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PMU-Assisted Local Optimization of the Coordination between Protective Systems and Reactive Power Compensation Devices

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Abstract

With increasing population, expansion of cities, raise in the number of large industries and the need for the development of societies, there is a steady increase in the demand of electric power resulting in issues with power system stability. This is reflected by the fact that, in several instances, a single equipment failure, mal-operation of the protection relay or operator's error, can lead the power system to a cascading failure and eventually to collapse.

It is indeed a necessity to verify the operation of the power system under all critical operating conditions and to confirm the coordination of various power system equipments with each other before they are commissioned in the real world. It is perhaps not possible to design a real power system just for experimental purposes so that one can apply different faults in the network and analyze the behavior of the system to propose a new refined and effective solution that guarantees the safe opearation of system. The most efficient way of carrying out such detailed and complex analysis is with the help of Real-Time Simulators.

Power system operators have already adopted synchrophasor data from phasor measurement units (PMUs) for real-time monitoring and control of power systems. The well-established standard (IEEE C37.118), the utilization of phasor measurements to improve power system reliability and frequent advancement in technology is paving the way to use synchrophasor data for not only monitoring and visualizing, but also to have a reliable and economical operation of power systems.

In this thesis an "All-in-One" system is modeled in SimPowerSystems (MATLAB/Simulink) and simulated in real-time using Opal-RT real time Simulator to investigate long term voltage instability scenarios. This proposed "All-in-One" power system model allows the analysis of the transient, voltage and frequency instabilities by implementing different faults and different generation and load scenarios. The time at which voltage instability is introduced and the system collapses is analyzed along with the impact of voltage instability on all the power system components present in the "All-in-One" test system. Later, an overcurrent relay is modeled and verified for different characteristic curves (standard inverse, long inverse and very inverse). This model of overcurrent relay is then implemented in all-in-one system at strategic locations and is coordinated to mitigate voltage collapse. Two different protection schemes are proposed to provide complete protection for the all-in-one system. In the next step, reactive power compensation devices are modeled and implemented in the all-in-one system to provide reactive power compensation for a system subject to voltage instability. Finally the coordination of overall system is carried out to optimize the performance of the power system in case of voltage instability and to ensure reliable and efficient supply of electrical power to the consumer end (load). This is achieved by using phasors from synchronized phasor measurement units to determine the most recent values of positive sequence voltages and currents in several critical components. Using this knowledge in conjunction with information from protective relays, alows for a local optimization on the system's response.

Acknowledgements

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Contents

Notation

ABB	Asea Brown Boveri
AC	Alternating Current
CT	Current Transformer
DC	Direct Current
FACTS	Flexible AC Transmission System
GE	General Electric
GUI	Graphical User Interface
HVDC	High Voltage Direct Current
OLTC	On Load Tap Changer
PMU	Phasor Measurement Unit
RAS	Remedial Action Scheme
SEL	Schweitzer Engineering Laboratories
SIPS	System Integrity Protection Schemes
SPS	SimPowerSystems
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TCSC	Thyristor Controller Series Capacitor
VT	Voltage Transformer

Chapter 1: Introduction

1.1. Background

With the ever-increasing raise in electricity demand across the globe and the continued dependence on electricity supply for all socio-economic activities in society, power systems all over the world continue to be interconnected into large-scale networks. This increases the capability of power grids to transfer power over the long distance to serve the desired power demand while decreasing the cost of operation. Unfortunately, it also enables the propagation of local failures into a wider scale. One of the most common ways in which blackouts become widespread is cascading failures. This type of failure originates after a critical component of the system has been removed from service, in many cases, damage to specific equipment and personnel is limited by the operation of protective relays [1]. As a consequence, the consumed, transmitted, or generated power related to the removed component needs to be redistributed across the network, a phenomenon that may cause an overload in other components of the system. To mitigate these phenomena, reactive power support is usually required. This can be in the form of switching capacitors, Static VAR Compensators (SVCs), Static Synchronous Compensators (STATCOMs) or Voltage Source Converters-based High Voltage Direct Current (VSC-HVDC) systems that have the ability to independently control reactive power, and maintain voltage to be at acceptable level [2]. Therefore, they are considered as flexible devices that, with an appropriately designed control algorithm, can substantially improve the performance and reliability of the power system.

In order to relief stressed conditions in aftermath of a contingency or large disturbance, protective systems and these reactive power compensation devices need to be coordinated to steer the system away from dangerous operating conditions. The concept of wide area protection may be taken into the consideration for establishing a decent coordination. This concept uses system-wide measurements and selected local information which is sent to a centralized location which may be able to design actions to counteract propagation of major disturbances in the power system [3]. The concept of coordination involves the use of feasible communication mechanisms which can be exploited by protective systems to send out their status and other data (a "protective information set" see below) to an algorithm which will determine preventive, corrective, and protective actions particularly by taking advantage of the availability of reactive power compensation devices in the network. The communication mechanisms used by state-of the- art protective systems is documented in [4].

This "protective information set" may include and is not limited to: status of the protective devices (stand-by or other), voltage and current phasor measurements, alarms when a limit has been reached. A PMU-data-assisted local optimization of the coordination between protective systems and the controllers of reactive power compensators will use this protective information set with an algorithm to optimize the system performance locally. A "protective information set" can be comprised of pick up current limits (or other) and the current value, the remaining time left for tripping (or protective device countdown), and other information available (depending of the protective devices). Although some of these functions are not enabled on today's protective relays, it is possible to speculate that these desired functionalities could be achieved with the microprocessors and other hardware used in today's protective relays, moreover, there does exist one manufacturer on the market (Schweitzer Engineering Laboratories) that provides a synchrophasor vector processing capability which allows for the transmission of phasor measurements and other protective data [5] satisfying protective relaying data transmission and processing requirements (such as end-to-end latency, etc.). It has been proven in [6] that the information obtained from protection systems can be used for implementing wide-area monitoring and control algorithms. The results in [6] have also been validated in a Real Time Digital Simulator, the use of this technology helps in bringing confidence to possible coordination algorithms that can be devised for mitigating the effect of contingencies leading to cascading failures.

1.2. Objectives

1.2.1. General Objectives

The ultimate purpose of this study is to develop a technique capable of optimizing the coordination between protective systems and reactive power compensation devices by exploiting synchronized phasor measurements and other information available from protective devices (the so-called "protective information set"). In this context coordination refers to the ability of the protective systems and reactive power compensation devices to cooperate and to synchronize their actions so that different instability scenarios can be avoided. To this aim, the coordination should be done between settings of the protection relays and reactive power compensation devices. The optimization could be done by taking into consideration the minimum operation of OLTC, the maximum power delivery to the load and utilizing the reactive power compensation efficiently and effectively. This concept can be considered as Remedial Action Scheme (RMA) or System Integrity Protection Scheme (SIPS), which include intelligent load shedding, adaptive protection, etc. Here, the technique adopted makes use of GPS time-synchronized measurements from PMUs located throughout the network to detect the inception of instabilities, and to provide information for the maximization of the time to voltage collapse.

To carry out this study, the first objective is to model an "all-in-one" stability test system in MATLAB/Simulink's SimPowerSystems Toolbox and simulate it in an Opal-RT real-time simulator. Next a voltage instability scenario is analyzed in real time.

The second major objective is to model the protection relays in SimPowerSystems and implement them in the all-in-one system. The protection scheme involving the coordination of relays with each other is carried out in such a way that it detects instabilities (voltage instability) and trips the faulted zone to protect the remainder of the network from collapsing.

The third major objective is to implement the reactive power compensation devices (switching capacitors and VSC-HVDC) in the all-in-one system and coordinate between protection relays and compensation devices in such a way that the time to voltage collapse increases even when the same settings of the protection relays are kept.

Finally the overall system is to be optimized in such a way that it accounts for the minimum operation of OLTC, maximizes the power delivery to the load and overall increases the time to voltage collapse.

1.2.1. Specific Objectives

- Modeling of all-in-one power system in SimPowerSystems (MATLAB/Simulink)
- Incorporating different instabilities in the system by opening breakers, applying three phase to ground faults, increasing load demand, etc.
- Modeling over-current relays (instantaneous and IDMT) and coordinating their settings to design protection system for all-in-one model
- Modeling of VSC-HVDC and reactive power compensation devices and strategically integrating it in all-in-one model
- Coordinating reactive power compensation devices and over-current relays to mitigate the effect of instabilities
- Optimizing the operation of the power system using the protective information set.
- Analyzing behavior of power system in real time using an OPAL-RT Real Time Simulator.

1.3. Literature Review

Most of the blackouts that have occurred were initiated by voltage instability due to the lack of reactive power support [1]. The IEEE working group on voltage stability has summarized the concepts, analytical tools and industrial experiences related to voltage instabilities [66]. The CIGRE Taskforce in their report has considered voltage indices as the efficient and effective parameters to detect voltage instabilities and to inform the operator about the proximity of the system towards voltage collapse [65].

The concept of optimizing the performance of power system by using synchrophasor data from PMUs and developing applications to detect voltage instability through voltage stability indices is presented in [62]. The real time simulator used for this study is the eMegaSim simulator from OPAL-RT. The documentation is provided in [32].

SimPowerSystems, the proprietary software used in this study, extends MATLAB Simulink with tools for modeling and simulating the generation, transmission, distribution and consumption of electrical power. It provides necessary components used in power systems studies and analysis. The introduction and data sheet are supplied in [67]; demos and examples can be found in SimPowerSystems library in Simulink.

1.4. Outline

This thesis includes several tasks and large number of simulation results and their analysis. Each chapter starts with a small introduction followed by a table of figures. Each chapter ends with a small summary emphasizing the major findings and results obtained through the work presented in that particular chapter. The rest of the thesis is organized as follows. Chapter 2 gives a basic introduction of power system protection and the major protection schemes used for protecting important component of the power system along with detailed comparison of the protection relays from different vendors. Chapter 3 presents the communication aspects of power system relaying, including different protocols and their utilization. Chapter 4 discusses the modeling of the all-in-one test system in SimPowerSystems (MATLAB/Simulink) and its simulation in real time for voltage instability analysis. The modeling of overcurrent relays and their coordination and implementation in all-in-one system is presented in Chapter 5. In Chapter 6, after a general introduction of HVDC systems, the modeling of VSC-HVDC and reactive power compensation devices along with their implementation in all-in-one system is covered. Chapter 7 presents the optimization of all-in-one system by utilizing states of the power system components. Finally, the thesis finalizes with conclusion in Chapter 8 and future work in Chapter 9.

Chapter 2: Power System Protection

2.1 Introduction

This chapter provides an overview of power system and power system protection. The chapter starts with the example of a simple power system and the power system components involved in the system. The importance of power system protection and the most common protections introduced for safeguard of important components of power system are also presented.

The chapter concludes with a comparison of protection relays from four vendors namely Schweitzer Engineering Laboratories (SEL), General Electric (GE), Asea Brown Boveri (ABB) and ALSTOM is provided. The comparison is done on the basis of protection functions, software for configuration, protection functions operating time, etc.

Table of Figures

2.2. Electric Power Systems

Electric Power Systems are electrical networks which ensure the supply of electrical power to consumers. It includes power generation, power transmission and power distribution. Fig. 2-1 shows a simple representation of an electric power system.

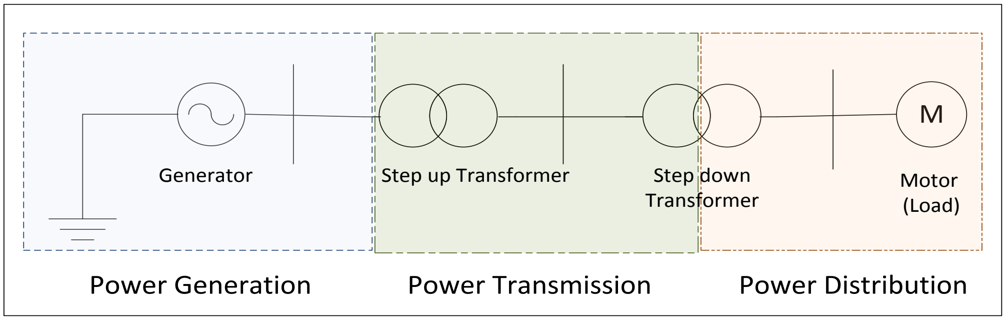


Fig. 2-1: A Simple Representation of Electric Power Systems

The figure shows three important sub-systems within an electric power system. These sub-systems are discussed briefly in order to revise important concepts.

2.2.1. <u>Power Generation</u>

These are the sites, at which electrical energy is generated, e.g. thermal power plants (convert energy from fossil fuels to generate electrical energy), nuclear power plants (utilizing nuclear energy to generate electrical energy), hydro power plants (using the kinetic energy of water to generate electricity), wind farms (where wind energy is converted to electrical energy through wind turbines), solar plants (converting solar energy to electrical energy through solar cells), etc. The heart of a power generation station is the electrical generator which transforms mechanical energy from its primary source into electrical energy.

2.2.2. <u>Power Transmission Networks</u>

Normally power generation stations are far away from load centers. In order to transfer bulk energy to the load centers, power transmission network are required. As such, they behave as a bridge between generating sites and distribution grids. Power transformers present at the generating sites step up the voltages, and feed this bulk of generated power into transmission lines. Voltages are stepped up in order to avoid transmission losses which are given by;

$$P_{Loss} = I^2 R$$

where, I is the current (inversely proportional to voltage), R is the resistance of the conductor (transmission line) and P_{Loss} are the electrical power losses. So higher the voltage, lesser will be the current and thus lesser transmission losses are.

2.2.3 ***Power Distribution Network***

At this level, the distribution transformers steps down transmission voltage to a level suitable and acceptable by the consumers (industrial, commercial and domestic).

2.2.4 ***Power System Protection***

A power system is vulnerable to faults, either due to natural disasters (e.g. earth quakes, lighting strokes, floods, etc.) or by mal-operation of the system due to operator's negligence. The power system is a very complex network and includes critical components (e.g. generators, transmission lines, transformers, etc.). In addition the permanent damage of such components can have a considerable cost and their replacement/procurement will result in longer disconnections of power supply to the customer, which is highly undesirable. So this calls a need for a power system which can sustain faults and protect while at the same time minimizing the important components from permanent damage and could minimize the effect of faults as much as possible. This is achieved by using power system protection techniques and methodologies.

2.3. Important Components of a Protection System

The main components of a protection system are briefly discussed below;

2.3.1. ***Current & Voltage Transformers***

These are also called instrument transformers and their purpose is to step down current (current transformer) and voltage (voltage transformer) to a level at which it can be fed to the protective relays for their operation.

2.3.2. ***Protection Relays***

Protection relays (modern microprocessor-based) are intelligent electronic devices (IEDs) which send a trip signal to circuit breakers to disconnect the faulted components from the power system. They take the inputs from the CTs and VTs and, based on their type and configuration, detect the fault and protect the component by limiting the fault by disconnecting a faulted area.

2.3.3. ***Circuit Breakers***

They act upon the commands from the protective relays to isolate elements or areas of the power system. They can also be manually opened to isolate a component for maintenance.

2.3.4. __Back Up Power Supply__

The protection system also includes back up power supply (e.g. batteries) to supply power to critical elements in the case of disconnection from the main grid.

2.3.5. __Communication Channels__

The protection system requires communication channels to send local information from substations/grid to central stations and also to other relays to ensure relays coordination. This topic of relay coordination will be discussed in detail in the later section.

2.4. Types of Protection Relays

Most of the modern day protection relays are the digital relays which are called microprocessor based relays. They are comprised by microprocessor which has its own algorithms for monitoring the power system through current and voltage inputs from CTs and VTs, respectively; detect faults and sends tripping signal to the circuit breaker to ensure safe and reliable operation of the power system. There is different protection schemes used to protect the power system. The choice of a protection scheme depends upon expected faults, budget, area, technical expertise of the protection scheme designer, etc. However given below are some of the most common protection schemes used to protect the main components of the power system.

2.4.1. __Transmission Line Protection__

The protection of a transmission line can be done in many ways. However a common practice is to use distance relays as a primary protection and over current relays as a backup. For simplicity and better understanding of relay operation, both these protection schemes are discussed briefly.

Line Protection through Distance Relay

The protection of a transmission line is mostly done by using distance protection relay. The transmission lines have a specific impedance of their own depending upon the type and cross-sectional area of the conductor of the transmission line. The distance protection relay tracks the impedance of the line and if it gets lesser than the pre-set impedance value, it will consider it as a faulty condition and will send the trip signal to the breaker to isolate the faulty line from the rest of the power system. The impedance of the line after the fault can be used to find the location of the fault.

Input Parameters: Current from the CT and voltage from the VT. Fig. 2-2 shows the protection of a transmission line using distance relay.

As previously mentioned, the protection scheme is designed by keeping into consideration the expected faults, area and budget. If we consider that a three phase short circuit occurs at a transmission line, then the current through the transmission line would increase abruptly and an over current relay will be enough to detect the fault and isolate the transmission line by sending the trip command to the circuit breaker.

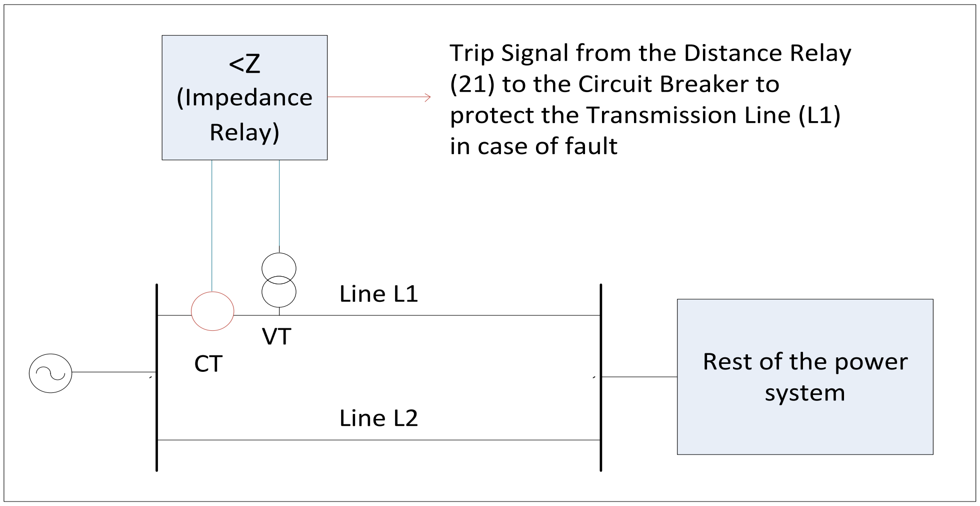


Fig. 2-2: Implementation of distance relays to protect a transmission line

<u>Notice:</u>

Most of the modern day's microprocessor-based relays are multi-functional and provide a number of protections within a unit. In other words they are considered as a complete protection package. In the case of line protection via distance protection schemes, the microprocessor-based relays also provide functions like over current protection, directional over current protection (for selectivity in case of multiple parallel lines), under/over voltage protection, breaker failure protection (in case the breaker fails to trip even after receiving the trip command), Auto Reclosure (automatically closing the breaker which has previously opened due to fault) and others [7].

