University of Southern Queensland

Faculty of Engineering and Surveying

Callide C Power Stations Generator Protection System "ride through capabilities" for various external faults

A dissertation submitted by

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In fulfilment of the requirements of

Course ENG4111/4112 Research Project

towards the degree of

Bachelor of Engineering (Electrical and Electronic)

Submitted October, 2010

Abstract

Callide C Power Station is half owned and operated by CS Energy. It was Australia's first supercritical coal-fired power station and was commissioned in 2001. CS Energy is a registered participant in the National Electricity Market (NEM) and has a connection agreement with the Australian Energy Market Operator (AEMO) with specified performance standards for Callide C Power Station that it must be capable of delivering at all times.

Australia has the largest electrical network in the world by distance and it is the specified performance standards that entire system models and contingencies are based upon. Because of this importance, if there is an incident resulting from a non compliance from CS Energy, they can incur large fines from the Australian Energy Regulator (AER). One major aspect of compliance is the ability for a connected generator to ride through external faults and maintain system voltage and frequency while the fault is cleared.

This project aims at building a model to represent a Callide C Generator and Transformer and then simulating large faults of different durations at the connection point. Using the output waveforms from the model, convert the data into the industry standard COMTRADE files so the fault scenarios can be "played" into the protection relays to determine their stability for each fault type, starting voltage and duration.

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ENG4111 Research Project Part1 &
ENG4112 Research Project Part2

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Date

Acknowledgements

Tracy, Caleb and Olivia

For years of allowing me to study and being patient during this project.

Derek Freeman

For providing assistance with the Nation Electricity Rules and compliance.

Dr Tony Ahfock

For supervising this project and providing much appreciated guidance throughout the duration of the project.

Glossary

AC: Alternating Current

AEMC: Australian Energy Market Commission

AEMO: Australian Energy Market Operator

AER: Australian Energy Regulator

AVR: Automatic Voltage Regulator

CB: Circuit Breaker

COMTRADE: Common Format for Transient Data Exchange

CT: Current Transformer

DC: Direct Current

DCS: Distributed Control System

EHG: Electro Hydraulic Governor

FRT: Fault Ride Through

GCB: Generator Circuit Breaker

GUI: Graphical User Interface

IEEE: The Institute of Electrical and Electronic Engineers

kA: kiloampere = 1000 amps

kV: kilovolt = 1000 volts

MFT: Master Fuel Trip

MW: Megawatt = 1000000 watts

MVA: Mega Volt Amperes

NEM: National Electricity Market

NEMMCO: National Electricity Market Management Company Ltd

NER: National Electricity Rules

NSP: Network Service Provider

OEM: Original Equipment Manufacture

PLU: Power Load Unbalance

VA: Volt Amperes

VT: Voltage Transformer

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CHAPTER 1 Introduction

1.1 Background

Due to factors such as advances in technology, industrial growth and resources boom, electricity has fast become a commodity that is crucial to the way we now live our lives. This has meant that consumer (industrial, mining, manufacturing, commercial and residential) demand and reliance upon a reliable electricity supply has increased to meet the needs of every day operations. Furthermore the need to keep economic growth high requires that the electricity price is maintained as low as possible so that production and user consumption costs are kept to a minimum.

Because large electrical infrastructure is expensive, the increased usage and dependence of electricity has put greater demands on the entire electricity infrastructure (generation, transmission and distribution) to expand and have a higher availability and utilisation factor for all installed electrical equipment in order to keep the price of electricity as low as possible.

To allow for times of shortfall in a State's capacity and added security there are various State to State electrical network interconnections between Queensland, New South Wales, Victoria, South Australia and Tasmania. With these States interconnected it forms the biggest (by distance) electrical network in the world (AEMO 2010). Whilst the capacity of the interconnections does not allow one State to completely supply the others they do provide a suitable capacity for planned outage contingencies.

Faults will occur on system no matter how well designed the system and equipment is, it is important for system reliability and stability that when a fault occurs on a system only the faulted section is disconnected from the system and that all other equipment remain connected to the system. Every generator connected to the system has a performance standard that outlines it capabilities that it must meet or exceed. It is the 'Response to Disturbances' section of the Callide C performance standards that the work of this project will be addressing.

1.2 Project Objectives

It is intended that the following aims get fulfilled by this project:

1. Research background information of the National Electricity Rules relating to required ride through capabilities for Callide C Generators.

2. Research large coal fired power plant generator protection scheme philosophies and testing.

3. Research details of Callide C Generators and the existing protection scheme and settings for the protection relays.

4. Analyse performance of Callide C Generators for external faults by building a model of the Generator using Simulink SimPowerSystems to check the Protection System.
5. Submit academic dissertation on the findings of the research.

As time permits:

6. Compile research of Generator Protection into a form that accommodates training at an Associate diploma level.

1.3 Importance to CS Energy

Callide C Power Station is half owned and operated by CS Energy. It was Australia's first supercritical coal-fired power station and was commissioned in 2001 (Power Technology 2010). CS Energy is a registered participant in the National Electricity Market and has a connection agreement with specified performance standards for Callide C Power Station that it is to be capable of delivering. Failure to comply with the agreed performance standards can cause the electrical network to become unstable and therefore compliance is paramount for system stability. It is these agreed performance standards that system models and contingencies are based upon.

Because of this importance, if there is an incident resulting from a non compliance from CS Energy, they can incur large fines from the Australian Energy Regulator (AER) and also the court proceeding costs. For this reason it is prudent that CS

Energy has an audited National Electricity Rules compliance program and methods for testing this compliance. Furthermore, CS energy is committed to the security of the electricity supply in Australia and wishes to maintain good electricity industry practise.

Unfortunately, there is not a transient monitoring system installed on Callide C generators so there is no facility to capture the actual voltage and current waveforms that have occurred during faults to analyse and be confident of ride through capability. Also CS Energy has no records of faults that occurred close to the connection point and for what duration. For this reason modelling is an option to produce expected waveforms seen at the generator when there is a fault on a transmission line close to the connection point. These waveforms can be injected into the protection relays to provide an insight into their behaviour during these fault conditions.

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CHAPTER 2 Literature Review

2.1 Generator Fault Ride Through (FRT) Capability

Generator Fault Ride Through is the ability for a Generator to remain operational and connected to the electrical network when there is a fault elsewhere in the electrical network. This philosophy is an essential component of maintaining the stability of the electrical network and is based on protective device coordination and protection zones.

For a power system to remain stable in the event of a fault, protection relays are employed to be selective, detect a fault and take actions to isolate the fault in an effective and timely manner to reduce the impact of the fault. Therefore it is critical that all connected generators remain connected so only the faulted equipment gets isolated from the system and the system can recover from the momentary voltage sags. If there was large loss of generator(s) then the result would be more severe or even entire system collapse (a ‘Black Out’) (Transpower, 2009).

Although there are many things that can disconnect the generator from the electrical network after a fault occurs such as high furnace pressure due to loss of control, the limits and time required to complete a study for every aspect is beyond the available time of this project. For that reason the interests of this project is concentrated on the generator protection scheme and its’ response when there are faults on a transmission line close to the generators connection point (effectively the infinite bus). Only transient time periods will be used, this allows for simplified models.

2.2 The National Electricity Market, Rules, Regulation and Enforcement

2.2.1 Development of the National Electricity Market

Through political motivation to have a competitive electricity market in the early 1990's the governments of New South Wales, Queensland, Victoria, South Australia, Tasmania and Australian Capital Territory agreed to create a National Electricity Network (NEM) for the wholesale of electricity (Department of Mines and Energy 2010). This agreement meant that there needed to be a reform of the rule structure and regulation for the market to operate. Previously State owned Electricity Commissions were split, restructured and the NEM commenced operations on 13 December 1998. Tasmania joined the NEM in May 2005 and became fully operational on 29 April 2006 when the Basslink interconnector was fully activated. Due to geographical locations and the vast distance between populous regions Western Australia and the Northern Territory are not connected to the NEM Electrical Network and are therefore not part of the NEM (Energy Supply Association of Australia 2010).

The National Electricity Market Management Company Limited (NEMMCO) was established in 1996 to administer and manage the NEM, develop the market and continually improve its efficiency and as of 1 July 2009 was replaced by The Australian Energy Market Operator (AEMO) (Australia Energy Market Operator, 2010).

2.2.2 Rules and Roles of the Regulating Bodies

The National Electricity Rules (NER) identifies how the NEM is to be run and the requirements of all participants in the NEM. The NER's are made under the National Electricity Law and may be amended from time to time in accordance with the National Electricity Law. The NER were implemented and are amended by The Australian Energy Market Commission (AEMC). These rules are then enforced and compliance is audited by the Australian Energy Regulator (AER). (Australia Energy Market Operator, 2010)

2.2.3 Performance Standards and the Rules Relating to Compliance

The National Electricity Rules can be found at the AEMC web site and are free to download. They consist of 11 Chapters that form an extremely lengthy document. They are a living document and are at revision 36 and are readily changed.

For this project the focus is on the following Chapters:

- Chapter 2 'Registered Participants and Registration'
- Chapter 4 'Power System Security' and
- Chapter 5 'Network Connection'

The performance standards either meet the automatic access standards, or are negotiated based on the minimum performance standards. These standards are for each generator and state the capabilities of the generator and are required before connection to the electrical network can be made.

Charter 5 Schedule 5.2 - Conditions for Connection of Generators is the section that outlines the requirements for automatic access and also minimum requirements for connection to the electrical network for generators. The performance standards for each generator are based on these and contain the requirements for all the following factors:

- Reactive power capability
- Quality of electricity generated
- Response to disturbances
- Partial load rejection
- Protection from power system disturbances
- Protection that impacts on power system security
- Asynchronous operation
- Frequency control

- Voltage and reactive power control
- Stability
- Excitation control system
- Remote monitoring
- Auxiliary transformers
- Fault level

In Chapter 2 Clause 2.2.1 (e)(3) it states;

2.2.1 Registration as a Generator

(e) To be eligible for registration as a *Generator*, a person must:

(3) satisfy *AEMO* that each *generating system* will be capable of meeting or exceeding its *performance standards.*

This is the very clause requiring CS Energy to be capable of meeting its performance standards.

In Chapter 4 clause 4.15 it states;

4.15 Compliance with Performance Standards

(a) A *Registered Participant* must:

(1) ensure that its *plant* meets or exceeds the *performance standard* applicable to its *plant*; and

(2) ensure that its *plant* is not likely to cause a material adverse effect on *power system security* through its failure to comply with a p*erformance standard*;

(b) A *Registered Participant* who engages in the activity of planning, owning, controlling or operating a *plant* to which a *performance standard* applies must institute and maintain a compliance program which complies with rule 4.15(c).

This is the clause that has the requirement of compliance and an instituted compliance program for the registered performance standards.

2.2.4 Callide C Performance standards for Fault Ride Through

Callide C has a negotiated performance standard and the section of the Callide C Performance Standards in particular importance for this project is the 'Response to Disturbances' (S5.2.5.3) in the rules. These requirements are listed below:

Each *generating unit* is capable of continuous uninterrupted operation during the occurrence of:

(1) (Standard determined under *Rules* clause 4.17.3) *Power system frequency* at any level within the following ranges for the given duration:

Table 2.1 Frequency range

Frequency range (Hz)	Duration
47 to 49	1 minute subject to stator voltage to frequency ratio remaining within the limits prescribed in item 3.5(4)
49 to 49.5	8 minutes subject to stator voltage to frequency ratio remaining within the limits prescribed in item 3.5(4)
49.5 to 50.5	continuous subject to stator voltage to frequency ratio remaining within the limits prescribed in item 3.5(4)
50.5 to 51	8 minutes
51 to 52	2 minutes

(2) The range of *connection point* voltage at any level within the following ranges for the given duration:

Table 2.2 Voltage range

Voltage range	Duration
nominal voltage (275 kV) +/- 10%	continuous

(3) (Standard determined under *Rules* clause 4.17.3) The voltage variation conditions corresponding to the voltage dip caused by a *transmission system* fault which causes voltage at the *connection point* to drop to zero for up to 0.100 seconds in any one phase or combination of phases, followed by a period of ten seconds where voltage may vary in the range 80-110 percent of the nominal voltage, and a subsequent period of three minutes in which the voltage may vary within the range 90-110 percent of the nominal voltage.

2.2.5 Examples of non compliance

Some examples of non compliances that have cost the participant can be found at the AER website and below is a brief explanation and fines imposed in a few instances (Australia Energy Regulator 2010).

<u>Millmerran Power Station</u>

Date	14 January 2005 in Queensland
Fine	\$40,000
Fault	Single phase to earth fault when a reactor shorted - 275kV Incomer on 2 phases – was 0.76pu for 0.06 seconds
Report	The voltage drop caused Millmerran Power Plant 1 coal feeder’s microprocessors to shut down to protect themselves. When these shut down the auxiliary relays which transfer signals to the Distributed Control System (DCS) also de-energised which initiated a coal feeder trip through the DCS logic for all running coal feeders which in turn caused a Master Fuel Trip (MFT).

<u>Pelican Point</u>

Date	14 March 2005 in South Australia
Fine	\$100,000
Fault	A 275 kV interconnector to Victoria opened causing a rapid frequency loss in South Australia. The frequency low point was 47.61 Hz and recovered in 9 seconds

Report	The AER was informed by Pelican Point Power Ltd that this trip may have been attributable to a sub-optimal version of software being used in the implementation of the digital control system. This system calculates and controls the response of the gas turbine in rapid changes in frequency. The unit was registered to operate for 2 minutes within the range of 47 – 49 Hz.

<u>Northern Power Station</u>

Date	14 March 2005 in South Australia
Fine	$300,000
Fault	A flashover of a single 275 kV insulator and subsequent reclosing and a second flashover 26 minutes later.
Report	The AER was advised by Northern Power Station (NPS) that this occurred because of the operation of the NPS Unit 1 Over-speed Protection Controller (OPC). NPS advised that the underlying cause of the loss of both units was the deterioration of the 14 Volt DC power boards associated with the OPC Systems on each of the NPS generating units. The units did not trip however, they reduced to zero power which is had the same effect as a trip (one each flashover).

It can be seen from these examples, that non compliance with the performance standards can burden large costs. Although none of these examples relate directly the failings in the Generator Protection System they do result from external faults on the system that the Generators did not 'Ride Through'.

2.3 Callide C Operation

Callide C Power Station comprises of 2 x 450 MW supercritical coal-fired boilers. The coal is sourced from the adjacent Anglo Coal Callide Mine with a supply contract. The water comes from nearby Callide Dam. If there is a shortage in water supply the water is pumped via an overland pipeline from Awoonga Dam near Gladstone into Callide Dam at a cost to CS Energy. The power is exported via 275 kV transmission lines to nearby Calvale switchyard. Callide C is half owned by CS Energy and half owned by Intergen Australia, CS Energy has the Operations and Maintenance contract for Callide C. General information for Callide C Power Station is shown below:

GENERAL	
Commissioned	2001
Capacity	810MW (900 MW Overload)
Units	2 X 450 MW
Transmission	275 kV
Fuel	Black Thermal Coal
TURBINE	
Type	Steam
Stages	Combined reheat 3 stage
Manufacturer	Toshiba
BOILER	
Manufacturer	IHI (Tokyo, Japan)
Type	One pass supercritical
Height	42 m
Operating Temperature	1400°C
Steam Pressure	25 100 kPa (~250 bar)
Steam Temperature	566°C
CHIMNEY	
Height	230 m
Flue Gas Temperature	135°C
GENERATOR	
Type	Cylindrical Rotor Hydrogen cooled 50 Hz
Manufacturer	Toshiba

EHG	
Type	Tosmap – Fast Valving
Manufacturer	Toshiba
AVR	
Type	Static
Manufacturer	Toshiba

2.4 Synchronous Generator Protection Systems

2.4.1 The Role of a Protection System

No matter how well designed a power system is, there will always be faults that occur on the system. The main thing is that that the system should operate in a safe manner at all times (Areva T&D, 2002). So for conditions that are outside normal safe operating conditions actions need to be taken promptly to isolate faults.

Furthermore large generators and generator transformers are typically items of large cost and damage from a fault can be very time consuming and costly to repair. The protection system is therefore crucial to reduce the damage in the event of a fault and even more importantly protecting the people who operate the equipment by isolating the fault quickly before catastrophic damage occurs (Klempner G & Kerszenbaum , 2004).

The main difference between protection systems and other systems on power equipment is that it is very rarely required to operate because faults on generators and generator transformers are rare. Because of this, their importance can be overlooked (Klempner G & Kerszenbaum, 2004).

As for any protection system the generator protection system must be designed with the following considerations in mind; (Areva T&D, 2002)

- ***Reliability*** Must operate when it has to and at the setting and time that it is required to do so.
- ***Selectivity*** When a fault occurs, only the circuit breakers required to isolate the faulted equipment are tripped.
- ***Stability*** That a protection device remains unaffected by the fault external to the protection zone.
- ***Speed*** To ensure that faults on the system are isolated as rapidly as possible thereby ensuring the disturbance does not become widespread.
- ***Sensitivity*** When the primary operating parameter is low the scheme needs to be able to detect this.

2.4.2 Generator Protection Philosophies and Schemes

Historically there were differences in the protection scheme philosophies that were employed on large synchronous generators and these were based on different approaches of protection engineers and the cost of the relays.

Traditional relay's were electromechanical in nature and each element of protection required a separate relay for that function. This meant extra relays, wiring complexity and panels. However, now with modern digital multi function relays that provide an extensive range of functions in the same single relay the differences in philosophies are reduced as the procurement and installation cost are not increased for the increased functions (Grigsby, 2007).

The reliability of the scheme is enhanced by having primary and backup protection in which some elements are duplicated. This system will have two separate protection relay panels that are normally called X protection and Y protection that are wired completely separate. This allows for complete isolation of either system at any time. Also a traditional requirement is that the relay employed in each scheme be proven of a different manufacture so type faults are not introduced into both the X and Y protection system or that if the relays are to be the same then they should have a proven reliability history so that schemes are reliable.

Table 2.3 is a list of generator protection elements and their numbers that are commonly employed in large synchronous generators.

Table 2.3 Generator Protection Elements

Device Number	**Function**	**Relay/comments**
21	Distance protection, backup for system faults	Distance relay
24	Over excitation protection	Voltage/Hertz relay
27	Under voltage	Voltage relay
32	Anti motoring protection	Reverse power relay
40	Protection against loss of field voltage or current supply	Offset mho relay
46	Protection against current imbalance, measure of negative phase sequence current	Time over current relay
49	Stator thermal protection	Time over current relay
50 B	Instantaneous overcurrent	Backup for generator ground faults
51N	Time overcurrent protection	Backup protection for ground faults
51V	Voltage controlled time overcurrent protection	Backup protection against system faults
59	Over excitation protection	Voltage/Hertz relay
60	Protection of blown voltage transformer fuses	Voltage balance protection
61	Time overcurrent protection	Detection of turn to turn faults in generator winding
62	Breaker failure protection	Backup protection
64F	Rotor earth fault protection	
78	Pole slipping protection	Out of step/ loss of synchronism
81	Under and over frequency protection	Frequency relays
86	Hand reset lockup relays	
87G	Generator differential protection	
87T	Transformer differential protection	
87U	Overall differential protection	Both generator and generator transformer
94	Self resetting auxiliary tripping relay	

Figure 2.1 shows a typical generator and generator transformer protection scheme single line diagram.

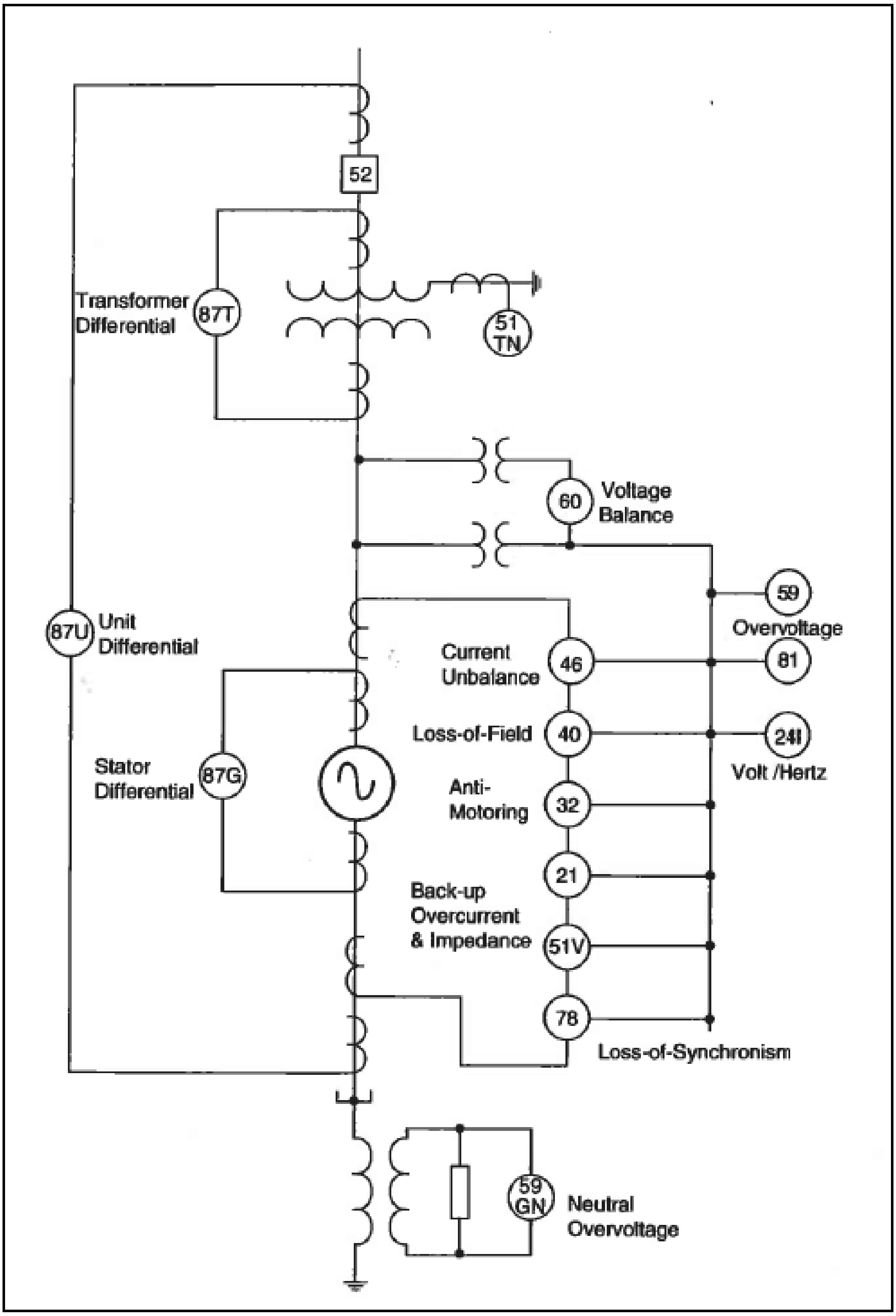


Figure 2.1 **Typical Generators Protection Scheme, (Grigsby 2007)**

2.4.3 Testing of the Protection System

For the purposes of this project it is intended to use the output waveforms generated by the model to test the protection relays to see if they are stable for the fault scenarios modelled. To do this a Doble F6150 Power System simulator will be used because it has the ability to replay a transient file that is in the COMTRADE file format which is a standard for power systems. Below is a picture of the F6150

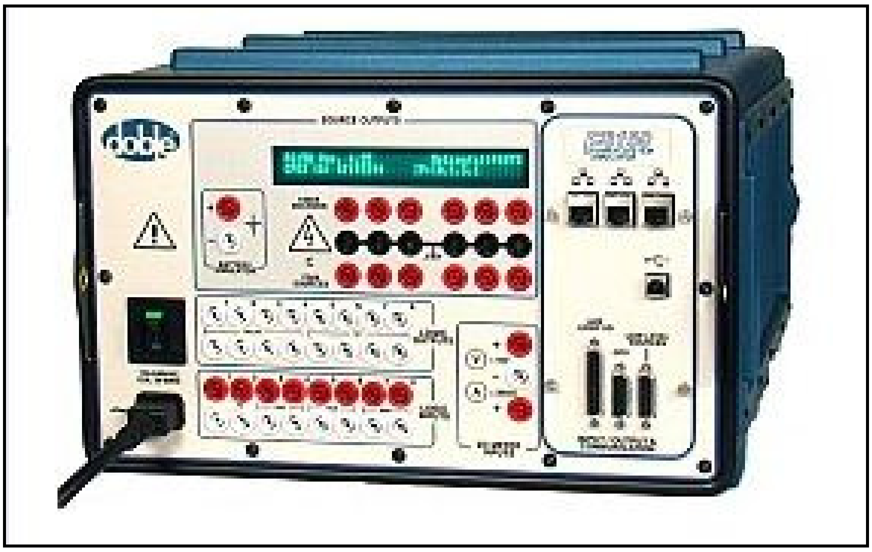


Figure 2.2 Doble F6150 Power System Simulator

2.5 Power System Modelling

2.5.1 The Need for Modelling

Even back early in the 1970's power systems were large and complex and using 'rules of thumb' for testing new ideas on the actual system was quite impractical (Monash University, 1972). Because of the impracticalities the concept modelling of a power system came about.

Initially scaled models of systems were used, then analogue models using operation amplifiers were introduced (Barret Bornard & Meyer, 1997). Now the modelling of a power system is performed using computer programs that contain various models to represent phenomena of the elements of a power system. Studies can be performed for many aspects such as load flow, short circuit, transient stability, optimal dispatch of generating units etc. The selection and complexity of the models and simulation is determined largely by the timescale in which you wish to model (Grigsby, 2007).

Barret Bornard & Meyer (1997) mention that all phenomena of an electrical system happens simultaneously and an overall approach to modelling is highly complex and representation for all timescale is not yet possible so models are limited in their designed time band and function. Figure 2.3 displays some phenomena and associated time bands.

For this project the analyses of short circuit faults will be performed. This simplifies the simulation model as Grigsby (2007) states that for transient analysis of only a few seconds that a prime mover model can be omitted completely. This leaves only the synchronous machine (generator) Automatic Voltage Regulator (AVR) and transformer models that need to be used.

The implementation of the models will use IEEE standard models and will be with known values where possible. If values are not known then 'typical values' will be used. These typical values are obtainable from IEEE standards and guides for the respective models listed below.

- IEEE Standard 1110-1991, IEEE guide for synchronous generator modelling practise in stability analysis 1991.
- IEEE 412.5 1992 - IEEE recommended practise for excitation system models for power system stability studies 1992.

