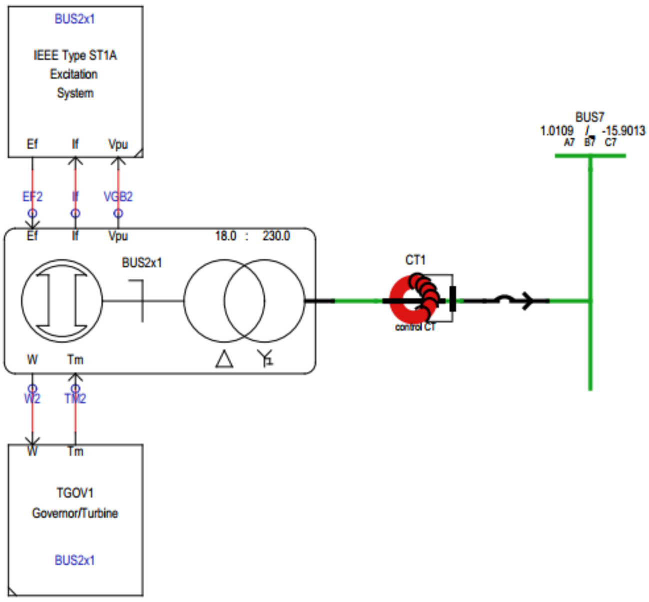


Figure 6.8: 8rotected zone (G2) of IEEE 9-Bus System

The G2 study area for the SEL 700G backup overcurrent protection relay is shown in Figure 6.8 and is modelled in RSCAD. As seen in Figure 6.8, it contains a circuit breaker and the CT1 to monitor the currents at the Bus 7 of the generator terminal.

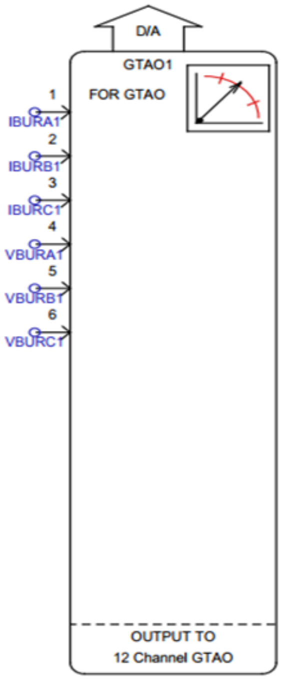


Figure 6.9: DAC component for input signals on RSCAD environment

Of this research scenario, the digital to analogue converter component in the RSCAD is utilized to communicate the current sensed by the CT1 to the protective relay equipment. Figure 6.9 illustrates the Digital to Analogue Converter (DAC) with its current and voltage signals. Current Transformer (CT1) currents IBURA1, IBURB1, and IBURC1 are designated.

The SEL700G relay receives the current signals (CT1) generated by a real-time digital simulator. The feedback connection from the actual SEL 700G relay to the Digital, I/O port of the RTDS's front panel is set up to provide trip signals, as seen in Figure 6.10. The generator current signals for the SEL700G relay are continuously tracked and updated. Digital signals are amplified and sent to the SEL 700G external relay.

For generator fault events, the SEL-700G generator back up overcurrent relay is designed to send trip signals. The AcSELarator Quickset software program is used to configure the relay.

As shown in Figure 6.10, the GTAO and CMS156 Omicron amplifiers transmit generator current signals from real-time digital simulator simulation constantly to the

(50) overcurrent element of the generator SEL700G relay. The SEL 700G relay is connected to the RTDS's generator terminal's current signals via the rear panel. When the fault current value exceeds the threshold value at Bus 7 of Gen 2, as shown in Figure 6.8, the SEL 700G relay overcurrent components trip the circuit based on their protective logic. As shown in Figure 6.10, the digital input port on the front panel of the RTDS hardware receives this trip signal from the SEL700G relay. The cables attached to the front panel (digital input port) of the RTDS are used to transmit the trip signal from the SEL700G relay. Figure 6.10 depicts the hardware-in-the-loop test configuration for the SEL 700G generator backup overcurrent relay and the RTDS.