2.4.2. <u>Transformer Protection</u>

Transformers are important components of power systems. The protection of a transformer is done with the help of differential relay.

<u>Transformer Protection through Differential Relays</u>

A differential relay senses any internal fault that occurred at the transformer, and sends a trip signal to the circuit breaker to isolate it from rest of the power system. The current inputs at both the high and low voltage side of the transformer should be equal (keeping into consideration the turn ratio of the transformer). The relay actually tracks the current at both the high voltage and low voltage side of the transformer, and sends a trip signal to the breaker in case of any difference in the two currents.

Input Parameters: The differential relay requires the current inputs from the CTs at both sides of the transformer. Fig. 2-3 shows the implementation of differential relay as a protection of transformer.

Notice:

In the case of transformer protection, differential protection provides protection against all internal faults, e.g. faults between turns or between windings on the same phase or on different phases. However microprocessor-based relays incorporate many other protection functions, along with the differential protection for the transformers, e.g. over/under current, over/under frequency (as transformer energy losses tends to increase with increasing frequency thus casing overheating and winding insulation can be damaged), thermal overload protection (tracks the thermal condition of windings and generates trip signal if beyond the operating limits) etc. [8]

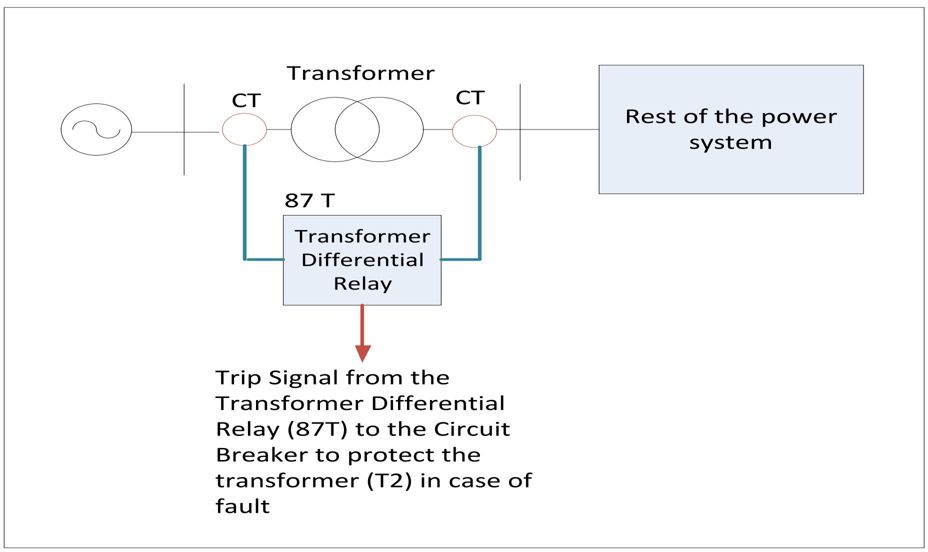


Fig 2-3: Implementation of differential protection relays to protect transformer

2.4.3. Load Protection

The whole power system is designed for a reliable supply of electrical power to the consumers (loads). Electrical loads like motors can be protected against internal faults by using differential relays in the same way as showed previously (transformer protection). Electrical loads are quite sensitive to voltage. Higher fluctuations in voltages can cause serious damages to the load.

Load Protection Using Over/Under Voltage Relay

Loads are protected by using over/under voltage relays which track the voltage at the load and, in case of any fluctuation in voltage; they send trip signals to breakers to isolate loads and thus preventing them from damage.

Input Parameters: The over/under voltage relay only requires the voltage input from the VT. Fig. 2-4 shows the implementation of over/under voltage relay to protect the load in case of fault.

Notice:

Electrical loads are quite sensitive to voltage and a fluctuation of voltage beyond the acceptable limits can greatly affect their performance and life expectancy. In addition to over/under voltage protection, microprocessor-based relays provide a variety of protections: under/over frequency (the motor speed is dependant on the frequency of feeding power), earth fault protection (safeguard against earth faults due to machine insulation damage), over-fluxing protection (due to over voltage or low system frequency and can result in overheating and severe damage to machine), and others [9].

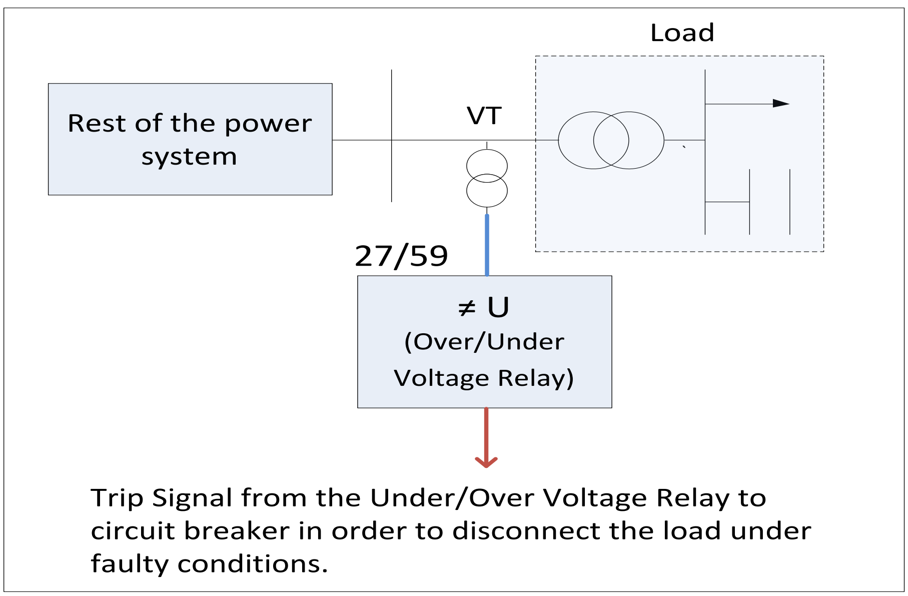


Fig. 2-4: Implementation of over/under voltage protection relays to protect load

2.4.4. Generator Protection

Generators are the most important components of power systems. There are different protection schemes which are applied to protect generators in case of faults. The most important protection for generator is against loss of synchronism. This is called out of step protection.

Generator Protection Through Out of Step Protection

Generators are mechanically driven by a prime mover (turbine) whose mechanical output is generally constant. However, in electrical power systems, connection/disconnection of heavy loads, electrical faults and line switching causes sudden changes in electrical power. This results in an imbalance between the supply (generation) and demand (consumption) of electrical power resulting in acceleration of rotating masses of synchronous generators. If the faults are too severe, then it is possible that the system will become unstable. This situation can occur when one or more (groups) of machines loose synchronism with one of the machines in the grid. This is known as “out of step” or “pole slip” condition. This situation can cause severe damage to the rotating shaft, winding stress, mechanical resonances, pulsating torques, faulty operation of other protection relays (due to large variations in system voltage and currents), etc[10]. Protection against such condition is very important as it can greatly damage the generator and can lead the system towards cascaded failure.

Input Parameters: The out of step protection relay tracks the impedance. This means that the relay gets voltage input from VT and current input from CT. The variations in the voltage/current during normal conditions or stable power swings (the changes in power system that leads the system to a stable operating point) are gradual. However, in case of a fault there is nearly a step change in voltage/current [11]. Fig 2-5 shows the implementation of out of step protection relay for generator protection.

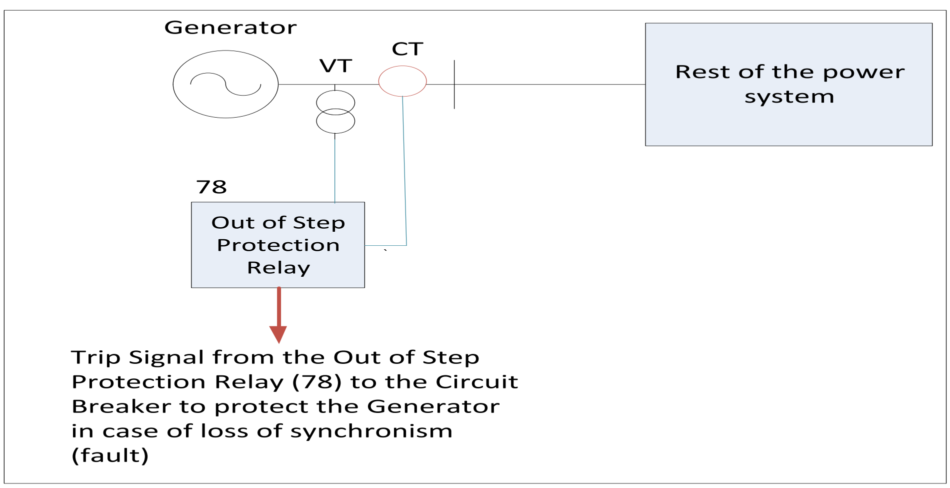


Fig. 2-5: Implementation of out of step protection relays to protect generator

Notice:

Out of Step Protection Relays isolate the generator in case of loss of synchronism. As it gets input from both CT and VT the microprocessor-based relay which offers this protection (Out of Step) has a built in feature of measuring phase angles and frequency (frequency is calculated from voltage measurements)[11]. In additon, microprocessor-based relays provide a full package of protections to safeguard generator against both internal and external faults, and even to protect components attached to it (prime mover, turbine etc.). Some of these additional protections which are incorporated in generator protection units are differential protection (safeguards the generator from all internal faults), overload protection (caused by abnormal heating of stator winding), protection against unbalanced loads (due to sudden disconnection of heavy loads), protection against reverse power (in parallel operation if a generator starts behaving like a motor), frequency protection (over speeding of machine), power swing detection (faults causing oscillations in machines rotor angles which results in swing in power flows) etc.[12].

2.5. Summary of Important Protection Functions and Feature Comparison of Industrial Implementation in Microprocessor-Based Relays

Important protections which are generally applied for power components (generator, transformer, transmission line and motor) have been summarized in the form of charts. The charts exhibit the causes and effects of various faults which occur frequently in the power system, and the necessary protection schemes which are applied to provide protection against such faults.

Furthermore, a feature comparison of microprocessor-based relays systems has been compiled in a chart also. The features are compared for five different microprocessor-based relays (Generator Protection, Transformer Protection, Line Protection, Over-current Protection and Under/Over Voltage Protection) manufactured by four different vendors (General Electric (GE), Schweitzer Engineering Laboratories (SEL), Areva-Alstom and ABB).

These studies were made to design a suitable protection scheme for the test system and to consider the functionalities (protection functions, communication protocols, additional features, operating times, available measurements, etc.) being offered by different manufacturers of microprocessor-based relays. The findings from these studies have been included in a tabular form in the Appendix-A

2.5.1. Comparison of the Software for The Microprocessor Based Relays

GE

ENERVISTA UR and ENERVISTA MII are Windows based software, allowing communication with the relay for data review and retrieval, as well as oscillography, I/O configurations and logics.

SEL

- ACSELERATOR QuickSet Software simplifies settings and provides analysis support for the SEL-relays. It helps to create/manage relay settings, monitor/commission/test relays.

- SEL-5077 SYNCHROWAVE Server is used to analyze voltage and current phase angles in real time to improve system operation with synchrophasor information.

ALSTOM

MICOM S1 Studio provides the user with global access to all IED's data. It is used to send and extract setting files and is used for analysis of events and disturbance records. It also acts as IEC 61850 IED configurator.

ABB

- IED Manager PCM 600 allows user to edit, retrieve setting files and to analyze fault and disturbance records.

- CAP 505 Relay Product Engineering Tool allows user for graphical programming for control and protection units, retrieving records and settings of relay, object oriented project data management.

- RELTOOL is a group of programs that supports some of the relays of ABB. It allows user to edit settings and to modify the control logics.

2.6. Chapter Summary

This chapter has provided some basic concepts related to electric power systems and especially power system protection. Details of different protection schemes which are being implemented to protect the important units in the power system are presented. The comparison of different relays manufactured by different vendors have been studied in detail and have been summarized in the form of charts for quick reviewing of concepts in later stages of this report.

Chapter 3: Power System Communication

3.1. Introduction

The chapter provides an overview of the communication systems used for power system protection applications. Communication protocols which are supported by different microprocessor based relay manufacturers are discussed in detail. The main aim of this chapter is to give a broad overview of the communication systems, techniques, protocols and whole data transfer procedure from one point (IED/Relay/Central Control) to the other one.

Table of Figures

3.2. Power System Relay Communication

Power systems are complex electrical networks that stretch over thousands of miles and are comprised of hundreds of components and serve millions of customers. A high level of technicality, technology and expertise is required to operate the system safely and to ensure reliable supply of electrical power to the customers at all the times. For this purpose, power system is equipped with different protection equipment to safeguard power system components and to isolate the faulted areas of the network from healthy ones. In order to monitor the state of the power system, measurements (voltage, current, phase angle, power, breaker status, etc.) needs to be transferred from the field (substations, power plants, etc.) to a central control system where this information can be processed to reveal the exact status of the entire system. In case there is a fault, actions must be coordinated with the central control system and also with central dispatchers to maintain safe and reliable operation of the power system [14]. Thus, communication plays a vital role in not only monitoring the power system but also controlling it by taking quick remedial actions against any fault/problem.

The table below shows various communications mechanism which is currently in use in the power system, and microprocessor-based relays from different vendors that support these communication techniques.

<table>
<tr><th colspan="2" rowspan="2">Protection Relay</th><th colspan="4">Vendors</th></tr>
<tr><th>General Electric (GE)</th><th>ABB</th><th>SEL</th><th>ALSTOM</th></tr>
<tr><td rowspan="5">Relay Type</td><td>Generator Differential Protection</td><td rowspan="3">RS232, RS485,
IEC 61850,
Modbus / TCP,
DNP 3.0,
IEC 60870-5-104</td><td rowspan="2">RS 232, RS485,
IEC 61850-8-1
IEC 60870-5-103
LON, SPA, DNP 3.0,
Modbus RTU/ASCII</td><td rowspan="4">SEL, Modbus, DNP, FTP, TCP/IP, Telnet, IEC 61850, MIRRORED BITS, EVMSG, C37.118 (synchrophasors), and DeviceNet</td><td rowspan="5">RS 232, RS 485,
Courier/K bus
Modbus,
IEC 60870-5-103,
DNP 3.0, IEC 61850</td></tr>
<tr><td>Transformer Differential Protection</td></tr>
<tr><td>Distance Protection</td><td>RS 232, RS485,
DNP 3.0, Modbus RTU/ASCII</td></tr>
<tr><td>Over/Under Voltage Protection</td><td rowspan="2">RS232, RS485,
IEC 61850,
Modbus / TCP,
IEC 60870-5-103</td><td rowspan="2">RS 232, RS485,
IEC 61850-8-1
IEC 60870-5-103
LON, SPA, DNP 3.0,
Modbus RTU/ASCII</td></tr>
<tr><td>Over-current Protection</td><td>EIA 485, Modbus RTU, EIA 232</td></tr>
</table>

In this project we will be dealing with phasor measurement units (PMUs). The communication standard at which we will be focusing is IEEE C37.118 (Standard for Synchrophasors for Power System). However before going into details of this standard, we start our discussion by summarizing the essential concepts related to communication systems and then discussing all these communication protocols (set of rules that allow devices connected together to communicate with each other).

3.3. Essentials for Power System Communication

A communication system requires a transmitter (IED/RTU/control center), a receiver (IED/RTU/control center) and a communication media (path) linking them together. Analog and digital communication systems [14] which are currently used in power system operation are listed in tabular form below [15].

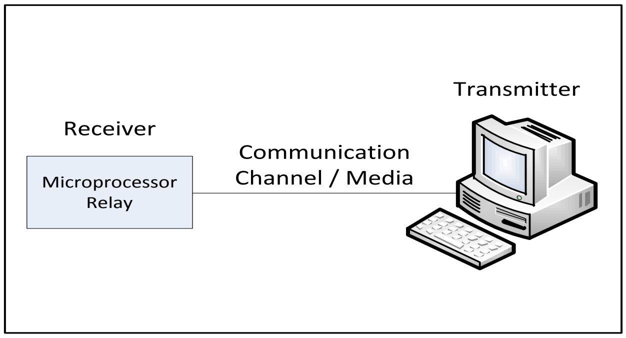
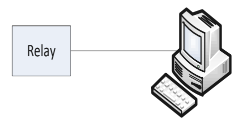
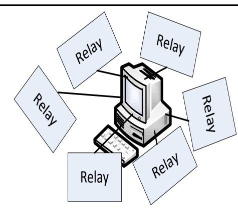
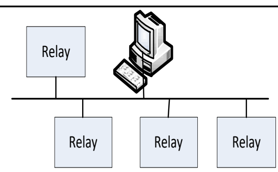
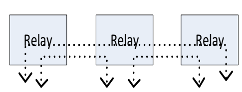
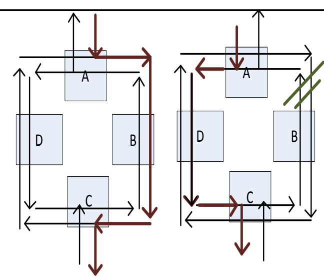
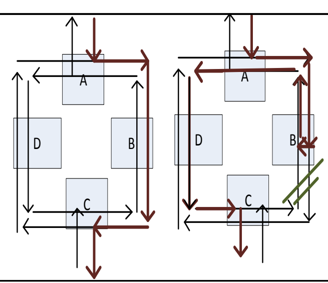


Fig. 3-1: Simple Communication Model

Comparison of Different Communication Medias		
Media	**Advantages**	**Disadvantage**
Transmission Power Line Carrier	Economical, suitable for station to station communication, equipment installed in utility owned area.	Limited distance of coverage, low bandwidth, Inherently few channels available, exposed to public access.
Microwave	Cost effective, reliable, suitable for establishing back bone communication infrastructure, high channel capacity, high data rates.	Line of sight clearance required, High maintenance cost, specialized test equipment and skilled workers requirement.
Radio System	Mobile applications, suitable for communication to inaccessible areas.	Limited bandwidth.
Satellite System	Wide area coverage, suitable to communicate with inaccessible areas, cost independent of distance, low error rates.	Total dependency to remote location, less control over transmission, continual leasing cost, subject to eavesdropping (tapping). End to end delays in order of 250 ms rule out most protective relay applications.
Spread Spectrum Radio	Affordable solution using unlicensed services.	Yet to be examined to satisfy relaying requirement.
Leased Phone	Effective if solid link is required to site served by telephone service.	Expensive in longer term, not good solution for multi channel application.
Fiber Optics	Cost effective, high bandwidth, high data rates, immune to electromagnetic interference. Already implemented in telecommunication, SCADA, video, data, voice transfer, etc.	Expensive test equipment, failures may be difficult to point out, can be subject to breakage.

3.4. Network Topologies

This refers to the physical layout of the connection of resources, cables, computers, IEDs etc. It characterizes how the devices communicate with each other [16]. The table below shows important network topologies and their comparison with each other [15].