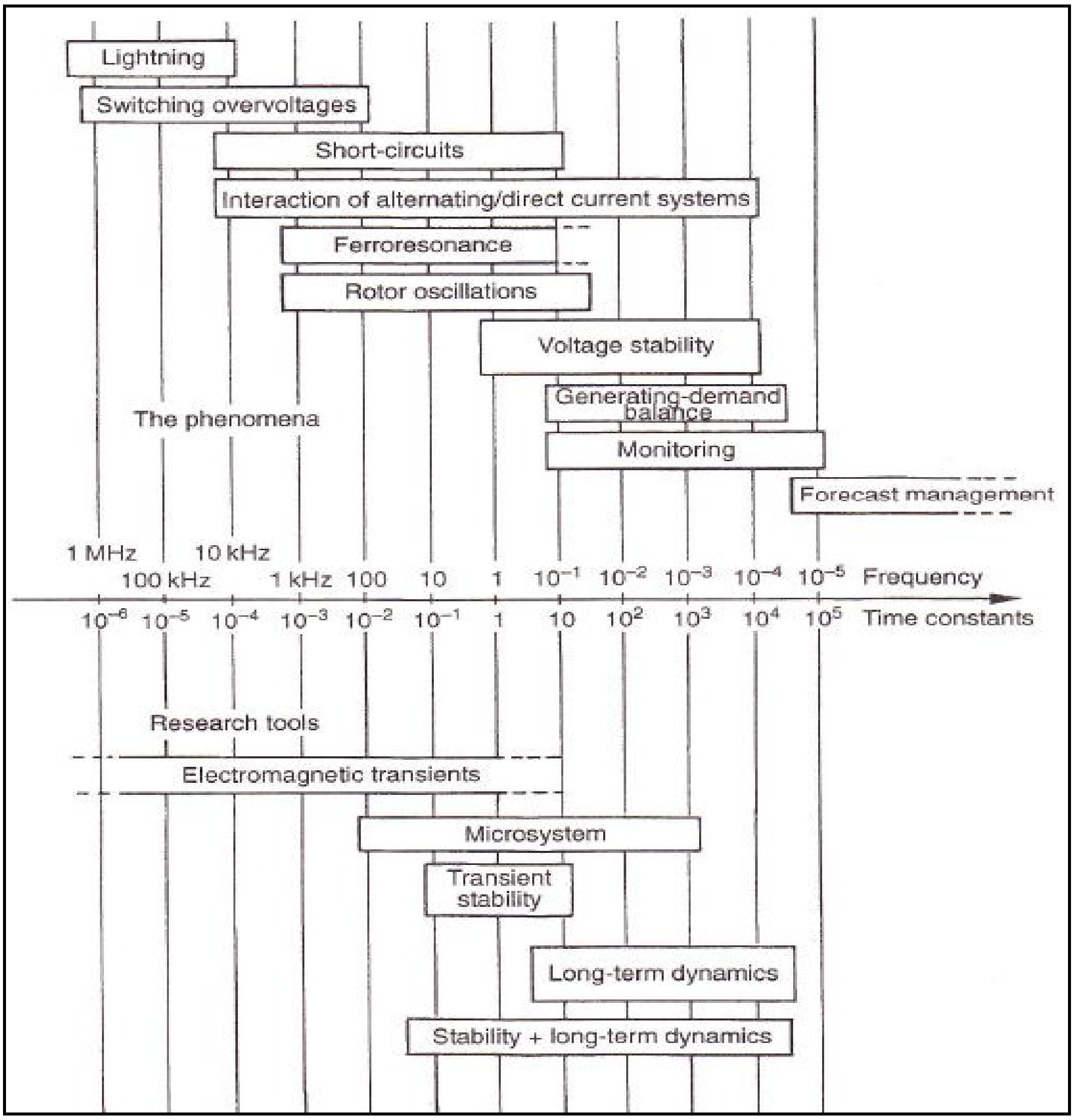


Figure 2.3 **Time scale of Phenomena, (Barret Bornard & Meyer, 1997)**

2.5.2 Software Packages

There are many commercial software packages available for analyses of a power system. For this project I intend on using Mathworks SimPowerSystem which is an extension of component libraries to Simulink. This package has generic models with adjustable parameters for Automatic Voltage Regulators, Transformers, Transmission lines and Synchronous Machines.

CHAPTER 3 Callide C Generator Protection

It is intended that the information presented in this chapter will easily be able to be translated into study material for students at an Associate Diploma level to learn about electrical protection for large utility generators. It should be noted that generally speaking the protection system cost and complexity tends to increase as the cost of the equipment that it protects increases. So for large utility generators the protection systems are more elaborate and have more protection elements.

3.1 General Details

The generator protection consists of two separate protection systems named "X Protection" and "Y Protection". There are two separate systems to increase the reliability. As discussed in the literature review, the protection system is very rarely called on to operate, however when it is required it must do so in an effective manner otherwise large system disturbances may occur. Most of the functions in the X Protection System are duplicated in the Y Protection System with the same settings.

Each Protection System has is own current transformers and voltage transformers. These items of plant are called "primary protection equipment". The Protection relays and tripping matrixes are named "secondary protection equipment". Each protection system also has it own secure DC 220 volt DC supply that comes from the Unit 220 DC Battery.

The Callide C unit protection cubicle contains protection equipment required for the following primary plant items:

- Unit Generator
- Generator Transformer
- Unit Transformer
- Excitation Transformer

- Generator Circuit Breaker
- 275 kV Transmission Feeder

The cubicle is separated into two panels and Table 3.1 indicates the functions found in each panel. Also to aid with the visualisation Figure 3.1 is included. Panel P1 is on the left and Panel P2 is on the right in Figure 3.1

Table 3.1 Unit Protection Panel functions

Panel P1	**Panel P2**
X Generator Protection	Y Generator Protection
X Tripping Matrix and Relays	Y Tripping Matrix and Relays
Generator Transformer Protection	Unit Transformer Overcurrent Protection
Unit Transformer Protection	Excitation Transformer Overcurrent Protection
Excitation Transformer Protection	X and Y 275kV Line Protection
X and Y Trip Circuit Supervision	GPS Clock

Figure 3.1 Unit Protection Panels

3.2 Generator Protection Settings

The majority of the following information and derivation of settings were obtained from Callide C PowerStation Generator Protection Panels - Protection Relay Setting Study. This study was performed by Alstom Protection and Control in November 2000 for CS Energy (Alstom, 2000). Only setting of the elements that are in the LGPG111 multi function relay will be explained as this multi function relay was the main focus of this project. A brief explanation of the remaining protection elements is provided for completeness, however the setting are not explained.

The following sections describe the reason for the protection element and how the settings are determined. The settings are the same for both the X and the Y protection so only one derivation is shown. This information should be able to be translated into study material for students at an Associate Diploma level to learn about electrical protection for large utility generators.

Table 3.2 lists the relevant information that is used for the derivation of the protection settings.

Table 3.2 Data for Protection Settings

Generator Voltage	19500
Generator MVA	560
Generator sub transient reactance Xd”	0.234 pu
Generator transient reactance Xd’	0.3137 pu
Generator synchronous reactance Xs	1.8556 pu
275 kV Grid Impedance (Z1) (19.5 kV Base)	0.00407 + j0.06445 Ω
Generator Transformer Impedance (Zgt) (19.5 kV Base)	0.00203 + j0.08782 Ω
CT ratio	19000/1
VT ratio	19500/110
Earthing Transformer Voltage ratio	19500/415
Earthing Transformer CT ratio	70/1

Also to aid with visualisation of the system a single line diagram of the arrangement of all of the electrical apparatus is shown in Figure 3.2

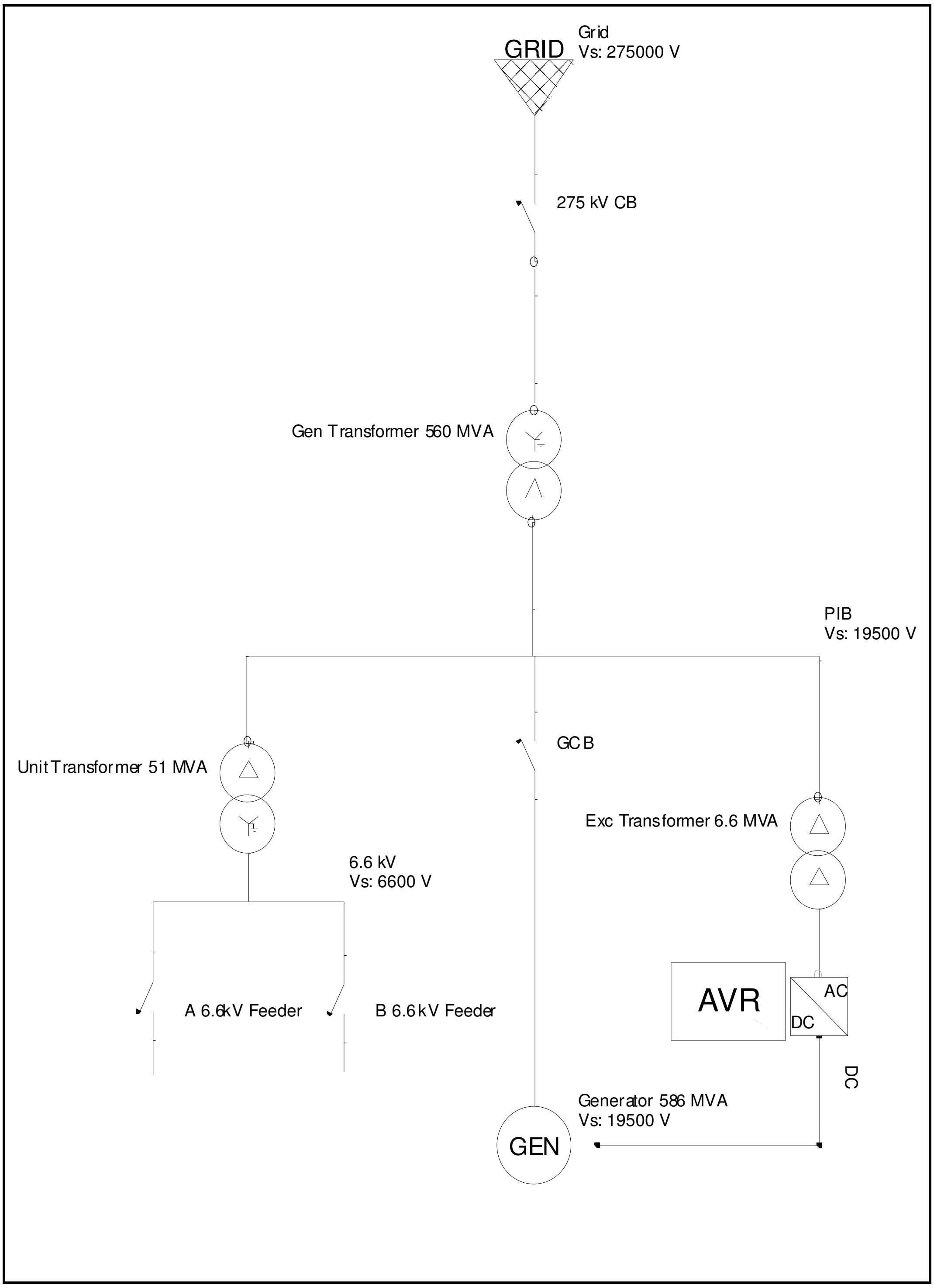


Figure 3.2 Single Line Diagram of Callide C Electrical Apparatus

3.2.1 Earth Fault Protection (51N, 59N)

The generator star point is earthed via a 19.5kV/415 earthing transformer with a resistor loading the secondary terminals to limit the fault current to 7.1 amps. There is a 70/1A CT in the generator to star point earth connection for detection of fault current.

The low set element should provide 95% stator earth fault protection. So the low set element is set to 5% of the maximum limited earth fault current. The 51N setting should be as follows:

Ie>	=	0.05 x 7.1 A (primary)
	=	0.355 A (primary)
	=	0.355/70 A (secondary)
	=	0.0051 A (secondary)

<u>Select Ie> = 5 mA</u>

A standard inverse characteristic with a time multiplier setting (TMS) of 50 ms is selected on this protection element to provide a time delay to stabilise the protection against earth leakage currents during external faults.

The inverse definite minimum time characteristics are defined in IEC 60255 as follows:

$$T(s) = \frac{K}{\left(\frac{I}{I_s}\right)^{\alpha} - 1} \times TMS$$

where	T	=	operating time in seconds
	TMS	=	time multiplier settings
	I	=	value of actual secondary current
	Is	=	value of relay settings
	α and K	=	constants that define the curve (see Table 3.3)

Table 3.3 Values of Constants in Inverse Curves

Type of curve	α	K
Standard inverse	0.02	0.14
Very inverse	1	13.5
Extremely inverse	2	80
Long-time inverse	1	120

So for the standard inverse time delay on the earth fault protection the formula is as follows:

$$T(s) = \frac{0.14}{\left(\dfrac{I}{I_s}\right)^{0.02} - 1} \times 0.05$$

This produces the curve shown in Figure 3.3

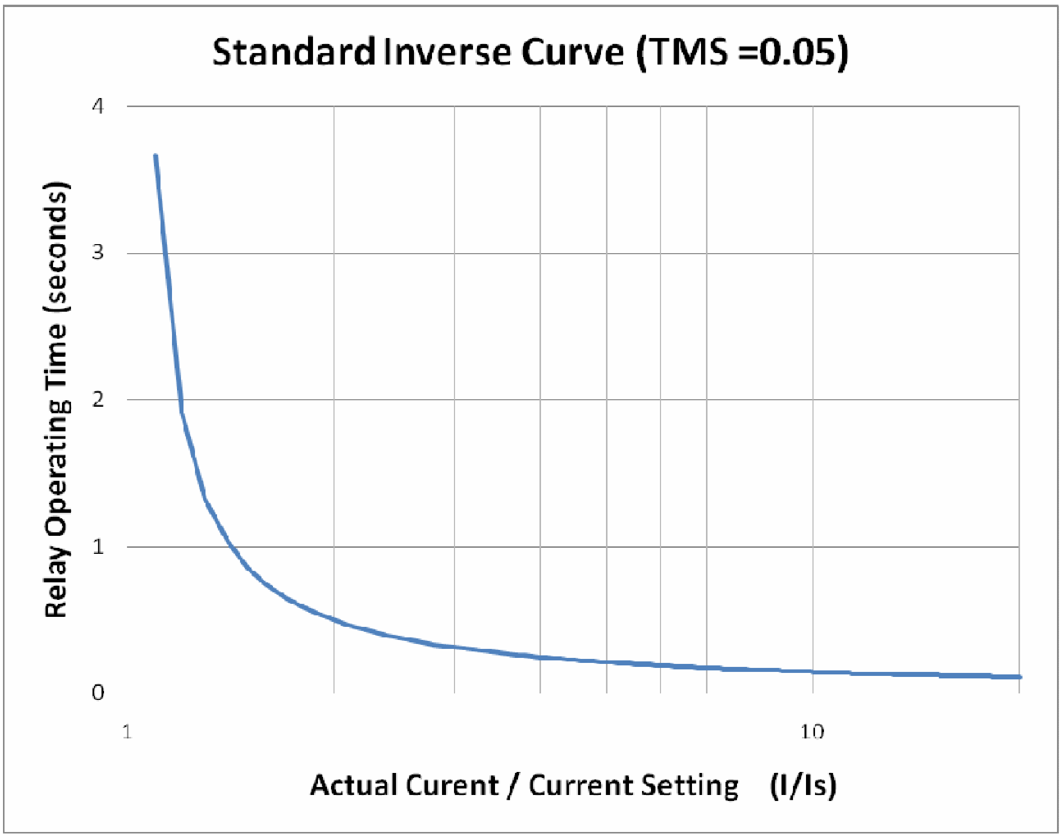


Figure 3.3 Standard Inverse Curve Operating Time (TMS = 0.05)

It is common practise to set the high set element to 10% of the maximum limited earth fault current with no time delay provided. This protection is for a flashover on the generator transformer HV terminal where an extremely high earth fault current would result, and would be cleared instantaneously by the 51N>> element.

$$
\begin{aligned}
Ie\!>> &= 0.1 \times 7.1 \text{ A (primary)} \\
&= 0.71 \text{ A (primary)} \\
&= 0.71/70 \text{ A (secondary)} \\
&= 0.0101 \text{ A (secondary)}
\end{aligned}
$$

<u>Select Ie> = 10 mA</u>

The neutral displacement protection (59 N) is set to complement the current operated stator earth fault protection; it uses a voltage level for detection. In order to provide 95% stator earth fault protection the Ve> setting is calculated as follows:

$$
\begin{aligned}
Ve\!> &= 0.05 \times 19500/\sqrt{3} \text{ V (primary)} \\
&= 562.9 \text{ V (primary)} \\
&= 562.9 \times (415/19500) \text{ V (secondary)} \\
&= 11.98 \text{ V (secondary)}
\end{aligned}
$$

<u>Select Ve> = 12 V</u>

To stabilise the protection against earth leakage currents during external faults a time delay of 3.0 s is selected.

3.2.2 Voltage Dependent Overcurrent (51V)

A voltage-dependent overcurrent element provides overcurrent protection for the alternator and backup overcurrent protection for associated power systems equipment. For the Callide C Generators it was assumed that the alternator terminal voltage will be essentially maintained during fault conditions due to boosting of the field excitation by the AVR, Because of this assumption the 51V element is set as a 'simple overcurrent' function, i.e. not voltage dependent.

In order to provide overcurrent protection for the alternator, without the protection operating due to load current, I> is set to approximately 110% of the alternator rated full load current.

$$
\begin{aligned}
I> &= 1.1 \text{ x } 586/(19.5 \text{ x } \sqrt{3}) \text{ kA (primary)} \\
&= 19085.1 \text{ A (primary)} \\
I> &= 19085.1/19000 \text{ A (secondary)} \\
&= 1.0 \text{ A (secondary)}
\end{aligned}
$$

<u>Select I> = 1.0 A</u>

An inverse time characteristic is selected with an operating time delay of approximately 400 ms at the maximum fault current to allow for the operation of any instantaneous/unit protection and associated CB Fail protection. The inverse time characteristic allows for generator short time overloads.

The maximum fault current supplied from the alternator based on the alternator sub-transient reactance, X_d" is calculated as follows:

$$
\begin{aligned}
I_{base} &= \text{MVA}/(\text{kV x } \sqrt{3}) \text{ kA} \\
&= 586/(19.5 \text{ x } \sqrt{3}) \text{ kA} \\
&= 17350 \text{ A} \\
I_f &= 17350/0.234 \text{ A} \qquad (X_d" = 0.234 \text{ pu})
\end{aligned}
$$

$$= \quad 74145 \text{ A}$$

Similarly, the maximum fault current supplied from the 275 kV network via the generator transformer is calculated as follows:

System impedances (19.5 kV base) are as follows:

275 kV Grid Impedance	: $Z1 = 0.00407 + j0.06445\ \Omega$
Generator Transformer Impedance	: $Zgt = 0.00203 + j0.08782\ \Omega$

$$I_f = V/(Z1 + Zgt)$$

$$= 19500/(\sqrt{3} \times ((0.00407 + 0.00203) + j(0.06445 + 0.08782))) \text{ A}$$

$$= 19500/(\sqrt{3} \times (0.15239 \arg(87.7°)))$$

$$= 73878 \text{ A}$$

Based on the above calculations the operating time of the LGPG111 relay overcurrent element at 74145 A is set to approximately 400 ms. With a standard inverse time characteristic selected and a time multiplier setting of 1.0, the operating time at 74145 A is given by:

$$t = 0.14/((I/I>)^{0.02} - 1) \text{ seconds}$$

$$= 0.14/((74145/19000)^{0.02} - 1) \text{ s}$$

$$= 5.071 \text{ s}$$

To achieve an operating time of 0.400 s at 74145 A, a time multiplier setting of 0.400/5.071 = 0.079 is required.

A time multiplier setting of <u>0.1 is selected</u>.

3.2.3 Reverse Power Protection (32R)

The setting for the reverse power protection is governed by the motoring load of the prime mover and the reverse power withstand of the prime mover drive. Typically the motoring load of a steam turbine is 0.5-6.0% of its rated load. To ensure that failure of the prime mover is detected, the relay setting must be less than the prime mover motoring power, and so that the system is not damaged the relay setting must be less than the reverse power withstand of the prime mover drive.

Because no information was available it was assumed that the percentage motoring power of the generator is 0.5%. The LGPG111 Service Manual states that the reverse power setting in single phase Watts (-P>) should be less than 50% of the secondary motoring power as determined below:

$$P_m(\text{sec}) = (\%P_m(\text{prim}) \times S_n)/(CT \times VT \times 3)$$

Where :

$P_m(\text{sec})$ = Secondary single phase motoring power

$\%P_m(\text{Prim})$ = Percentage motoring power of generator set

S_n = Generator rating (VA)

CT = Protection CT ratio

VT = Protection VT ratio

$$P_m(\text{sec}) = (0.005 \times 586 \times 10^6)/((19000/1) \times (19500/110) \times 3)$$

$$= 0.277 \text{ W}$$

As a setting of less than 50% of this value is less than the minimum available reverse power setting, the minimum setting of <u>200 mW is selected</u>.

The trip is time delayed by 5 seconds to avoid nuisance operation of the relay due to power reversal during synchronising or power swings on the system.

3.2.4 Frequency Protection (81U-1, 81U-2, 81O)

This function of this protection is to protect the turbine.

The first stage of under frequency is used for an alarm only.

A frequency setting F1< = 47.5 Hz with a time delay t1 = 100 ms is selected.

The second stage under frequency element is set to trip prior to rotor speed decreasing to the ‘2nd critical speed’ (2590 rpm); for a synchronous speed of 3000 rpm. This is equivalent to 43.17 Hz.

A frequency setting F2< = 45 Hz with a time delay t2 = 1.0 s is selected.

The over frequency is set to provide a backup protection function in the event of governor failure.

A frequency setting F> = 55 Hz and a time delay t = 1.0 s being selected.

3.2.5 Voltage Protection (27, 59, 60)

The LGPG111 relay incorporates a single stage time delayed undervoltage protection element. This function provides backup protection in the event of an uncleared system fault or in the event of failure of the alternator AVR.

A voltage setting of 90% of the nominal voltage (V< = 99 V) with a time delay of 3 seconds is selected to prevent operation during system faults and during spurious undervoltage conditions.

A two stage overvoltage element is provided in the event of a sudden loss of load or failure of the AVR.

Stage 1 is set to operate at 115% of the alternator nominal voltage (127 V) with a time delay of 2 seconds to prevent operation due to transient overvoltages.

Stage 2 is set to operate instantaneously with a voltage setting of 140% of the alternator nominal voltage (V>> = 154 V).

The voltage balance element of the LGPG111 relay provides a VT supervision function by comparing the secondary voltages of two separate VTs (3VT2 and 3VT3). A voltage unbalance threshold setting of V_s = 5 V is selected as advised in the LGPG111 relay service manual for similar VTs.

3.2.6 Negative Phase Sequence (46)

This protection element provides protection against current imbalance. If there is an imbalance in the three phase currents, negative phase sequence currents flow in the stator. This produces double frequency currents on the surface of the rotor which in turn causes excessive heating to the rotor.

The LGPG111 negative phase sequence element settings are determined basically in accordance with Chapter 3, section 2.8 of the LGPG111 Relay Service Manual. Based on Table 3 of the above section, taken from IEC 60034-1, the per-unit continuous negative phase sequence withstand current (I_{2cmr}), and the per-unit current thermal capacity constant (K_g) for the alternator are calculated as follows:

For a directly cooled rotor

$$
\begin{aligned}
I_2/I_n &= 0.08 - ((S_n - 350)/3 \times 10^4) \qquad S_n = \text{Rated MVA(586 MVA)} \\
&= 0.08 - ((586 - 350)/3 \times 10^4) \\
&= 0.0721 \text{ pu} \\
I_{2cmr} &= 0.0721 \text{ pu} \\
&= 0.0721 \times (586 \times 10^6/(19500 \times \sqrt{3})) \text{ A} \\
&= 1250.9 \text{ A}
\end{aligned}
$$

$$(I_2/I_n)^2t = 8 - 0.00545 \text{ x } (S_n - 350) \text{ s}$$

$$= 8 - 0.00545 \text{ x } (586 - 350) \text{ s}$$

$$= 6.714 \text{ s}$$

$$K_g = 6.714 \text{ s}$$

Based on the above parameters settings for the negative phase sequence element of the LGPG111 relay are calculated as follows:

$$I2>> = I_{2cmr} \text{ x } (I_{flc}/I_p) \text{ x } I_n$$

$$= 0.0721 \text{ x } (586 \text{ x } 10^6/(19500 \text{ x } \sqrt{3} \text{ x } 19000)) \text{ A}$$

$$= 0.0658 \text{ A}$$

<u>Select I2>> =0.07 A</u>

$$K = K_g \text{ x } (I_{flc}/I_p)^2$$

$$= 6.714 \text{ x } (586 \text{ x } 10^6/(19500 \text{ x } \sqrt{3} \text{ x } 19000))^2$$

$$= 5.599 \text{ s}$$

<u>Select K = 5.0 s</u>

To ensure tripping in the event of negative phase sequence currents only slightly in excess of the I2>> setting, a maximum tripping time of 500 s is selected.

To prevent tripping of the negative phase sequence elements during unbalanced faults in equipment adjacent to the alternator, a minimum tripping time of 500 ms is selected to allow time for clearance of transformer faults by the appropriate unit protection.

The negative phase sequence alarm element is set to approximately 70% of the trip setting, I2> = 50 mA, with a time delay of 5.0 seconds to allow time for clearance of remote unbalanced faults.

3.2.7 Field Failure (40)

This protection element provides protection against loss of field through automatic voltage regulator failure. When this occurs, the generator voltage gradually decreases and the current increases to compensate. Then the generator becomes under excited and absorbs negative reactive power and will eventually settle. The locus of the field failure is shown in Figure 3.2.

The offset mho relay is used to detect field failure. The mho relay provides a circle in the R jX plane which is shown in Figure 3.4 By measuring the current and voltage the impedance (or admittance) of the load can be calculated by the relay. There are two parameters that the field failure offset mho relay requires:

- The diameter of the circle, and
- The amount of offset the circle has from the resistance plane.

When the impedance is in this circle for the required time period, the protection element will operate.

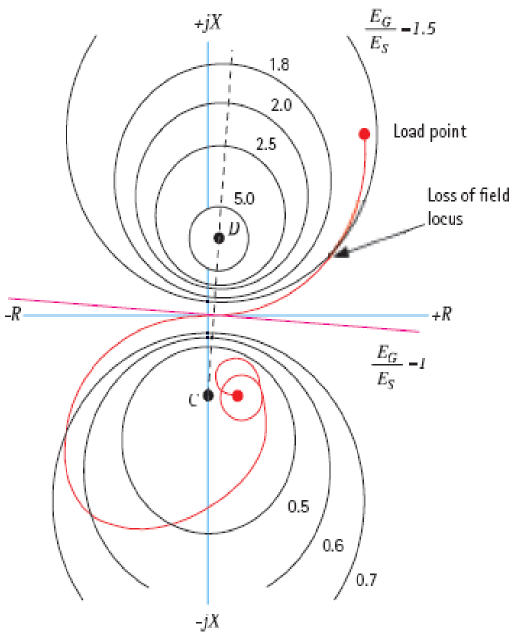


Figure 3.4 Field Failure Locus (Areva T&D, 2002)

The field failure element settings are determined in accordance with Chapter 3, section 2.9 of the LGPG111 Relay Service Manual. As the alternator is capable of operating at leading power factors, the characteristic circle parameters would normally be selected as follows:

Circle Offset, $-X_a$ = $3X_d'/4$

Circle Diameter, X_b = $X_s/2$

Where

Alternator transient reactance, X_d' = 0.3137 pu

Alternator synchronous reactance, X_s = 1.8556 pu

And, Z_{base} = kV^2/MVA

= $19.5^2/586$ ohms

= 0.6489 ohms

However, as the field failure element is also being used to provide some degree of back-up protection for pole-slipping, a larger circle diameter and a smaller offset is selected to ensure that the pole slip impedance is detected. To guard against tripping for stable power swings a longer time delay is selected.

Based on the above information the relay settings are calculated as follows:

Circle Offset, $-X_a$ = $X_d'/2$

= (0.3137 x 0.6489)/2 ohms (primary)

= 0.1018 ohms (primary)

Conversion to secondary ohms gives:

= 0.1018 x (CT ratio/VT ratio) ohms (secondary)

= 0.1018 x (19000 x 110/19500) ohms (secondary)

$= \quad$ 10.91 ohms (secondary)

Select $-X_a = 11.0$ ohms

Circle Diameter, $X_b = \quad X_S$

$= \quad 1.8556 \times 0.6489$ ohms (primary)

$= \quad 1.2041$ ohms (primary)

Conversion to secondary ohms gives:

$X_b \quad = \quad 1.2041 \times$ (CT ratio/VT ratio) ohms (secondary)

$= \quad 1.2041 \times (19000 \times 110/19500)$ ohms (secondary)

$= \quad 129.05$ ohms (secondary)

Select $X_b = 130.0$ ohms

A field failure trip time delay (t) of 1.5 seconds is selected to prevent tripping during stable power swings.

3.2.8 Other Protection Elements

It will be seen in Tables 3.4 and 3.5 (in section 3.3) that there are more elements that form part of the generator protection than those which have been explained so far. The elements that have been explained are all in the multi function protection relay which was the major focus of this project. However to ensure completeness the elements that are in the tripping matrix that have not been explained will be explained briefly now.