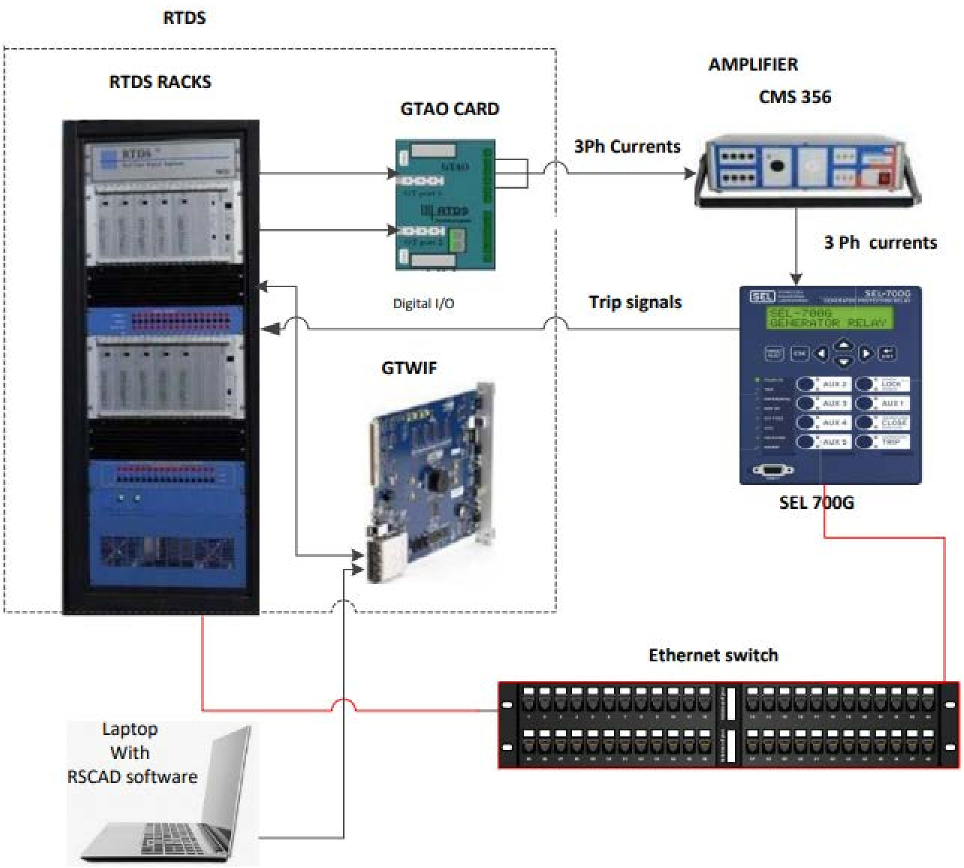


Figure 6.10: Hardware in the loop test bed for Backup overcurrent protection scheme

As illustrated in Figure 6.10, the CMS 356 Omicron amplifier is connected to the GTAO card to transform 10V analogue current signals into the generator current channels of the SEL700G relay.

6.3.4 HIL simulation results for overcurrent fault events

Hardware in the loop test for (50) overcurrent function of SEL700G generator protection relay was implemented and the overcurrent conditions were studied. The fault was placed on bus 7 as an external fault of the generator as shown in Figure 6.5. For this case study, the overcurrent relay was test for three phase fault and single phase to ground fault.

6.3.4.1 Three phase fault simulation results

The results of the SEL 700G overcurrent relay is analysed AcSELerator Synchro wave tool which provides 1022 Amps for three phases (L1-L2-L3) fault loop, and it is the same as the test universe simulation result. 50PX1P instantaneous element picks up the fault 0.66 seconds and 50PX1T element issues the trip signal at 0.0125 seconds after the pickup as shown in Figure 6.11. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0125 after the pick up

Figure 6.11: HIL 3 phase fault simulation results

6.3.4.2 Single phase to ground fault simulation

The results of the SEL 700G overcurrent relay is analysed AcSELerator Synchro wave tool which provides 1022 Amps for three phases (L1-E) fault loop, and it is the same as the test universe simulation result. 50PX1P instantaneous element picks up the fault 0.67 seconds and 50PX1T element issues the trip signal at 0.0125 seconds after the pickup as shown in Figure 6.11. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.0125 after the pick up

Figure 6.12: HIL 3 Single phase to ground fault simulation results

6.3.5 The implementation of hardware in the loop test-bed for generator overvoltage (59) protection scheme using SEL 700G IED.

This section provides the test bed implementation of generator overvoltage protection scheme. The hardware in the loop test bed of SEL 700G over and under voltage relay implementation is similar to one of generator over-excitation relay explained in section 6.3.1. The SEL-700G generator overvoltage (59) relay is defined to provide trip signals for generator overvoltage condition due to various system disturbances. The relay is configured using AcSELarator Quickset software tool

6.3.6 HIL simulation results for generator overvoltage conditions

The hardware in the loop tests were implemented and the generators overvoltage conditions were studied. The generators are designed to operate at rated voltage below 1.05pu. For this case study, the generator overvoltage conditions were achieved decreasing load beyond generator voltage limits in RSCAD runtime as shown in Figure 6.5. The overvoltage relay was tested the level of overvoltage exceeded by 110%

6.3.6.1 HIL Simulation results for overvoltage level at 110 %

This section discusses the hardwired overvoltage simulation results for instantaneous element (59PPX1). The results of the SEL 700G overvoltage relay are analysed AcSELerator Synchro wave tool. AcSELerator Synchro wave tool provides a phase to phase voltage of 199.694kV and it is the same as the test universe simulation result. 59PPX1P instantaneous element picks up the overvoltage condition after immediately after load reduction and 59PPX1T element issues the trip signal at 0.072 seconds after the pickup as shown in Figure 6.13. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.072 after the pickup.