Comparison of Different Network Topologies			
Topology	Graphical Model	Advantages	Disadvantages
Point to Point: Simplest configuration with channel available only between two equipment		Suitable for situations where there is a lot of communication required between two points, simplest, easy to implement	Information can only be transferred between two nodes, disconnection in communication channel will halt the process
Star: It consists of multiple point to point systems with one common points		Simple, easy to add and remove nodes, easy management and monitoring, node breakdown does not affect rest of the system	Single point of failure (i.e. central point or hub)entire network depends on it, no node to node communication, cabling (communication path) will increase as network will increase
Bus: All nodes are connected to a single communication path which runs throughout the system.		Bus is not dependant on single machine (hub), High flexibilty in configuration, easy to remove or add nodes, direct node to node communication can be done	Heavy traffic slows down network, All nodes receive information packets which are not even meant for them (unefficient utilization of media), Limitation of number of maximum nodes, hard to troubleshoot
Linear Drop and Insert: Multiple sites to communicate with each other. Information between two non adjacent nodes directly passes through intervening node		When a certain communication channel drops, its bandwidth can be used for other channels	Lack of channel backup against fiber or equipment failure
SONET Path Switched Ring: Comprises of two separate optical fiber links connecting all the nodes in counter rotating configuration as shown in figure. All traffic moves in both direction. In normal case, the data from A to C moves as shown in first figure (left). However if network failure occurs, the data is transferred through the secondary ring in reverse direction as shown in figure (Right)		Simpler, more dependable, network failure will not affect communication process, Suitable for teleprotection applications,	Unequal channel delays between transmitter and receiver in case of network failure which can result in faulty operation of protective relays
SONET Line Switched Ring: *Consists of two optical fiber paths connecting all the nodes in the form of ring. One path is active and other is reserved. Under normal condition, the active path transfers information (figure on left). In case of network fault, the backup (reserved) path is activated to transfer information in reverse direction (Figure on right)*		More efficient use of fiber communications for some applications	Complex handshaking (Synchronizing) that causes start up delays of as long as 60ms (that can cause false operation of protection relay) so making it worse than SONET Path Switched Ring for teleprotection applications

3.5. Advancement in Relay Communication Techniques

Electric utilities are expanding communications infrastructure to handle increased need of information. Communication requirements needed for protection systems are more rigid than needed for telecommunications (due to fast operation requirements in power systems). Efforts are being made to develop communication techniques which are not only cost effective but also reliable. One such technique which is being explored for relay communication is Packet Switching Networks.

3.5.1. Packet Switching Networks

The main principle of the technique is to divide the digital data (information) into groups or packets and transmit it over shared data networks rather than over dedicated lines of telecommunications. It is the same technique which is used for Internet.

Advantage

Allows multiple users to communicate over single network which results in reduce of communication network cost.

Limitation

Packet transmission time can be variable (depending upon the path which is followed by the packet to reach the destination) which can result in delay in operation of protective relays (as its operation depends on the information contained in the packet). However, with adequate bandwidth, new packet technologies and new relay designs may overcome these limitations [15].

Digital communication techniques are being implemented for directional comparison (to identify the direction of a fault and trip the faulted zone), current differential (in case of protection of short line with differential relay in which local and remote relays communicate current values with each other continuously and trip signal is generated if difference in currents exceeds relay settings), transfer trips (in case of distance protection where remote signal is required to trip the line), Breaker Failure Initiation (if a breaker does not isolate a fault even after receiving a trip signal then this scheme sends trip signal to rest of breakers on the bus), interlocking (between breaker and disconnector) etc [17].

3.6. Description of Different Communication Protocols

As discussed earlier, protective relays manufactured by different vendors support different communication protocols (set of rules that allow devices connected together to communicate with each other). Below is the brief description of all these protocols which were mentioned earlier.

3.6.1. <u>RS 232 Protocol</u>

This is the most basic communication protocol which specifies the criteria for communication between two devices. The type of communication can be simplex (one device acts as transmitter and other acts as receiver and there is only one way traffic i.e. from transmitter to receiver), half duplex (any device can act as a transmitter or receiver but not at the same time) and full duplex (any device can transmit or receive data at the same time). A single twisted pair connection is required between the two devices as shown in Fig. 3-2.

<u>Application:</u> All microprocessor-based relays have serial ports that allow serial communication by utilizing RS 232 protocol. It is used to interface relays with computers to edit the settings file or retrieve event records from the relay.

<u>Limitation:</u> communication is only limited between two devices. So it can only be used for point to point communication.

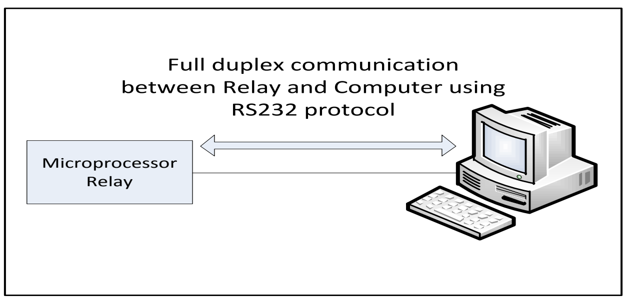


Fig. 3-2: Communication using RS232

3.6.2. <u>RS 485 Protocol</u>

This protocol is same like RS 232 but the advantage is one can connect as many as 32 devices together. The devices can be present anywhere in the substation and are connected serially with each other. The problem with such a technique is that it is half duplex, i.e. a device can either transmit or receive at one time. The Master unit (the one which initiates the communication and controls it) sends commands to the other units called slave which responds to these commands. Polling is used for such type of communication (Master keeps on interrogating each slave after regular interval to check if it needs to communicate the information).This is shown in Fig. 3-3.

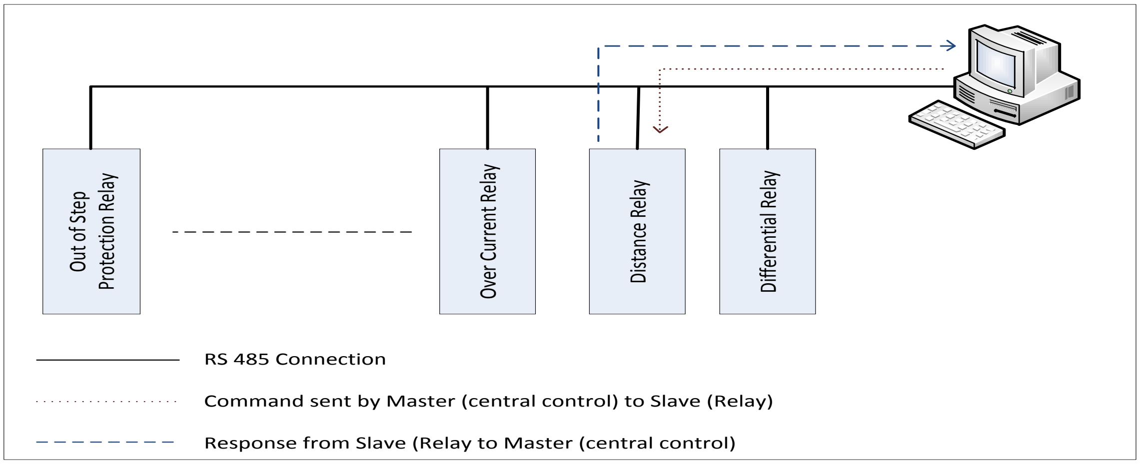


Fig. 3-3: Serial Communication using RS485

These protocols are applicable over a relatively restricted geographical area. Phasor Measurement Units (PMUs) are meant for wide area monitoring which deals with large geographical area. This highlights the need for suitable communication protocols for this purpose.

3.6.3. <u>Essential Requirement for Communication Protocols</u>

All communication protocols have at their core, payload of information that is to be transferred. The protocol is designed for safe, reliable and efficient transfer of this data to its destination.

In order to clarify several parts of protocol functioning, "Reference Model for Open Source Interconnections" was developed (which is simply called "OSI Reference Model"). All other network protocols are derived from this model.

3.6.4. <u>OSI Reference Model</u>

It's a seven layer model and each layer performs specific tasks. Each layer provides services to the adjacent layer above it by utilizing services presented by the adjacent layer below it. A brief description of the layers and their functions is given below. When data is to be transferred from one device to another (at different place) then each layer would add its header which includes specific information and at the destination end, these headers would be decrypted to reveal the exact information [16].

Layers	***Functions***
Application	Offers direct interaction between the user and the software application. Adds an application header to the data which defines which type of application has been requested. This forms an application data unit. There are several standards for this layer e.g. HTTP, FTP, etc.
Presentation	Handles format conversion to common representation data and, compresses and decompresses the data received and sent over the network. It adds a presentation header to the application data unit having information about the format of data and the encryption used.
Session	Establishes a dialogue and logical connection with the end user and provides functions like fault handling and crash recovery. It adds a session header to the presentation data unit and forms a session data unit.
Transport	Manages the packet to the destination and divides a larger amount of data into smaller packages. Here we consider that the data to be sent is not big enough and thus we are having a single data packet. This layer adds transport header to the session data unit which handles information about error and flow control and the sequence of the packet.
Network	Controls the routing and addressing of the packages between the networks, and conveys the packet through the shortest and fastest route in the network. Adds a network header to the Transport Data Unit which includes the Network Address.
Data Link	Specifies Physical Address (MAC Address) and provides functions like error detection, resending etc. This layer adds a Data Link Header to the Network Data Unit which includes the Physical Address. This makes a data link data unit
Physical	Determines electrical, mechanical, functional and procedural properties of the physical medium.

Now let's assume that the RTU (Remote Terminal Unit) that serves as a gateway to transfer the information outside of substation at Substation-A is transmitting a measured value of voltage to the Central Station through a communication network (WAN). This communication can be represented as shown in Fig. 3-4.

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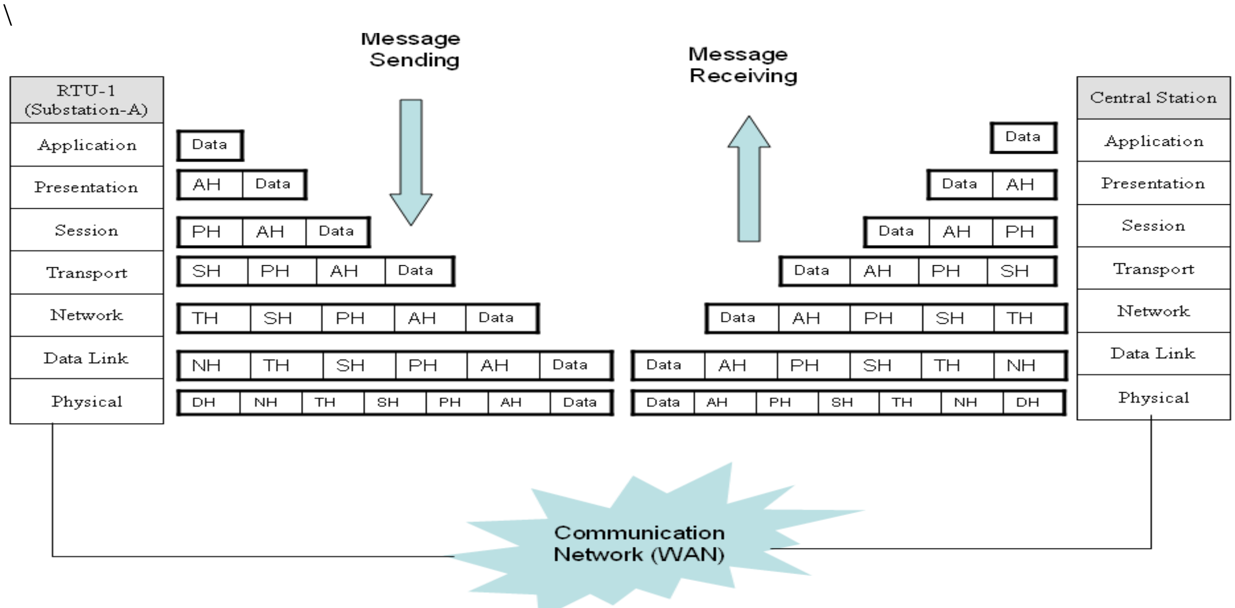


Fig. 3-4: Data communication using OSI Model

3.6.5. <u>TCP/IP</u>

Transfer control protocol and Internet protocol are used to transfer data over internet. It is four layers model. Each layer adds its header to the payload (data) and sends it to the next layer and at the receiving end, this header is removed and eventually the actual information is revealed.

Layer	Function
Application	Provides user interface and constitutes the application itself.
Transport	Flow control, error handling, sequencing and reliable delivery.
Internet	Reliable transfer of data from source network to destination network.
Host to Network	It is hardware independent. So any hardware networking technology can be used.

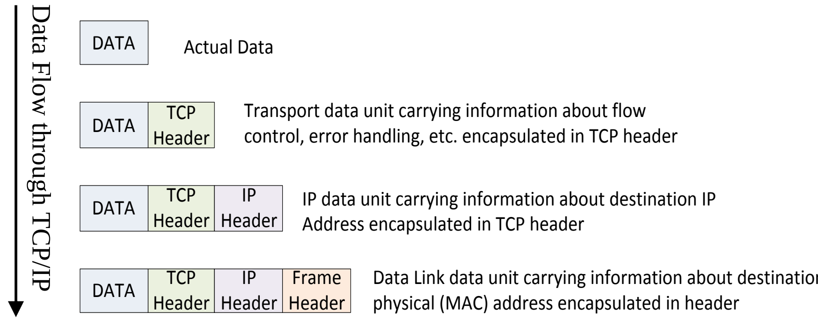


Fig. 3-5: TCP/IP Model

3.6.6. <u>Need for Other Protocols</u>

The OSI Model explains how the data is communicated between source and destination. However in order to increase the throughput and reduce overheads which are imposed by intermediate layers, some of the layers of OSI model are omitted or sometimes merged with other layer. Other protocols which are derived from OSI Model and are currently being used in power system communication are explained below.

3.6.7. <u>IEC 61850</u>

It is a standard which defines the rules for substation automation. One of its applications is SCADA (Supervisory Control & Data Acquisition) systems. There are several communication protocols which are implemented for substation automation using IEC 61850 standard. The most common are:

3.6.7.1. <u>DNP 3.0</u>

It is designed specifically for SCADA (Supervisory Control and Data Acquisition) systems, i.e. used for SCADA to IED (Intelligent Electronic Device e.g. Microprocessor based relay) or IED to IED communication. It uses layers 1, 2 and 7 from the OSI model [18].

3.6.7.2. MODBUS

Modbus is supported by all the microprocessor based relays. Therefore, this protocol has been discussed in detail [19].

Description of Modbus

Allows an easy communication within all types of network architectures and supports all types of devices like PLC, HMI, Control Panel, Drivers, Motion Control, I/O devices, etc

Communication Principle

Communication can be done on a serial line as on an Ethernet TCP/IP networks

Advantage

It is an open protocol, meaning that its free for manufacturers to build their equipment without paying royalties.

Application

Mostly used to transmit signals from instrumentation and control devices back to main controller or data gathering system

Variants of Modbus

The Modbus protocol is a three layer protocol. However there are variations e.g. Modbus RTU (serial communication using RS 232/RS 485), Modbus TCP/IP (for communication over TCP/IP network), etc [20].

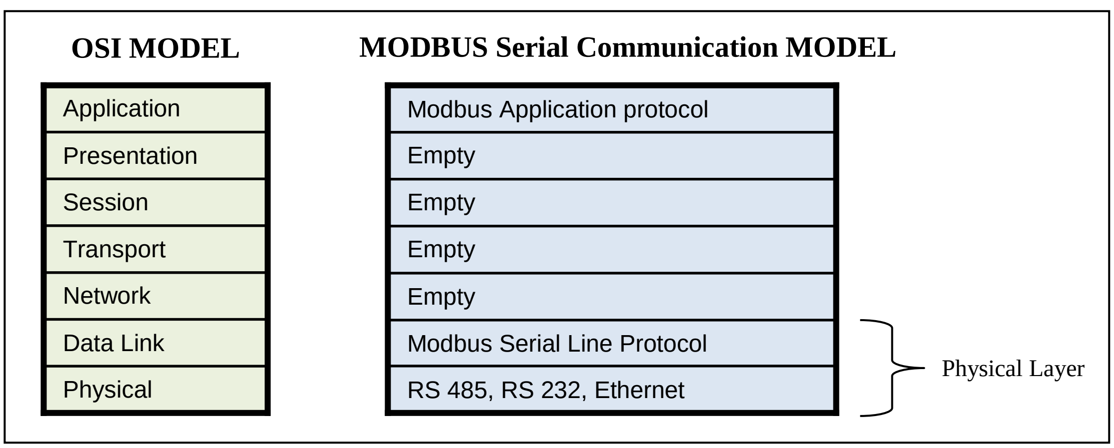


Fig. 3-6: Comparison of Modbus with OSI Model

Key Features of Modbus Protocol

- It is a Master-Slaves protocol
- Only one master is connected to the bus.
- One or several slave nodes are also connected to the same serial bus
- MODBUS communication is always initiated by the MASTER
- Slave node will never transmits data without receiving a request from the master node
- Slave nodes will never communicate with each other
- The master node initiates only one MODBUS transaction at the same time.
- Fig 3-7and Fig 3-8 shows the Modbus implementation in unicast and broadcast mode respectivily.

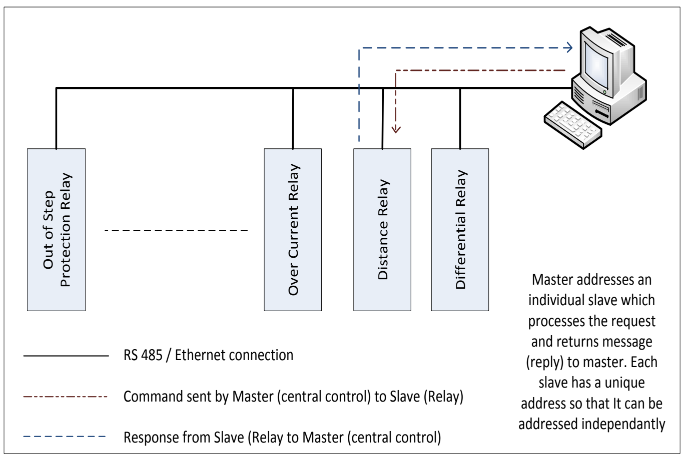


Fig. 3-7: Modbus operation in unicast mode

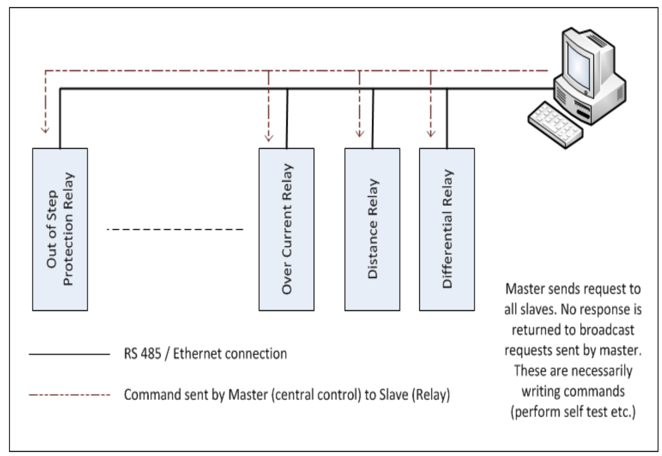


Fig. 3-8: Modbus operation in broadcast mode

Modbus Frame Description

Modbus defines a simple protocol data unit (PDU) irrespective of the underlying layers. The frame format is shown below.