If further information is required there are many good references of Generator and Generator Transformer Protection, two are listed below:

- The Art and Science of Protective Relaying (Mason C. R, 1967)
- Network Protection and Automation Guide (Areva T&D, 2002)

Pole Slip (Out of Step) (78)

This protection element is to protect the generator and the electrical network when pole slipping (out of step) conditions occur. Because under these conditions the rotor field and rotating stator field are not in synchronism there can be large damages to the generator stator winding and rotor as the magnetic coupling between the two keeps oscillating as the rotor advances with respect to the stator. Because of this, early detection is required to prevent large damage and network instability.

Pole Figure 3.5 shows a two source network where we have the generator impedance Z_G, generator transformer impedance Z_T and the bundled grid impedance Z_S.

Figure 3.5 Two Source Network (Grigsby 2007)

When out of step conditions occur due to factors such as sudden loss of generation, or network fault, the generator will no longer be in synchronism with the grid and the locus of the impedance as seen by the out of step relay is shown by the dotted lines in Figure 3.6. Depending on the magnitude of the generator voltage E_G compared with the System voltage E_S will determine trajectory of the locus.

Detection is by measuring the angle θ and using timers between set angles to operate the protection relay. Typically when the angle θ increases past 130^o then synchronism has been lost and the relay will operate to trip the generator.

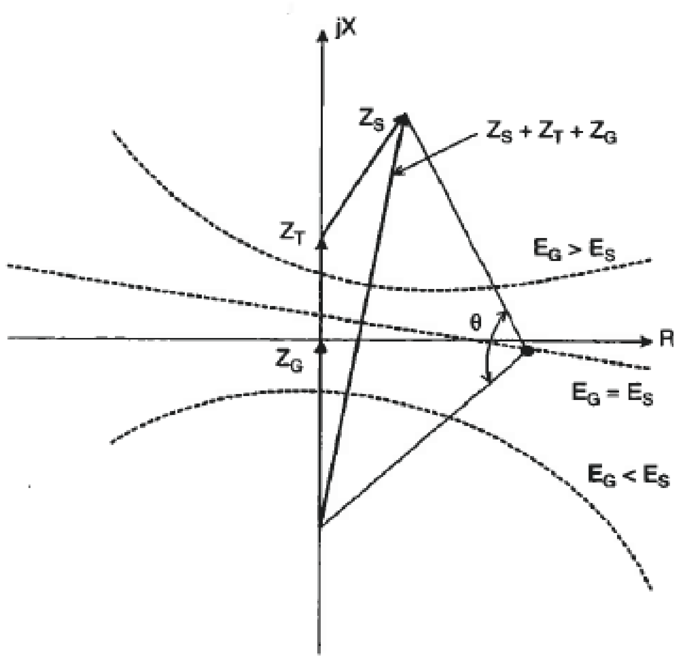


Figure 3.6 Impedance Locus During Pole Slipping (Grigsby 2007)

Generator Differential (87G)

This element provides high speed protection against stator faults. It is great for detected phase to phase faults but in the case of the high impedance grounded generator (which is the case for Callide C generators) the fault current is low and may be below the pick up point. That is why the earth fault protection (51N and 59N) is used.

Because the generator is slowly excited it does not have large inrush currents producing 2^{nd} and 5^{th} harmonic components like a transformer when energised. This means that the generator differential protection element does not need 2^{nd} and 5^{th} harmonic restraint on the protection to prevent false operation.

The differential protection compares the currents going into each winding at the star point side of the generator with the current going out of the high voltage side of the generator. If there is a large enough difference between these two values (due to a fault in the generator windings) then the protection will operate. Figure 3.7 shows the current transformer connections and configuration for Generator

Differential Protection with the pick up relay when the differential is greater than the setting.

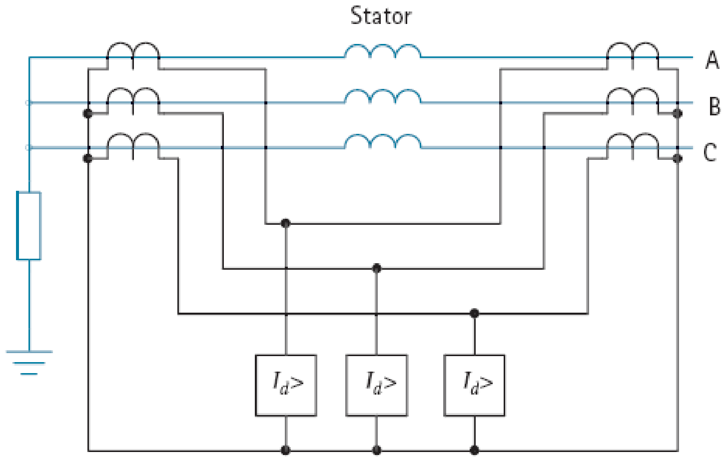


Figure 3.7 Generator Differential Protection (Areva T&D, 2002)

For external faults there will be large currents present on both the star point and high voltage side of the generator so the protection will not operate. All differential relays have a "restrain" curve that allows for slight error in CT ratios. Figure 3.8 shows a retrain curve for the differential protection. The restrain curve normally starts (I_{S1}) at a 10% difference (*I diff*) and the gradient of *K2* is of the order 2-5 depending on the generator. The point (I_{S1}) where the gradient *K2* starts is normally at full load current. This provides security because there is a greater retrain for high current values from large external faults that will prevent false operation of the relay. This is just one example of a restrain curve, there are many different curves used in differential protections systems.

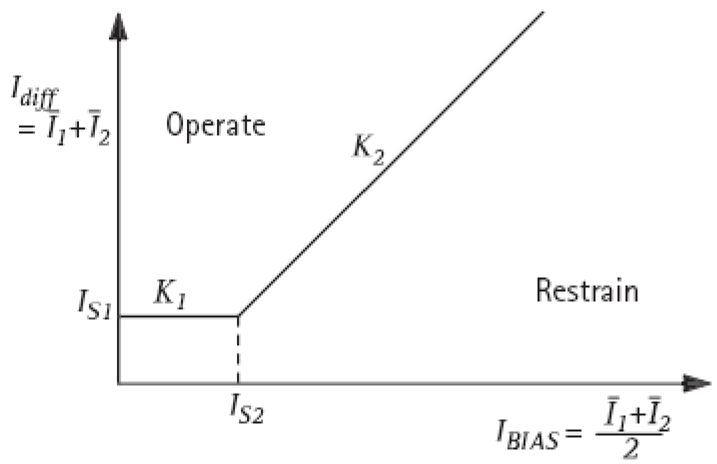


Figure 3.8 Generator Differential Restrain Curve (Areva T&D, 2002)

Turbine Trip & GCB Open & Field CB closed + DT 5 sec

This is protection to trip the AVR after a turbine trip for the circumstance of start up when the AVR is on and the stator is excited but the Generator Circuit Breaker (GCB) has not been closed.

Turbine Trip + DT 10 sec

This is a back up protection should the reverse power protection fail. It function is to trip the CGB and AVR 10 seconds after a turbine trip has occurred. Normally after a turbine trip the reverse power protection will operate within 2 seconds. Note this protection logic is under review and will most likely be changed in the future.

Rotor Earth Fault (64R)

This protection element has it own relay and is used to detect if there is an earth fault on the rotor. Because the rotor is isolated from earth it can handle a single earth fault, however should another fault develop there will be an alternative path for current to flow. This can cause damage to the rotor and also if a winding is shorted there will be abnormal flux distribution causing large vibrations. This protection normally provides two levels, the first being an alarm and the second being a trip.

275 kV Line Protection

This is like any standard line protection, because there is fibre optics between each end of the transmission line this allows for use of differential current protection to be used. This differential relay operates in a similar manner to transformer differential relay, however due to the distance between each end of the line, the secondary of the CTs go into a relay at each end of the line. The current values from each relay are transmitted over the optic fibre link where they are compared to see if there is any differential. If there is a large enough differential then the circuit breaker at each end of the line are tripped.

Circuit Breaker Fail (62 BF)

As the name suggests this protection is for the scenario of when the generator circuit breaker fails to open after a trip command. This protection element utilises a timer that is started when then GCB get a trip command, should the GCB not open, the timer will time out and operate the next protection device which is the 275 kV circuit breaker to provide isolation. Typical GCB operating and arc extinguishing times are about 150 ms and a safety margin of 150 ms is used. This means a typical timer setting is 300 ms for CB fail protection.

AVR Heavy Fault

This is a trip condition provided to the protection system from the Automatic Voltage Regulator (AVR). This can be for many problems that occur in the AVR and a few will be listed below:

- Three thyristor failures in any phase (9 are paralleled together)
- Loss of control power to the AVR
- Over excitation protection provided from the AVR

Generator Transformer Differential and Overflux (87GT)

The differential protection element provides protection for winding faults of the transformers. The protection is similar to that of the generator differential which has already been explained however because of inrush currents there is harmonic restraint of the protection.

Transformers are energised by the closing of circuit breaker and this causes inrush currents to flow for a small period of time. These inrush currents are not sinusoidal and Figure 3.9 shows a typical phase current waveform immediately after energisation. These waveforms produce 2^{nd} and 5^{th} order harmonics and to prevent false operation of the protection relay during energisation transformer differential relays are provided with 2^{nd} and 5^{th} harmonic restraint elements.

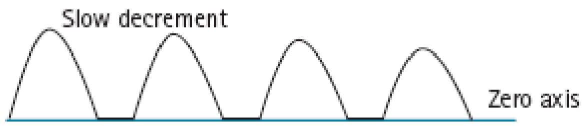


Figure 3.9 Typical inrush current waveform (Areva T&D, 2002)

Overfluxing protection is provided to protect against large heat rise cause by greater iron losses and much greater magnetising current when the voltage/ frequency ratio increases. This increased heat is because the increased flux begins to flow in the structural steel parts of the transformer (winding hold down bolts etc). This protection looks at the V/f ratio of the transformer to detect over fluxing conditions.

Generator Transformer Overcurrent

This protection element provides protection for internal faults in the transformer in which large currents will flow. It also provides protection for overloading of the transformer. Time delay characteristics (standard inverse, very inverse etc) with time multiplier settings are chosen to protect the windings and insulation from degradation due to over heating and also to ensure discrimination of the protection devices.

Generator Transformer Main Oil Tank Surge

This protection element provides protection when there is an internal explosion inside a transformer. It looks at the rate of rise of pressure in the main oil tank of the transformer. So in the event of an internal explosion a large pressure rise in the main tank of the transformer will be detected and all sources of supply to the transformer will be rapidly tripped to minimise the impact. This protection signal comes from a devise that is attached to the transformer.

Generator Transformer (oil temp, Buckholtz, winding temp)

Oil temperature protection is provided by a temperature switch that has the detection bulb located in the transformer. This protects the oil from degradation that occurs at high temperatures.

The Buckholtz relay is located between the main tank of the transformer and the conservator. It provides protection for a large internal explosion and also detection of arcing in the main tank. A trip contact is operated when a large flow of oil or gas passes through the relay in the event of an internal explosion. An alarm contact is operated when there is an accumulation of gases that get trapped in the relay and a float switch operates. The accumulation of gases is due to arcing at a faulty connection inside the transformer.

Due to the voltage present on the windings, direct measurement is not possible. So the winding temperature is measured using a current transformer on the main winding with the secondary of the current transformer suppling a heater contained in a small vessel in the main tank to simulate the actual winding temperature. There is a temperature switch with the detection bulb located in the vessel. This temperature switch has a setting arm and provides contacts that are used to trip the generator and transformer in the event of high temperatures to protect from damage to the insulation, winding and oil.

Overall Differential (87)

This differential protection element does what the name suggests. It compares the currents (going in and out) of all of the overall unit power system equipment; generator, generator transformer, unit transformer and excitation transformer. It provides back up protection to the other individual differential protection elements and the settings are deliberately a little higher than the highest individual differential protection setting, so to provide some grading (allow individual differential relays to operate first). Figure 3.10 depicts a simplified overall differential protection with the protected zone in between the CTs.

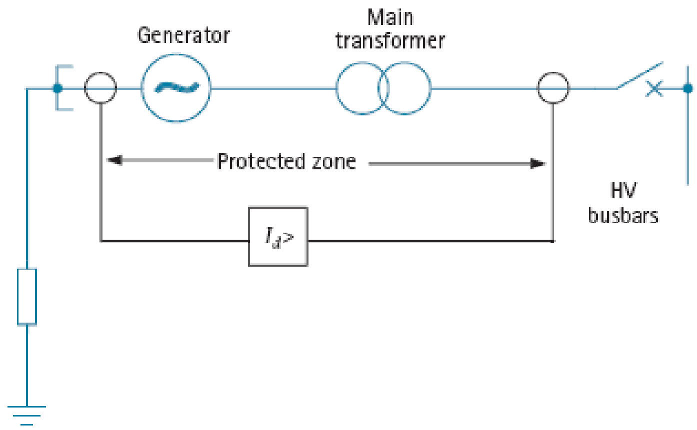


Figure 3.10 Overall Differential Protection (Areva T&D, 2002)

Unit Transformer and Excitation Transformer Differential and Overflux

Explanation is the same as the Generator Transformer.

Unit Transformer and Excitation Transformer Overcurrent

Explanation is the same as the Generator Transformer.

Unit Transformer and Excitation Transformer Main Oil Tank Surge

Explanation is the same as the Generator Transformer.

Unit Transformer and Excitation Transformer (bucholtz and winding temp)

Explanation is the same as the Generator Transformer.

Neutral Earthing Transformer Temperature Trip

This protection element is provided by a temperature trip device that is located on the neutral earthing transformer. This is to protect the transformer from destruction.

GCB Intertrip from Y

This is a trip that is sent to the X Protection system when the Y Protection intertrip relay has operated.

GCB Intertrip from X

This is a trip that is sent to the Y Protection system when the X Protection intertrip relay has operated.

275 kV Intertrip from Calvale

This protection element comes from the Powerlink 275 kV switchyard (located approximately 1 km away from Callide C Power Station). This trip is provided for bus zone protection in the Calvale Switchyard and 275 kV Circuit Breaker Failure.

Control System Trip - Loss of DC to 6.6 kV boards

This is a trip provided from the generators Distributed Control System (DCS) to the generator protection system. A loss of 220 VDC control power to the 6.6 kV distribution boards means that all the protection and control relays on the 6.6 kV distributions cannot operate which inturn means the circuit breakers (incomers, motor drives and feeders) cannot trip. This is a very dangerous situation because no protection is provided which is why all sources of supply to the 6.6 kV distributions (the Generator and 275 kV feeders) are tripped in this scenario.

Control System Trip - Generator Transformer control power loss

This trip is also provided from the generators Distributed Control System (DCS) to the Generator Protection System. Should the generator transformer lose control power an immediate trip is required as the cooling fans will stop and the transformer will overheat.

3.3 Diode Tripping Matrix

In the Callide C Generator Protection System there are eight devices that can be tripped by the protection system. These are listed below:

1. GCB - Tripping this opens the 19.5 kV Generator Circuit breaker.
2. A 6.6 kV Incomer (This is the A supply to the Unit 6.6 kV switchboard, it is fed by the Unit transformer).
3. B 6.6 kV Incomer (This is the B supply to the Unit 6.6 kV switchboard, it is fed by the Unit transformer).
4. AVR - The Automatic Voltage Regulator, tripping this stop voltage going to the rotor.
5. Turbine - Tripping this closes the main steam valves (2 of) and takes power away from the turbine.
6. MFT- Master Fuel Trip, tripping this stops all fuel sources going into the boiler and therefore trips the boiler.
7. 275 kV CB, tripping this opens the 275 kV Circuit Breaker in Powerlinks switchyard (1 km away).
8. Intertrip - on X Protection it trips Y Protection relays and on Y Protection it trips X Protection relays.

To control what devices you wish to trip when a certain protection element is operated, tripping diode matrixes are used in generator protection schemes to provide necessary logic and coordinate which device(s) to trip.

Table 3.4 shows the tripping logic Callide C X protection and Table 3.5 shows the tripping logic Callide C Y protection. They are mostly the same however the transformers (Generator, Unit and Excitation) protection is not duplicated on both X and Y. They have their differential and buckholtz protection on the X Protection and the overcurrent and oil surge protection are on the Y Protection.

Table 3.4 X Tripping Matrix

	GCB	A 6.6 kV Incomer	A 6.6 kV Incomer	AVR Trip	Turbine Trip	MFT	275 kV CB	Inter trip Y panel
Undervoltage (27)	■			■	■			
Under Frequency (81U)	■			■	■			
Over Frequency Trip (81O)	■			■	■			
Overvoltage (59)	■			■	■			
Earth Fault (51N, 59N)Non urgent	■			■	■	■		
Earth Fault (51N, 59N)Urgent	■			■	■	■		
Voltage Controlled Overcurrent (51V)	■			■	■	■		
Reverse Power (32R)	■			■				
Turbine Trip & GCB Open & Field CB closed + DT 5 sec	■			■				
Turbine Trip + DT 10 sec	■			■				
Negative Phase Sequence (46)							■	
Field Failure (41)	■			■	■	■		
Generator Differential (87G)	■			■	■	■		
275 kV Line Protection	■	■	■	■	■	■	■	■
Circuit Breaker Fail (62 BF)	■	■	■	■	■	■	■	■
Rotor Earth Fault (64R)								
Control System Trip- Loss of DC to 6.6 kV boards	■	■	■	■	■	■	■	■
AVR Heavy Fault	■			■	■			
Generator Transformer (oil temp, buckholtz, winding temp)	■	■	■	■	■	■	■	■
Neutral Earthing Transformer Temperature Trip	■			■	■			
Generator Transformer Differential and Overflux (87GT)	■	■	■	■	■	■	■	■
Unit Transformer Differential and Overflux (87UT)	■	■	■	■	■	■	■	■
Excitation Transformer Differential and Overflux (87ET)	■	■	■	■	■	■	■	■
Pole Slip (78)	■			■	■			
GCB Intertrip from Y	■	■	■	■	■	■	■	
275 kV Intertrip from Calvale	■	■	■	■	■	■	■	■
Unit Transformer (bucholtz and winding temp)	■	■	■	■	■	■	■	■
Excitation Transformer (bucholtz and winding temp)	■	■	■	■	■	■	■	■
Control System Trip - GT control power loss	■	■	■	■	■	■	■	■

Table 3.5 Y Tripping Matrix

	GCB	A 6.6 kV Incomer	A 6.6 kV Incomer	AVR Trip	Turbine Trip	MFT	275 kV CB	Inter trip Y panel
Undervoltage (27)	■			■	■			
Under Frequency (81U)	■			■	■			
Over Frequency Trip (81O)	■			■	■			
Overvoltage (59)	■			■	■			
Earth Fault (51N, 59N)Non urgent	■			■	■	■		
Earth Fault (51N, 59N)Urgent	■			■	■	■		
Voltage Controlled Overcurrent (51V)	■			■	■	■		
Reverse Power (32R)	■			■				
Turbine Trip & GCB Open & Field CB closed + DT 5 sec	■			■				
Turbine Trip + DT 10 sec	■			■				
Negative Phase Sequence (46)							■	
Field Failure (41)	■			■	■	■		
Generator Differential (87G)	■			■	■	■		
275 kV Line Protection	■	■	■	■	■	■	■	■
Circuit Breaker Fail (62 BF)	■	■	■	■	■	■	■	■
Control System Trip- Loss of DC to 6.6 kV boards	■	■	■	■	■	■	■	■
AVR Heavy Fault	■			■	■			
Generator Transformer Overcurrent	■	■	■	■	■	■	■	■
Generator Transformer Main oil tank surge	■	■	■	■	■	■	■	■
Overall Differential (87)	■	■	■	■	■	■	■	■
Excitation Transformer gas surge relay	■	■	■	■	■	■	■	■
Excitation Transformer Overcurrent	■	■	■	■	■	■	■	■
Unit Transformer Main oil tank surge	■	■	■	■	■	■	■	■
Unit Transformer Overcurrent	■	■	■	■	■	■	■	■
GCB Intertrip from Y	■	■	■	■	■	■	■	
275 kV Intertrip from Calvale	■	■	■	■	■	■	■	■
Control System Trip - GT control power loss	■	■	■	■	■	■	■	■

CHAPTER 4 Model Development

4.1 Information about Simulink SimPowerSystems

SimPowerSystems extends Simulink with tools for modelling and simulating the generation, transmission, distribution, and consumption of electrical power. It provides a library of models for many components used in these systems.

SimPowerSystems utilises the “drag and drop” procedures. Because of this system models can be built rapidly with relative ease. Calculation of initial steady state, load flow, and other key power system analyses are automated. SimPowerSystems models can also be discretised to speed up simulations if required. (Mathworks, 2010).

The models are proven ones and their validity is based on the experience of the power system testing and simulation laboratory of Hydro - Québec a large North American utility located in Canada. (TransÉnergie Technologies, 2003)

4.2 Obtaining all required modelling data

For the model, a lot of data about the system being modelled is required if an accurate representation is to be obtained. Most of the data was available through CS Energy Commissioning and The Original Equipment Manufactures (OEM) manuals.

However, model data for the Generator and AVR was obtained through Powerlink, the network service provider (NSP). The bundled impedance of the grid at the connection point was also sourced from Powerlink. The values that were used are included the appropriate block parameter tables in section 4.4.

4.3 Building of the Model

For this project it was intended that the model be as simple as possible yet maintaining a close representation of the actual system for the purposes of data validity. The relays that were targeted for the project were the LGPG111 multi function generator protection relays. This enables the unit transformer and ancillary loads to be bundled as one parameter. Due to the short time period of the required model the governor model was omitted and a constant power block was used, that represents a constant power source from the prime mover. Also the 275 kV feeder is only 800 m long so it was omitted from the model for simplicity. The values that were outputted to the workspace representing the voltage and currents values at each sample interval were appropriately scaled for CT and VT ratios by gain blocks. Figure 4.1 shows the model that was created for representation of the Callide C generator and generator transformer.

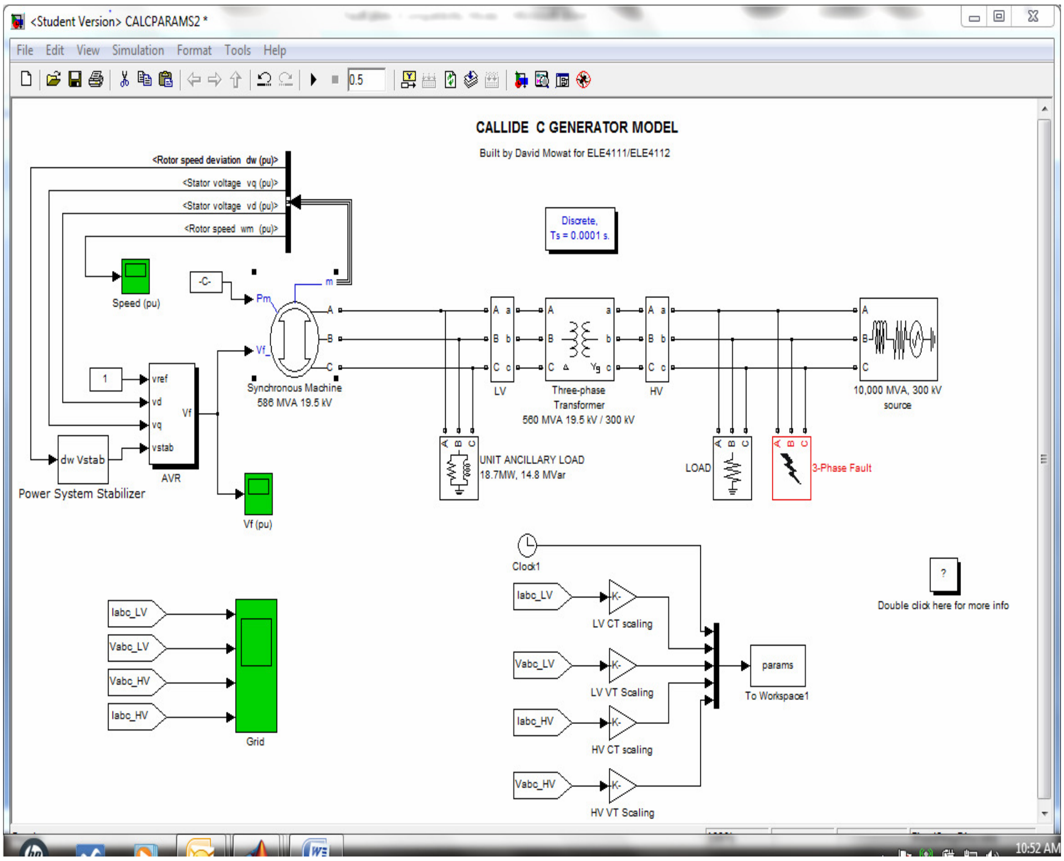


Figure 4.1 **Model of Callide C Generator**

4.4 Discussion of Elements used in the Model

4.4.1 The Power Graphical User Interface (GUI)

The Power GUI block is a graphical user interface that provides tools for the analysis of SimPowerSystems models. The Power GUI block allows you to choose one of three methods to solve the circuit:

1. Continuous method, which uses a variable step solver from Simulink
2. Discretisation of the electrical system for a solution at fixed time steps
3. Phasor solution method

The Power GUI block also allows you to:

1. Display steady-state values of measured current and voltages as well as all state variables in a circuit.
2. Modify the initial states in order to start the simulation from any initial conditions.
3. Perform load flows and initialise three-phase networks containing three-phase machines so that the simulation starts in steady state.
4. Display impedance versus frequency plots when impedance measurement blocks are present in your circuit.
5. Generate a report containing steady-state values of the measurement blocks, the sources, the nonlinear models, and the states of your circuit. The report is saved in a file with the .rep extension.
   (TransÉnergie Technologies, 2003)

4.4.2 The Synchronous Machine

This block implements a three phase synchronous machine that is modelled in the dq rotor reference frame (qd frame). The stator windings are connected in star to an internal neutral point. All rotor parameters and electrical quantities are viewed from the stator. They are identified by primed variables. The subscripts used are defined as follows:

- *d,q*: d and q axis quantity
- *R,s*: Rotor and stator quantity
- *l,m*: Leakage and magnetising inductance
- *f,k*: Field and damper winding quantity

The Electrical model of the machine is shown in Figure 4.2

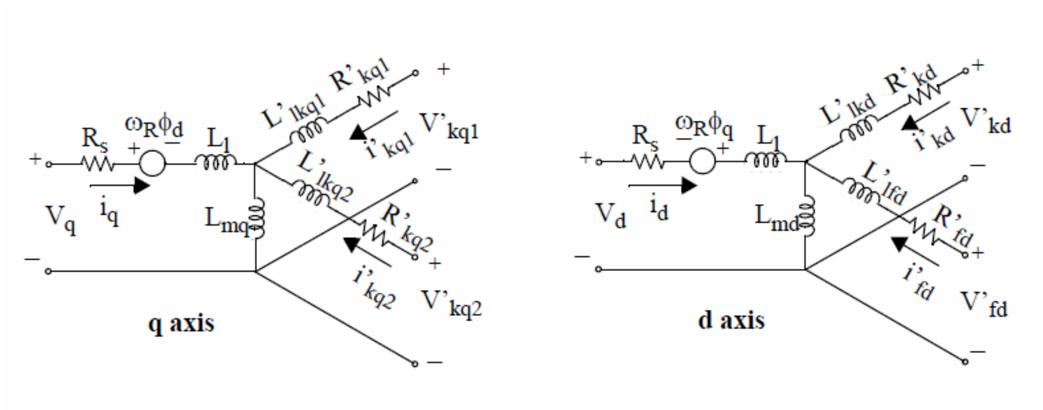


Figure 4.2 Electrical Model of Synchronous Machine

The electrical model has the following equations from 1 to 12.

$$Vd = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \quad (1)$$

$$\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd}) \quad (2)$$

$$Vq = R_s i_q + \frac{d}{dt}\varphi_q - \omega_R \varphi_q \quad (3)$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq} \quad (4)$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd} \quad (5)$$

$$\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd}) \quad (6)$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd} \quad (7)$$

$$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd}) \quad (8)$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \quad (9)$$

$$\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \quad (10)$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \quad (11)$$

$$\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \quad (12)$$

The model has two inputs, the first is P which is the input power in pu, this can be supplied by a governor model block or a constant block. The second input is Vf which the field voltage. This can be supplied by either excitation system block output Vfd or a constant block. There is a set or three phase voltages and currents labelled ABC for output from the generator to connect to a transformer or load. Also, there is an output M which has selectable machine parameters that can be monitored or used by other blocks.