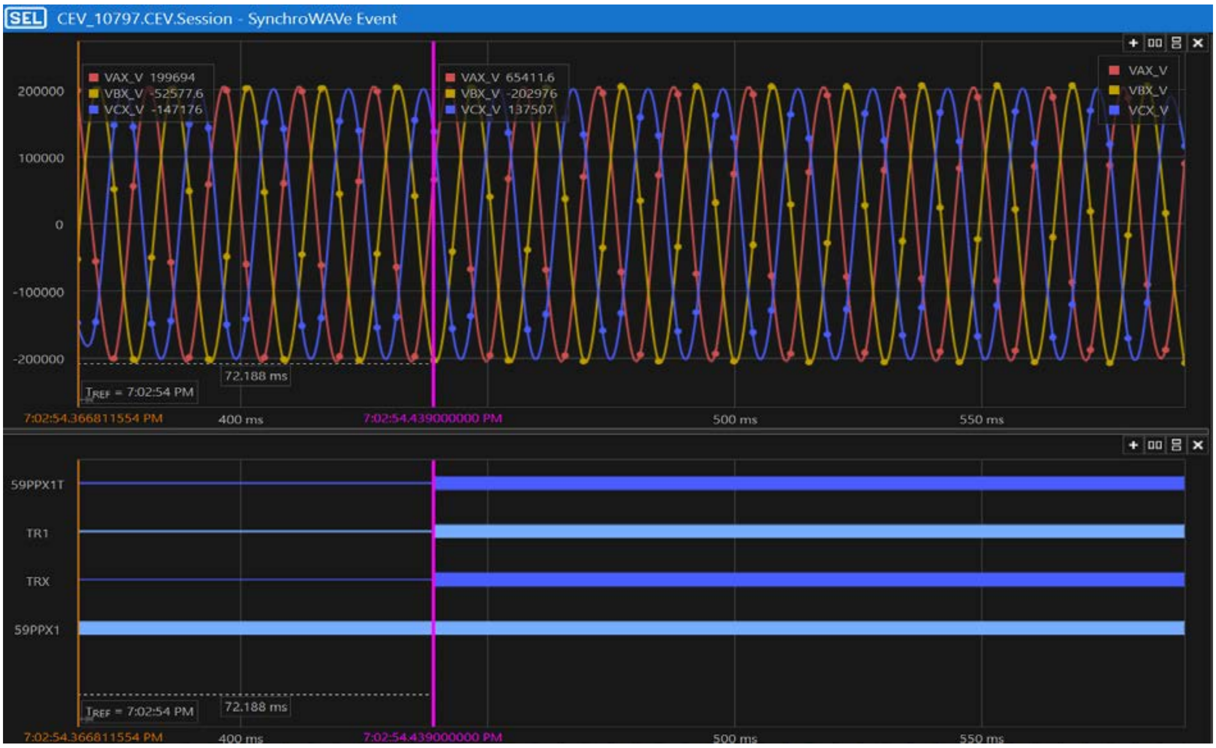


Figure 6.13: HIL results of the SEL 700G IED overvoltage relay

6.3.7 The implementation of hardware in the loop test-bed for generator under voltage (27) protection scheme using SEL 700G IED.

This section provides the test bed implementation of generator overvoltage protection scheme. The hardware in the loop test bed of SEL 700G over and under voltage relay implementation is similar to one of generator over-excitation relay explained in section 6.3.1. The SEL-700G generator under voltage (27) relay is defined to provide trip signals for generator under voltage condition due to various system disturbances. The relay is configured using AcSELarator Quickset software tool.

6.3.8 HIL simulation results for generator under voltage conditions

The hardware in the loop tests was implemented and the generators under voltage conditions were studied. The generators are designed to operate at rated voltage over 0.95pu. For this case study, the generator under voltage conditions were achieved increasing the load below generator voltage limits in RSCAD runtime as shown in Figure 6.5. The under voltage relay was tested the level of under voltage lowered by 95% of the rated voltage.