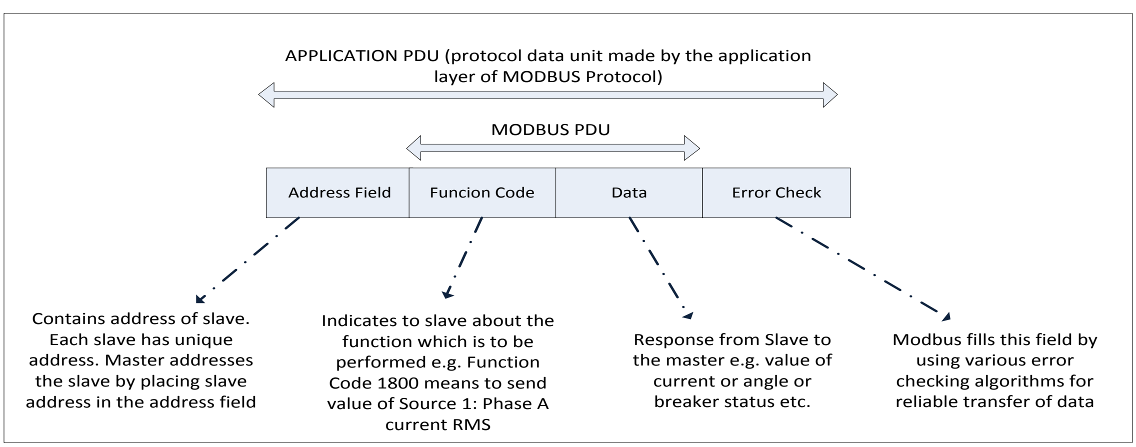


Fig. 3-9: Modbus frame description

Fig. 3-10 shows the implementation of Modbus protocol for exchanging data between the relays and the master unit (Workstation/Control Center).

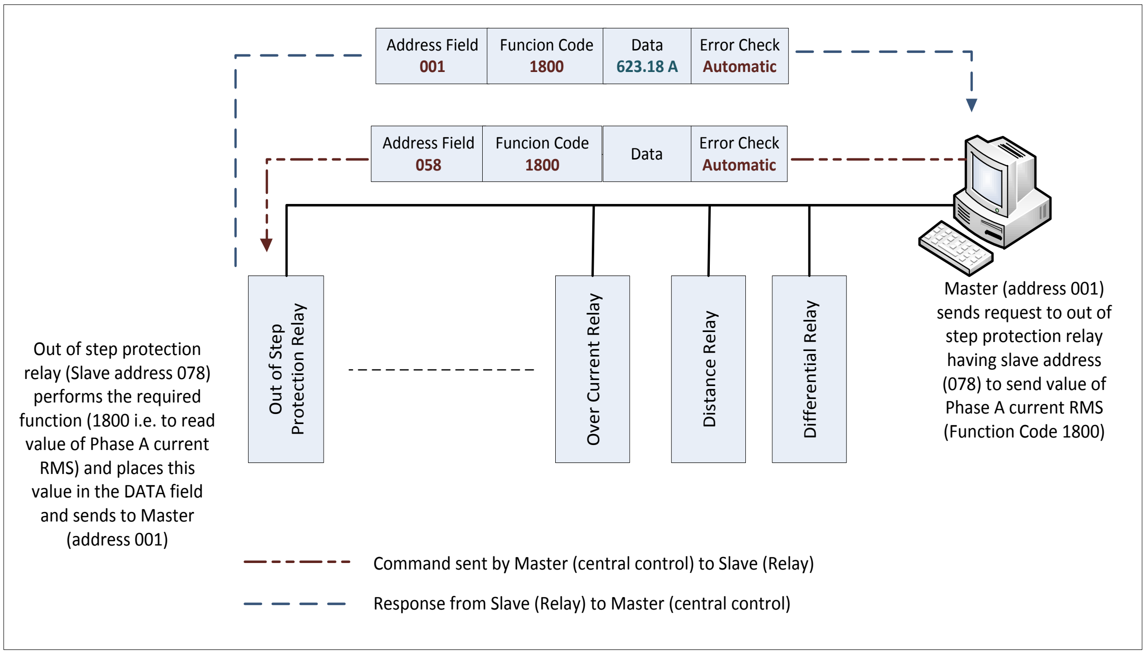


Fig. 3-10: Implementation of Modbus protocol to communicate information

Advantages of Modbus

- High data rate
- Less complex
- Easy to administer
- Well understood and documented protocol
- Widely supported by most of the host PLC (Programmable Logic Controllers), DCS (distributed control system), and IEDs.

3.6.8. IEC 60870-5-103

IEC 60870-5 is collection of standards for open transmission SCADA telemetry and control information [21]. It uses enhanced architecture protocols like Modbus to reduce the overheads and ensure high data rates.

3.6.9. IEC 60870-5-104

It is extension of IEC 60870-5-101 (Companion standard for basic telecontrol tasks) which is used for SCADA telemetry. IEC 104 has TCP/IP layers to allow data of IEC 101 to be routed over internet (Wide Area Protection).

3.6.10. LON

"Local Operating Network" provides network configurations for factory automation, process control, building networks, vehicle networks etc. [22]. It uses all the seven layers of OSI Reference Model. It is not very common in the power system protection world as it has a lot of overheads due to increased layers and thus gives lesser data rates than other EPA (Enhanced Protocol Architecture like Modbus and DNP).

3.6.11. SPA

SPA-bus is also a protocol for Master-Slave communication just like Modbus but it is owned by ABB [23].

3.6.12. K-Bus

It is also an enhanced protocol architecture (EPA) which was developed for substation automation and uses layer 1, 2 and 7 of OSI Reference Model. It is used by Areva-Alstom [24].

3.6.13. Mirrored Bits

It is standard feature of SEL protection and automation products. It is relay-to-relay communication technology that sends internal states of one relay to the other relay. It replaces the need of physical control wiring between the relays to a simple common channels e.g. fiber optics, analog microwave, spread spectrum radio, etc. connection between relays[25]. It is property of SEL.

3.6.14. EV MSG

It is alarm and event notification system that converts incoming computer text messages to voice messages delivered via telephone or through speakers [26]. It is registered product of SEL.

3.6.15. Device Net

It is a low level communication network that provides direct connectivity among industrial devices thus resulting in improved device-level diagnostics. Measuring data (voltage, current, power, etc.) can be retrieved with the help of device net interface [26].

3.6.16. Telnet

It is very similar to direct serial communication to the relay port. Telnet is a part of TCP/IP [27].

3.7. IEEE C37.118

It is known as "IEEE Standard for Synchrophasors for Power System" which is used to integrate measurement systems into power system environment. It is used for data communication between Phasor Measurement Units (PMUs). The standard describes the synchronization requirements and message format to communicate with PMUs [28].

We will start our discussion with some basic concepts related to Synchrophasors and their applications in power systems.

3.7.1. Synchrophasor Data

Synchrophasor data consists of both analog data (voltage, current, etc.) and digital data (breaker status, disconnector status, etc.) which have been measured by metering devices (IED, PMU, etc.) and associates this data to a precise time stamp (the measured data is associated with a time at which it was actually measured). The devices that measure synchrophasor data and communicate them are called phasor measurement units or simply PMUs.

3.7.2. Applications of Synchrophasor Data

Synchrophasor data ensures the availability of measured data in real-time. This information is currently being utilized for voltage stability monitoring (by monitoring voltages at all buses in real-time and providing reactive power compensation), load/generator shedding (by monitoring frequency and phase angles), grid interconnection (by monitoring phase angles and detecting island mode of operation of generator), System wide monitoring (allows monitoring of whole system in a real-time), and others [29].

3.7.3. Communication Protocol for Synchrophasor Data

This protocol is used to transmit phasor data information to other device (central control / PMU / etc.). However, this protocol is not required if a PMU is used only for phasor data archiving or recording [30].

3.7.4. Protocol Description

It is a single layer protocol. The entire frame of data is written into and read from the application layer. It can be implemented using any communication systems or media. The frame also contains error check which uses CRC-CCITT (Cyclic redundancy check - 16 bits) to ensure reliable data transfer.

3.7.5. <u>Message Framework</u>

In this standard, four types of messages are defined. These have been presented in tabular form on the next page.

Message Types Supported By IEEE C37.118			
Message Type	**Functions**		**Status**
Data	These are measurements made by PMU (Voltage Phasors, Current Phasors, Frequency, etc.)		Data messages are transmitted from PMUs
Configuration	These are the machine readable messages describing the data PMUs send and calibration factors.		Configuration messages are transmitted from PMUs
	Config 1: Complete data set that can be provided by PMUs	***Config 2:*** Data which are currently being sent by PMU	
Header	Header information is human readable descriptive information provided by user		Header messages are also transmitted by PMUs
Command	Machine readable codes sent to PMUs to take necessary actions.		Command messages are received by PMUs

3.7.6. <u>Overall Message Format</u>

As mentioned above, the protocol provides with four types of standard messages. Any of these four messages can be sent and will utilize the same frame format. Below is shown a typical data message frame format by considering that a PMU is sending the data (measured values) to a central control.

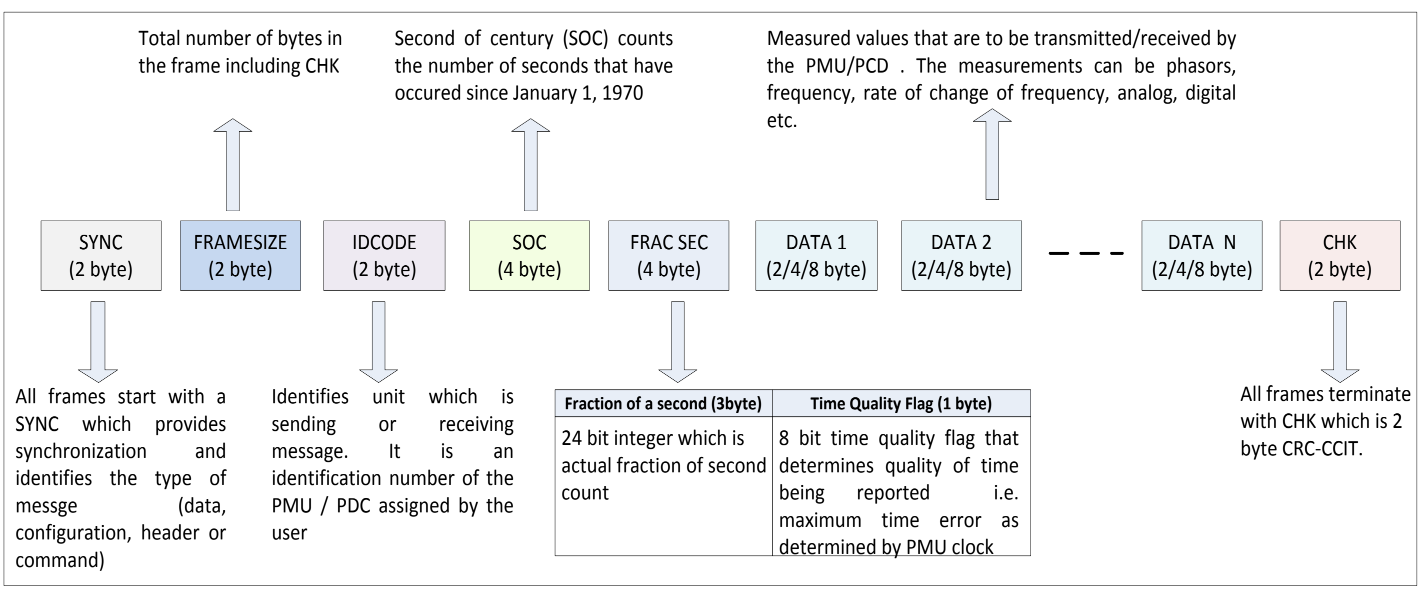


Fig.3- 11: Frame Format for the Synchrophasor Data Protocol

Now we consider that a PMU is transmitting the value of frequency to the central control. We assume that the ID Code for the PMU is 189. We assume that the communication media is fiber optics and they are serially connected. The message frame for this scenario is shown in Fig. 3-12.

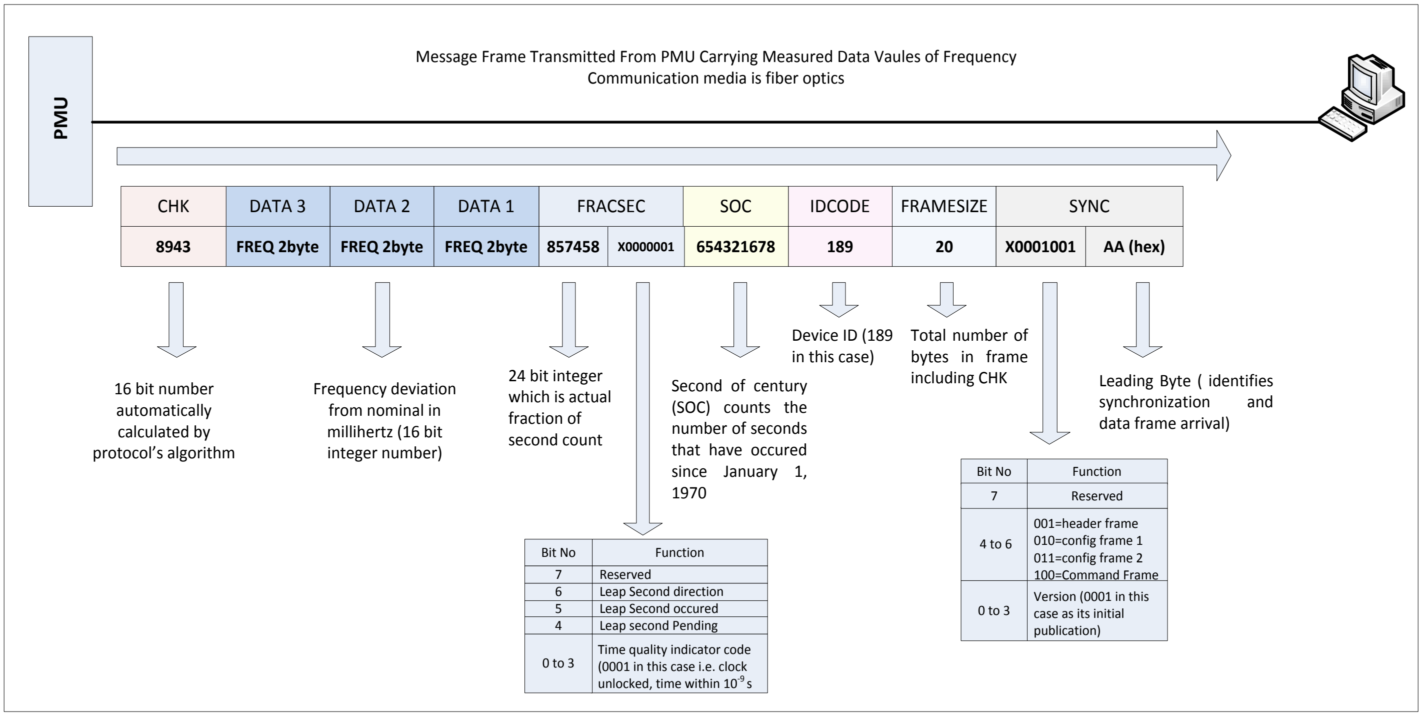


Fig. 3-12: Implementation of Synchrophasor Data Protocol

3.8. Chapter Summary

The chapter gives a brief overview of the importance of power system communications and different protocols and standards used for this purpose. More emphasis is made on substation automation (IEC-61850 and related protocols like DNP and MODBUS). In the end of this chapter, the protocol for synchrophasor data is presented i.e. IEEE C37.118. Power system operators have already adopted PMUs for real time monitoring and control of power systems. The standard IEEE C37.118, utilization to improve power system reliability and frequent advancement in technology (communication techniques, protection relay operation, etc.) is paving the way to use synchrophasor data for not only monitoring and visualizing but also to achieve a more reliable, secure, and economical operation of power systems. With this strong motivation, we have used PMUs measurements for this project.

Chapter 4: Power System Modeling and Implementation for Real-Time Simulation

4.1. Introduction

This chapter discusses the modeling of the All-in-One Test System in SimPowerSystems and its implementation for real-time simulation using the OPAL-RT eMEGAsim real- time simulator.

The chapter starts with an introduction to the all-in-one system, and the power system components present in the system. The details of the blocks and the models used for the overall SimPowerSystems model are discussed. After off-line modeling is complete, changes required for real-time simulation are presented. The challenges and complexities involved in real time modeling with SimPowerSystems are also listed in this chapter.

Finally the library of Opal-RT dedicated for real-time simulation is presented and the details of steps required to make the “All-in-one” test system compatible with the real-time simulator are presented. In the end the power system analysis is done using real time simulation. The chapter concludes with a real-time voltage stability analysis of the test system.

Table of Figures

4.2. Power System Modeling

The first task towards the accomplishment of this study was the implementation of an "All-in-One" test system in the MATLAB/Simulink SimPowerSystems Toolbox. The reason for using the SimPowerSystems Toolbox is because it operates in the Simulink environment and is a dedicated tool for modeling and simulating the generation, transmission, distribution and utilization of electrical power. It includes models of three phase electric machines, electric drives, transmission lines, loads and libraries of application specific models [31] (e.g. FACTS and HVDC). Another motivation in using SimPowerSystems is because SimPowerSystems is compatible with the OPAL-RT Real Time Simulator [32] which was used to simulate the power system model in real-time. This report focuses on power system modeling in SimPowerSystems and modifications required to simulate the power system model in real-time.

4.2.1. <u>Power System Modeling in SimPowerSystems</u>

The single line diagram of "All-in-One" Test System which was modeled in SimPowerSystems is shown in Fig. 4-1

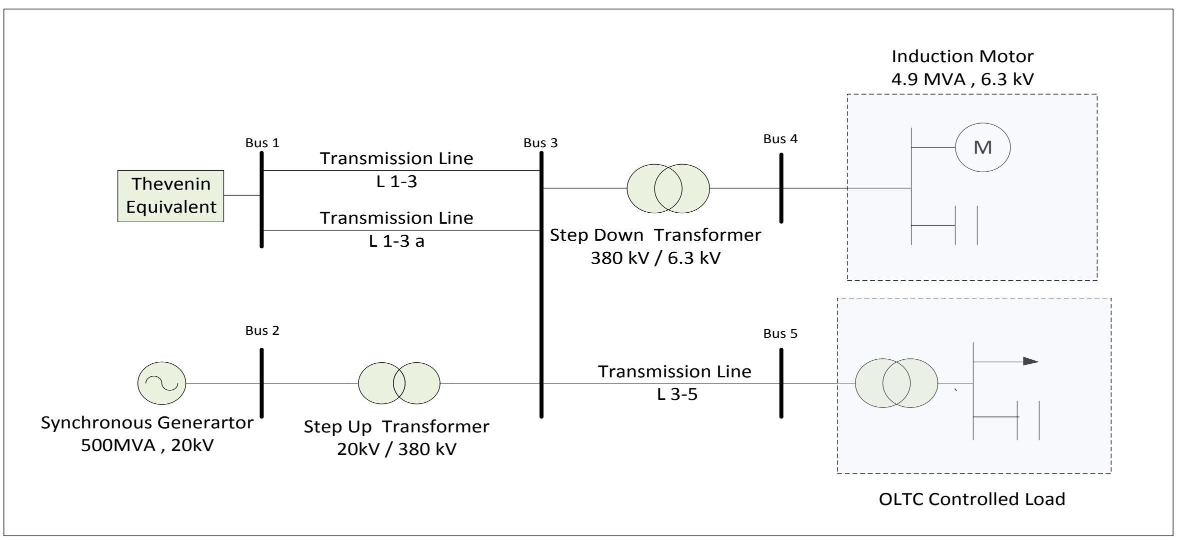


Fig. 4-1: Single Line Diagram of the "All-in-One" Test System

The figure shows various power system components connected together to form a power system model. The details of these components and their respective parameter's settings are discussed below.