Table 4.1 shows the configuration and parameters that were used in the synchronous machine block for the model.

Table 4.1 Synchronous Machine Configuration and Parameters

Parameter	**Entered Value**
Rotor Type	round
Nominal Power (watts)	586 000 000
Line to Line Voltage (V rms)	19500
Frequency (Hz)	50
Reactances [Xd Xd´ Xd´´ Xq Xq´ Xq´´ Xl] (pu)	[1.856, 0.337, 0.268, 1.87, 0.526, 0.268, 0.228]
Time Constants [Tdo´ Tdo´´ Tqo´ Tdo´´] (s)	[6.34, 0.034, 1.4, 0.04]
Stator resistance Rs (pu)	0.0025
Inertia Coefficient H(s)	2.99
Friction factor F(pu)	0
Pole pairs p()	1

4.4.3 The Excitation System

This block provides an excitation system for the synchronous machine and regulates its terminal voltage by controlling the field voltage to the rotor. The model that is implemented is the IEEE type 1 synchronous machine voltage regulator combined to an exciter. The output of the block is the field voltage Vfd in pu to be applied to the Vf input of the synchronous machine block. The excitation system block has four inputs, $Vref$ the desired output voltage, Vd the direct axis voltage, Vq the quadrature axis voltage and $Vstab$ the input from a power system stabiliser block.

Table 4.2 shows the parameter used in the excitation system block for the model

Table 4.2 Excitation System Parameters

Parameter	**Entered Value**
Low pass filter time constant Tr(s)	0.015
Regulator gain Ka()	9.32
Regulator time constant Ta(s)	0.001
Exciter gain Ka()	1
Exciter time constant Te(s)	0.001
Damping filter gain Kf()	0.001
Damping filter time constantTf(s)	0.001
Regulator output EFmin (pu)	-1.2
Regulator output EFmax (pu)	1.7
Regulator gain Kp()	30.91

4.4.4 The Generic Power System Stabiliser

The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system's stability. Electromechanical oscillations can be classified in four main categories: (TransÉnergie Technologies, 2003)

- Local oscillations: between a unit and the rest of the generating station and between the latter and the rest of the power system. Their frequencies typically range from 0.8 to 4.0 Hz.
- Interplant oscillations: between two electrically close generation plants. Frequencies can vary from 1 to 2 Hz.
- Interarea oscillations: between two major groups of generation plants. Frequencies are typically in a range of 0.2 to 0.8 Hz.
- Global oscillation: characterised by a common in-phase oscillation of all generators as found on an isolated system. The frequency of such a global mode is typically under 0.2 Hz.

The Generic Power System Stabiliser Block implements the Power System Stabiliser for a synchronous machine. The input for the block comes from machine speed deviation $d\omega$ and the output Vs goes to the $Vstab$ input of the excitation system block.

The model consists of a low pass filter, a gain, a washout high pass filter, two lead-lag time constants and a limiter. This block adds damping to the rotor oscillations of the synchronous machine by controlling its excitation. The general gain controls the amount of damping produced by the stabiliser. The washout high-pass filter eliminates low frequencies that are present in the $d\omega$ signal and allows the PSS to respond only to speed changes. The phase-compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine. Figure 4.3 shows the model of the Power System Stabiliser.

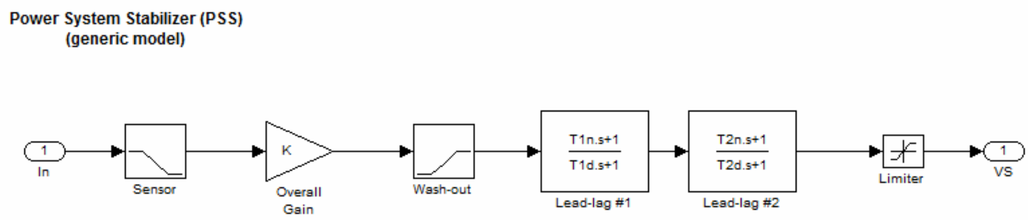


Figure 4.3 Generic Power System Stabiliser Model

Table 4.3 Generic Power System Stabiliser Parameters

Parameter	**Entered Value**
Sensor time constant	30e-3
Wash out filter time constant	2
Lead lag #1 Time constants [Tnum Tden]	[50e-3 20e-3]
Lead lag #2 Time constants [Tnum Tden]	[3 5.4]
Output limits [Vs min Vs max]	[-0.15 0.15]

4.4.5 The Transformer

The Three-Phase Transformer (two windings) block implements a three phase transformer using three single phase transformers. The two windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

The leakage inductance and resistance of each winding are given in pu based on the transformer nominal power Pn and on the nominal voltage of the winding ($V1$ or $V2$).

Table 4.4 shows the parameters used in the Three Phase Transformer (two winding) block for the model.

Table 4.4 Three Phase Transformer (two winding) Block parameters

Parameter	**Entered Value**
Winding 1 connection (ABC Terminals)	D11
Winding 2 connection (abc Terminals)	Yg
Nominal Power Pn(VA)	560 000 000
Frequency (Hz)	50
Winding 1 Voltage Ph-Ph V1(Vrms)	19 500
Winding 1 Leakage resistance R1(pu)	0.0027
Winding 1 Leakage inductance L1(pu)	0.07
Winding 2 Voltage Ph-Ph V2(Vrms)	300 000 000
Winding 2 Leakage resistance R2(pu)	0.0027
Winding 2 Leakage inductance L2(pu)	0.07
Magnetisation resistance Rm(pu)	500
Magnetisation inductance lm(pu)	500

4.4.6 The Three Phase RLC load

This block was used to represent the ancillary load of the generator. The three phase parallel RLC load block implements a three phase balanced load as a parallel combination of RLC elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage. Table 4.5 shows the parameters used in the three phase RLC load block for the model.

Table 4.5 Three Phase RLC Load Block Parameters

Parameter	**Entered Value**
Nominal ph-ph voltage Vn(Vrms)	19 500
Nominal frequency (Hz)	50
Active power (W)	18 700 000
Inductive reactive power Ql(negative var)	14 800 000
Capacitive reactive power Qc(negative var)	0

4.4.7 The Three Phase Source

This block was used to represent the high voltage grid. The three phase source block implements a balanced three phase voltage source with internal R-L impedance. The three voltage sources are connected in Y with a neutral connection that can be internally grounded or made accessible. You can specify the sources internal resistance and inductance either directly by entering R and L values, or indirectly by specifying the source inductive short-circuit level and X/R ratio. Table 4.6 shows the parameters used in the three phase source block for the model.

Table 4.6 Three Phase Source Block Parameters

Parameter	**Entered Value**
Nominal Ph-Ph Voltage Vn(Vrms)	300 000
Nominal Frequency (Hz)	50
Phase angle of phase A	0
3 Phase short circuit level (MVA)	10 000
Base Voltage	300 000
X/R ratio	15.3

4.4.8 The Three Phase fault

This block was used to simulate the different external faults that were being applied. The three phase fault block implements a three phase circuit breaker where the opening and closing times can be controlled by parameter setting.

Each phase and earth connection can be individually switched on and off to program phase-to-phase faults, phase-to-ground faults, or a combination of phase-to-phase and ground faults.

Table 4.7 shows the parameters used in the three phase fault block for the model.

Table 4.7 Three Phase Source Fault Parameters

Parameter	Entered Value
Fault Resistance Ron (ohms)	0.001
Ground Resistance Rg (ohms)	0.001
Transition Status (on off)	[1 0]
Transition Times (s)	[0.1 0.2]
Snubbers Resistance Rp(ohms)	inf (infinity)
Snubbers Capacitance Cp(farad)	Inf (infinity)

4.5 Difficulties experienced with Model

The following sections gives an overview of the problems I encountered with the model and modelling process. It also states the steps taken to overcome these problems.

4.5.1 Fixed time step and selection of the time step interval

Because the project required that the output of the model was to be "played" into the protection system with the Doble F6150 Power System Simulator it then required that the output be calculated with a fixed time step. The fixed time step requirement is because of the COMTRADE file format which is discussed in Chapter 6.

I found that when I changed the calculation method in the Power GUI from continuous (variable step) to discrete (fixed step) that the model did not run. This problem was overcome by going to the configuration screen in the model and changing the selection there to fixed step and the solver to discrete also.

Choosing the time step in which calculations were made was helped by the maximum sampling rate that the Doble F6150 Power System Simulator could replay a COMTRADE file at. The maximum rate was 10,000 samples per second which equated to a fixed time step of 100 microseconds. This time step allowed for maximum accuracy while not be too long to run the model. It took my computer about 5 seconds to run the model for a 1 second period. The speed would be dependant on the specifications of the computer that it was run on.

4.5.2 Excitation System Model not exactly the same as system

Although SimPowerSystems is a relatively simple program to use and the creation of a system model is fast when compared to other programs such as EDSA Design Base, it unfortunately only has a single model for elements such as the excitation system. This is a major limitation if ultimate accuracy is required.

The Excitation System Model as explained earlier is based on IEEE Type 1 Model however, the actual excitation system at Callide C is a static exciter and the model provided by Powerlink is different to that of the Model in SimPowerSystem. I attempted creation of my own excitation system model in Simulink however when I went to use it there was problem with the output (Vf) not being able to be adjusted by the Power GUI for steady state initial conditions. This prevented me from being able to create any of my own blocks and I believe it would require an entire project to learn the art of creating a block to work in SimPowerSystem.

By comparison between the Type 1 model and Powerlink model there was not a large enough difference to prevent use of the Type 1 model. Figures 4.4 shows the Type 1 Model and Figure 4.5 shows the Powerlink model.

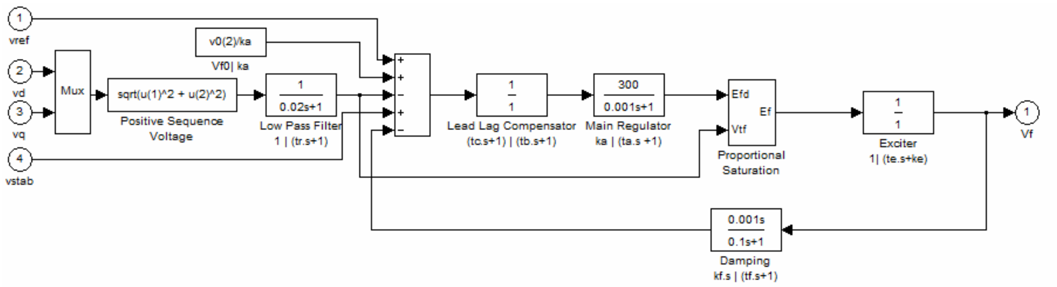


Figure 4.4 SimPowerSystem IEEE Type 1 Excitation System Model

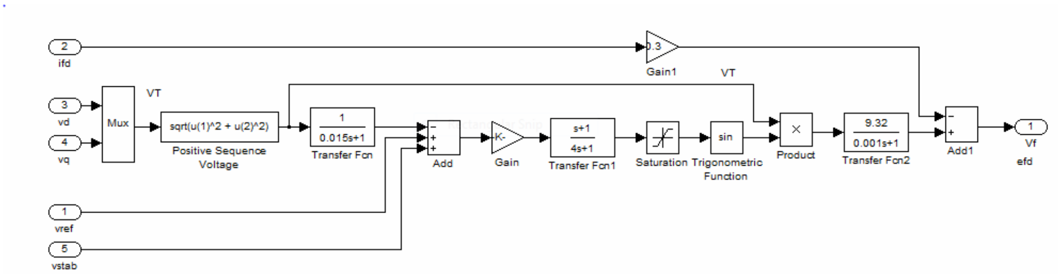


Figure 4.5 Powerlink Model of Callide C Excitation System

By making the gain of the exciter equal to 1 and reducing the exciter time constant to 0.001 seconds made the effect of the exciter insignificant. Likewise with the damping feedback, by reducing the damping filter gain to 0.001 nullified its contribution. With these changes made to the settings all the other settings could be used and the only contribution missing was the effect of the field current contribution in Powerlink model. Although not perfect this would still make the model a good representation of the system.

4.5.3 Governor Model not being able to be fixed time step

I had made the decision not to use a governor model because the modelling period was short enough that it could be omitted. However, I used the Steam turbine governor model block when I was experimenting to find the critical clearing time of the fault before the generator lost synchronism with the system. I wanted to see what effect, the governor model would make to the results.

When I went to run the model with discrete time steps between iterations it would not run because of a state space block in the Governor Model. This was not a major problem as I just ran the model in continuous mode, because I was only experimenting and not going to use the output data that was in variable time steps. The problem was noteworthy though because if you needed to use the governor block and required discrete time sample step for output data you would have had to run in continuous mode and then apply some sort of interpolation algorithm to the variable time step output data to get it back to discrete time steps. The results of this experiment are discussed in Chapter 7.

4.5.4 No COMTRADE file output

As the COMTRADE file is an industry standard it was surprising to me that it does not include a function block for writing COMTRADE suite of files of outputs from the model. I searched for any scripts already written for Matlab and was unsuccessful. Because of this I choose to use the Sample COMTRADE writer that was made by Doble rather than write my own script. This COMTRADE writer is discussed more in Chapter 5.

4.5.5 Simulink scope block not configurable.

The scope that is provided within Simulink allows you to graphically view a signal as it changes in time. Although the scope was very good as a quick reference to see the dynamics of the signals, it is not very configurable. Because of this I had to create my own plots from the data I saved to the workspace for the COMTRADE files. This allowed me to add titles, axis labels, choose suit colours for the phase signals, A phase (red) B phase (yellow) C phase (blue) and change the background colours so the plots could be included in the dissertation.

The script used for the plots is shown in Appendix D.

4.6 Faults used in test

With short circuit fault analysis, the aim is to:

- Calculate and implement adequate system protective device settings.
- Evaluate the effect of fault currents on power system components (thermal, mechanical stress and withstand capability).
- Evaluate the system-wide voltage profile during a localised fault.
- Fine-tune the network design to minimise the effect of system faults.
- Calculate and implement adequate grounding systems to control step potentials.

The most common faults are:

- Three phase fault (with or without ground involvement)
- Single line to ground
- Line to line and line to line to ground faults

Generally speaking three phase faults lead to the highest current levels available in a system. Consequently it is one commonly used to evaluate the most severe conditions. But under some circumstances, single-phase fault current could exceed the levels of three phase fault currents. In circumstances like this, it is highly recommended that a single Line to Ground fault analysis and even Line to Line fault analysis be conducted. It is important to keep in mind that even though a Line to Ground faults can experience a higher fault current with respect to the three phase fault, three phase faults still contains more power (MVA) since it is receiving contribution from all three phases. (Areva T&D, 2002)

For the purposes of the tests to prove compliance, Callide C Generators must be capable of riding through zero voltage at the connection point for 100 milliseconds and run continuous between 0.9 to 1.1 Volts pu. To satisfy these requirements the faults listed in Table 4.8 were the faults simulated for this analysis. Also the generator was set to its full load of 450 MW for these simulations.

Table 4.8 Simulated Faults used for the Relay Tests

Fault Number	Description of Fault type	Duration (mS)	Starting Voltage (pu)
1	3 phase to ground	100	1
2	3 phase to ground	100	1.1
3	3 phase to ground	100	0.9
4	3 phase to ground	200	1
5	3 phase to ground	300	1
6	Phase to phase to ground	100	1
7	Phase to phase to ground	100	1.1
8	Phase to phase to ground	100	0.9
9	Phase to ground	100	1
10	Phase to ground	100	1.1
11	Phase to ground	100	0.9
12	Phase to phase	100	1
13	Phase to phase	100	1.1
14	Phase to phase	100	0.9

4.7 Validation of Model

For any model to be considered accurate it requires validation. For validation of the model used in this project I am using the critical clearance time of 260 ms for the three phases to ground fault as an indicator that the parameters and component models are accurate. The method of validation is by asking Powerlink what critical clearing time their system model produces for a three phases to ground fault. If the results of my model are similar to that of the Powerlink model then I can be confident with my model.

At the time of completing this project I had not received any information back from Powerlink.

CHAPTER 5 COMTRADE file format

The COMTRADE file format is explained and examples shown because of its importance to the project. It is the industry standard that is used for transient files and COMTRADE files were created to test the protection relays as part of this project.

5.1 The need for a common file format

The COMTRADE file format is IEEE Std C37.111-1999 and had an earlier version which was IEEE Std C37.111-1991. It is a common format for data files and exchange medium used for the interchange of various types of fault, test and simulation data for electrical power systems.

The need for this came about due to the increasing use of digital technology in electrical power system devices such as protection, measurement and control systems and devices. These devices have the potential of accumulating large amount of data files and more importantly the many different file formats the utility owner has to deal with. So to create a standard file format that the manufactures of these devices can use for storage of records was a sensible solution (IEEE Standard C37.111-1999).

Each COMTRADE record has a set of up to four files associated with it. These are listed below:

1) Header
2) Configuration
3) Data
4) Information

All files in the set must have the same file name, differing only by the extensions that indicate the type of file. The following sub-sections give a brief overview of each of the file types. This information was obtained from the IEEE Standard.

5.1.1 Header file (xxxxxxxx.HDR)

This is an optional ASCII text file. It is intended to be printed and read by the user.

5.1.2 Configuration file (xxxxxxxx.CFG)

This is an ASCII text file that is intended to be read by a computer program and therefore, must be saved in a specific format. The configuration file contains information needed by a computer program in order to properly interpret the data (.DAT) file. This information includes items such as sample rates, number of channels, line frequency, channel information.

5.1.3 Data file (xxxxxxxx.DAT)

This file contains the value for each input channel and each sample in the record. The number stored for the sample is a scaled version of the value presented to the device that sampled the input wave form. The stored data may also have a zero base or a zero offset. The conversion factors (scale and zero offset) specified in the configuration file defines how to convert the data values back to the actual sample engineering units. This data file contains a sequence number and time stamp for each set of samples.

5.1.4 Information file (xxxxxxxx.INF)

The information file is an optional file containing extra information that, in addition to the information required for a minimum application of the data set, file originators may wish to make available to the users. The format provides for public information that any user can read or use, and private information that may be accessible only to users of a particular class or manufacture.

5.2 Creation of COMTRADE files

It was mentioned in Chapter 4 that SimPowerSystem did not output the data in COMTRADE file format. The data was outputted in pu values based on the Generators rating of 586 MVA and 19.5 kV.

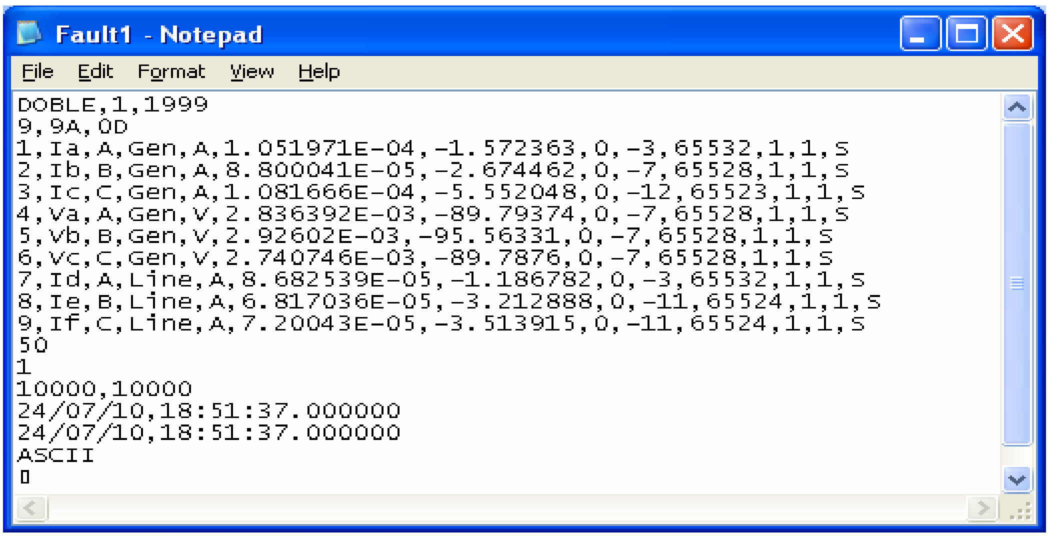
For the creation of the COMTRADE files that were used to test the relays a "Sample COMTRADE Writer" was used. This writer is a Macro in an excel spreadsheet. The data is entered (copied and pasted) and the necessary parameters are inputted. Instructions are on how to use Sample COMTRADE Writer are documented in Appendix C.

This writer was created by Doble for the very use of creating COMTRADE files so that they could be entered into their Power System Simulator and "played" into power system equipment to analyse the behaviour of the equipment during those conditions. Because such a writer was readily available it was a chosen over writing a script in Matlab to convert data into a set COMTRADE files.

The Doble Power System Simulator only requires the two mandatory COMTRADE files (configuration and data files) for correct operation and "play back" of the data files. Because of this, the sample COMTRADE writer only produces the .DAT (data) and .CFG (configuration) files.

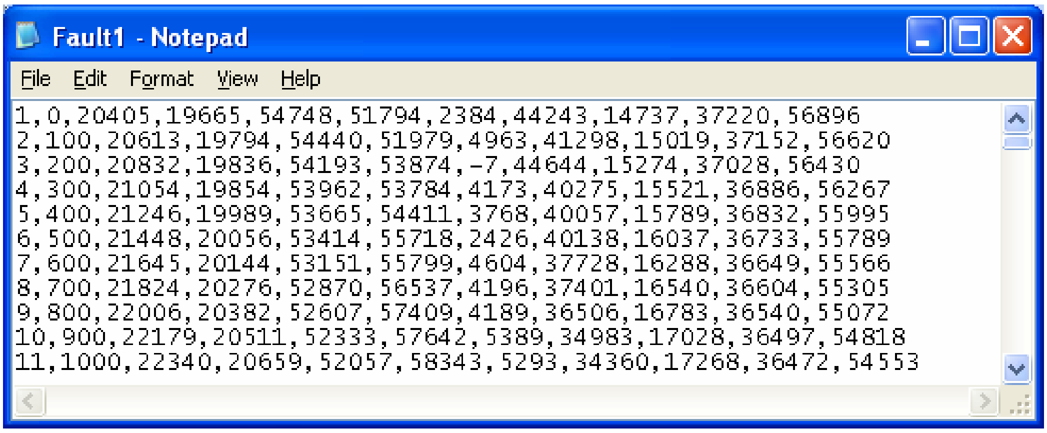
5.3 Sample of Files Created

For the purposes of illustration the Fault1 configuration (Fault1.cfg) file and the first 11 samples of the Fault 1 data file (Fault.dat) are shown, note there were 10000 samples in the Fault 1.dat file. These files were opened with windows notepad.


Fault1 - Notepad
File Edit Format View Help

```
DOBLE,1,1999
9,9A,0D
1,Ia,A,Gen,A,1.051971E-04,-1.572363,0,-3,65532,1,1,S
2,Ib,B,Gen,A,8.800041E-05,-2.674462,0,-7,65528,1,1,S
3,Ic,C,Gen,A,1.081666E-04,-5.552048,0,-12,65523,1,1,S
4,Va,A,Gen,V,2.836392E-03,-89.79374,0,-7,65528,1,1,S
5,Vb,B,Gen,V,2.92602E-03,-95.56331,0,-7,65528,1,1,S
6,Vc,C,Gen,V,2.740746E-03,-89.7876,0,-7,65528,1,1,S
7,Id,A,Line,A,8.682539E-05,-1.186782,0,-3,65532,1,1,S
8,Ie,B,Line,A,6.817036E-05,-3.212888,0,-11,65524,1,1,S
9,If,C,Line,A,7.20043E-05,-3.513915,0,-11,65524,1,1,S
50
1
10000,10000
24/07/10,18:51:37.000000
24/07/10,18:51:37.000000
ASCII
0
```

Figure 5.1 **Fault1.cfg file**



Fault1 - Notepad

File Edit Format View Help

```
1,0,20405,19665,54748,51794,2384,44243,14737,37220,56896
2,100,20613,19794,54440,51979,4963,41298,15019,37152,56620
3,200,20832,19836,54193,53874,-7,44644,15274,37028,56430
4,300,21054,19854,53962,53784,4173,40275,15521,36886,56267
5,400,21246,19989,53665,54411,3768,40057,15789,36832,55995
6,500,21448,20056,53414,55718,2426,40138,16037,36733,55789
7,600,21645,20144,53151,55799,4604,37728,16288,36649,55566
8,700,21824,20276,52870,56537,4196,37401,16540,36604,55305
9,800,22006,20382,52607,57409,4189,36506,16783,36540,55072
10,900,22179,20511,52333,57642,5389,34983,17028,36497,54818
11,1000,22340,20659,52057,58343,5293,34360,17268,36472,54553
```

Figure 5.2 **First 11 samples of the Fault1.dat file**

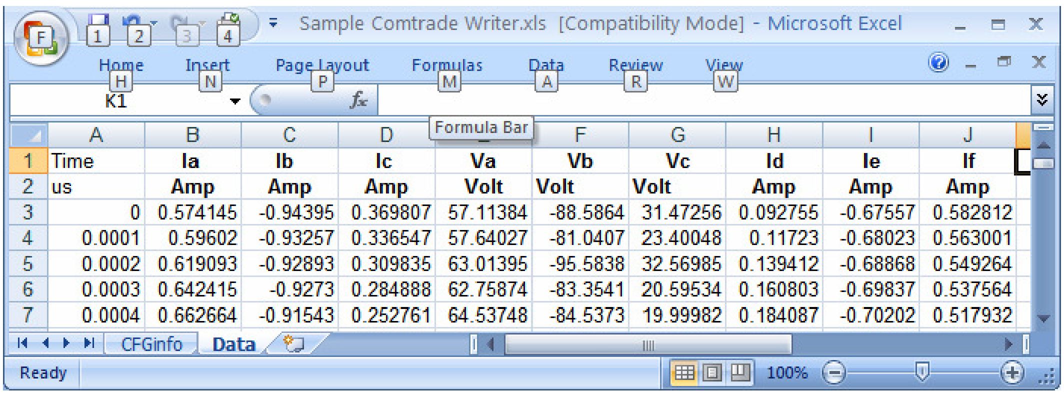
From Figure 5.1 Fault1.cfg file (configuration file) the sixth and seventh entry in the row of channel 1 configuration data represents the channel scaling factor (1.0572363e-4) and channel offset (-1.572363) respectively. These values are used to covert the numbers in the data for channel 1 file back to the original engineering value. From Figure 5.2 Fault1.dat file (data file) we can see that the first entry for channel 1 is 20405.

So putting the numbers back together we have:

Channel 1 first value x channel 1 scale + channel 1 offset = original value

$$20405 \times 1.0572363\text{e-}4 \ + \ -1.572363 \ = \ 0.5741$$

By observing the number in cell B3 in Figure 5.3 which is the first entry for channel 1 we see it is also 0.5741.