6.3.8.1 HIL Simulation results for under voltage level at 95 %

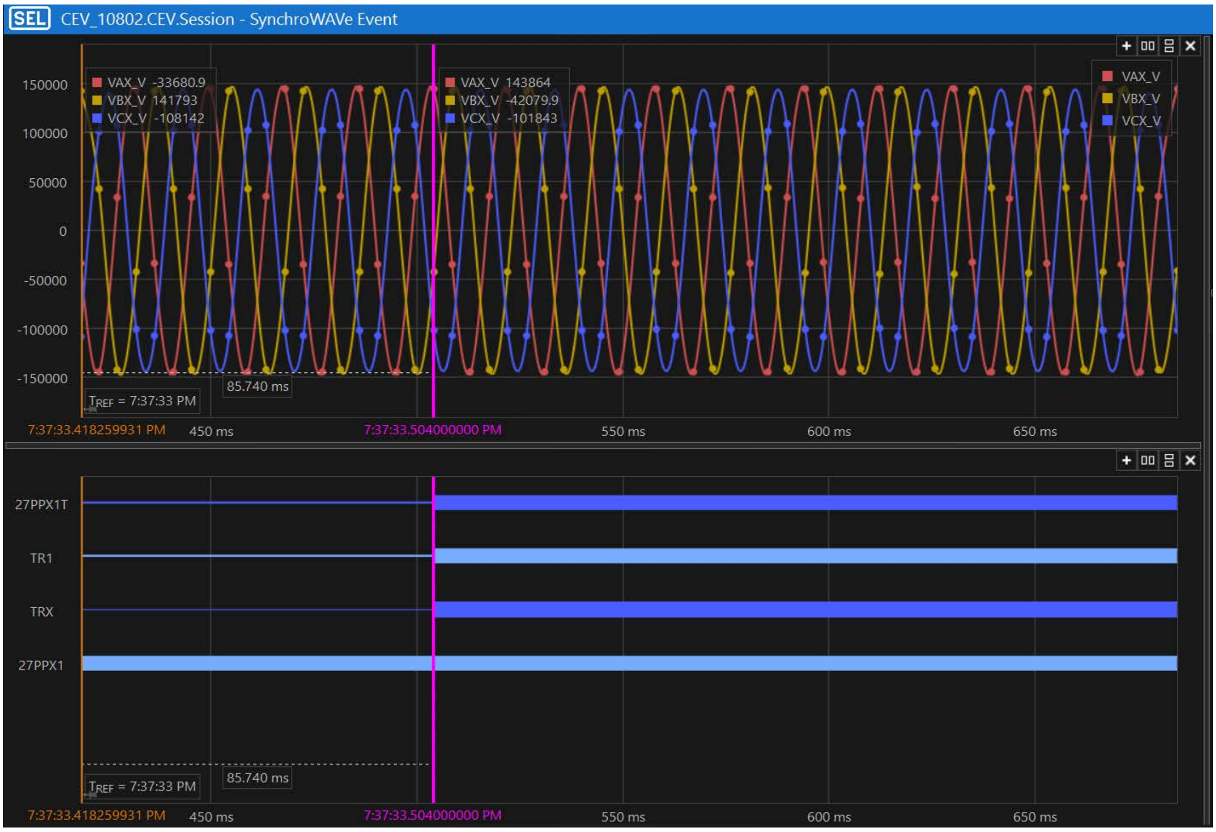


Figure 6.14: HIL results of the SEL 700G IED under voltage relay

This section discusses the hardwired under voltage simulation results for instantaneous element (27PPX1). The results of the SEL 700G under voltage relay are analysed AcSELerator Synchro wave tool. AcSELerator Synchro wave tool provides a phase to phase voltage of 141.793kV. 27PPX1P instantaneous element picks up the under voltage condition after immediately after load was increased and 27PPX1T element issues the trip signal at 0.085 seconds after the pickup as shown in Figure 6.14. The TRX and TR1 elements of the generator X-side breaker and generator field breaker also issue a trip at 0.085 after the pickup.

6.4 Conclusion

This chapter provided the hardware in the loop test-bed implementation and the simulations of volts per hertz, simple back up overcurrent, and overvoltage and under voltage protection schemes. The HIL test bed was implemented using real time digital simulator and SEL 700G IED. This chapter also presented the HIL simulation results for over excitation conditions, overcurrent fault events, over and under voltage conditions of a generator.

Chapter 7 discusses the thesis the findings, deliverables, application of results, and the future field of research.

CHAPTER SEVEN
CONCLUSION

7.1 Introduction

In many power plants, generators are the most important electrical equipment. These generators actually belong to a special class of expensive power network equipment. The generator noteworthy expense goes into providing the highest level of protection inclusion due to the prohibited cost of replacing them. The purpose of these protective systems is to lessen the possibility of physical damage to the equipment caused on by a system fault or by the equipment operating abnormally.

This research focused on generator over excitation system and aimed to implement the hardware-in-the-loop simulation of volts-per-hertz protection scheme for generator over excitation system. This research also aimed to implement HIL simulations for generator protection scheme such as a simple back up overcurrent (50), overvoltage (59) and under voltage (27) for generator disturbance conditions.

The lab scale test bench set up and implementation a generator protection scheme focusing on volts per hertz, overcurrent, over and under voltage relays was performed. The lab scale test was implemented using the SEL 700G IED, Test universe software and CMC 256 omicron test universe. AcSELartor Quick set software tool was used to configure the SEL 700G relay for both lab scale and hardwired applications.

Hardware-in-the-loop implementation of the above mentioned generator protection schemes were conducted using real time digital simulator and SEL 700G protective IED. The HIL simulations were conducted using RSCAD software.

The outcomes, major findings, and thesis deliverables are summarized in this chapter. Section 7.2 of the thesis presents the deliverables, and section 7.3 of the thesis describes potential academic, research, and industrial applications of the deliverables. Section 7.4 proposes further study in the area of generator protection for disturbances systems as presented in Figure 7.0.