4.2.1.1. Synchronous Generators

In the SimPowerSystems library, the machines category contains various synchronous machines which are classified on the basis of the way a machine is modeled and the type of input data for various parameters. For this thesis we have used the Synchronous Machine pu Standard block from the SimPowerSystems Library. Fig. 4-2 shows the synchronous machine block used in the model

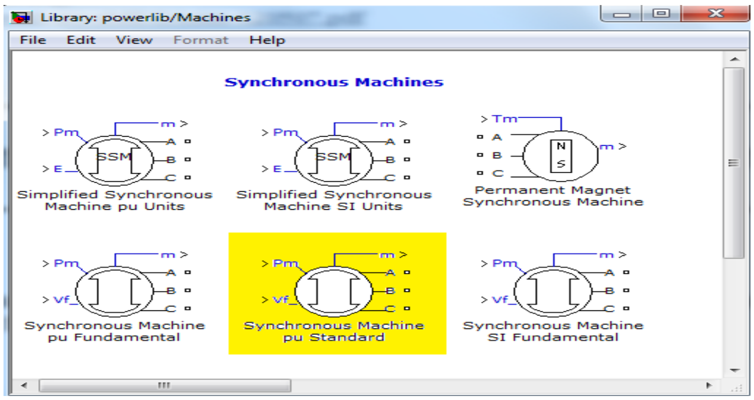


Fig. 4-2: Synchronous Machine pu Standard

Inputs & Outputs of Block

This block models the dynamics of three phase salient pole or wound rotor machine. The model takes into account the dynamics of the stator, field and damper windings [33].

"Pm" is the mechanical power input to the machine's shaft. The positive mechanical power input represents generator mode of the synchronous machine and negative mechanical power input represents motor mode. In this study, the synchronous machine is used in generator mode and the mechanical power input is supplied by a prime mover.

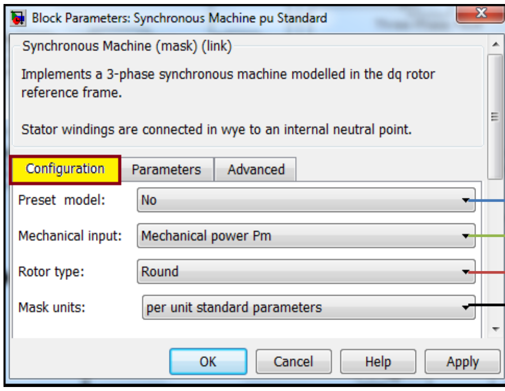
"Vf" is the field voltage for the synchronous machine. In motor mode this input is constant. However in generator mode, this input is fed by a voltage regulator. In this thesis, an Excitation System is used to regulate the field voltage of the synchronous generator.

"m" is an output which provides metering facilities for various signals which can be chosen with the help of the "bus selector" block of Simulink.

"ABC" are the output terminals of the synchronous machine that represent three phases.

Parameters Detail

The synchronous machine block demands values of the following parameters from the user.

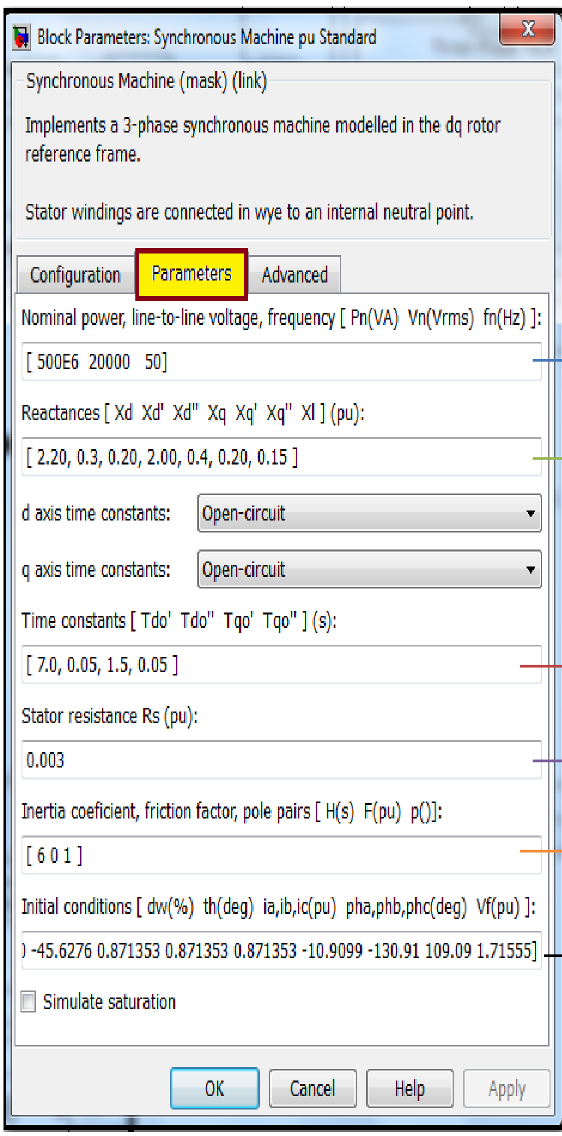


This option provides set of pre-determined mechanical and electrical parameters for various ratings of synchronous machines. This option was not selected so that we can design machine according to our parameters

This option allows selecting either the mechanical power or rotor speed as the input to the synchronous machine shaft. For this model, the mechanical power input was selected which was fed by the prime mover (steam turbine)

Provides an option for selecting either round rotor or salient pole type of rotor. As we are modeling generator with a steam turbine and governor system, so we have considered the round rotor type.

Only provides information that the parameters values should be entered in terms of per unit values



Determines the rating of the synchronous machine. In our case we have designed a synchronous generator with the following rating;

Nominal Power = 500 MVA
Line to Line Voltage = 20 kV
Frequency = 50 Hz

d-axis synchronous reactance Xd = 2.20
Transient reactance Xd' = 0.3
Sub-transient reactance Xd'' = 0.20
The q-axis synchronous reactance Xq= 2.00
Transient reactance Xq' = 0.4
Sub-transient reactance Xq'' = 0.20
Leakage reactance Xl = 0.15

All values are in per unit (p.u.)

Either open circuit or short circuit time constants can be supplied. We have set the open circuit time constants for both d-axis and q-axis.

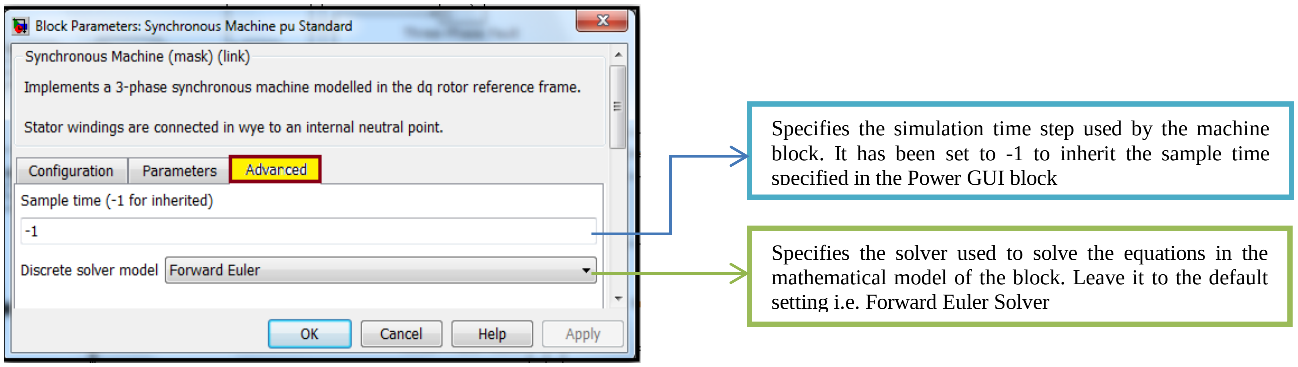
d-axis open circuit transient time constant Tdo' = 7.0
d-axis open circuit sub-transient time constant Tdo''= 0.05
q-axis open circuit transient time constant Tqo'= 1.5
q-axis open circuit sub-transient time constant Tqo''= 0.05

The value of stator's resistance in per unit. For this machine Stator Resistance Rs=0.003 pu

The inertia constant H (s) = 6 where H is the ratio of kinetic energy at rated speed to the rated apparent power.
Friction factor F (pu torque/pu speed) = 0
Number of pole pairs p = 1 (considering turbo generator)

The initial conditions are calculated automatically by using "Load Flow and Machine Initialization" feature of Power GUI block. It is discussed in detail later in this section

H represents the time a machine will take to accelerate itself from zero to rated speed using full rated power (assuming rated MVA can actually be output as MW). High H corresponds to a machine which changes speed over long time periods (responds slowly to transient mismatch of power input to power output). Low H corresponds to a machine which changes speed faster [34].



4.2.1.2. <u>Steam Turbine & Governor System</u>

This block models the dynamics of a speed governing system and a steam turbine. Fig.3 shows the steam turbine and governor system block in the SimPowerSystems library in the machines' category.

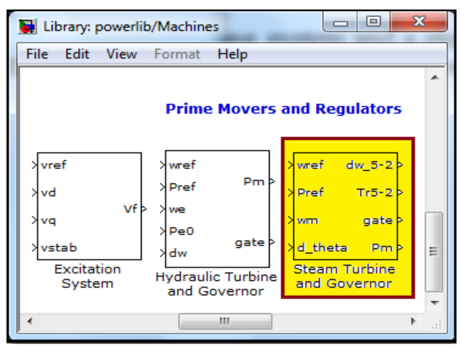


Fig. 4-3: Steam Turbine and Governor Block

The speed governing system of the block consists of a proportional regulator, speed relay and a servo-motor controlling the gate opening. It is exactly the same model as the Approximate Mathematical Model for General Electric Electro Hydraulic Systems [35].

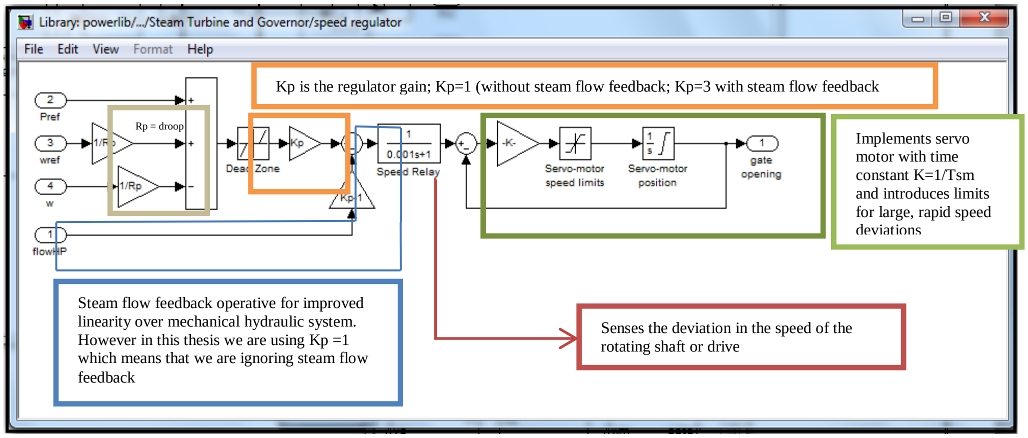


Fig. 4-4:Detail Model of Speed Governing Block

The steam turbine part of this block implements a Tandem Compound Double Reheat [36] Steam Turbine and a shaft with up to four masses. However for this report we are considering a single mass shaft i.e. the entire four mass shaft subsystem in the steam turbine and governor block is disabled and all the torque from the turbine is added together and applied to the machine's mass

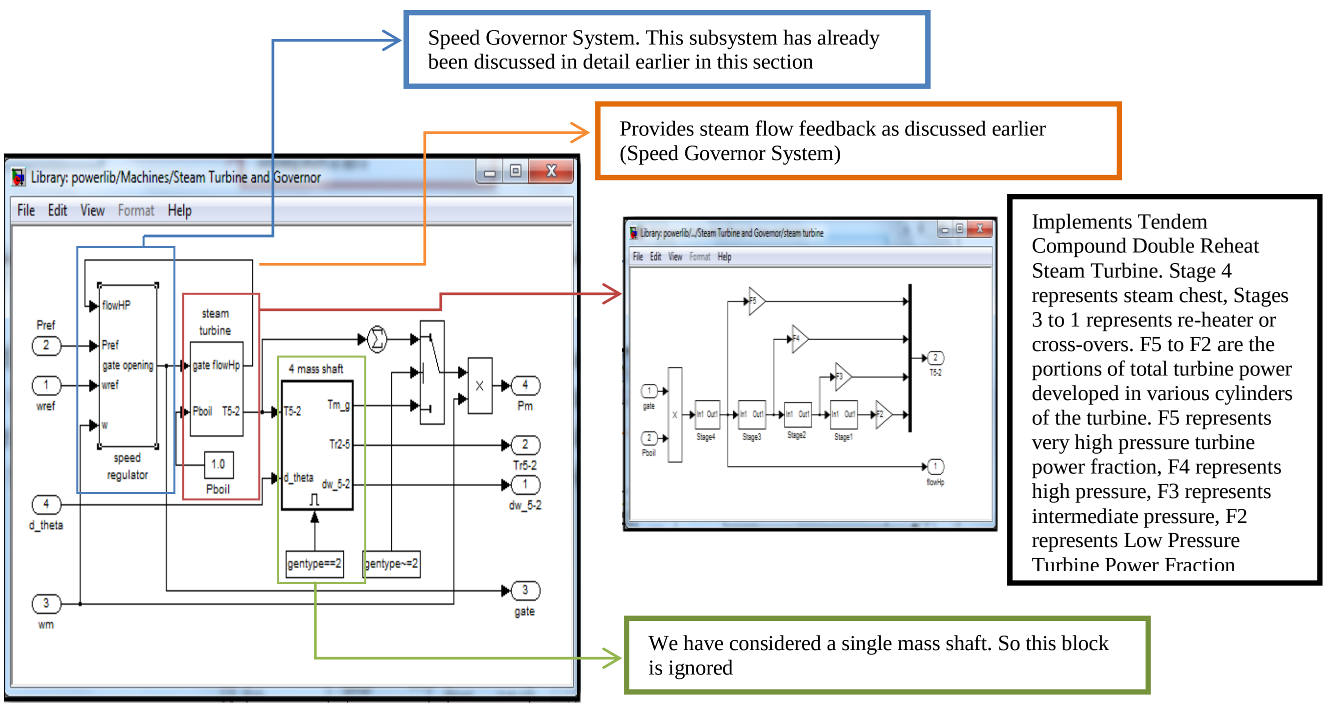
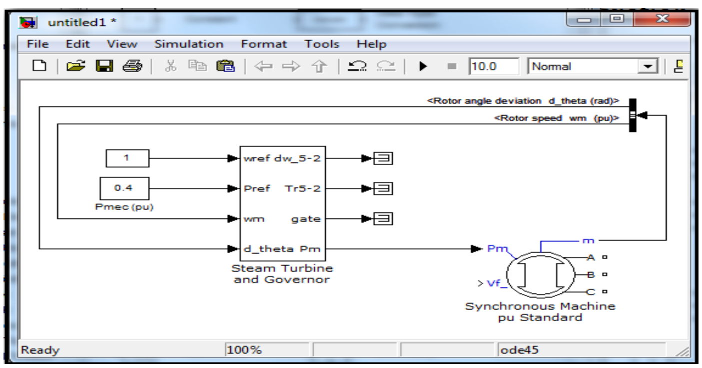


Fig. 4-5: Detail Model of the Steam Turbine and Governor Block Showing Different Sub-Systems

Inputs & Outputs of Block

The first input w_{ref} is the speed reference in per unit. It is connected to the constant block with value set to 1 p.u. The second input P_{ref} is electrical power reference in per unit. It is a constant value equal to the active power initially drawn from the synchronous machine connected to the steam turbine. The third input w_m is speed of generator in per unit. This input is fed by the synchronous machine as shown in Fig. 4-6. The fourth input d_{theta} is generator's power angle deviation. It is also fed by the synchronous machine as shown in Fig. 4-6.

The first output $dw\_{5\text{-}2}$ is a vector containing speed deviations in per unit of masses 5 to 2 (ignored in our case because of considering a single mass shaft). The second output $Tr\_{5\text{-}2}$ is the vector containing the torques in per unit transmitted by masses 5 to 2 (ignored in our case because of considering a single mass shaft). The third output is gate opening in per unit. The fourth output P_m is mechanical power which is fed to the synchronous machine as shown in Fig. 4-6. The values of different parameters are in accordance with the values proposed in [65].