Sample Comtrade Writer.xls [Compatibility Mode] - Microsoft Excel

Home Insert Page Layout Formulas Data Review View

K1 Formula Bar

	A	B	C	D	E	F	G	H	I	J
1	Time	Ia	Ib	Ic	Va	Vb	Vc	Id	Ie	If
2	us	Amp	Amp	Amp	Volt	Volt	Volt	Amp	Amp	Amp
3	0	0.574145	-0.94395	0.369807	57.11384	-88.5864	31.47256	0.092755	-0.67557	0.582812
4	0.0001	0.59602	-0.93257	0.336547	57.64027	-81.0407	23.40048	0.11723	-0.68023	0.563001
5	0.0002	0.619093	-0.92893	0.309835	63.01395	-95.5838	32.56985	0.139412	-0.68868	0.549264
6	0.0003	0.642415	-0.9273	0.284888	62.75874	-83.3541	20.59534	0.160803	-0.69837	0.537564
7	0.0004	0.662664	-0.91543	0.252761	64.53748	-84.5373	19.99982	0.184087	-0.70202	0.517932

CFGinfo Data

Ready 100%

Figure 5.3 **Data in Sample COMTRADE Writer**

CHAPTER 6 Testing of Protection relays

6.1 TransWin 3.1 Software

The testing was carried out using the TransWin 3.1 software. This software is produced by Doble for playing COMTRADE files with their F6150 power system simulator. The front screen of TransWin 3.1 is shown in Figure 6.1. By selecting "Transient Playback" will allow you to open COMTRADE files.

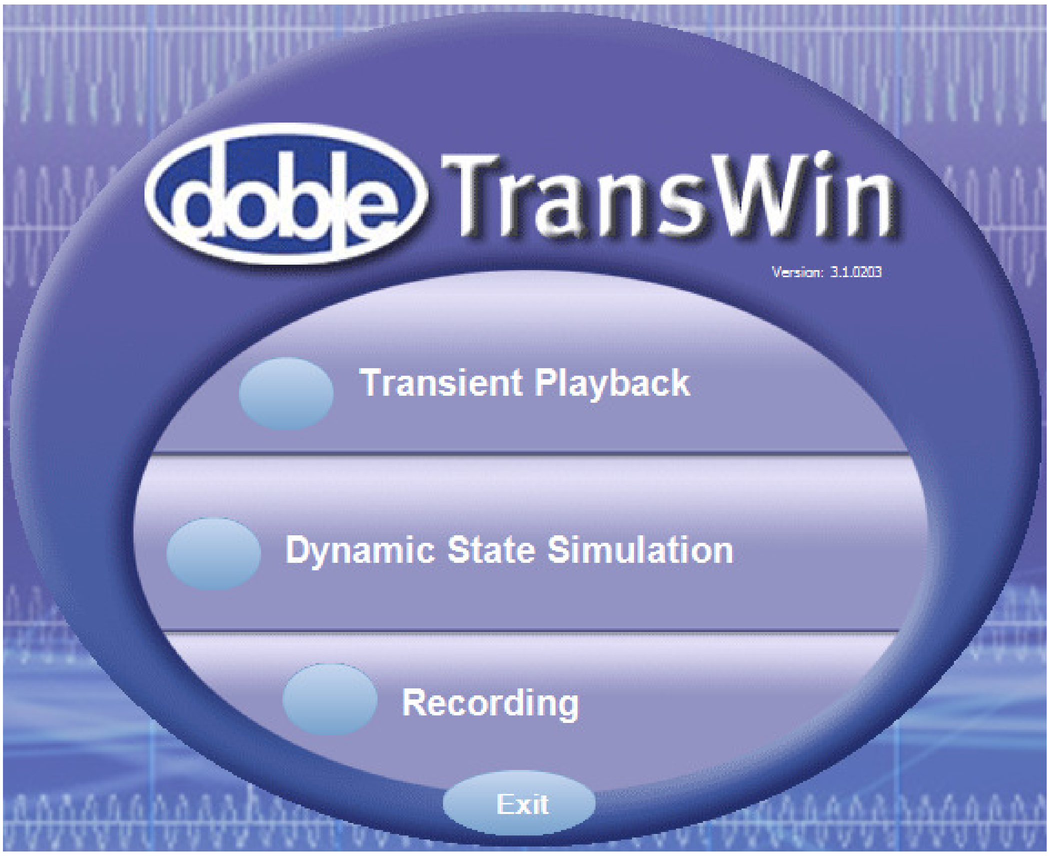


Figure 6.1 TransWin Software Front Page

Figure 6.2 shows the TransWin software once the "Transient Playback" has been selected. You simply browse to the directory where your files are stored and select which file you wish to open.

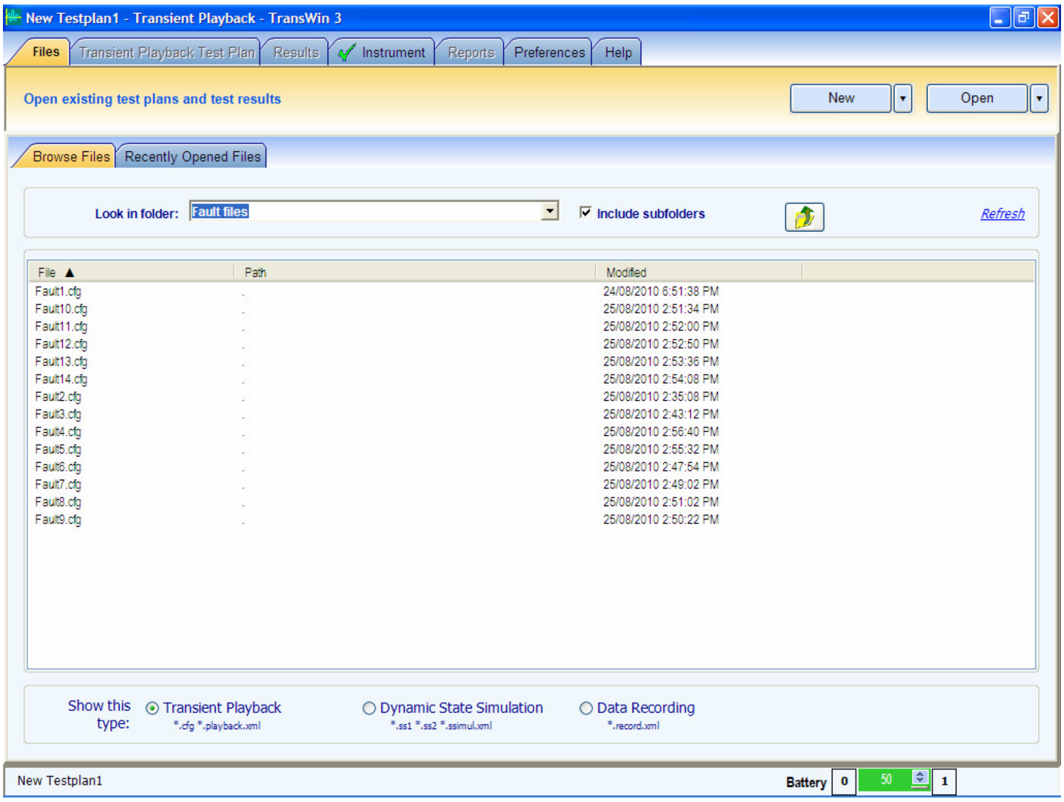


Figure 6.2 TransWin 3.1 File Selection

Once the desired COMTRADE file has been selected you can go to the "Transient Playback Test Plan" tab as shown in Figure 6.3 to set up the F6150 Power System simulator for the Test.

You can also view the waveforms that will be played from each source of the F6150 Power System Simulator by opening the "Plots" tab. This is the tab that is shown in Figure 6.3. The plots for Fault1 and will resemble the same waveform as the output plot from the Model for Fault1.

The COMTRADE channels tab allows you to enable the channels that you wish to use in the test, i.e. you may only need to use 6 of the 9 channels in COMTRADE file for a particular test.

The "Sources" Tab allows you to allocate an output source on the F6150 Power System Simulator to a particular COMTRADE channel (this is normally done automatically however, this allows for manual selection if required). Also in this tab is the Master Configuration for to select what type of output sources are required. Some configurations are listed below:

- 3 Voltages and 3 Currents 150 VA
- 4 Voltages and 4 Currents 150 VA
- 6 Voltages and 6 Currents 75 VA
- 9 Voltages and 3 Currents 75 VA
- 3 Voltages and 9 currents 75 VA

The Doble F1650 Power System Simulator also has 8 inputs that can be used to control the test. This allows the test to be stopped or timers started when contacts are opened or closed. The inputs can be configured for contacts opened or closed and voltage on or off.

Figure 6.3 **TransWin Plots**

6.2 Relay setup

The connection between the F6150 Power System Simulator output source to the protection relay under test are the same as for empirical testing of relays. Before testing is performed on the protection system a regimented isolation procedure (switching instruction) is performed. This procedure is performed to protect both the personnel and the equipment. Some of the main reasons for the procedure are listed below;

- Ensures that protection does not get isolated on in-service equipment leaving the in-service equipment unprotected. This would have major safety and system stability issues if a fault was to develop on the equipment while it was unprotected.
- Ensures that current transformers are <u>not</u> open circuited on in-service equipment which would cause destruction of the current transformers. Again this would be unsafe to personnel and very destructive to the equipment. There would be a severe effect and cost due to the generator being offline and not able to be generating revenue. Also because there are many Current Transformers (CT's) required for metering and protection they are usually stacked on top of one another, this can mean also that damage to one CT can cause damage to adjacent CT's.
- Ensures that Voltage Transformers (VT's) are isolated and that back energisation is not possible from the 110 volt secondary circuits which would put people in danger of electrocution.

The tests were performed on a spare Alstom LGPG111 multi function generator protection relay as a trial run before tests were performed on the actual relays on Unit 4. Unit 4 was chosen because of availability, it was out of service for a minor shutdown. It is proposed that tests will be performed on Unit 3 protection system next time the unit is offline for a shutdown.

Figure 6.4 shows the test setup for the spare LGPG111 multi function generator protection relay. This figure shows the power system simulator on the left, computer running TransWin 3.1 in the middle and LGPG11 multifunction relay under test on the right. The three phase voltage and current test lead connections from the Power System Simulator to the relays can be seen.

Figure 6.4 Spare relay test setup

Figure 6.5 shows the test setup for testing the actual generator protection system of Unit 4. This Figure shows the power system simulator and associated computer running TransWin 3.1 in the front centre of the picture, the protection panels P1 on the back left and protection Panel P2 on the back right. The three phase voltage and current test lead connections from the Power System Simulator to rear of the protection panels can also be seen.

Figure 6.5 **Protection Relay Test Setup**

CHAPTER 7 Results and Analysis

The project involved both the developing of the waveforms using the model in SimPowerSystem and the testing of the relays with the developed waveform. Because the development of the waveform was a large percentage of the project I have included a brief analysis of the main observations from a waveform for each fault type.

7.1 Model Output Waveform Analysis

Only the model outputs for the pre fault voltage of 1 pu will be analysed because the general waveforms are the same for each fault type. Also Fault 5, the three phase fault for a duration of 300 milliseconds will be discussed as this plot shows the generator going out of synchronism with the grid. All of the plots from the model outputs are shown in Appendix B - Model Output Waveforms.

Note Even though the plots shown are for 0.5 second duration (with the exception of Figure 7.5 which is for 1 second, the actual model time duration was one second and the associated COMTRADE files were for one second duration.

Each fault plot is arranged with subplots with the same time on the x axis. The order of the subplots from top to bottom is as follows:

1. Generator Current
2. Generator Voltage
3. Line Current
4. Line Voltage

Each subplot contains the three phase waveforms for the plot. The red line represents A phase, the yellow line represents B phase and the blue line represents C phase.

Fault 1- Three phase to ground fault, Prefault voltage = 1pu, fault duration = 100 milliseconds

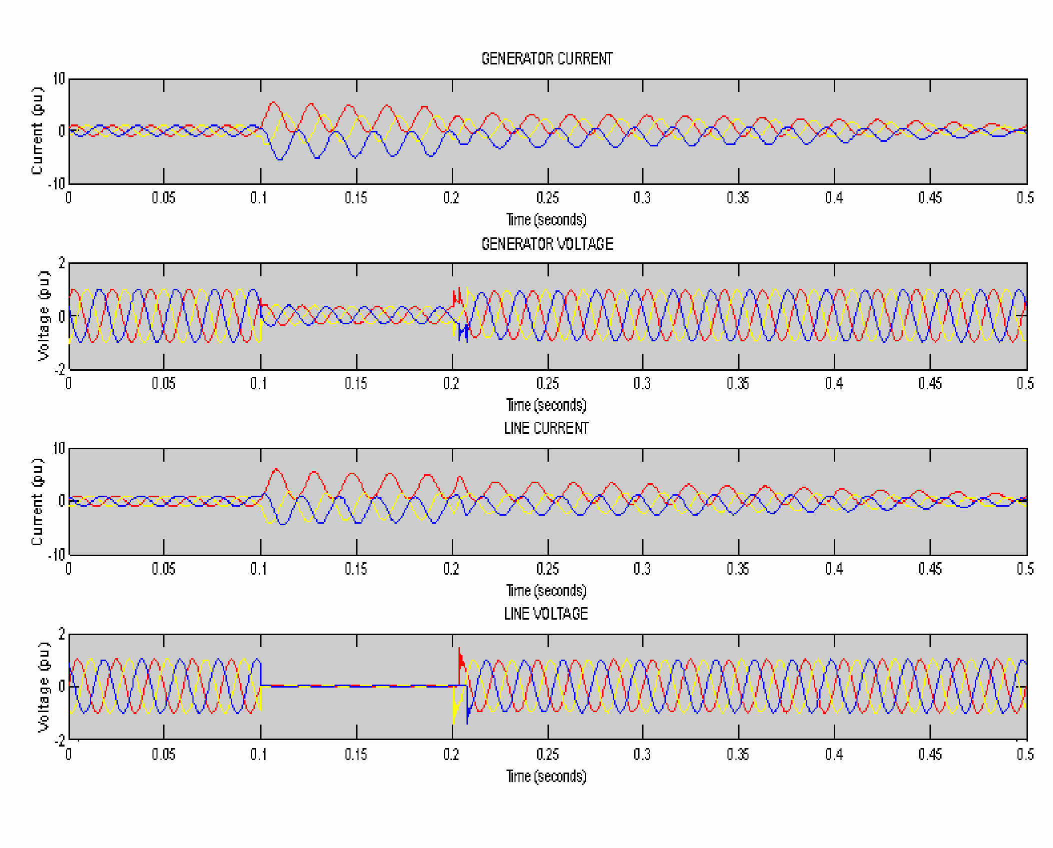


Figure 7.1 Fault 1 Plot - Three Phase to Ground Fault

For this fault it was seen that terminal voltage of the generator has reduced to 0.30 pu at the end of the 100 millisecond fault (0.28 pu when prefault voltage was 0.9 pu). This is useful for further studies on "fault ride through ability" of the generator. After the fault is cleared the voltage recovers.

It can be seen that the line voltages were all at zero volts as expected for a fault with zero fault resistance (bolted joint fault). The current values in both the generator and line have increased and each phase has a DC offset component due to subtransient and transient effects on the waveform. All the waveforms are however still synchronous during the fault.

Fault 6 - Line to Line to ground fault, Prefault voltage = 1pu, fault duration = 100 milliseconds

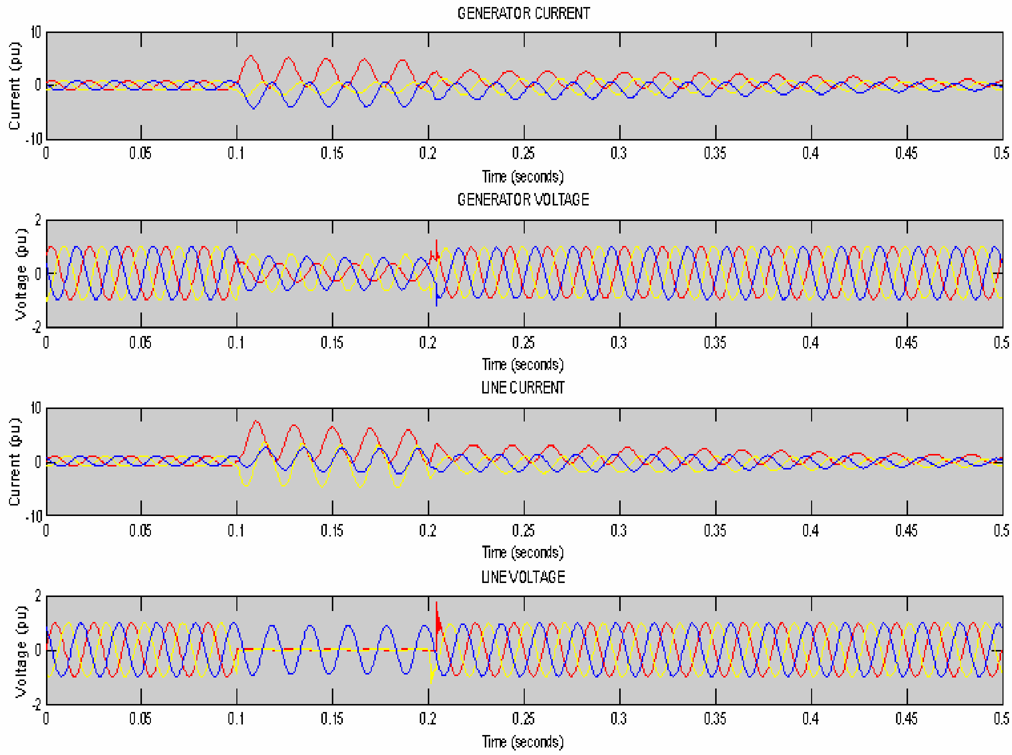


Figure 7.2 Fault 6 Plot - Line to Line to Ground Fault

For this fault it was seen that terminal voltage of the generator was at different levels for each phase. The voltage was approximately 0.4 pu for A phase, 0.7 pu for B phase and 0.6 pu for C phase. Although the voltages are at different levels they still have approxiamately 120^{o} separation. After the fault is cleared the voltage recovers.

It can be seen that the A and B phase (red and yellow lines respectively) line voltages went to zero volts as expected for a fault with zero fault resistance (bolted joint fault). The current values in the line have increased in each phase and have a DC offset component due to subtransient and transient effects on the waveform. Only the the A and C phase generator currents have increased however the DC offset component is on all three phases. Both the generator and line current waveforms are now asynchronous.

Fault 9 - Line to ground fault, Prefault voltage = 1pu, fault duration = 100 milliseconds

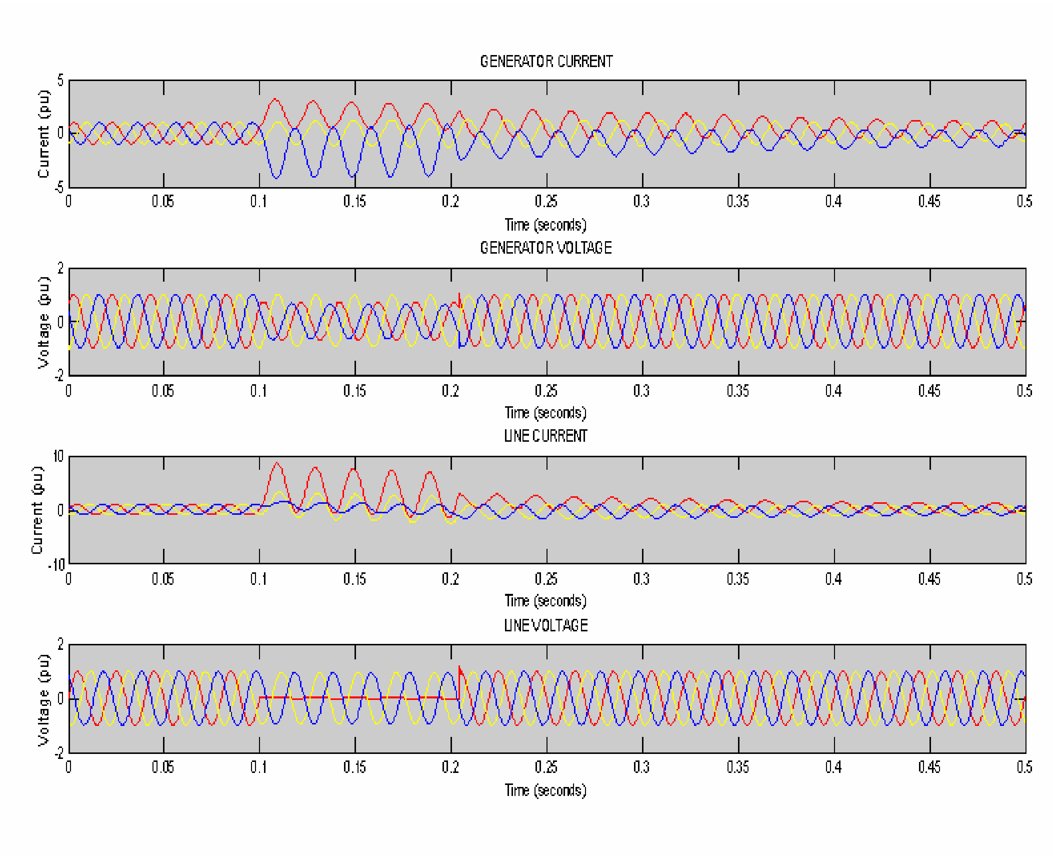


Figure 7.3 Fault 9 Plot - Line to Ground Fault

For this fault it was seen that terminal voltage of the generator was at different levels for each phase. The voltage was approximately 0.6 pu for A phase, 0.85 pu for B phase and 0.5 pu for C phase. Although the voltages are at different levels they still have approxiamately 120^{o} separation. After the fault is cleared the voltage recovers.

It can be seen that the A phase (red lines) line voltages went to zero volts as expected for a fault with zero fault resistance (bolted joint fault). The current values in the line have increased in A & B phase and all phases have a DC offset component due to subtransient and transient effects on the waveform. The A and C phase generator currents have increased and the DC offset component is on all three phases. Both the generator and line current waveforms are now asynchronous.

Fault 12 - Line to Line fault, Prefault voltage = 1pu, fault duration = 100 milliseconds

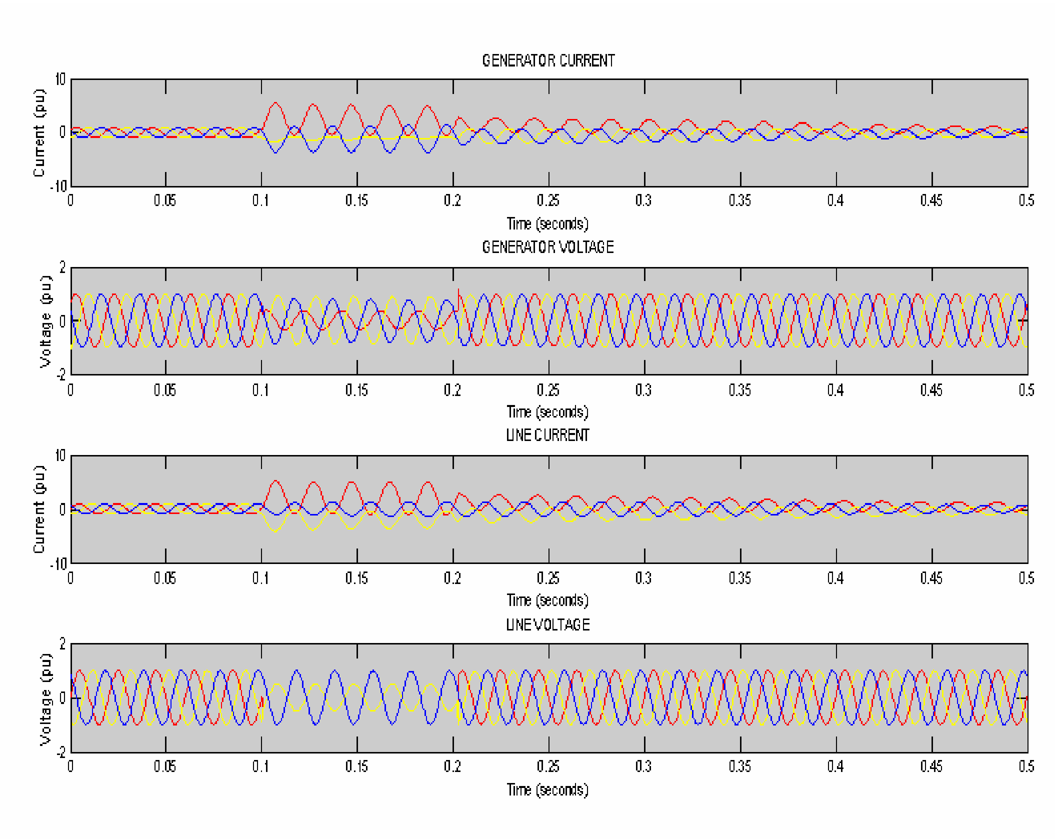


Figure 7.4 Fault 12 Plot - Line to Line Fault

For this fault it was seen that terminal voltage of the generator was at different levels for each phase. The voltage was approximately 0.5 pu for A phase, 0.8 pu for B phase and 0.7 pu for C phase. Although the voltages are at different levels they still have approxiamately 120^{o} separation. After the fault is cleared the voltage recovers.

It can be seen that the A phase (red lines) line voltages went to zero volts as expected for a fault with zero fault resistance (bolted joint fault). The current values in the lines have increased in A & B phase and they also have a DC offset component due to subtransient and transient effects on the waveform. The A and C phase generator currents have increased and B phase decreased. There is a DC offset component is on all three phases. Both the generator and line current waveforms are now asynchronous.

Fault 5 - Three Phase to ground fault, Prefault voltage = 1pu, fault duration = 300 milliseconds

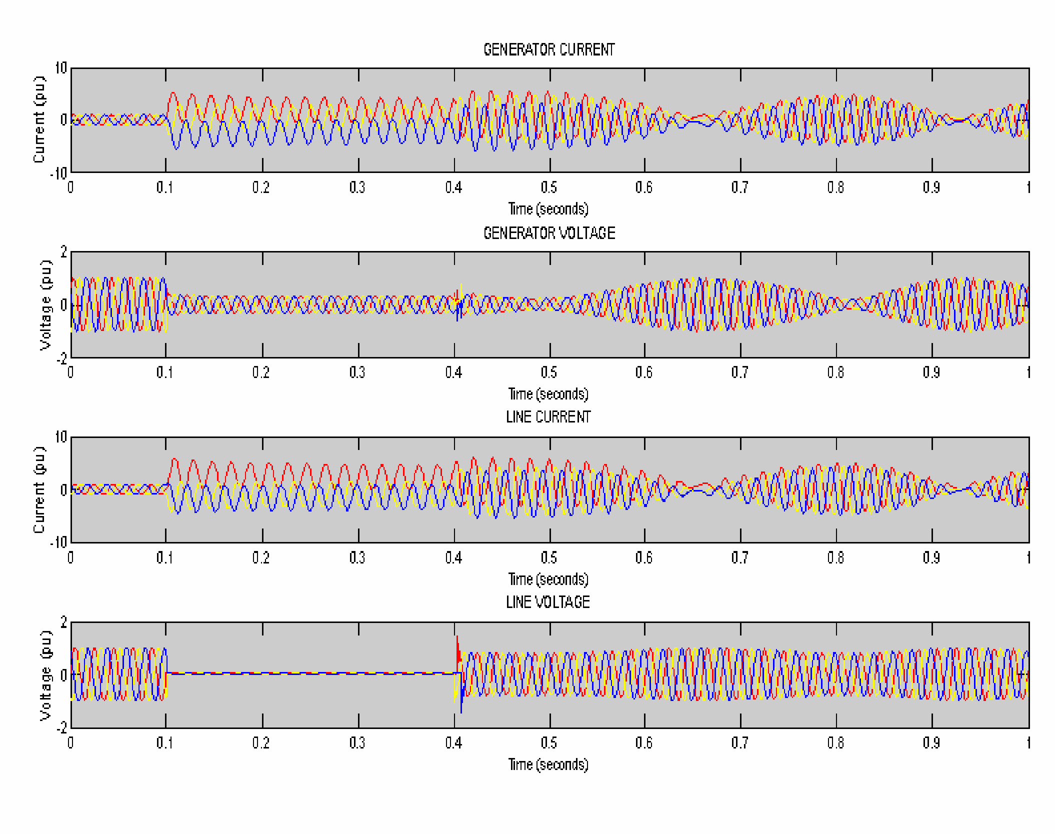


Figure 7.5 Fault 5 Plot - Three Phase to Ground Fault, 300 milliseconds

Figure 7.5 shows that the voltage never recovers and oscillates after a fault of 300 milliseconds is applied. In this scenario the generator has lost synchronism with the Grid. It would be expected that this waveform would cause a trip due on the Out of Step (78) protection element and Field Failure (40) as a backup protection to Out of Step.