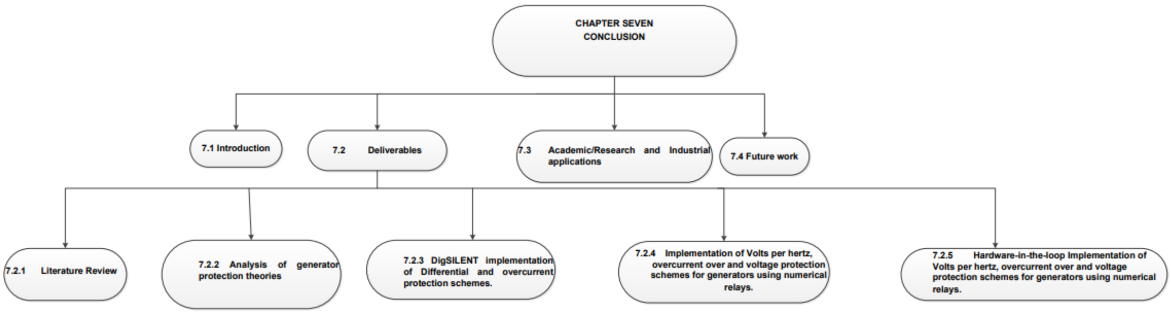


Figure 7.0: Summary of content covered in chapter seven

7.2 Deliverables

The ANSI code 24 protection function of the SEL 700G relay detects an over-excitation condition and sends the trip signal to the generator circuit break, restoring normal operating circumstances, when the level of volts per hertz of a generator exceeds the allowable value. The key deliverables of the thesis are as follows:

7.2.1 Literature Review

Literature review analyses various technique used for generator protection. The digital algorithms for generator protection schemes in terms of speed, stability ,security ,simplicity redundancy and dependability has been reviewed .The literature review presented the investigation which includes the generator over excitation system and its volts per hertz protection scheme, hardware-in-the-loop simulation using real time digital simulator. A comprehensive review of various works completed in the field of the generator is also presented, as are various types of generator protection schemes.

7.2.2 Analysis of generator protection theories

In Chapter three, brief descriptions of generator protection schemes that are presently in use and their operation are provided.

7.2.3 DigSILENT implementation of Differential and overcurrent protection schemes.

For both internal and external faults, the generator differential and overcurrent performance is examined. The DIgSILENT power factory software environment was used to develop and simulate the generator protection strategy, and analyze the load flow results. As a case study, the IEEE 9-Bus Grid-network is used.

7.2.4 Implementation of Volts per hertz, overcurrent over and voltage protection schemes for generators using numerical relays.

The lab scale test bench set was implemented to test volts per hertz, backup overcurrent, over and under voltage protection schemes. Various faults pertaining to generator were simulated using the OMICRON test injection device.

7.2.5 Hardware-in-the-loop Implementation of Volts per hertz, overcurrent over and voltage protection schemes for generators using numerical relays.

Hardware-in-the-loop test-bed was implemented and the simulated of volts per hertz, simple back up overcurrent, and overvoltage and under voltage protection schemes. . The HIL test bed was implemented using real time digital simulator and SEL 700G IED. The RSCAD software environment was used to build and model the IEEE 9 bus system network. The HIL simulation results for over excitation conditions, overcurrent fault events, over and under voltage conditions of a generator was also presented in Chapter 6.

7.3 Academic/Research and Industrial applications

The developed lab scale test bench set up for generator protection schemes can help the students learn the fundamental generator protections during system disturbances using newly advance numerical relays.

The thesis provides a standard benchmark for both academic and industry through the implementation of hardware in the loop test beds and simulation of over-excitation, over and under voltage protection schemes for a generator in a RSCAD environment using RTDS and numerical relays. Therefore, it is highly recommended to implement HIL simulations to test protective functions because it provides a platform for power systems networks to be investigated in a virtual system under a wide range of realistic conditions repeatedly, safely, and economically.

7.4 Future work

This thesis projected only focused on over-excitation, over and under voltage conditions for generator system on hardwired application. It will be very interesting for future work to investigate over-excitation condition using GOOSE messaging.

The future research will consider investigating all the generator protective functions using Real Time Digital Simulators, numerical relay and IEC 61850 standard-based GOOSE messaging applications and Interoperability of various IEDs for generator protection.

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APPENDICES

APPENDIX A: IEEE 9-BUS SYSTEM DATA

A.1 Introduction

The network consists of 3 loads, 6 transmission lines, 3 two-winding transformers (TF1, TF2, and TF3), 9 buses, 3 two-winding transformers, and 3 generators. Figure A1 displays the IEEE 9-Bus system's single line diagram. The Western System Coordinating Council (WSCC) section of the system is modeled after a comparable system with nine buses and three generators in the IEEE 9-Bus test case.