The terminals A,B,C of the synchronous generator are connected to the rest of the system (Three Phase). V_f is the field voltage of the synchronous generator which in our case is supplied by excitation system discussed later in this section. P_{ref} is taken as 0.4 pu. The rating of the synchronous generator (discussed earlier) is 500MVA. So 0.4 pu means that we are considering an active power output from the generator equal to 0.4 * 500 = 200MW

Fig. 4-6: Connection of the synchronous machine with the steam turbine

Parameters Detail

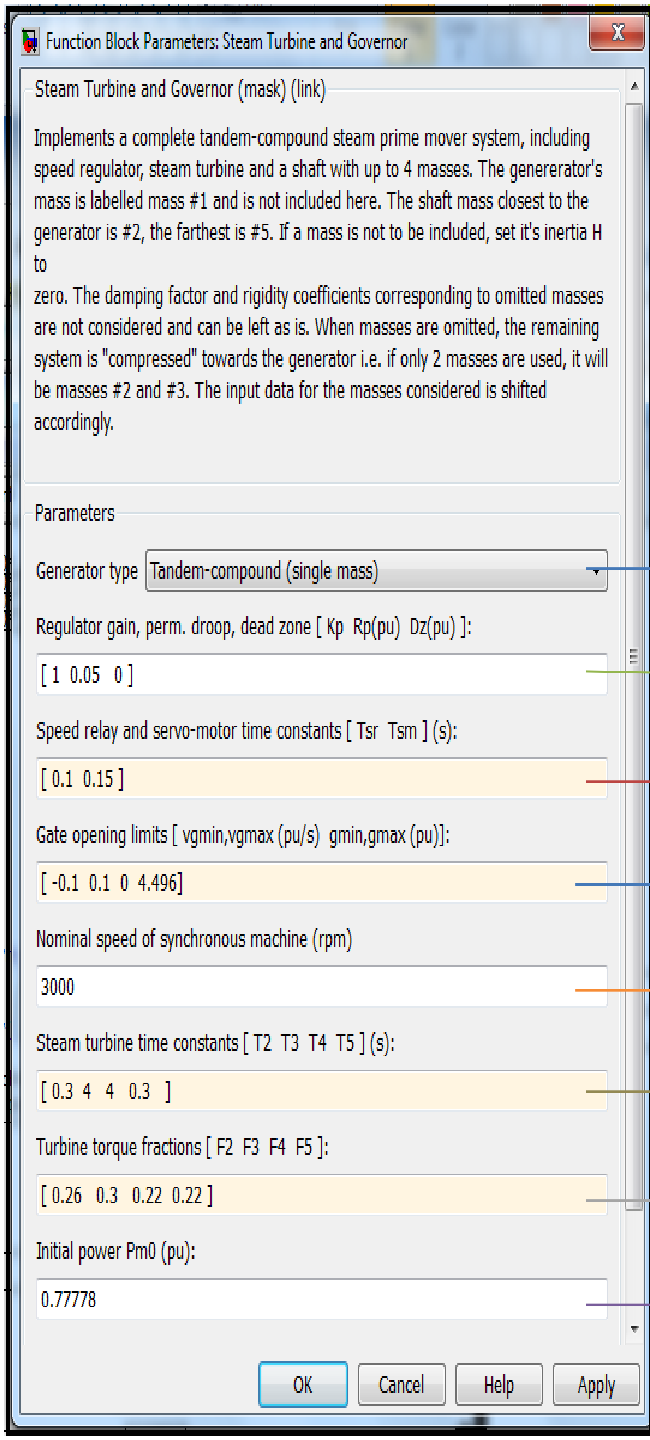


Fig. 4-7: Parameter details of steam turbine and governor block

One can select either multi mass or single mass shaft. As we have considered a single mass shaft for this study. So we have selected the same over here.

Kp is the gain of the regulator and is set to 1.0 because we are not using the steam flow feedback as discussed earlier. This value should be changed to 3 if one wants to take the steam flow feedback into account.

The permanent droop determines the part of the load which will be supplied by the generator in case of any load change. Its typical value is 0.05 pu

Dz is the dead zone which means that the minimum variation below which the governor system will not operate. It has been set to 0 to allow governor operation for slightest changes in the speed

A speed relay senses the deviation in the speed of the rotating shaft or drive. The value of time constant Tsr = 0.1 sec

A servo motor changes the valve position. Its time constant is Tsm=0.15 sec

vgmin and vgmax are the minimum and maximum gate opening speed while gmin and gmax are the limits of the gate opening. vgmin and vgmax have a typical value or 0.1 and -0.1 p.u. /s while we are using the default values for the gmin and gmax i.e. 0 and 4.496 p.u. respectively

As we have considered a single pole pair machine (turbo generator). So synchronous speed will be 2*pi*f=2*pi*50=314.16rad/sec = 3000rpm

T5 is time constant for the turbine chest and inlet piping. Its typical value is 0.1-0.4 sec
T4 and T3 are time constants for reheater 1 and reheater 2 respectivily and have typical values of 4-11sec.
T2 is the time constant for the crossover and has typical value of 0.3-0.5sec

F5 to F2 are the portions of total turbine power developed in various cylinders of the turbine. F5 represents very high pressure turbine power fraction, F4 represents high pressure, F3 represents intermediate pressure, F2 represents Low Pressure Turbine Power Fraction

This is automatically calculated by using Power GUI block and its function “Load Flow and Machine Initialization”.

4.2.1.3. Excitation System

The field voltage of the synchronous generator can be supplied by a voltage regulator or an excitation system. For this study we are using the excitation system block from the machines category of SimPowerSystems to regulate the field voltage of the synchronous generator. Fig. 4-8 shows the excitation system block from the library.

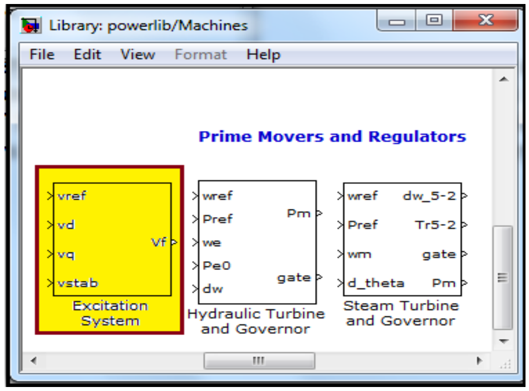


Fig. 4-8: Excitation System Block

The mathematical model of the Excitation System is shown in Fig.4-9. The model is similar to the IEEE DC1A Excitation System [37].

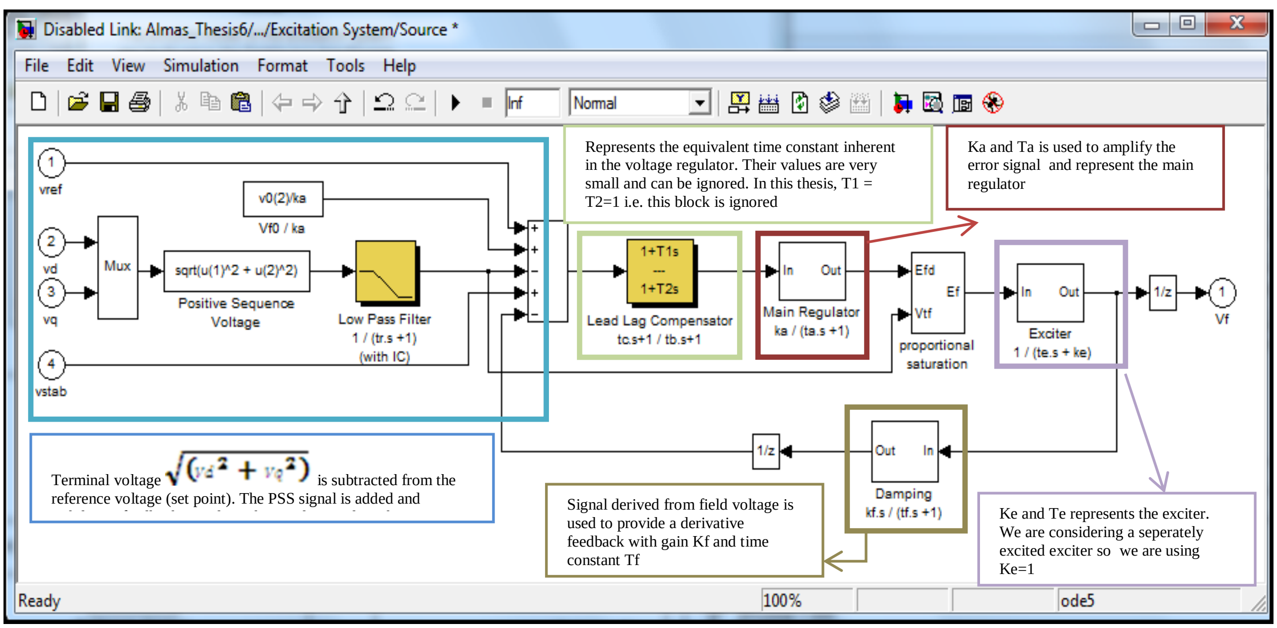


Fig. 4-9: Excitation System Mathematical Model

Inputs & Outputs of the Block

The first input v_{ref} is the reference voltage (set point) which is normally equal to 1 p.u. The second and third input V_d and V_q are the terminal voltages of the synchronous generator in dq-reference frame. These inputs are fed directly by the synchronous generator as shown in Fig. 4-10. The fourth input is the signal from the output of power system stabilizer. As we are not modeling a power system stabilizer in our system, so this input is ignored.

The output of this block is V_f i.e. field voltage and is fed directly to the synchronous generator as shown in Fig. 4-10. The values of different parameters are in accordance with the values proposed in [66].

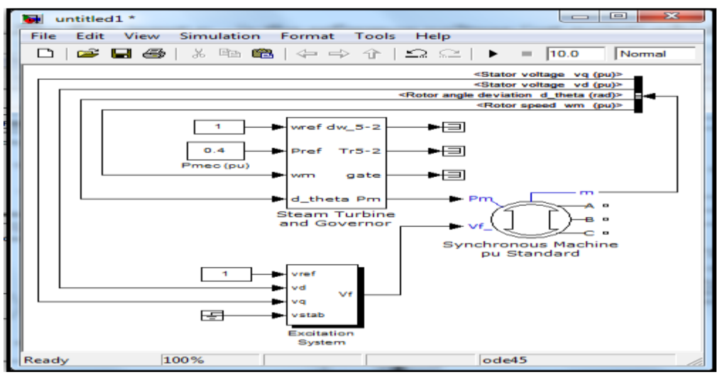
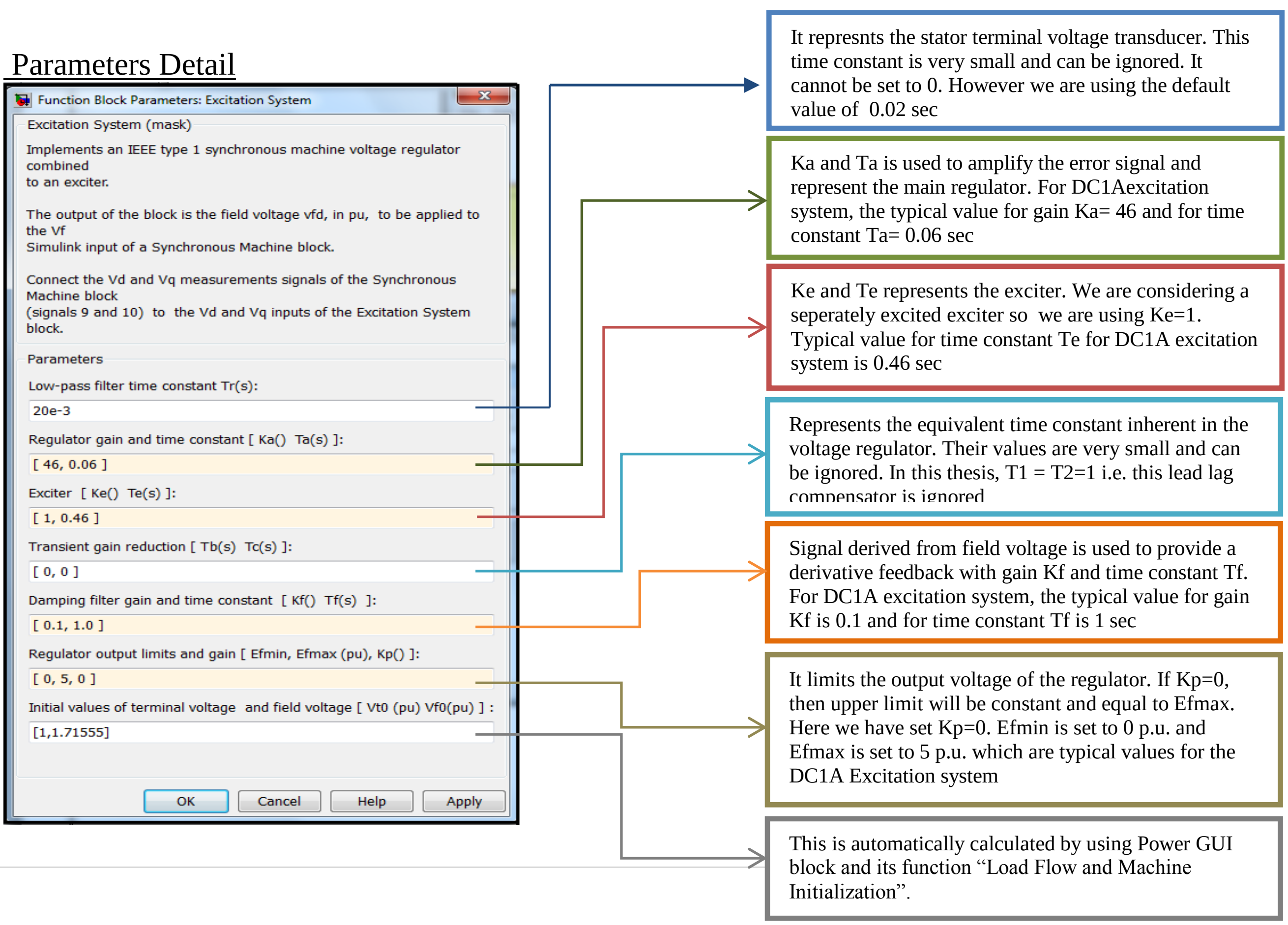


Fig. 4-10: Connection of a synchronous machine with an excitation system

Parameters Detail



4.2.1.4. Three Phase Transformers

The power system model shown in Fig. 1 consists of two three phase transformers. These transformers are modeled by using three phase transformer (two winding) block in the elements category of SimPowerSystems library as shown in Fig. 4-11.

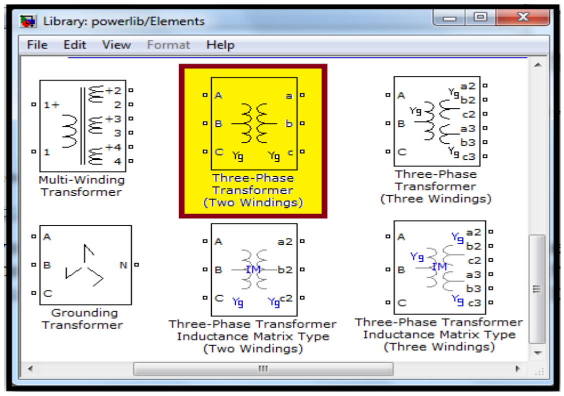


Fig. 4-11: Three Phase Transformer (Two Windings) Block

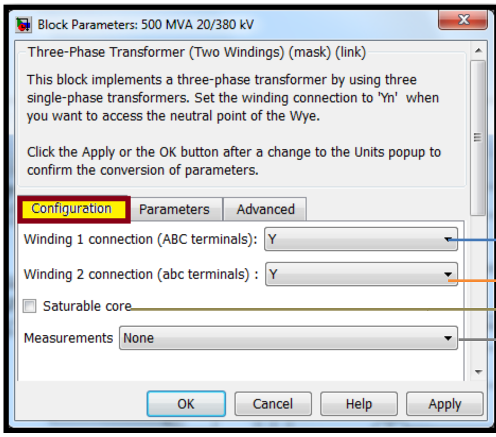
The block models three phase transformers using three single phase transformers. The model takes into account the winding resistances and inductances along with the magnetizing characteristics of the core.

Both the transformers (between Buses 2-3 and 3-4) have same parameters except for the voltages at the primary and secondary side and the transformer ratings. From Fig. 4-1 it is clear that transformer between Bus 2 and Bus 3 is a step up transformer and has primary side connected to 20kV and secondary side connected to 380kV. The transformer between Bus 3 and Bus 4 is a step down transformer and steps down 380 kV to 6.3 kV.

Inputs & Outputs of Block

The terminals A, B, C represents the primary side of the transformer and the terminals a, b, c represent the secondary side of the transformer. Each transformer can be modeled as a step up or step down transformer by using appropriate voltage levels at the primary and secondary windings of the transformer.

Parameters Detail

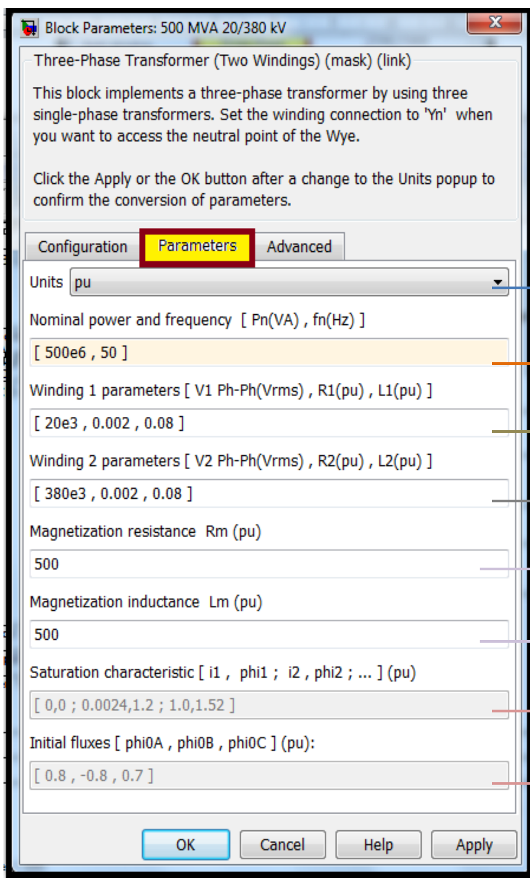


Winding 1 represents the primary side of the transformer. The transformer between Bus 2 and Bus 3 has a primary side connected to a generator with a generator having a specific line to line voltage. So primary side is connected as Y so that line voltage from generator terminal and line voltage seen by transformer is same.

The secondary winding of transformer is also connected as Y to make the turns ratio calculations simpler. If the windings are connected differently then turns ratio calculations becomes more complicated due to Y-delta transformation of voltages. So in this model we have used Y connecting windings for both primary and secondary sides of both the transformers (Bus 2-3 and Bus 3-4)

If selected then implements a saturable three phase transformer. We have ignored this part in our system modeling.

It provides option to measure voltages, flux or currents at the terminals of the windings. We are not using this option as we have used three phase VI measurement blocks from the SimPowerSystems library to serve the same purpose



It provides an option to enter the parameters values in either per unit or SI units. We have chosen per unit values.

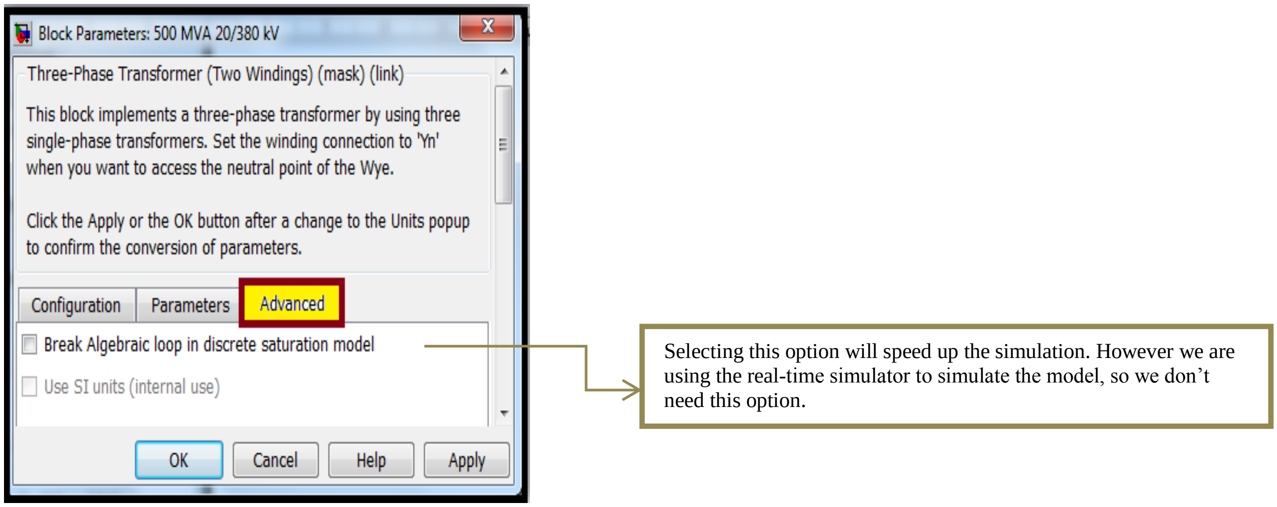
It represents the nominal power (rating) of transformer and the frequency of the power system. Both the transformers (2-3 and 3-4) are operated at a 50 Hz frequency. The nominal power of transformer 2-3 is 500MVA as it is connected to the generator with a rating of 500MVA. The nominal power of transformer 3-4 is 50 MVA as it is connected to an induction motor of 4.9 MVA and keeping into account that the motor draws 4-6 times the rated current at startup. So the nominal power of transformer 3-4 is kept to 200MVA.