Further experimentation was performed and it was found that for a three phase to ground fault the critical clearance time (time allowed to clear fault before synchronism is lost) was 260 milliseconds. I also added a Governor block to the model the result was the same as the governor did not remove power to the rotor quick enough for it make any effect.

There is also a Power Load Unbalance (PLU) function on Callide C and most modern governors. The PLU function has two conditions required for detection:

1. An imbalance of 40% power between the power being supplied to the turbine and the load being supplied by the generator.
2. A decrease in load at a rate of 4000% per second (40% in 10 ms).

This protection is only meant for complete loss of supply from the generator and is for early detection to protect the turbine from over speeding and doing damage to the turbine and rotor. The action that the PLU takes is a fast close on all the turbine steam control valves (0.4 seconds) and then after a second the governor is selected to speed control (from load control) and the valves will only open to control the speed to 3000 rpm. Note when a PLU occurs there is no external load on the generator only its own load (house load).

7.2 Results of Relay Testing

The simulation of 14 faults were performed, with the exception of faults 4 and 5 the faults were for duration of 100 milliseconds at a starting voltage of 0.9, 1 and 1.1pu of voltage. Table 5 shows the results with a tick indicating that a trip occurred because of operation of the respective protection element.

Table 7.1 Results of Protection Relay Tests

Protection Element	Fault No (✓ indicates a trip)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Earth Fault Protection (51N)														
Voltage Dependent Overcurrent (51V)														
Reverse Power Protection (32R)														
Frequency Protection (81)														
Voltage Protection (27 & 59)														
Negative Phase Sequence (46)														
Field Failure (40)					✓									
Out of Step (78)					✓									
Generator Differential (87G)														
Generator Transformer Differential (87GT)														
Overall Differential (87)														

The outcome of the test on the relay was positive because the protection relays showed stability for external faults and transient asynchronous conditions, as no trips occurred for the external faults.

The protection relays also showed selectivity in operating only the required elements for the out of step (loss of synchronism fault) for Fault No 5 which had out of step conditions.

These results showed the following;

- That the settings for the relays are appropriate and the guide for these setting from the relay manufacturer were also appropriate with the exception of the note below.
- The relays behaved correctly for the asynchronous transient conditions that they were tested under.

However it should be mentioned that these results are limited by the accuracy and complexity of the model.

Note: During the testing the Field Failure element took 1.5 seconds to operate when presented with loss of synchronism conditions (the Field Failure is also used as a backup for "Out of Step Relay"). The delay was due to a timer that is used to prevent a trip occurring during stable power swings. The Out of Step relay only took 50 ms to operate for the same conditions. The problem here is that if the Out of Step relay failed, the time to operate the Field failure relay is too long and major damage would occur during this time. This problem is currently being investigated to see if a smaller time value can be used.

CHAPTER 8 Conclusions

The protection relays did not trip for the range of simulated faults which shows that CS Energy are serious about their requirements and are taking necessary actions to ensure compliance. It is recommended though that a transient monitor should be purchased and installed to capture actual data during fault conditions to aid with compliance.

8.1 Achievement of Project Objectives

The specified project objectives have been met as follows;

The research into background information of National Electricity Rules relating to required ride through capabilities for Callide C Generators was the first task of the project. It was completed using the Callide C Performance Standards and also Charter 5 Schedule 5.2 of the National Electricity Rules - Conditions for Connection of Generators. These requirements are listed in the literature review.

Research large coal fired power plant generator protection philosophies and schemes. This task is covered in the literature review.

Research details of Callide C generators protection scheme and settings for the protection relays. This task is covered in Chapter Three of the dissertation. The information in Chapter 3 is compiled into a form that accommodates training at an Associate diploma which addresses that project objective also.

The performance of Callide C Generators Protection System for external faults was analysed by building a model of the Generator using Simulink SimPowerSystems. The output of the model was played into the protection system using the DOBLE power system simulator to check the Protection System. This was the most time consuming task of the project. Although a model was created the limitations of SimPowerSystem were realised during this project where it only had a single Excitation System Model. It was also realised during this project the modelling a Power System is a very complex and specialised field. The simple model created is only suitable for this single purpose.

8.2 Project Outcomes

The aim of this project was Callide C Power Stations Generator Protection System "ride through capabilities" for various external faults. The faults that were used were as follows;

- Three phases to ground,
- Phase to phase to ground,
- Phase to ground and
- Phase to phase

The model that was created and used for this purpose was simple and some modelling values were unknown so assumed values were used. The model provided good output data however it should be mentioned that these results are limited by the accuracy and complexity of the model.

With this in mind it is recommended that the purchase and installation of Transient Monitor (disturbance recorder) for each unit is a good investment. This would allow CS Energy to capture generator and system data of system disturbances. This data would be analysed to see how the generator behaved during the disturbance. This would extremely useful to prove compliance to AEMO and also accuracy of the model. This would further demonstrate to AEMO that CS Energy are serious about their requirements and are taking necessary actions to ensure compliance.

With changes in parameters to this model, this process would be able to be used on each of CS Energy's generators to check the behaviour of the protection system and find the expected voltages at the generator terminals for large system faults. Callide B Units are due to get a new protection system installed in 2011 and it is planned to use the same process to test the new protection system. CS Energy would need to purchase the necessary software for this though.

8.3 Future Work

In the current state of this project it would be appropriate to start testing the behaviour of ancillary devices such as major motor drives, coal feeders' controllers at the expected low voltages that were found during this project. If they were to also remain stable and not trip and cause the unit to run back in load or even trip, CS Energy would be more confident in "fault ride through ability" of the Unit, not just the protection system.

Also the selection of what transient monitor to use and system and generator data to capture would be required as lead on work from this project.

REFERENCES

Alstom , 2000, Callide C PowerStation Generator Protection Panels - Protection Relay Setting Study, Alstom Protection and Control, Sydney.

Areva T&D, 2002, Network Protection and Automation Guide, Areva T&D, Paris

Australia Energy Market Operator 2010, Energy Markets, Australia Energy Market Operator, viewed 12 May 2010, <http://www.aemo.com.au/energymarkets.html#nem>

Australia Energy Regulator 2010, Australia Energy Regulator, Investigations, viewed 12 May 2010, <http://www.aer.gov.au/content/index.phtml/itemId/656186>

Barret, J.-P, Bornard, P & Meyer, B 1997, Power System Simulation, Chapman and Hall, London

Department of Mines and Energy 2010, National Electricity Market, Depart of Mines and Energy, Queensland Government, viewed 12 April 2010, <http://www.dme.qld.gov.au/Energy_national_electricity_market.cfm>

Energy Supply Association of Australia 2010, Factsheet, National Electricity Markets, viewed 12 April 2010, <http://www.esaa.com.au/images/stories/FactSheets/2009electricitymarkets.pdf>

IEEE Standard 1110-1991, IEEE guide for synchronous generator modelling practise in stability analysis 1991.

IEEE Standard 421.5-1992, IEEE recommended practise for excitation system models for power system stability studies 1992.

IEEE Standard C37.111-1999, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems 1999.

IEC Standard 60034-1 Ed. 12.0 (Bilingual 2010): IEC Standard for Rotating electrical machines - Part 1: Rating and performance 2010.

IEC Standard 60255-151 Ed. 1.0 (Bilingual 2009): IEC Standard for Measuring relays and protection equipment - Part 151: Functional requirements for over/under current protection 2009.

Grigsby, L 2007, Power System Stability and Control, Taylor & Francis, New York

Klempner G & Kerszenbaum, 2004, Operations and Maintenance of Large Turbo-Generators, Wiley & Sons, New Jersey

Mason C. R, 1967, The Art and Science of Protective Relaying, GE Consumer and Electrical series, Wiley, New York,

Mathworks 2010, SimPowerSystem 5.3 Product Overview, viewed 21 June 2010, <http://www.mathworks.com/products/simpower/>

Monash University, 1972, Article, "Power System in a black box", The Monash Review Publication, Monash University, viewed 16 April 2010, <http://www.adm.monash.edu.au/records-archives/assets/docs/pdf/monash-review/1972-17.pdf>

Power Technology 2010, Callide Coal Project, viewed 25 March 2010, <http://www.powertechnology.com/projects/callide-coal/>

TransÉnergie Technologies 2003, SimPowerSystem User Guide Version3, Canada, viewed 14 June 2010, <http://www.mathworks.de/help/releases/R13sp2/pdf_doc/physmod/powersys/powersys.pdf>

Transpower,2009, Generator Fault Ride Through (FRT) Investigation Stage 1 Literature review, Transpower New Zealand, viewed 25 March 2010, <http://www.electricitycommission.govt.nz/pdfs/opdev/comqual/windgen/ride-through/GEN-FRT-Stage1-Lit-review.pdf>

Appendix A Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **DAVID BRYAN MOWAT**

TOPIC: Callide C Power Stations Generator Protection System "ride through capabilities" for various external faults

SUPERVISOR: Dr Tony Ahfock

ENROLMENT: ENG4111 – S1 2010 EXT
ENG4112 – S2 2010 EXT

SPONSERSHIP: CS Energy

PROJECT AIM: This project aims to access the Callide C Generators "fault ride through" performance requirements by modelling of the Generator for large external faults and then testing the Generator protection system with the output from the model.

PROGRAMME:

1. Research background information of the National Electricity Rules relating to required ride through capabilities for Callide C Generators.
2. Research large coal fired power plant generator protection philosophies and schemes.
3. Research details of Callide C Generators and the existing protection scheme and settings for the protection relays.
4. Analyse performance of Callide C Generators for external faults by building a model of the Generator using simulink SimPowerSystems to check the Protection System.
5. Submit academic dissertation on the findings of the research.

As time permits

6. Compile research of Generator Protection into a form that accommodates training at an Associate diploma level.

AGREED: _______________ (student) Date: / / 2010

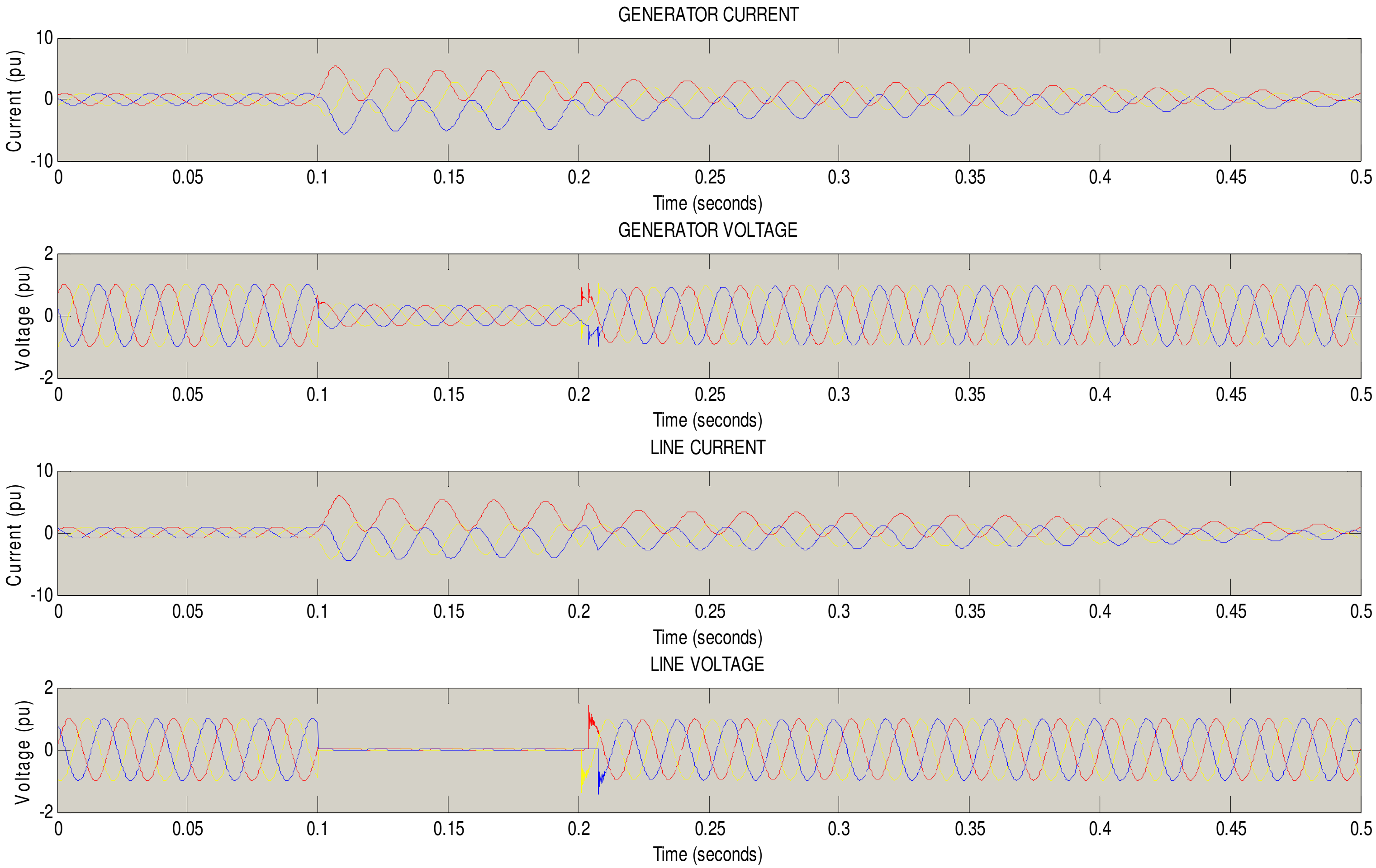
_______________ (supervisor) Date: / / 2010

Examiner/Co – examiner _________________

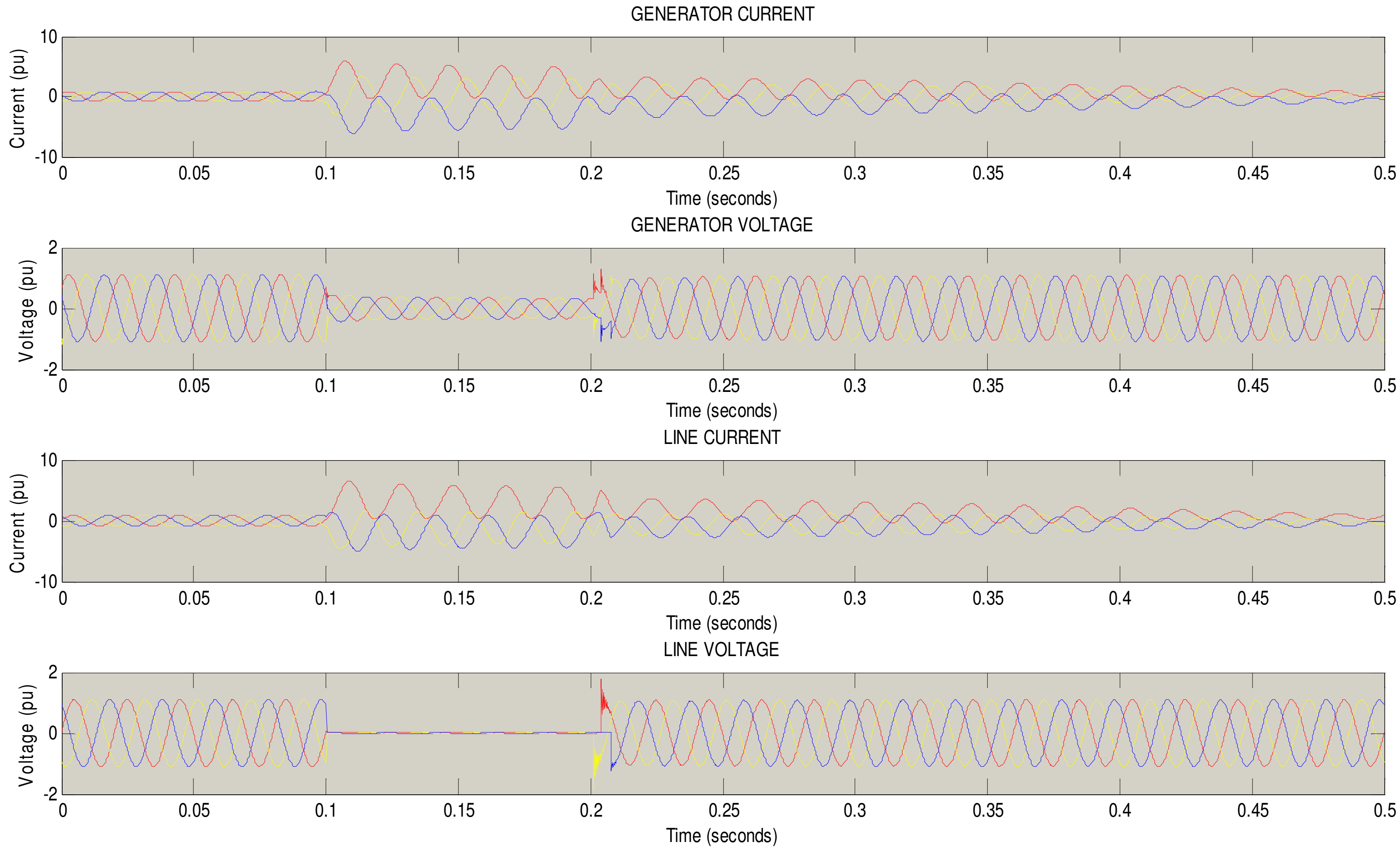
Appendix B Model Output Waveforms

Three Phase faults

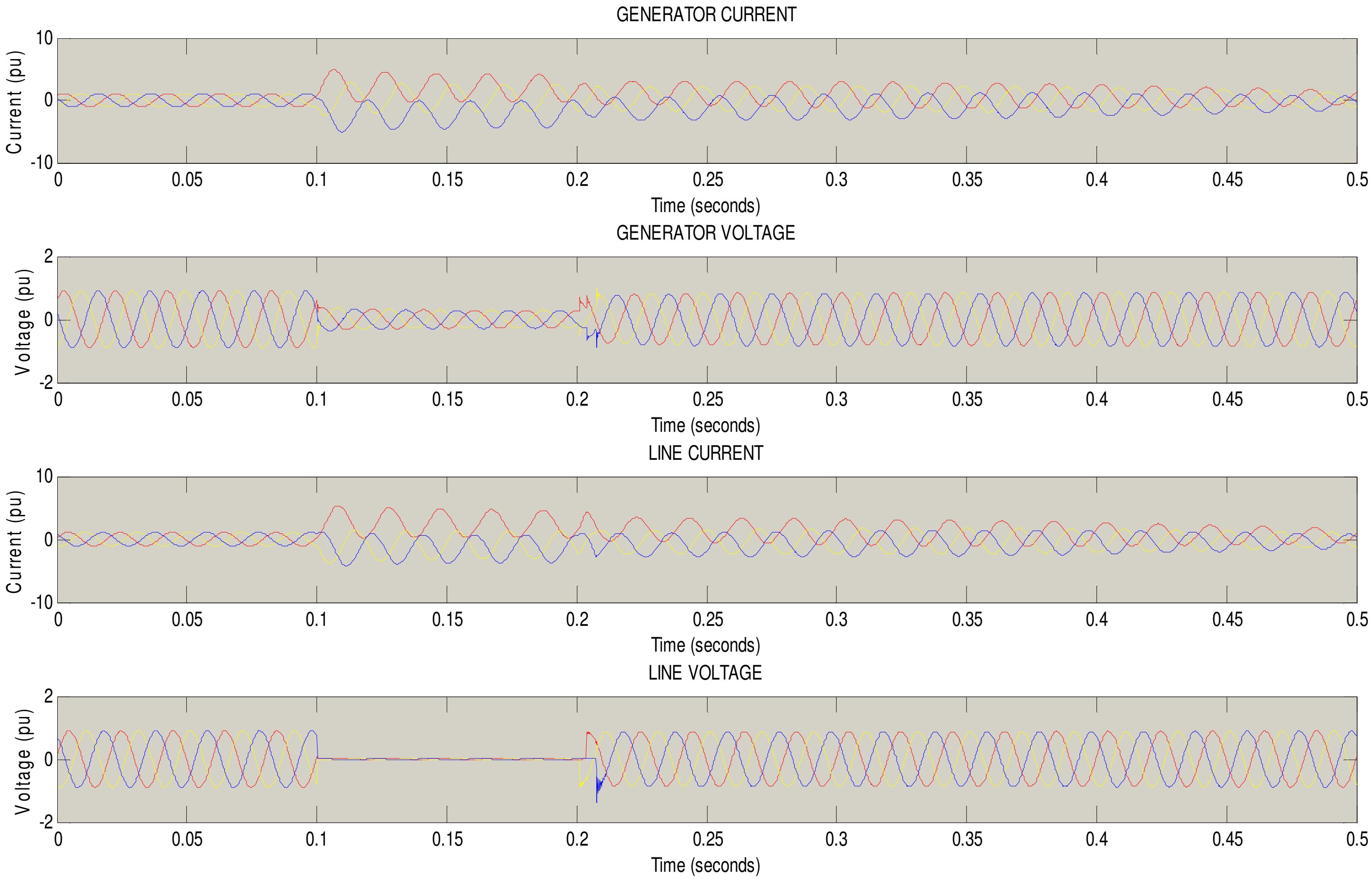
Fault 1 Prefault voltage = 1pu, fault duration = 100 milliseconds



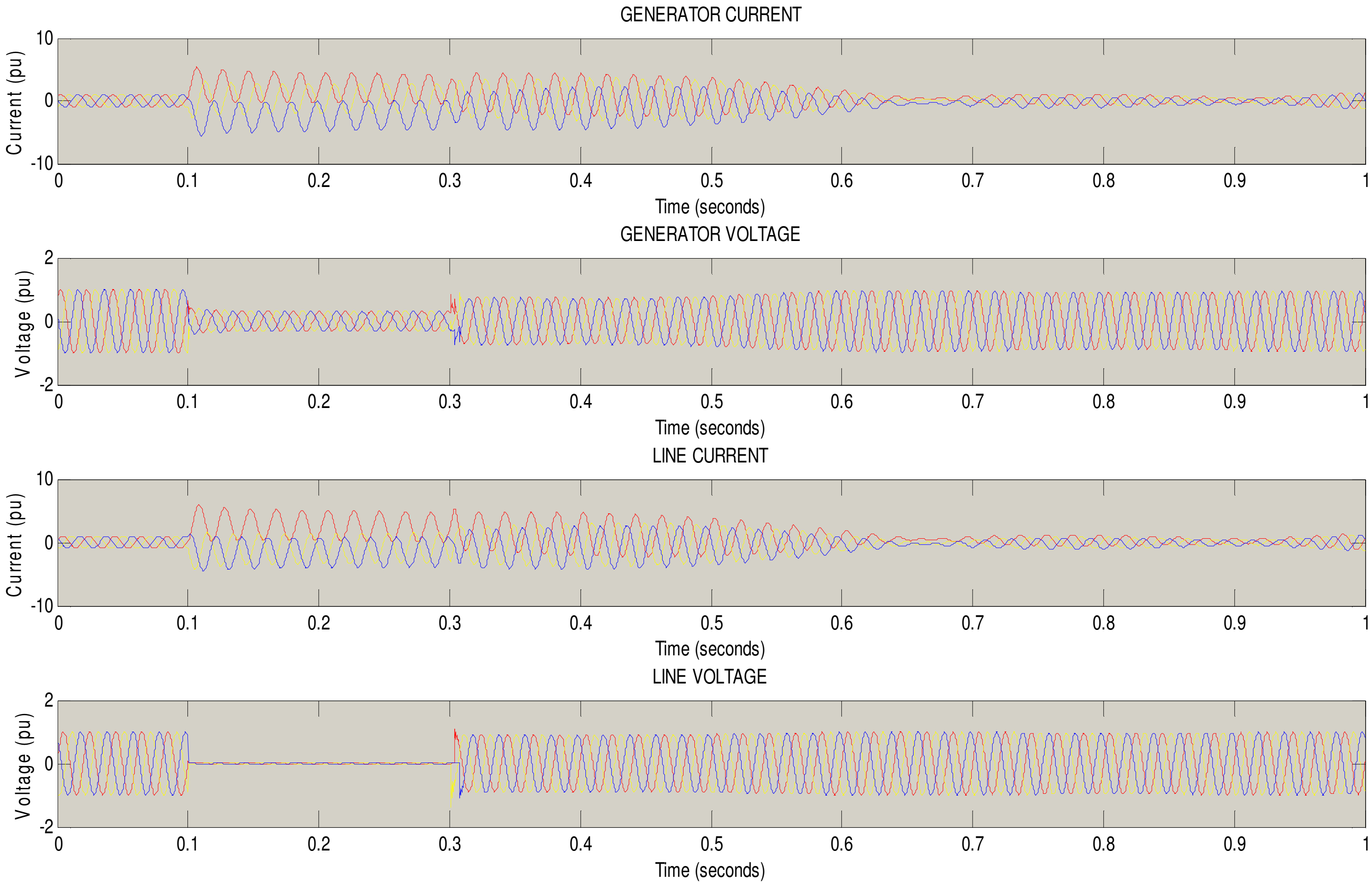
Fault 2 Prefault voltage = 1.1 pu, fault duration = 100 milliseconds



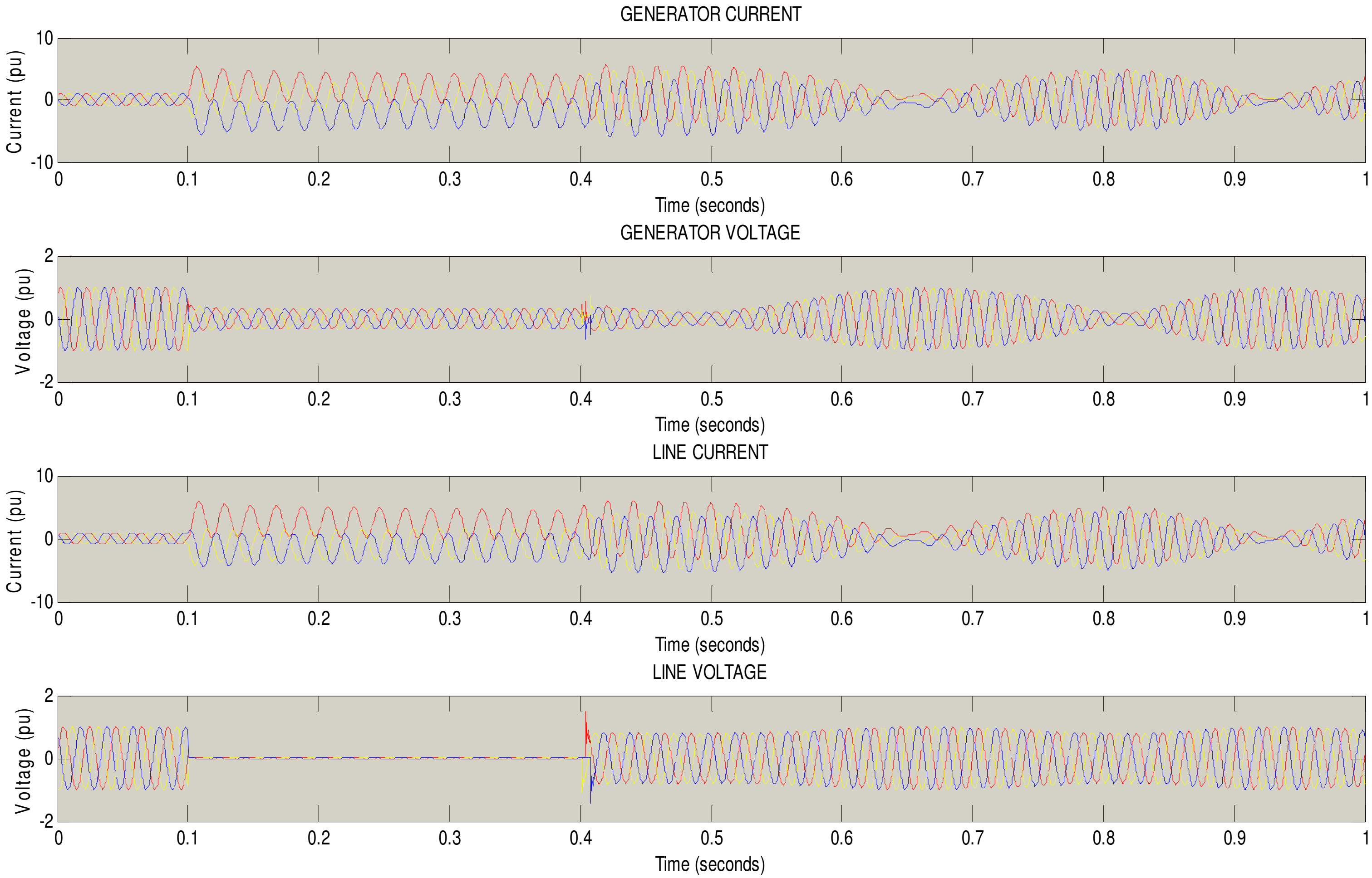
Fault 3 Prefault voltage = 0.9 pu, faul duration = 100 milliseconds