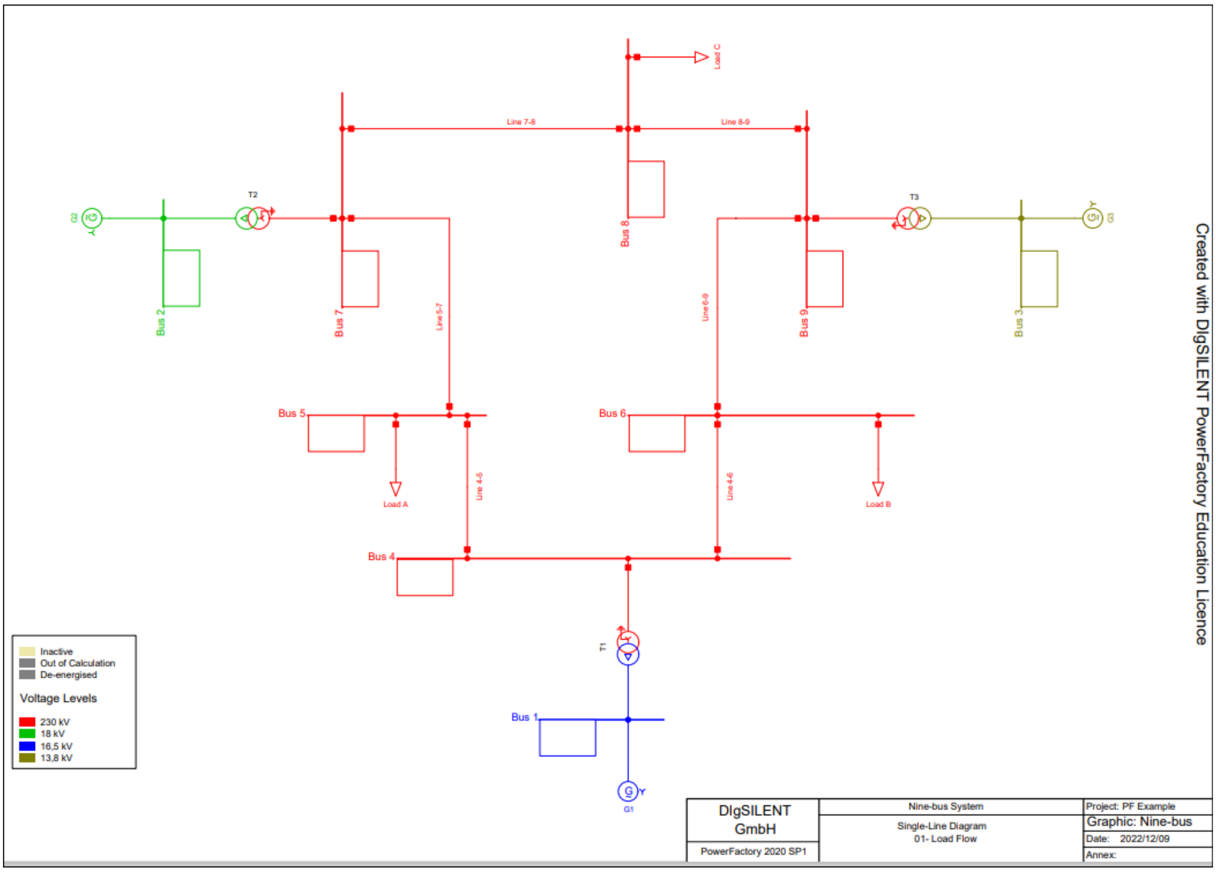

Figure A.1: Single line diagram of the IEEE 9 Bus system

A.2 IEEE 9-Bus system

In this section, the IEEE 9 bus system's input data is presented. The bus voltage magnitudes are shown in Table A.1 as rated and per unit values. In Table A.3, the buses that have generators and loads are also included.

Table A.1: Bus data of the IEEE 9 Bus system

Bus no	Rated voltage in (KV)	V (pu)	Angle (deg)
1	16.5	1.04	0
2	18	1.02	9.3
3	13.8	1.02	4.7
4	230	1.03	147.8
5	230	1.00	146
6	230	1.01	146.3
7	230	1.03	153.7
8	230	1.02	150.7
9	230	1.03	152

A.2.1 Transformer data

IEEE 9 Bus system consists of three transformers and its information data are given in Table A.2. The short circuit percentages are also provided in table A.2

Table A.2: Transformer data of the IEEE 9 Bus system

Transformer	S MVA	I rated in kA	HV in KV	LV in KV	Sc. voltage uk in %	Sc. voltage uk0 in %	F in Hz	Vector group
1	250	1	230	16.5	14.4	3	60	Yn/D
2	200	1	230	18	12.5	3	60	Yn/D
3	150	1	230	13.8	8.78	3	60	Yn/D

A.2.2 Load data

The load data of the IEEE 9 bus system is provided in Table A.3.the active power, reactive power and the location of these loads is given in Table A.3.