The phase to phase voltage for the primary side of transformer 2-3 is 20 kV and the winding resistance and inductances are 0.002 and 0.08 pu respectively. As transformers windings have usually very small resistance so this value of 0.002 p.u. is acceptable. The value of inductance is normally within the range of 0.05 to 0.15 p.u. As these values are important only for saturable transformers, so we are using the typical values of 0.08 pu in our case.
Transformer 3-4 has exactly the same setting except the voltage which is 380kV in its case.

All the settings are exactly same as that of primary winding except the voltage level. The voltage at secondary winding of transformer 2-3 is 380 kV (i.e. step up transformer) and the secondary voltage for transformer 3-4 is 6.3 kV (i.e. step down transformer)

These parameters correspond to the magnetizing impedance of the transformer. These values are generally very high. We are using the default values of 500 p.u. (To specify a magnetizing current of 0.2% (resistive and inductive) based on nominal current, you must enter per unit values of 1/0.002 = 500 p.u. for the resistance and the inductance of the magnetizing branch.)

As we are not using the saturable transformer, so these parameters are neglected



4.2.1.5. <u>Three Phase PI Section Line</u>

The transmission lines between Buses 1-3 are modeled by using three phase PI section Line Block available in the elements category of the SimPowerSystems Library as shown in Fig. 4-12.

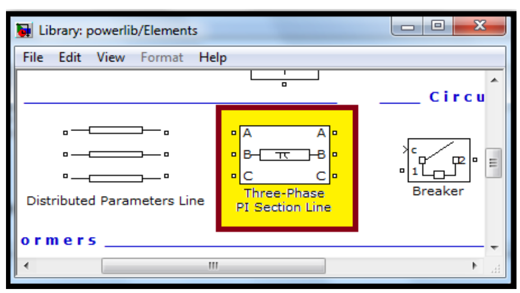


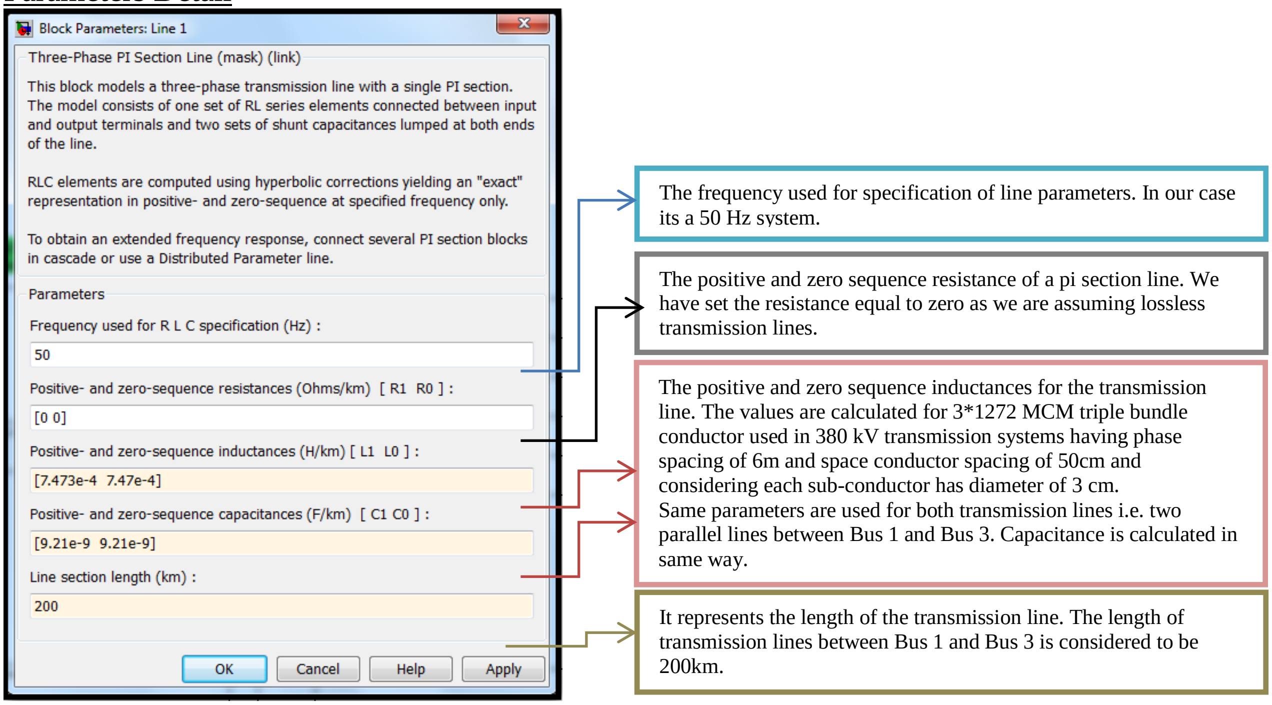
Fig. 4-12: Three Phase PI Section Line Block

This block implements a balanced three phase transmission line with parameters lumped in a PI section line. The transmission line between Buses 3-5 is modeled by using distributed parameters lines (modifications are required for making it compatible with the real time simulator and is discussed in detail in later sections).

<u>Inputs & Outputs of Block</u>

The terminals A B C on both sides of the block represent the two ends of a transmission line. The parameters provided for the transmission line will implement a pi section line within these two terminals of a block.

Parameters Detail



The values are calculated for 3*1272 MCM (MCM means thousands of circular mills) triple bundle conductor used in 380 kV transmission systems having phase spacing of 6m and space conductor spacing of 50 cm and considering each sub-conductor has diameter of 3 cm.

4.2.1.6. Thevenin Equivalent

We have modeled the rest of the power network as a thevenin equivalent i.e. a voltage source in series with thevenin impedance. As each power system model requires one Swing Bus to carry out the load flow calculation, so this thevenin equivalent also serves as a swing bus. It is modeled by using three phase voltage source block available in the electrical source category of SimPowerSystems Library as shown in Fig. 4-13.

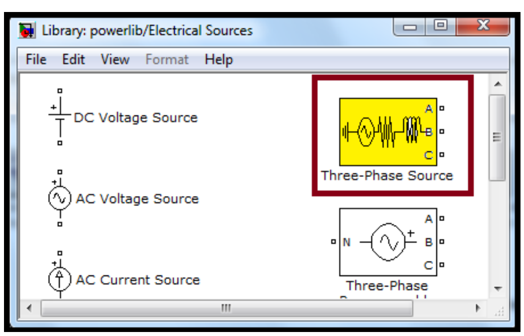
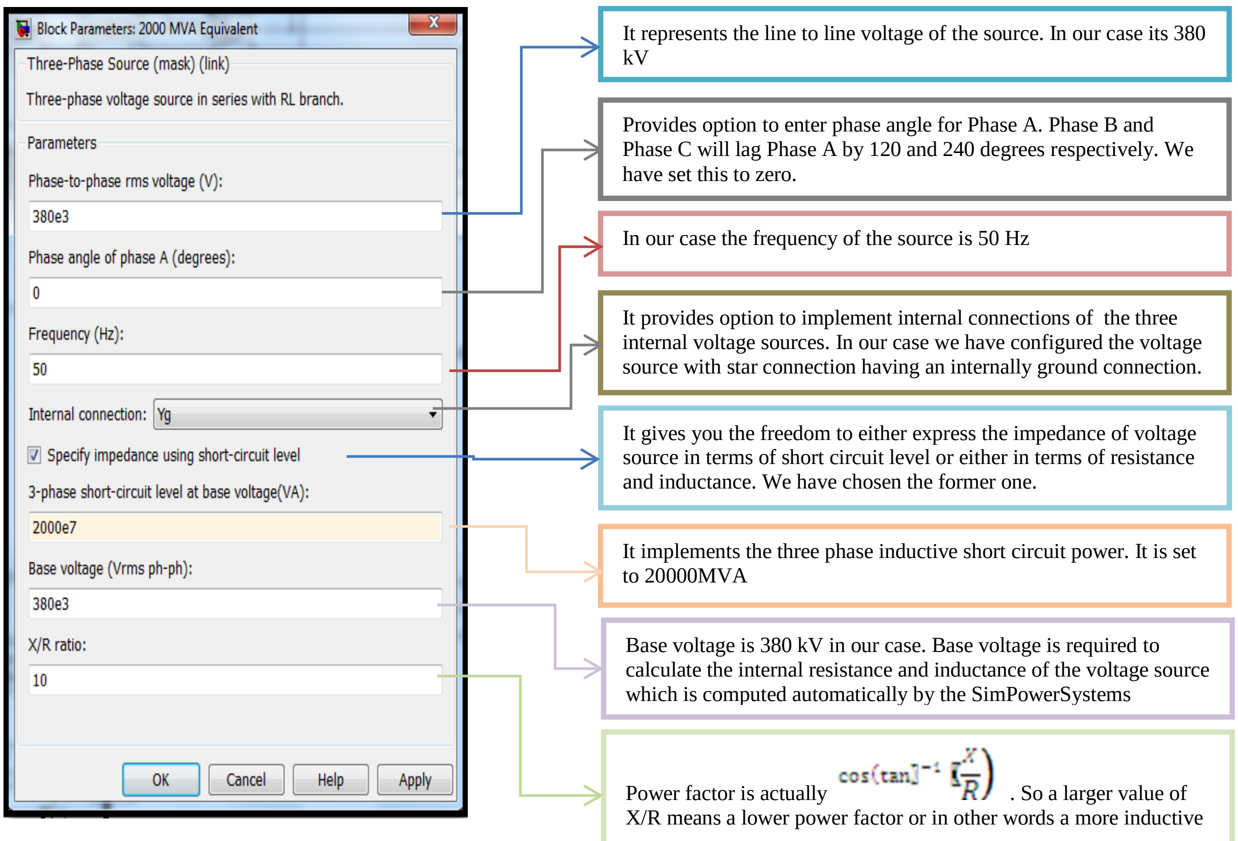


Fig. 4-13: Three Phase Voltage Source Block

Inputs & Outputs of Block

The terminals A B C represents three phases of the voltage source which are connected to the rest of the system.

Parameters Detail



4.2.1.7. Induction Motor

The induction motor shown in Fig.1 is modeled by using Asynchronous machine S.I. block available in the machine category of SimPowerSystems Library as shown in Fig. 4-14.

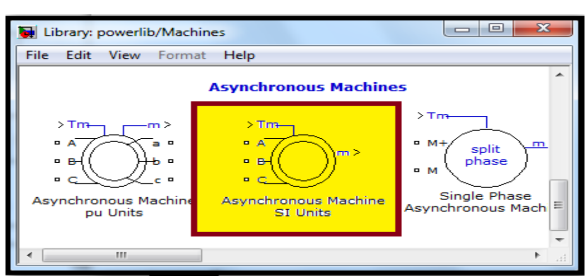


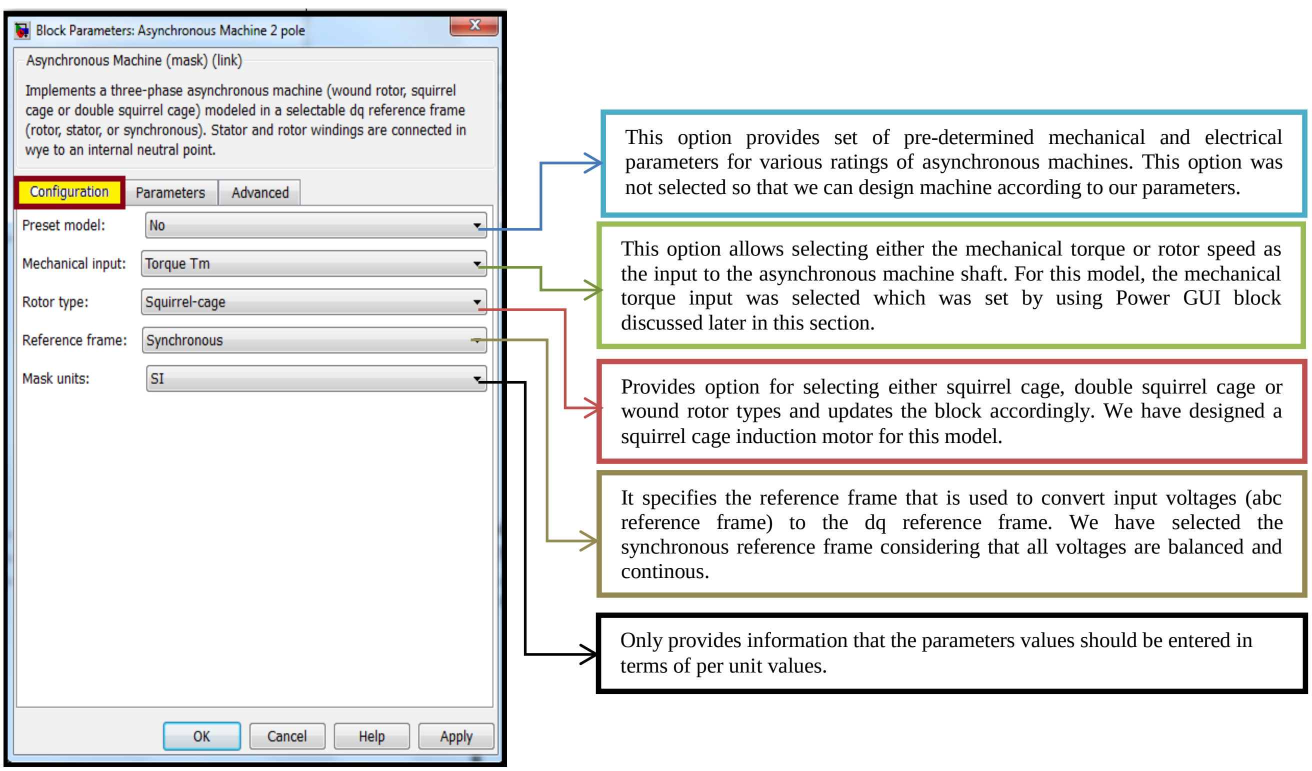
Fig. 4-14: Three Phase Asynchronous Machine SI Block

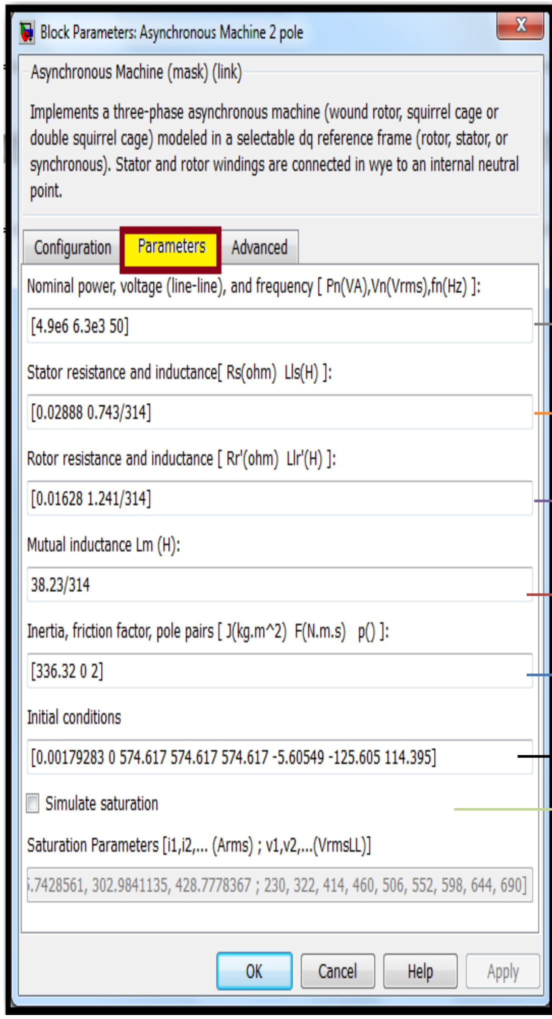
The block models the dynamics of three phase induction machine which can operate either in generator or motor mode. The sign of the mechanical torque input T_m identifies the mode of operation of the machine. A positive T_m represents motor mode and negative T_m represents generator mode.

Inputs & Outputs of Block

The terminals A B C represents stator terminals of the machine and is connected to the three phases of the power system (voltage source etc.) T_m identifies the mode of operation of the machine which is motor mode in our case. “m” is an output which provides metering facilities for various signals which can be chosen with the help of “bus selector” block of Simulink.

Parameters Detail





It determines the rating of the induction motor. In our case we have designed an induction motor with the following rating:

Nominal Power = 4.9 MVA
Line to Line Voltage = 6.3 kV
Frequency = 50 Hz

These fields represents the stator resistance and leakage inductance. We have set Rs=0.02888 ohm. The leakage inductance is calcualted from the leakage reactance which was Xls = 0.743. So $Lls = \frac{Xls}{2 * pi * 50}$ = 0.743/314 H

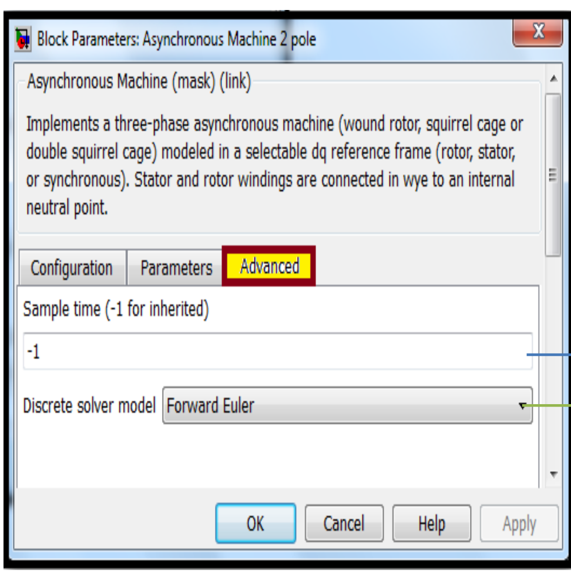
These fields represents the rotor resistance and leakage inductance both referred to the stator side. We have set Rr'=0.01628 ohm. The leakage inductance is calcualted from the leakage reactance which was Xlr = 1.241. So $Llr' = \frac{Xlr}{2 * pi * 50}$ = 1.241/314 H

It represents magnetizing inductance. The magnetizing inductance is calcualted from the magnetizing reactance which was Xm = 38.23. So $Lm = \frac{Xm}{2 * pi * 50}$ = 38.23/314 H

J is the combined machine and load inertia. For this particular motor its value is 336.32 kg. m^2. Fricition coefficient is set to zero. The number of pole pairs for this motor is 2.