Fault 4 Prefault voltage = 1.0 pu, fault duration = 200 milliseconds

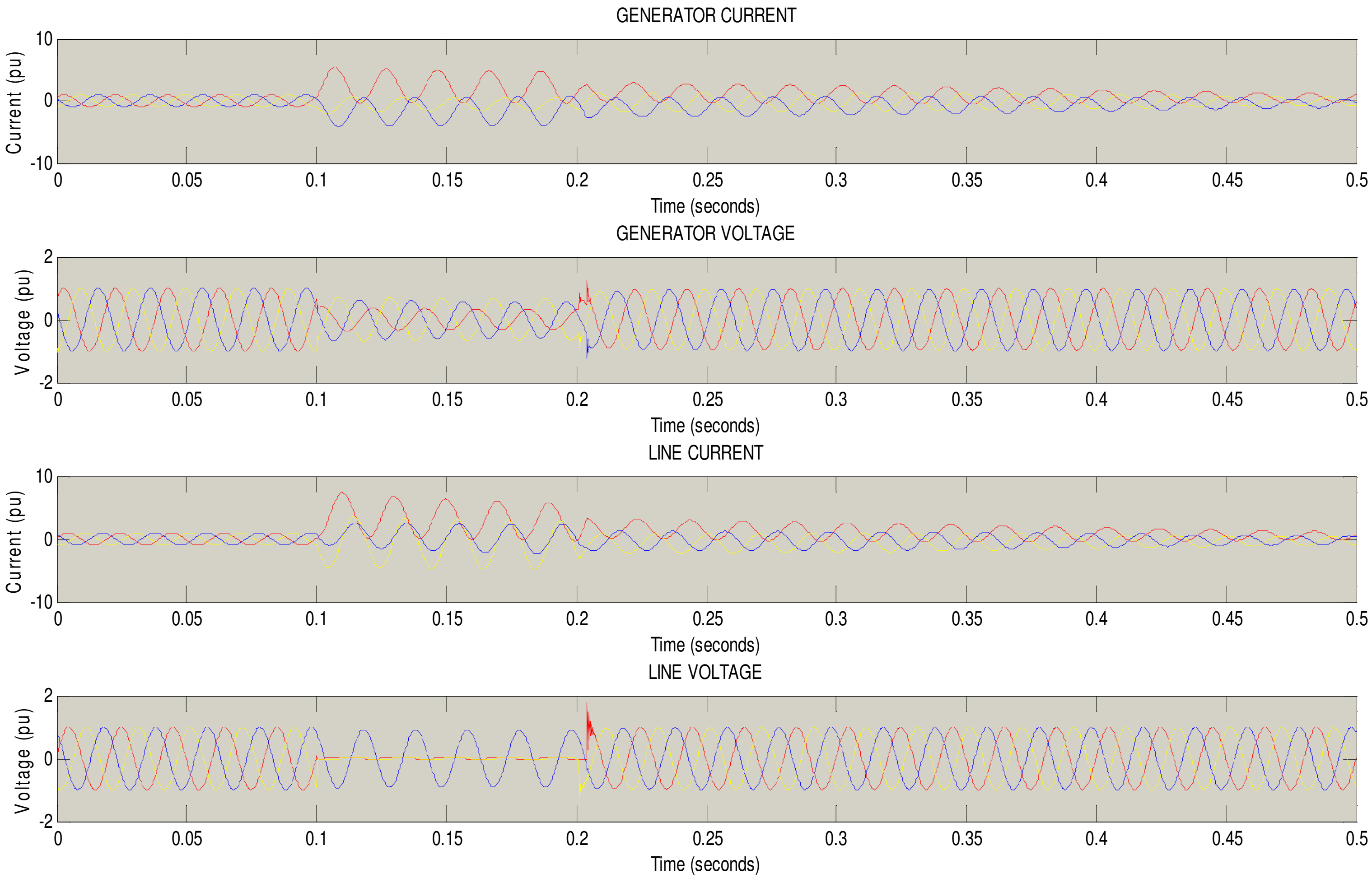


Fault 5 Prefault voltage = 1.0 pu, fault duration = 300 milliseconds

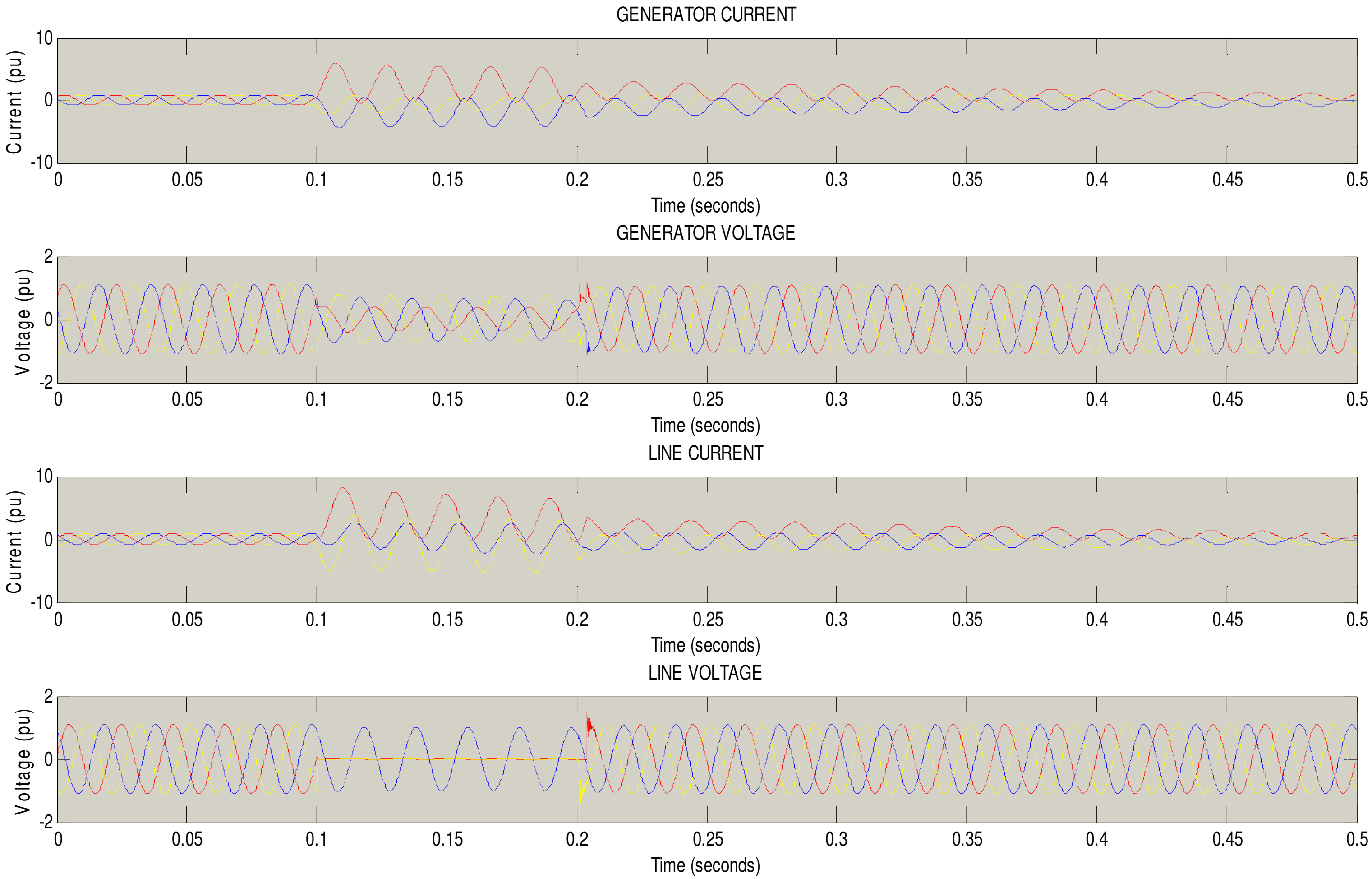


Line to line to ground Faults

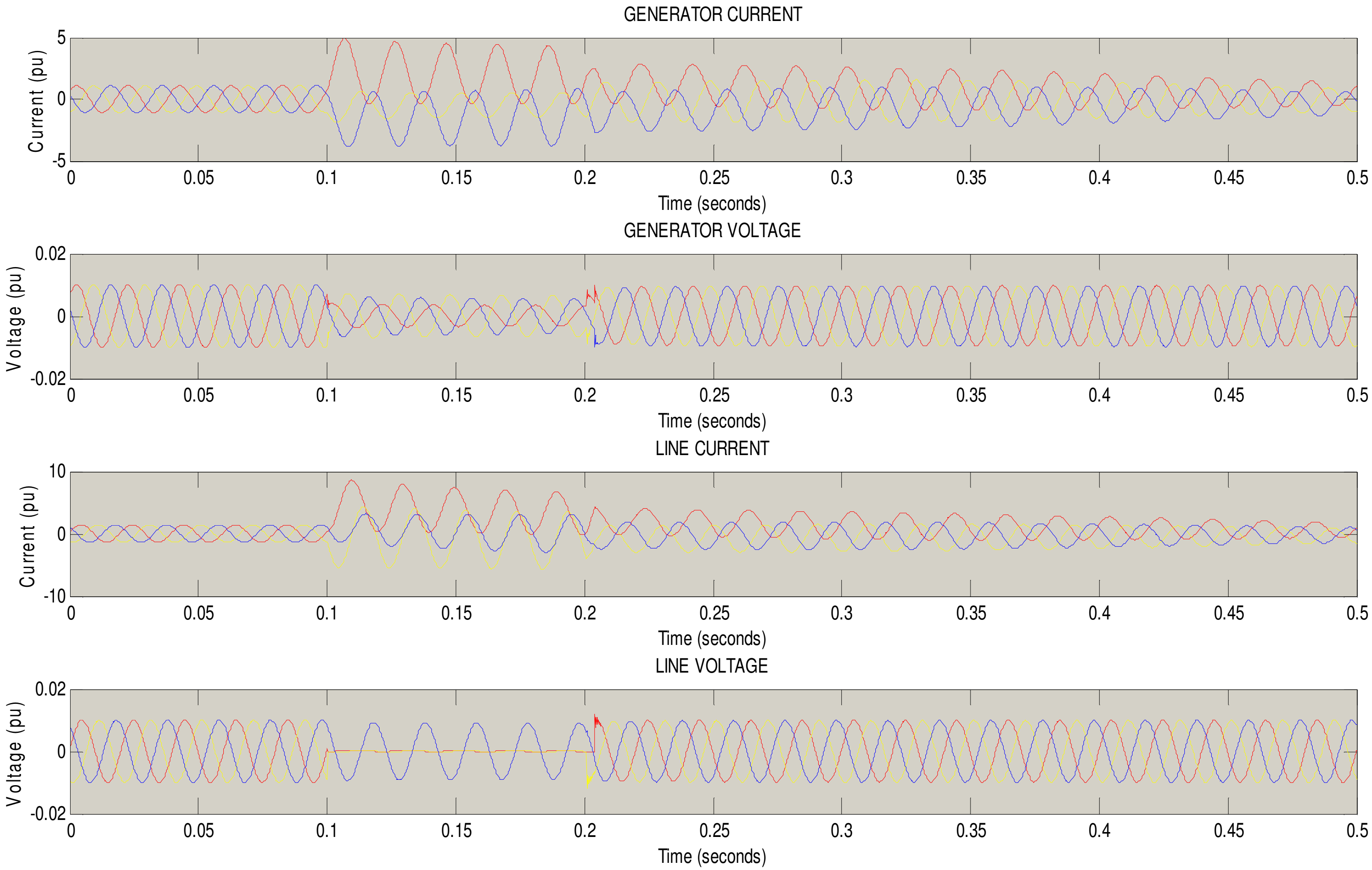
Fault 6 Prefault voltage = 1.0 pu, fault duration = 100 milliseconds



Fault 7 Prefault voltage = 1.1 pu, fault duration = 100 milliseconds

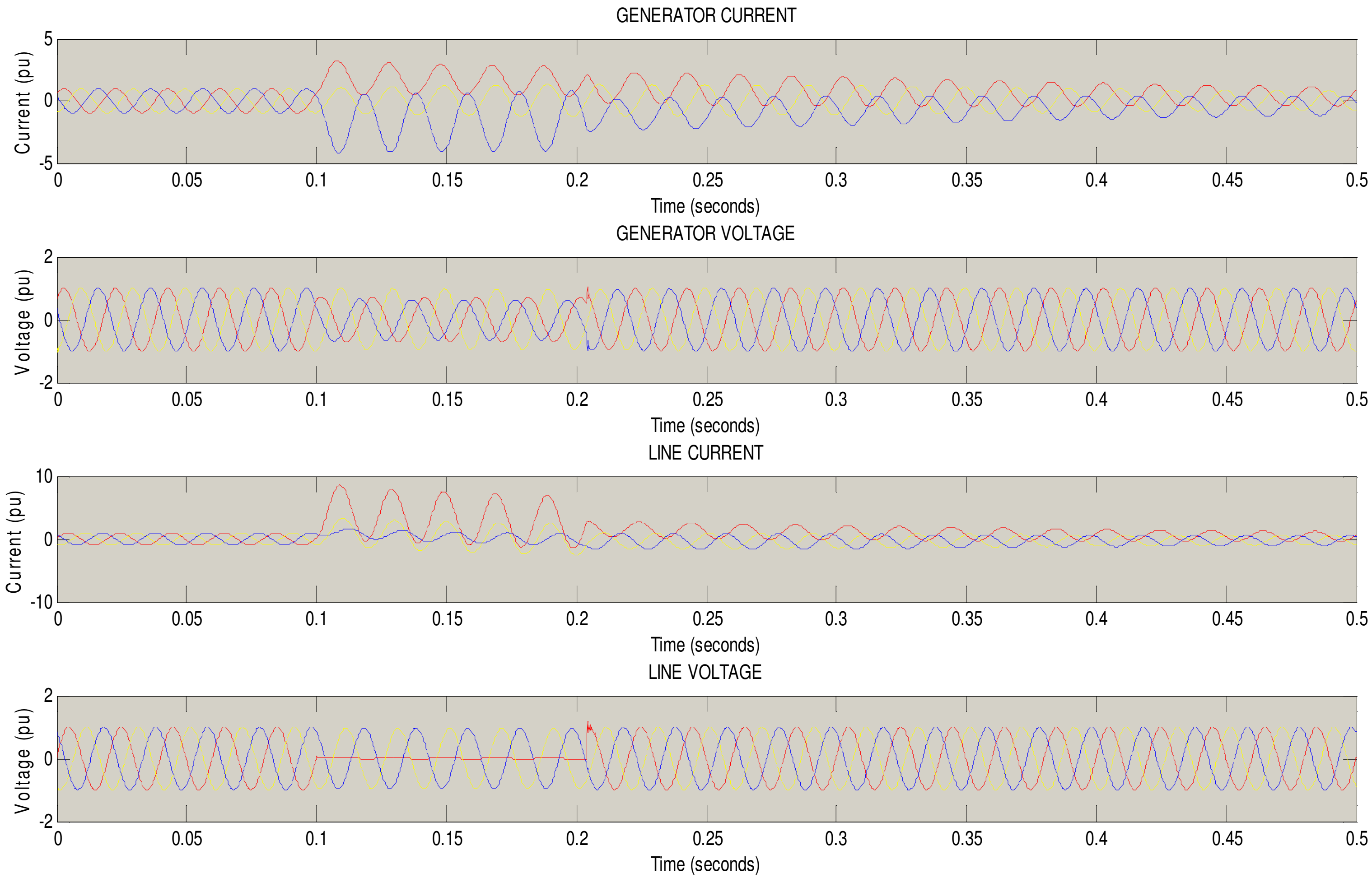


Fault 8 Prefault voltage = 0.9 pu, fault duration = 100 milliseconds

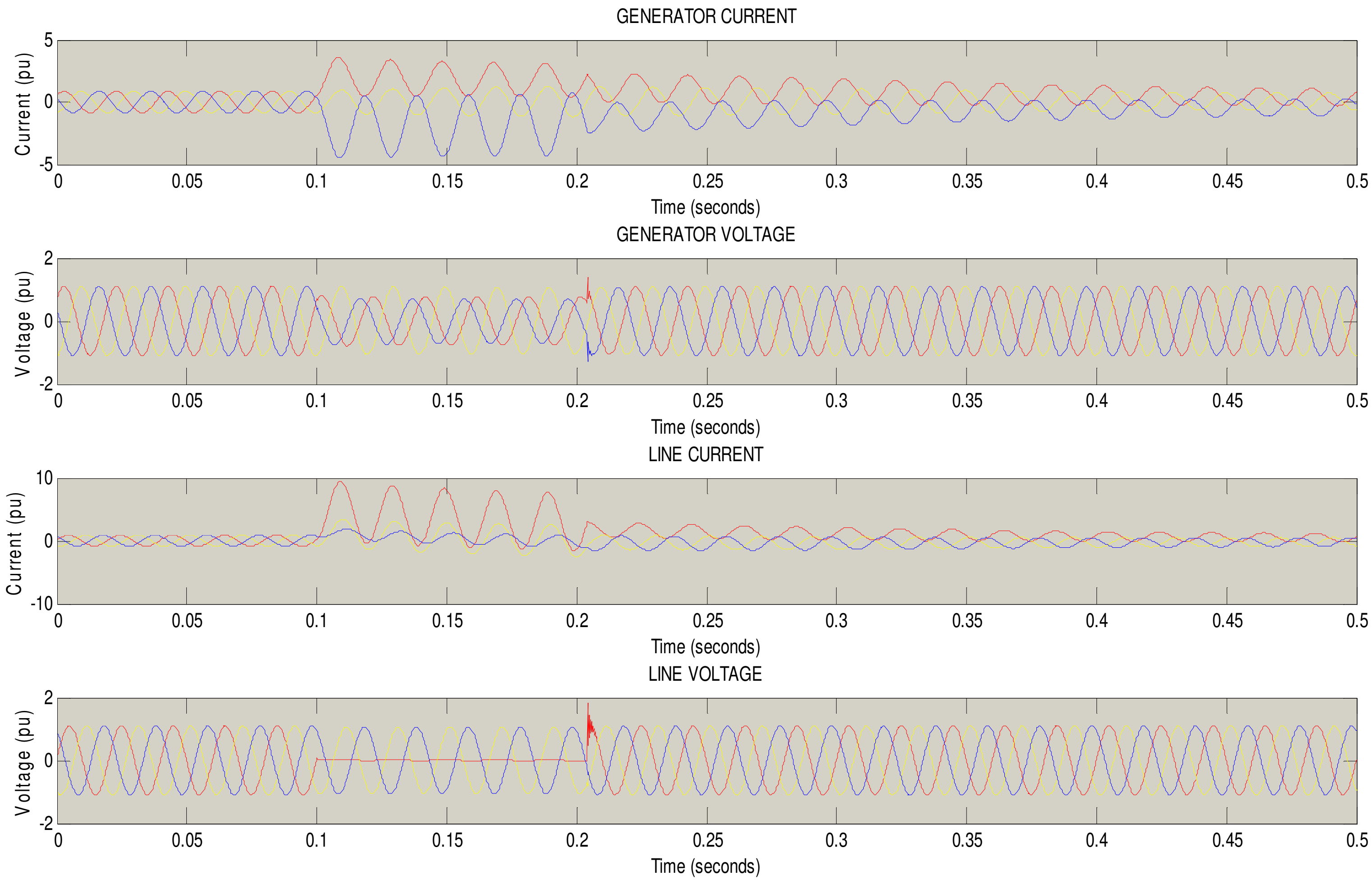


Line to ground Faults

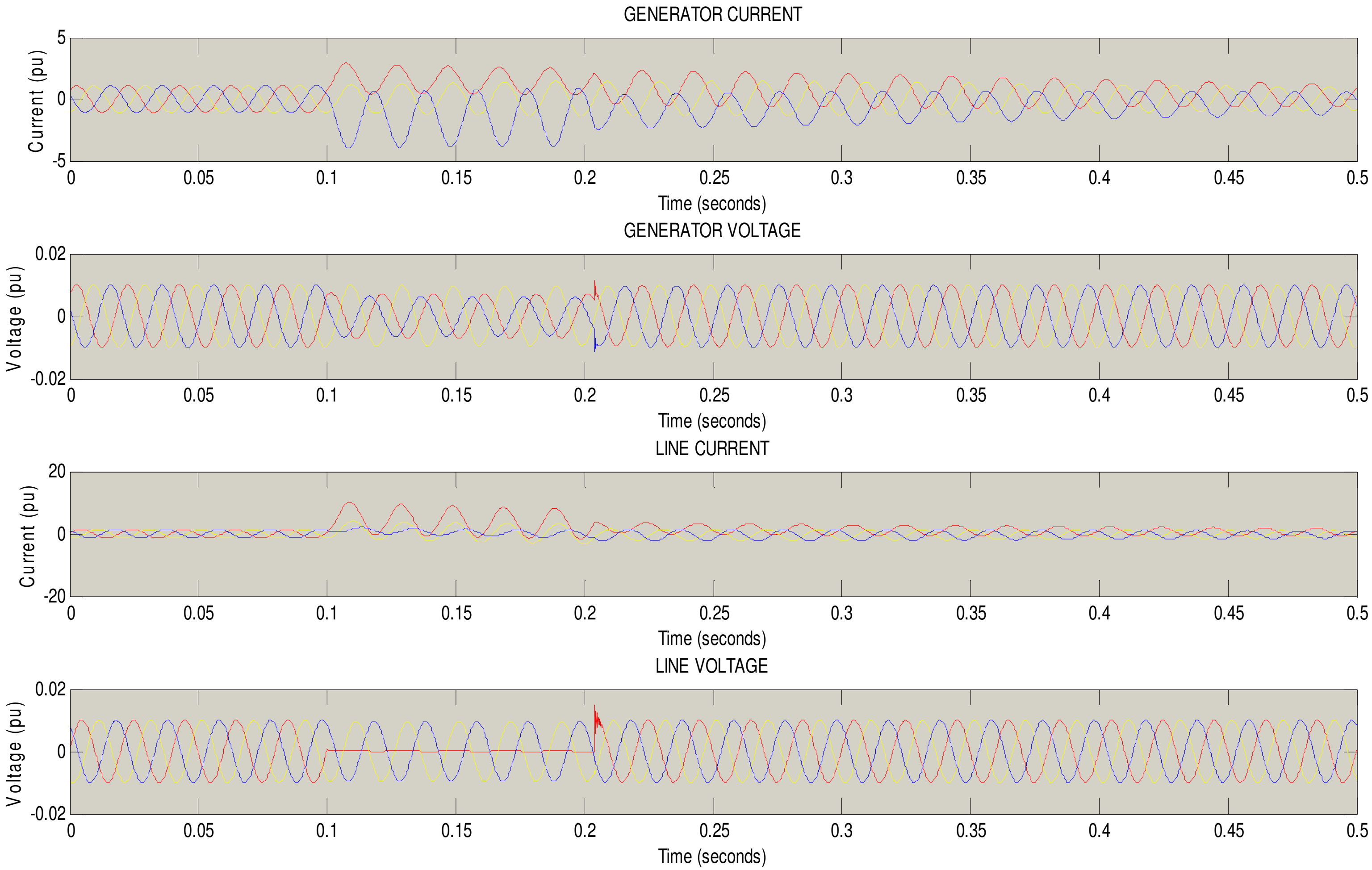
Fault 9 Prefault voltage = 1.0 pu, fault duration = 100 milliseconds