Table A.3: Load data of the IEEE 9 Bus system

Load	Active power in (MW)	Reactive power(Mvar)	Technology	location
A	125	50	3ph-phe	Bus 5
B	90	30	3ph-phe	Bus 6
C	100	35	3ph-phe	Bus 8

A.2.3 Generator data

Table A.4 provides the generator information data. The active power, reactive power and voltage magnitudes are given in Table A.4.

Table A.4: Generator data of the IEEE 9 Bus system

Generator	Bus type	P (MW)	Q(Mvar)	V(pu)	pf	Xd(pu	Xd in pu	S (MVA
1	slack	0	0	1.04	0.9	1.7	1.65	512
2	PV	163	6.7	1.025	0.85	1.7	1.62	270
3	PV	85	-10.9	1.025	0.85	1.22	1.16	125

A.2.4 Transmission line data

Both reactance and resistance values are provided for transmission lines in ohms per kilometre. The IEEE 9-Bus system's length has been assumed to be 1 kilometre because it was not specified. Table A.5 contains the information for the IEEE 9 bus system, which consists of 6 transmission lines.

Table A.5: Line of the IEEE 9 Bus system

Line Name	Vrated (kV)	Type of line	Conductor material	R Ω/km	X in Ω/km	Susceptance (μS/km)
Line 1	230	Overhead	Aluminium	5.29	44.965	332.7
Line 2	230	Overhead	Aluminium	16.928	85.169	578.45
Line 3	230	Overhead	Aluminium	4.4965	38.088	281.66
Line 4	230	Overhead	Aluminium	6.2951	53.3232	395.08
Line 5	230	Overhead	Aluminium	20.631	89.93	676.75
Line 6	230	Overhead	Aluminium	8.993	48.668	298.69

A.3 IEEE 9-Bus system in RSCAD environment

A single line diagram of the IEEE 9-Bus system in the RSCAD environment is shown in Figure A.2. Using the information provided in Tables A.1 through A.5, the network is constructed and modelled using the RSCAD software environment.