Fault 10 Prefault voltage = 1.1pu, fault duration = 100 milliseconds

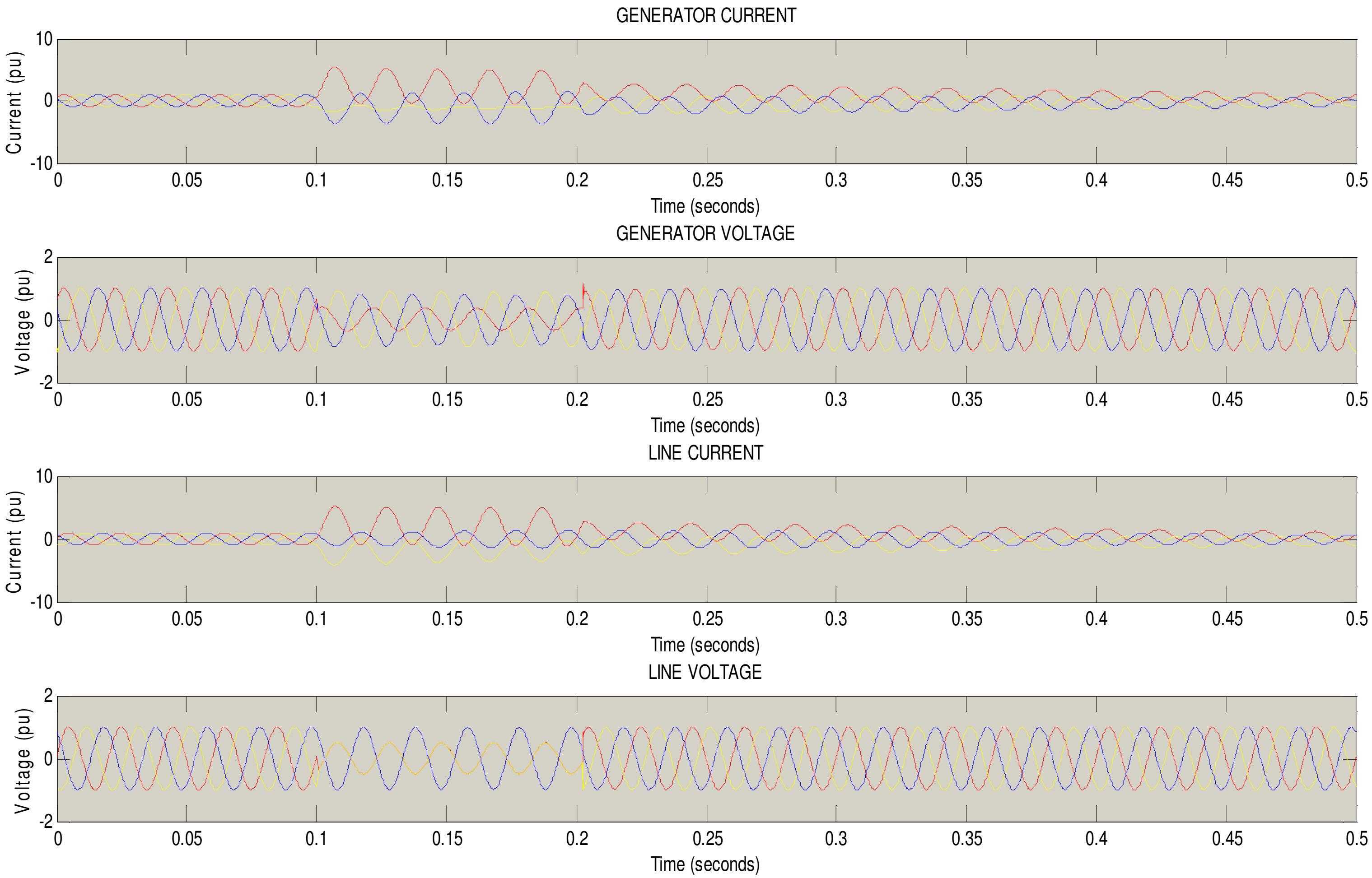


Fault 11 Prefault voltage = 0.9 pu, fault duration = 100 milliseconds

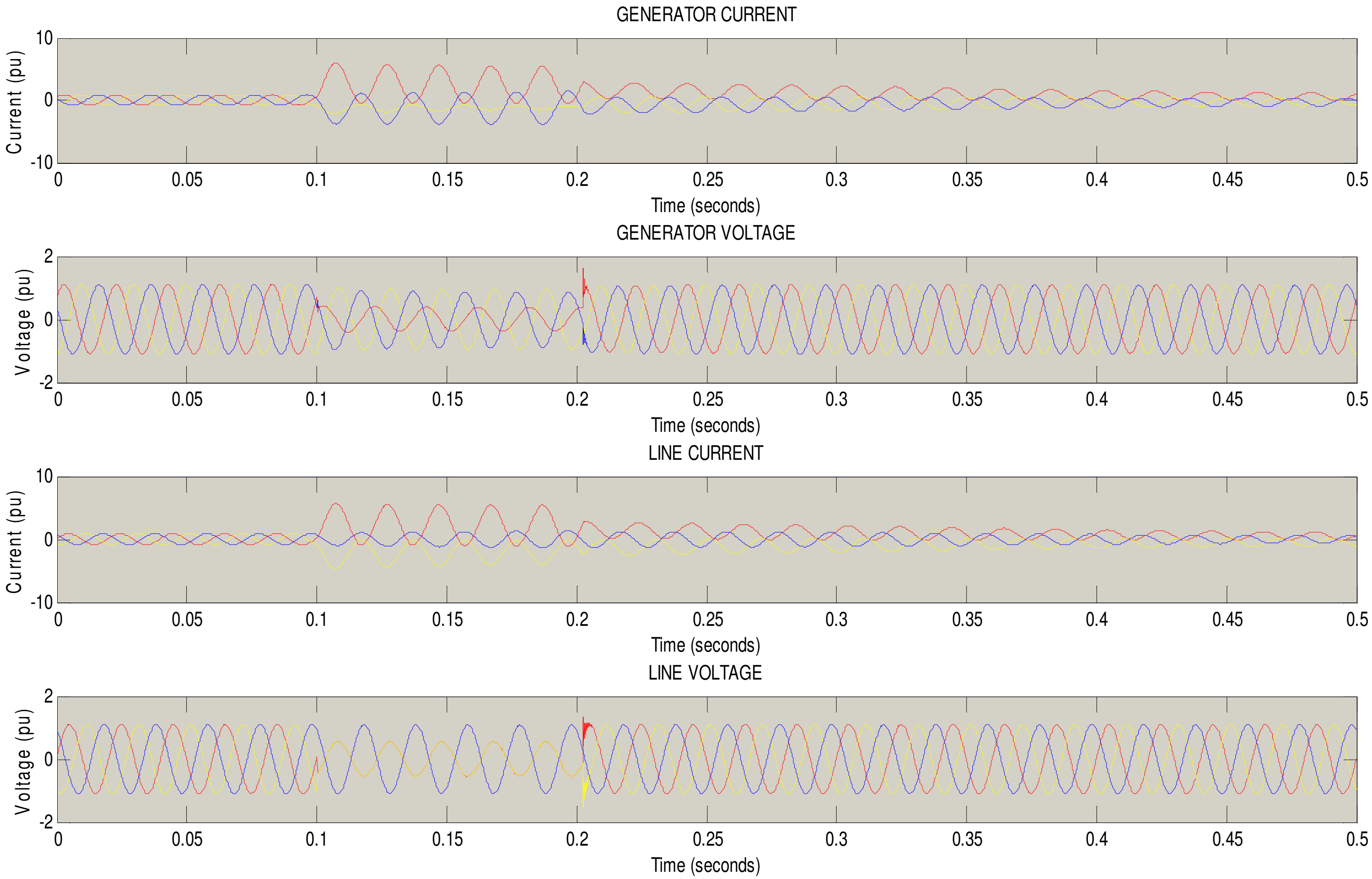


Line to line Faults

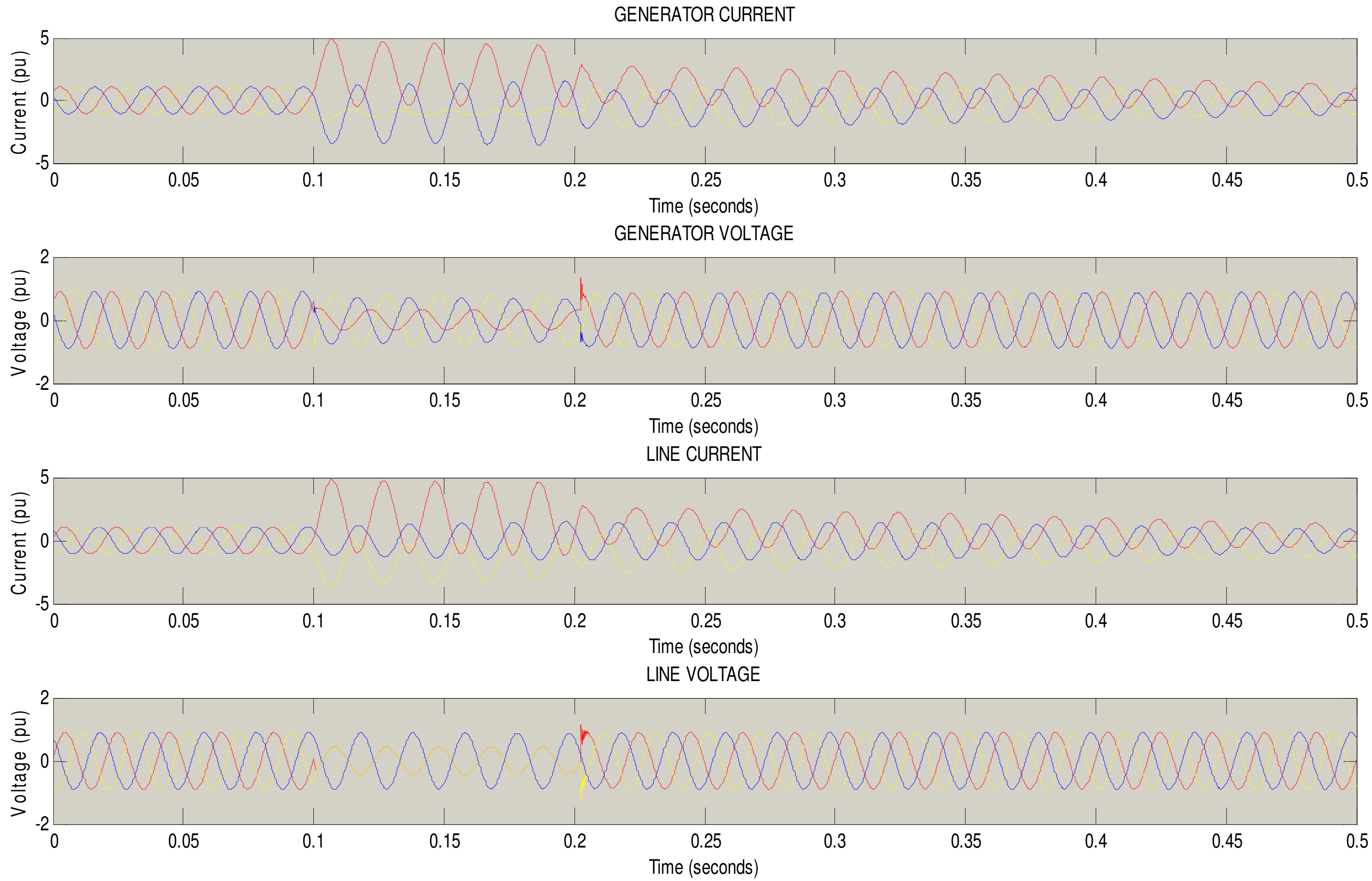
Fault 12 Prefault voltage = 1.0 pu, fault duration = 100 milliseconds



Fault 13 Prefault voltage = 1.1 pu, fault duration = 100 milliseconds



Fault 14 Prefault voltage = 0.9 pu, fault duration = 100 milliseconds



Appendix C Using Sample COMTRADE Writer

Open Excel Sample Comtrade writer – CFGinfo worksheet

Then Enter in the following variables

System frequency

Sampling rate

Number of analogue channels

Number of digital channels

Total number of samples in waveform

Channel names

Channel units

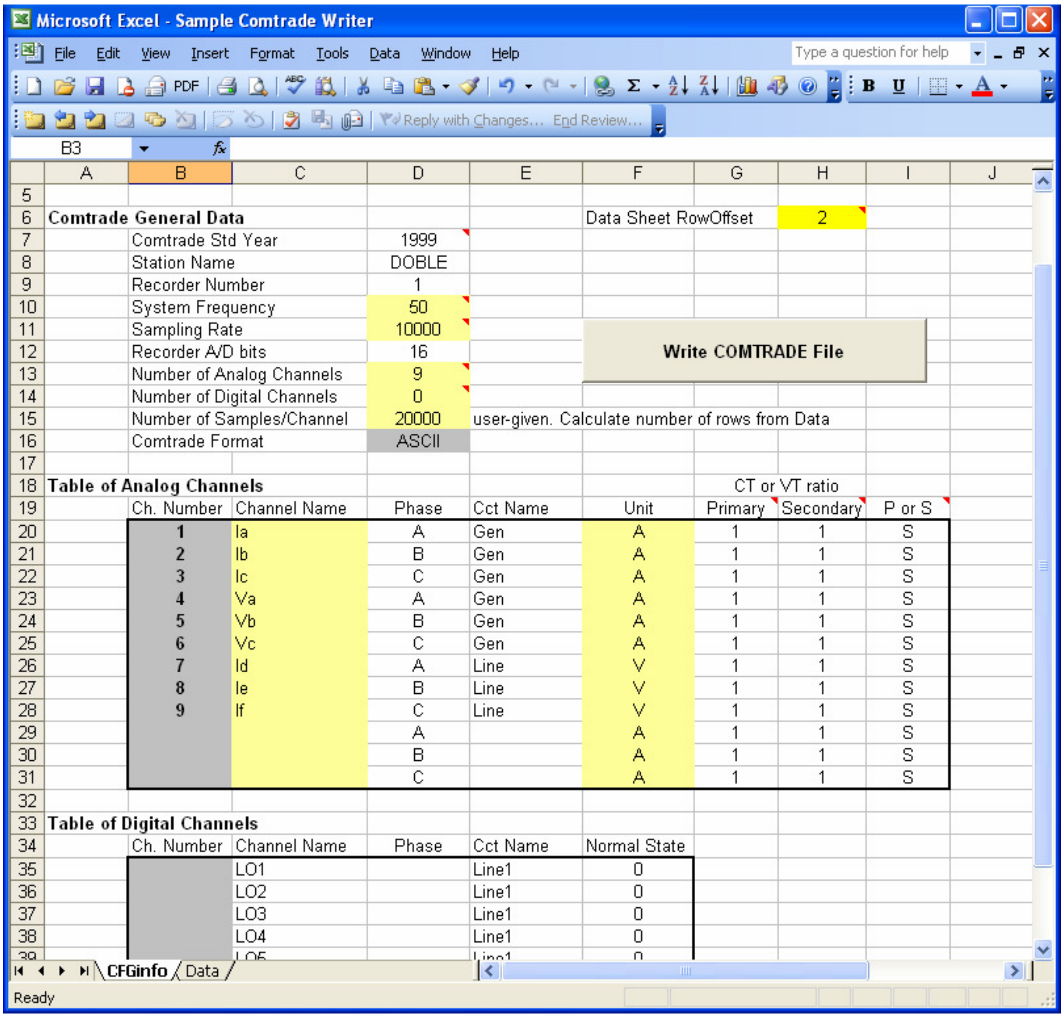
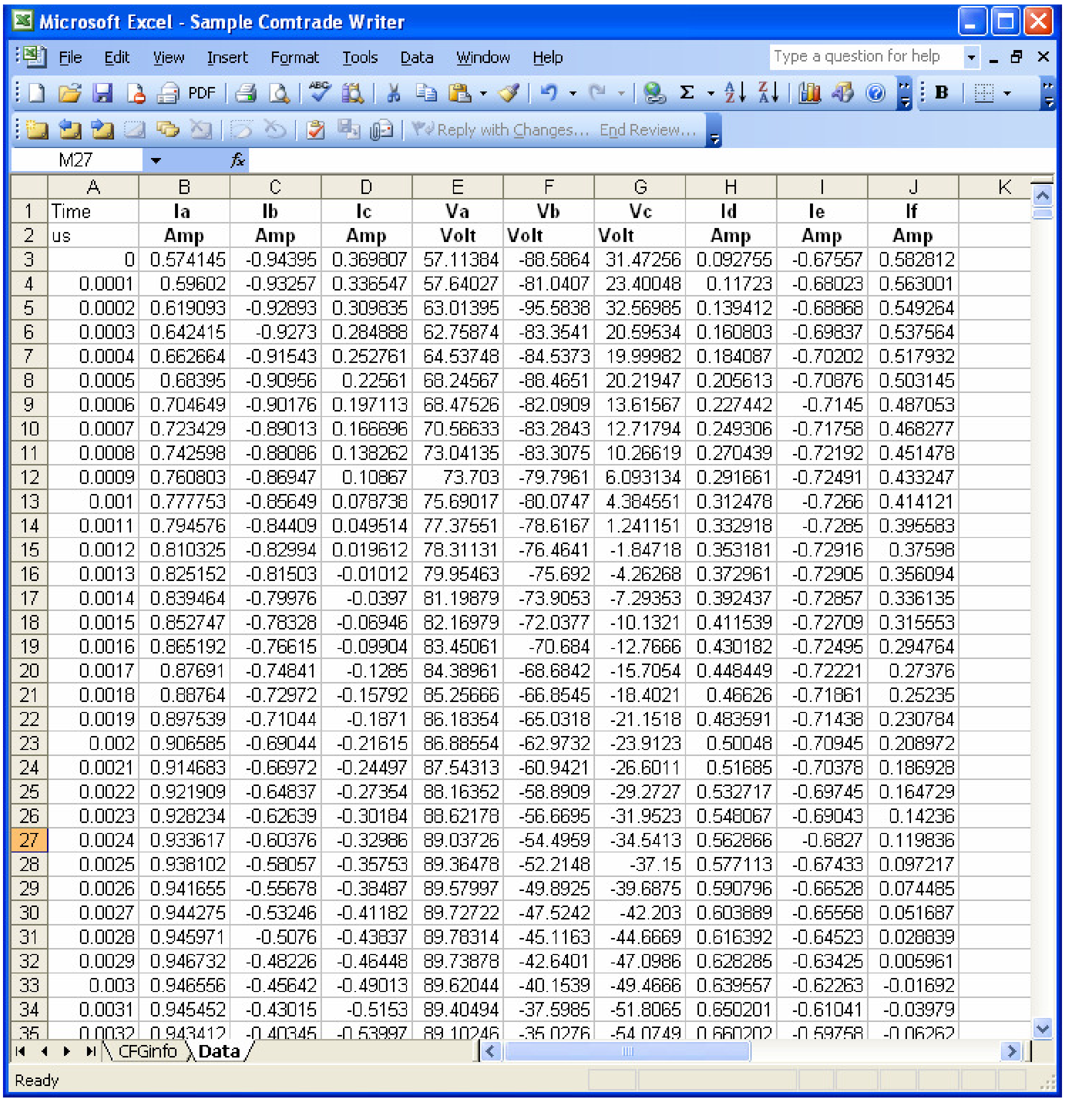


Figure C.1 CFG info Sheet of Sample COMTRADE Writer

Then select the ‘Data’ worksheet

Enter the time base values for each sample in micro seconds and the sample data for each of the required analogue and digital channels in the appropriate units.



	A	B	C	D	E	F	G	H	I	J	K
1	Time	Ia	Ib	Ic	Va	Vb	Vc	Id	Ie	If	
2	us	Amp	Amp	Amp	Volt	Volt	Volt	Amp	Amp	Amp	
3	0	0.574145	-0.94395	0.369807	57.11384	-88.5864	31.47256	0.092755	-0.67557	0.582812	
4	0.0001	0.59602	-0.93257	0.336547	57.64027	-81.0407	23.40048	0.11723	-0.68023	0.563001	
5	0.0002	0.619093	-0.92893	0.309835	63.01395	-95.5838	32.56985	0.139412	-0.68868	0.549264	
6	0.0003	0.642415	-0.9273	0.284888	62.75874	-83.3541	20.59534	0.160803	-0.69837	0.537564	
7	0.0004	0.662664	-0.91543	0.252761	64.53748	-84.5373	19.99982	0.184087	-0.70202	0.517932	
8	0.0005	0.68395	-0.90956	0.22561	68.24567	-88.4651	20.21947	0.205613	-0.70876	0.503145	
9	0.0006	0.704649	-0.90176	0.197113	68.47526	-82.0909	13.61567	0.227442	-0.7145	0.487053	
10	0.0007	0.723429	-0.89013	0.166696	70.56633	-83.2843	12.71794	0.249306	-0.71758	0.468277	
11	0.0008	0.742598	-0.88086	0.138262	73.04135	-83.3075	10.26619	0.270439	-0.72192	0.451478	
12	0.0009	0.760803	-0.86947	0.10867	73.703	-79.7961	6.093134	0.291661	-0.72491	0.433247	
13	0.001	0.777753	-0.85649	0.078738	75.69017	-80.0747	4.384551	0.312478	-0.7266	0.414121	
14	0.0011	0.794576	-0.84409	0.049514	77.37551	-78.6167	1.241151	0.332918	-0.7285	0.395583	
15	0.0012	0.810325	-0.82994	0.019612	78.31131	-76.4641	-1.84718	0.353181	-0.72916	0.37598	
16	0.0013	0.825152	-0.81503	-0.01012	79.95463	-75.692	-4.26268	0.372961	-0.72905	0.356094	
17	0.0014	0.839464	-0.79976	-0.0397	81.19879	-73.9053	-7.29353	0.392437	-0.72857	0.336135	
18	0.0015	0.852747	-0.78328	-0.06946	82.16979	-72.0377	-10.1321	0.411539	-0.72709	0.315553	
19	0.0016	0.865192	-0.76615	-0.09904	83.45061	-70.684	-12.7666	0.430182	-0.72495	0.294764	
20	0.0017	0.87691	-0.74841	-0.1285	84.38961	-68.6842	-15.7054	0.448449	-0.72221	0.27376	
21	0.0018	0.88764	-0.72972	-0.15792	85.25666	-66.8545	-18.4021	0.46626	-0.71861	0.25235	
22	0.0019	0.897539	-0.71044	-0.1871	86.18354	-65.0318	-21.1518	0.483591	-0.71438	0.230784	
23	0.002	0.906585	-0.69044	-0.21615	86.88554	-62.9732	-23.9123	0.50048	-0.70945	0.208972	
24	0.0021	0.914683	-0.66972	-0.24497	87.54313	-60.9421	-26.6011	0.51685	-0.70378	0.186928	
25	0.0022	0.921909	-0.64837	-0.27354	88.16352	-58.8909	-29.2727	0.532717	-0.69745	0.164729	
26	0.0023	0.928234	-0.62639	-0.30184	88.62178	-56.6695	-31.9523	0.548067	-0.69043	0.14236	
27	0.0024	0.933617	-0.60376	-0.32986	89.03726	-54.4959	-34.5413	0.562866	-0.6827	0.119836	
28	0.0025	0.938102	-0.58057	-0.35753	89.36478	-52.2148	-37.15	0.577113	-0.67433	0.097217	
29	0.0026	0.941655	-0.55678	-0.38487	89.57997	-49.8925	-39.6875	0.590796	-0.66528	0.074485	
30	0.0027	0.944275	-0.53246	-0.41182	89.72722	-47.5242	-42.203	0.603889	-0.65558	0.051687	
31	0.0028	0.945971	-0.5076	-0.43837	89.78314	-45.1163	-44.6669	0.616392	-0.64523	0.028839	
32	0.0029	0.946732	-0.48226	-0.46448	89.73878	-42.6401	-47.0986	0.628285	-0.63425	0.005961	
33	0.003	0.946556	-0.45642	-0.49013	89.62044	-40.1539	-49.4666	0.639557	-0.62263	-0.01692	
34	0.0031	0.945452	-0.43015	-0.5153	89.40494	-37.5985	-51.8065	0.650201	-0.61041	-0.03979	
35	0.0032	0.943412	-0.40345	-0.53997	89.10246	-35.0276	-54.0749	0.660202	-0.59758	-0.06262	

Figure C.2 **Data sheet of Sample Comtrade Writer**

On the CFG info worksheet, select the button to ‘Write COMTRADE file’, then browse to the file directory you want to save the files to, enter the file name and select save to create and save the COMTRADE records.

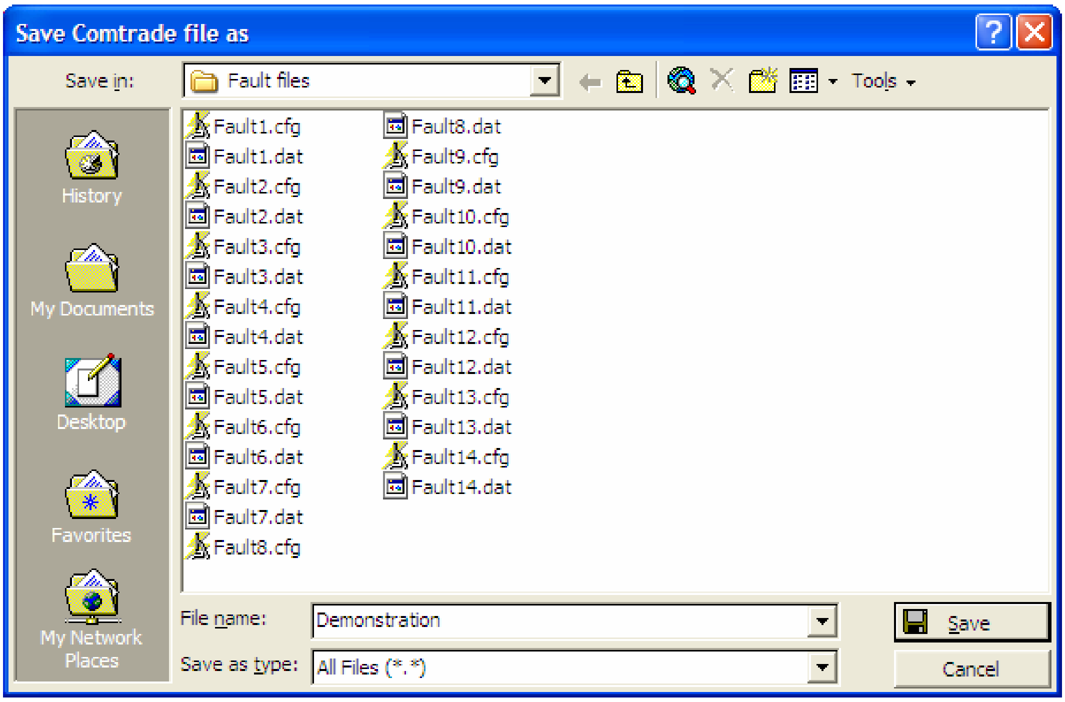


Figure C.3 Fault File Directory Before Save

Two files will be added to the directory.

.cfg is the COMTRADE configuration file

.dat is the COMTRADE data file.

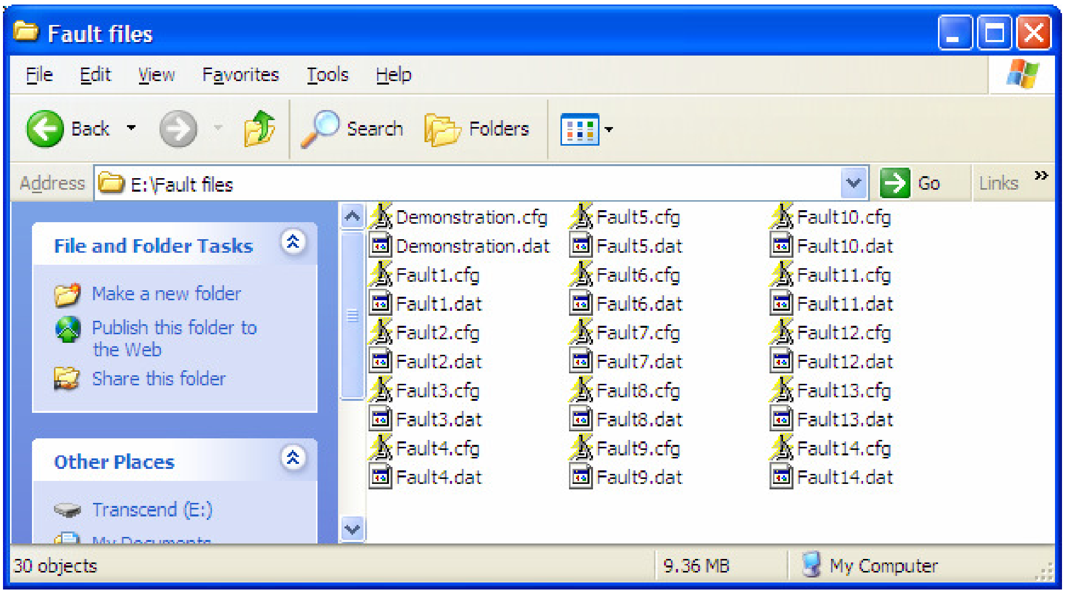


Figure C.4 Fault File Directory After Save

Appendix D Matlab Plot Script

```
%PLOTSCPRIT.M
%
%Written By David Mowat for ELE4112 RESEARCH PROJECT
%
%This script does the scaling and plotting of the output data of the model
%The data was presented by the model in the array called "params" this data
%was in secondary peak values ready for preparing the COMTRADE files
%this is why scaling was necessary.
%
%Date   2/7/2010

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                   Scaling of the Data                                     %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Scalling generator current in PU
params(:,2:4)=params(:,2:4)*19000/(13323.5*sqrt(2));
%Scalling generator voltage in PU
params(:,5:7)=params(:,5:7)./89.81;
%Scalling line current in PU
params(:,8:10)=params(:,8:10)*1600/(866.025*sqrt(2));
%Scalling line voltage in PU
params(:,11:13)=params(:,11:13)./89.81;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                  Plotting of the Data                                     %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%create subplot and plot the data for generator current
subplot(4,1,1)
plot(params(:,1),params(:,2),'r',params(:,1),params(:,3),'y',params(:,1),...
    params(:,4),'b')
title('GENERATOR CURRENT')
xlabel('Time (seconds)')
ylabel('Current (pu)')

%create subplot and plot the data for generator voltage
subplot(4,1,2)
plot(params(:,1),params(:,5),'r',params(:,1),params(:,6),'y',params(:,1),...
    params(:,7),'b')
title('GENERATOR VOLTAGE')
xlabel('Time (seconds)')
ylabel('Voltage (pu)')

%create subplot and plot the data for line current
subplot(4,1,3)
plot(params(:,1),params(:,8),'r',params(:,1),params(:,9),'y',params(:,1),...
    params(:,10),'b')
title('LINE CURRENT')
xlabel('Time (seconds)')
ylabel('Current (pu)')

%create subplot and plot the data for line voltage
subplot(4,1,4)
plot(params(:,1),params(:,11),'r',params(:,1),params(:,12),'y',params(:,1),...
    params(:,13),'b')
title('LINE VOLTAGE')
xlabel('Time (seconds)')
ylabel('Voltage (pu)')

% Now change background to grey
set(gcf,'Color',[0.83 0.82 0.78])

%EOF
```