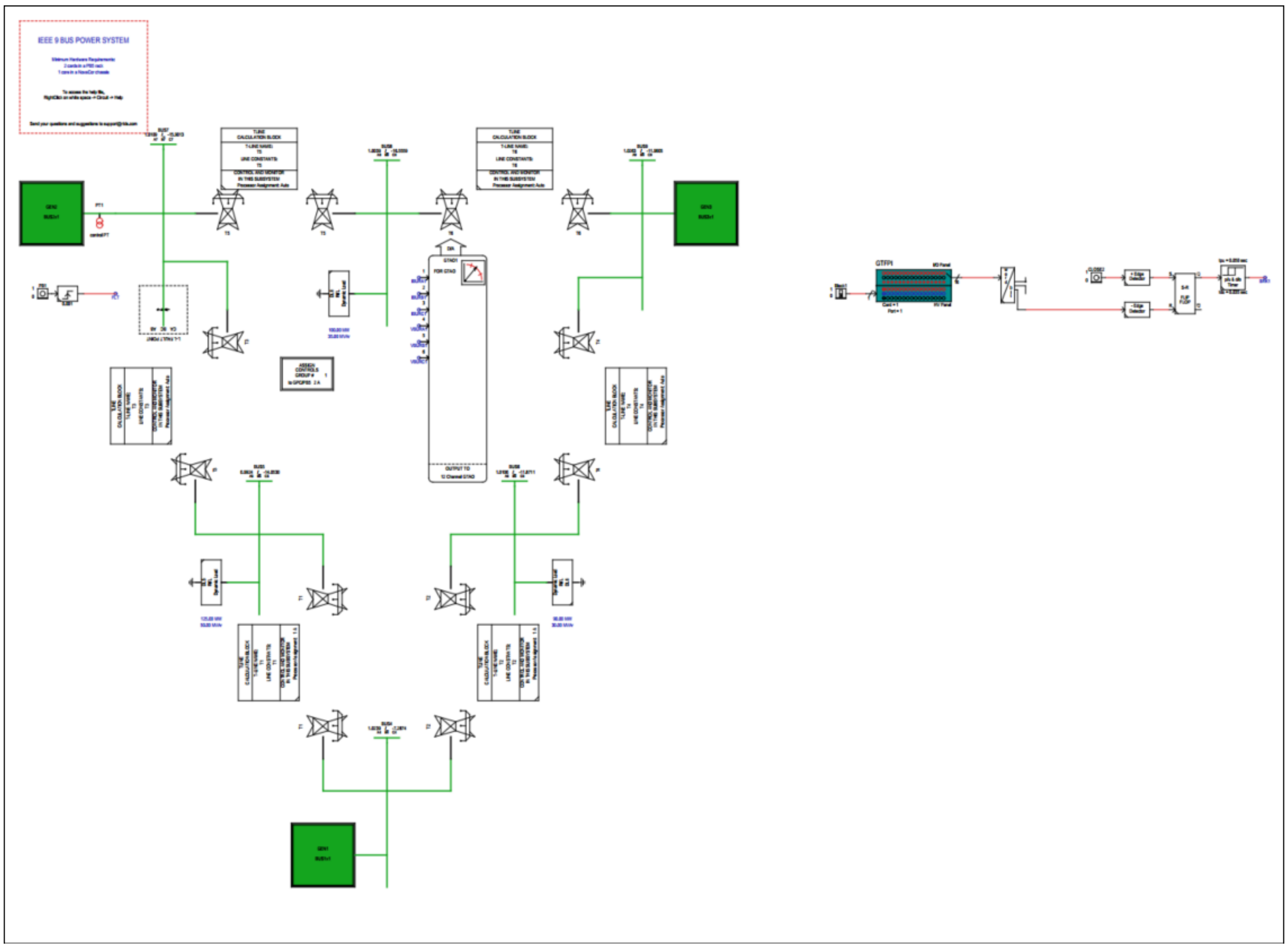

Figure A.2: Single line diagram of IEEE 9-Bus system in RSCAD environment

APPENDIX B: SEL 700G IED configuration settings

B.1 Introduction

The SEL 700G used in this thesis has been configure using Quickset AcSELarator software tool. Appendix B contains the parameters of settings configuration for SEL 700G volts per hertz relay used for this thesis.

B.1.1 SEL 700G Device Information

This section provides the SEL700G IED which include setting version number, part number, firmware ID and SELBoot FID as shown in Table B.1

Table B.1: SEL 700G device information

Device	SEL 700G
Setting version Number	006
Part Number	0700GT1HGH6X7581A671
Firmware ID	SEL-700G-R200-V0-Z06003-D20180629
SELBoot Firmware ID	BOOTLDR-R501-V0-Z000000-D20140224

B.1.2 Port configuration setting of SEL 7OOG

This section provides the port F configuration setting which includes data on speed, bits, parity and stop settings.

Table B.2: Port configuration setting of SEL 7OOG

Settings	Description	Range	Value
EPORT	Enable port	Select: Y,N	Y
PROTO	Protocol	Select :SEL,MOD	SEL
MAXACC	Maximum Access Level	Selecr: 1,2,C	2
SPEED	Data Speed(bps)	Select :300,1200,2400,9600	9600
BITS	Data Bits	Select:7,8	8
PARITY	Parity	Select:O,E,N	N
STOP	Stop Bits(bits)	Select:1,2	1
RTSCTS	Hardware Handshaking	Select: Y,N	N
T_OUT	Port-Time-Out	Range 0-30	5
LANG	Language	Select: Eng,Spa	English
AUTO	Send auto message to port	Select: Y,N	N

B.1.3 Volts per hertz element configuration setting

Table B.3 provides the over-excitation elements configuration for SEL 700G generator IED. The range and value of the setting are also given in Table B.2

Table B.3: volts per hertz elements configuration settings

Parameter Name	Parameter Value	Description
Frequency	60Hz	Nominal system frequency
Generator Data	270MVA	Rated power
	13.8 kV	Rated voltage of the generator
VT data	230000 V/110 V	VT ratio of the x side of a generator
Dual level definite time volts per hertz characteristics(DD)	24D1P= 105%	Level 1 volts/hertz element as an over-excitation alarm
	24D1D=1s	Time delay of 1.0 second to allow time for correction of an over excitation condition prior to an alarm.
	24D2P1=110%	Dual-level definite-time level1 pickup
	24D2T1=45s	Dual-level definite-time level1 time delay
	24D2P2=120%	Dual-level definite-time level 2 pickup
	24D2T2=4s	Dual-level definite-time level 2 time delay
Simple time universe characteristics(I)	24IP=106%	Level 2 Inverse time pick up
	24IC=0.5	Level 2 Inverse Time Curve
	24ITD=4s	Level 2 Inverse Time factor
composite definite/universe time characteristics(ID)	24IP=106%	Level 2 Inverse time pick up
	24ITD=4	Level 2 Inverse Time Curve
	24D2P2=118%	Dual-level definite-time level 2 pickup
	24D2D2=3s	Dual-level definite-time level 2 time delay

B.1.4 output configuration setting of volts per hertz setting

This section provides the output settings of SEL 700G volts per hertz relay as shown in Table B.4.

Table B.4: the output settings of SEL 700G volts per hertz relay

OUT101FS	OUT101 fail-safe	Select: Y,N	N
OUT101	SELogic	Valid range = the legal operation: AND OR NOT R_TRIG F_TRIG	0
OUT102FS	T101 fail-safe	Select: Y,N	N
OUT102	SELogic	Valid range = the legal operation: AND OR NOT R_TRIG F_TRIG	0
OUT103FS	T101 fail-safe	Select: Y,N	N
OUT103	SELogic	Valid range = the legal operation: AND OR NOT R_TRIG F_TRIG	24C2T OR 24D1T