The initial conditions are calculated automatically by using "Load Flow and Machine Initialization" feature of Power GUI block. It is discussed in detail later in this section.

This option is used to simulate the saturation of the motor. It has been ignored in this model.



Specifies the simulation time step used by the machine block. It has been set to -1 to inherit the sample time specified in the Power GUI block.

Specifies the solver used to solve the equations in the mathematical model of the block. Leave it to the default setting i.e. Forward Euler Solver.

The parameters of induction motor are in accordance with the parameters of the same rating of an induction motor by most of the vendors (ABB, etc.). These parameters can be obtained from the data sheet of these motors.

4.2.1.8. Three Phase OLTC

The three phase OLTC transformer block available in the transformer category of the application library of SimPowerSystems is phasor type. However we are modeling this system in discrete mode. This phasor block cannot be used in discrete mode. The OLTC block thus used for this purpose is available in the demo OLTC Regulating Transformer (Phasor Model).
This demo contains simple three phase OLTC regulating transformer and three phase OLTC regulating Transformer (Phasor Type). For this model, we have used the former block as shown in Fig. 4-15.

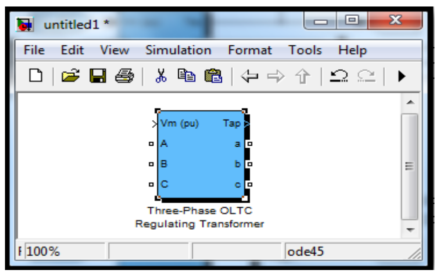


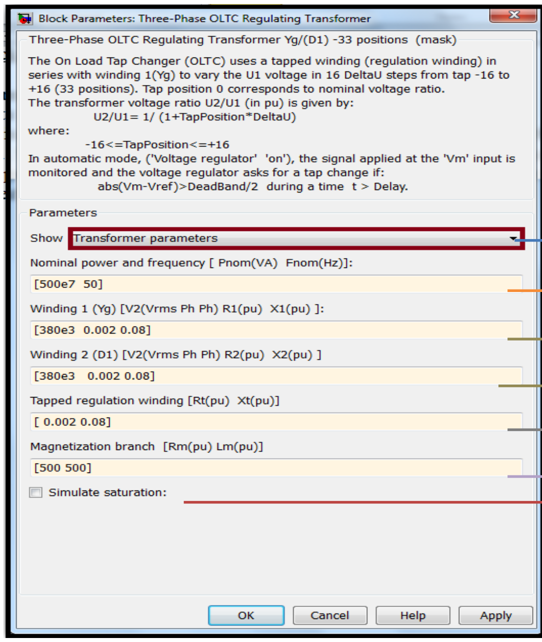
Fig. 4-15: Three Phase Regulating OLTC Transformer

This block models a three phase two winding transformer with on load tap changer to regulate the voltage on the transmission or distribution network. This model basically provides 17 taps i.e. +8 to -8 and tap position 0 represents nominal voltage ratio. However we have made this model for 33 taps i.e. +16 and 16 with 0 as nominal voltage ratio. This block contains the information and steps required to convert this 17 tap model to a 33 tap position model.

Inputs & Outputs of Block

The terminals A B C represents three input terminals connected to winding 1.
Terminals a b c represents the three output terminals connected to winding 2 .
V_m is the voltage which is to be controlled. In our case we have load at bus number 6 whose voltage is to be regulated. So we are feeding this input with a voltage magnitude at bus 6.
“m” is an output which provides metering facilities for various signals which can be chosen with the help of “bus selector” block of Simulink.

Parameters Detail



It allows the option to show the settings for either transformer parameters or OLTC and Voltage Regulator Parameters. First we are discussing the transformer parameters.

It represents the nominal power (rating) of transformer and the frequency of the power system. Nominal power is set to 5000MVA as we will be over-loading this line to reproduce a voltage instability scenario which will be explained later in this section. A higher rating of transformer is chosen so that the increase in load doesn't affect its operation. The nominal frequency is 50 Hz.

As we are using only the OLTC and voltage regulation features of this block. So we have kept the same voltage levels at both sides of the transformer. Which actually means that transformation ratio is one. The winding resistances and reactance are the same as discussed in the three phase two winding transformer parameter's detail earlier.

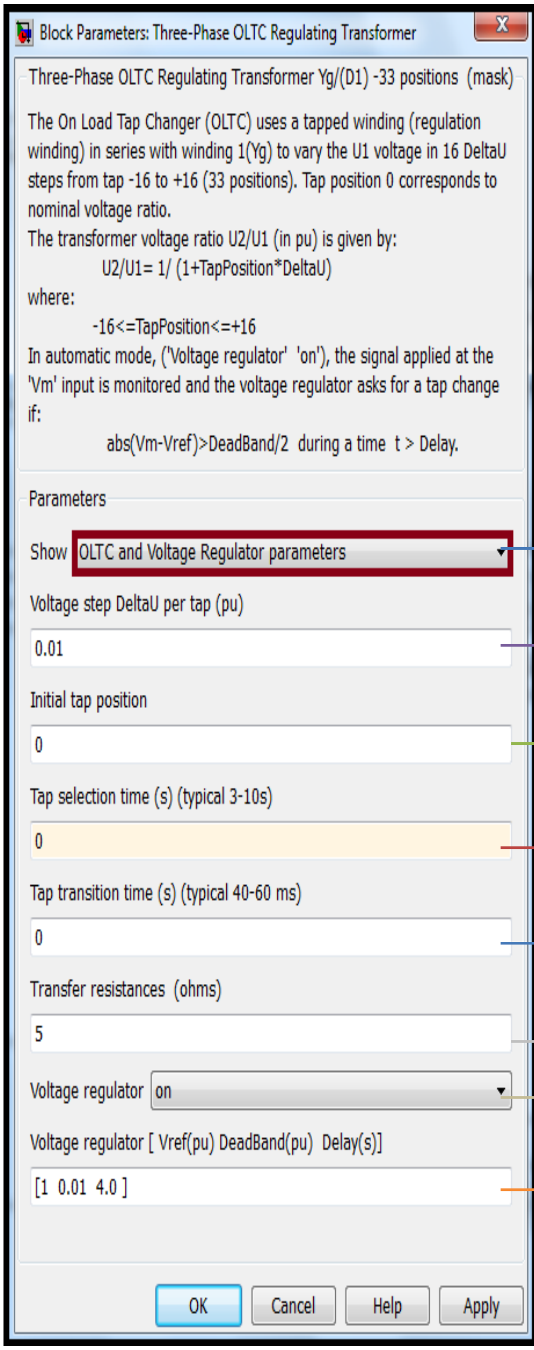
It corresponds to the tapped winding. Tapping is actually making a wire connection at some point of the winding. It behaves as multiple winding transformer with no electrical isolation between them. We have used same values for the tapped windings as well.

These parameters correspond to the magnetizing impedance of the transformer. These values are generally very high. We are using the default values of 500 p.u. same as discussed before (Three phase two winding transformer).

As we are not using the saturable transformer, so these parameters are neglected.

We have chosen 33 taps for the OLTC because we are interested to reproduce a long term voltage instability scenario. This actually means 16 taps in positive and 16 taps in negative direction, i.e. if OLTC step size is 0.01 pu, then with 33 steps it can regulate within 1.16 pu and 0.84 pu.

Details of Parameters



It allows the option to show the settings for either transformer parameters or OLTC and Voltage Regulator Parameters. Now we are discussing the OLTC parameters for this block.

As we have modeled it for a 33 step i.e. +16 and -16 tap positions. So we have kept the voltage step size to 0.01 p.u. It means that whenever the OLTC changes its step by 1, there will be a change in voltage magnitude by 0.01 pu

Initial tap position is set to 0 which corresponds to nominal voltage ratio

It is the mechanical time delay required for the OLTC to change its tap. We have selected it 0 as we are considering this time delay in the voltage regulator field.

This time is also not considered here and has been taken into account in the voltage regulator field

To avoid arcing when the tap changer operates. It has been set to 5 ohm which is the default value for it.

Selecting it on will allow the tap changer to operate whenever the voltage goes below the reference voltage and the difference is greater than half of the dead band and this condition remains for a certain time which can be set in the parameter setting delay.

V_{ref} is the voltage reference which will be the set value for the voltage regulator. It is set to 1 p.u. Whenever the voltage at bus 6 varies from 1 p.u. and this difference is greater than 0.005 pu (half of the dead band) and this condition remains for 4 sec (delay i.e. checking this condition whether it persists till this time or not. If the condition persists then OLTC will operate after 4 sec otherwise it won't operate).

4.2.1.9. Dynamic Load

The load which is connected to OLTC (Fig.1) is modeled by using dynamic load block in the elements category of SimPowerSystems as shown in Fig. 4-16.

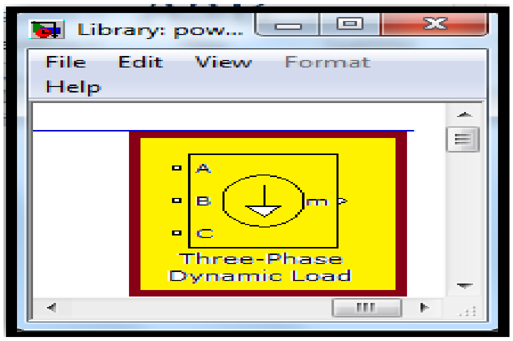


Fig. 4-16: Three Phase Dynamic Load Block

This block models a three phase three wire dynamic load which can be configured as a constant current, constant impedance or constant power load. If the terminal voltage at the load goes below a pre-set value (i.e. V_{min} discussed later in parameters detail) then the load will automatically behave as a constant impedance load. The active and reactive power of load is given as:

$$P(s) = P_0 \left(\frac{V}{V^0} \right)^{np} \frac{1 + sT_{p1}}{1 + sT_{p2}}$$

$$Q(s) = Q_0 \left(\frac{V}{V^0} \right)^{nq} \frac{1 + sT_{q1}}{1 + sT_{q2}}$$

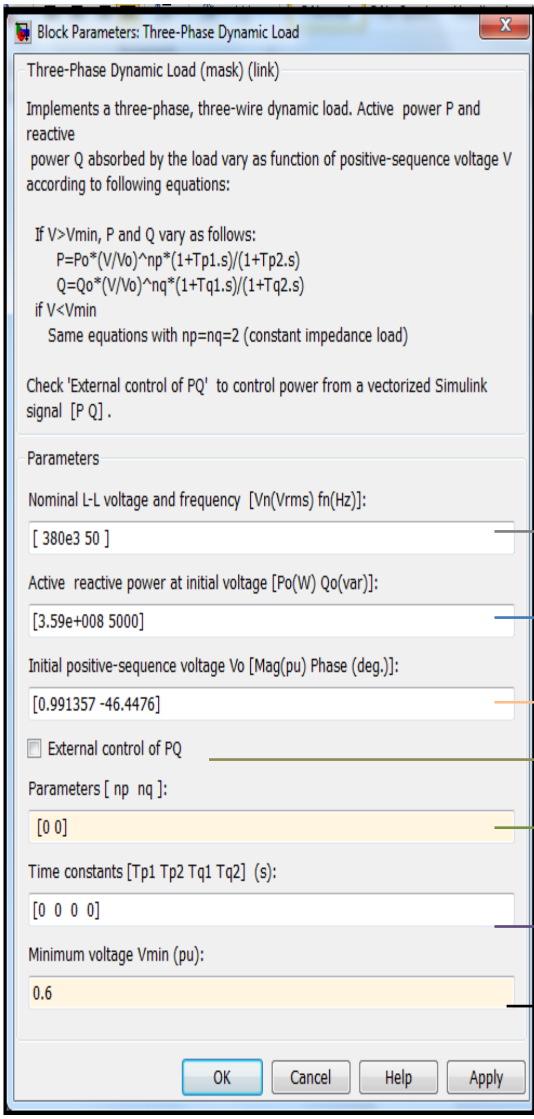
Where V is the actual voltage, V^0 is the reference voltage or initial positive sequence voltage, P_0 and Q_0 are the active power and reactive power at initial voltage V^0. np and nq are exponents and determine the nature of load (np=nq=0 for constant power, np=nq=1 for constant current, np=nq=2 for constant impedance). We are using the constant power load model, as we are interested to reproduce a voltage collapse scenario which is more likely to happen if the load power remains constant even with the fluctuation of voltage. The OLTC operation coupled with a constant power load will demand more reactive power from the system to step up the voltage at load terminal in case of any dip in voltage at that end; as a result will contribute more towards voltage collapse.

Inputs & Outputs of the Block

The terminals A B C represents three input terminals i.e. the three phase power supply for the dynamic load.

"m" is an output which provides metering facilities for various signals which can be chosen with the help of "bus selector" block of Simulink.

Parameters Detail



It specifies the nominal voltage and frequency at which the load will operate. As the load is connected to secondary side of OLTC transformer which has been set to 380 kV (has been discussed in detail in the OLTC Transformer) So the load is configured for same voltage level.

Line to Line Voltage = 380 kV
Frequency = 50 Hz

The initial active and reactive power consumed by the load at the initial voltage V_0 as discussed earlier. SimPowerSystem considers this bus as PQ bus and allows the user to set these values in the Power GUI block which is discussed later in the section. These values were set to reproduce a long term voltage instability scenario.

The initial conditions are calculated automatically by using "Load Flow and Machine Initialization" feature of Power GUI block. It is discussed in detail later in this section

This option can be selected to externally control the active and reactive power values for the load.

As we have discussed earlier that we are modeling a constant power load connected to the OLTC transformer, so these exponential parameters are set as np=nq=0

These parameters specifies the time constants for the dynamics of the load. These are set to zero as we are interested in modeling the load as a constant power load.

Below this voltage the load will behave as a constant impedance load. We have deliberately kept this low, as we want the load to behave as a constant power even at low voltages to further contribute towards the voltage collapse

4.2.1.10 Three Phase Circuit Breaker

As one of the task of this study is to design the protection scheme for this model, which means that in case of any fault, the respective power system component i.e. transmission lines, load, motor etc. should be disconnected from the system. In addition the circuit breakers are also used to connect additional load at the OLTC in order to reproduce the voltage collapse scenario. The three phase circuit breaker is modeled by using three phase breaker block from the elements library of SimPowerSystems as shown in Fig. 4-17.

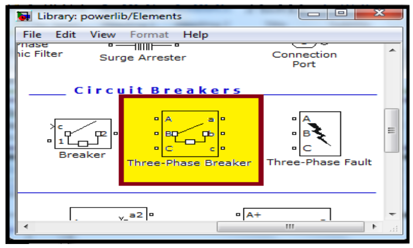
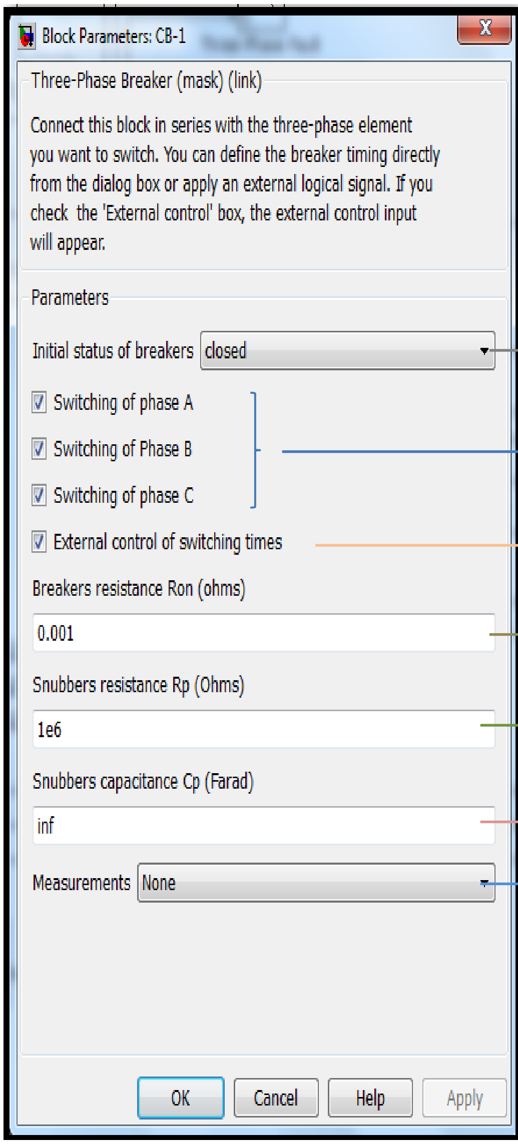


Fig. 4-17: Three Phase Breaker Block

Inputs & Outputs of the Block

The terminals A, B, C and a, b, c represent two ends of the breaker. When the circuit breaker operates i.e. opens or closes, it connects or disconnects the link between these two ends. In addition there is an option to control the operation of circuit breaker externally. We have used this option to operate the circuit breaker for some particular conditions, .e.g. opening of a breaker if the current goes above a certain level etc. The detail of the protection part of this study will be explained in the second part of the report.

- **Parameters Detail**



It provides the option to set the initial status of the breaker. It can be either close or open. In this model we have used some breakers with inital open status e.g. breakers connected to the transmission line and some breakers with initally open status e.g. breaker connected to the OLTC which operates to connect the additional load at bus 6 to reproduce voltage collapse scenario.

It provides option to either switch individual phases or three phases in case of breaker operation. We have selected three phase operation for the breaker so breaker operation in case of fault should completely disconnct the component from rest of the power system, etc.

This option has been selected to control the breaker externally so that we can automatically operate the breaker in case of fault.

It specifies the internal breaker resistance. It cannot be set to 0. We are setting the default value for this parameter.

Snubbers are required in case of serial connection of three phase breaker with an inductive component or a current source. We are using the resistive snubbers with a default value. The resistive snubber can be eliminated by using inf (infinity) value for this parameter.

It provides option for a series Rs-Cs snubber circuit. It has been set to inf i.e. we are ignoring the capacitive snubber.

This option can be used to measure the breaker voltage or currents etc. We are not using this option as we have used three phase VI measurement block to serve the same function.

4.2.1.11. Three Phase Fault

As this model is actually designed to study dynamics of power systems, i.e. transient stability, voltage stability, frequency stability, so we have given a provision for the user to apply a three phase fault at two parallel transmission lines between Bus 1 and Bus 3 to check the response of the system under these circumstances. However in this study we are strictly limiting ourselves to longterm voltage instability scenario, but still this information is provided for the user to have an overview of the capability of this all-in-one system. The three phase fault were applied by using three phase fault block available in the elements category of SimPowerSystems library as shown in Fig. 4-18.

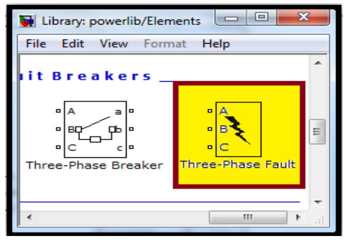
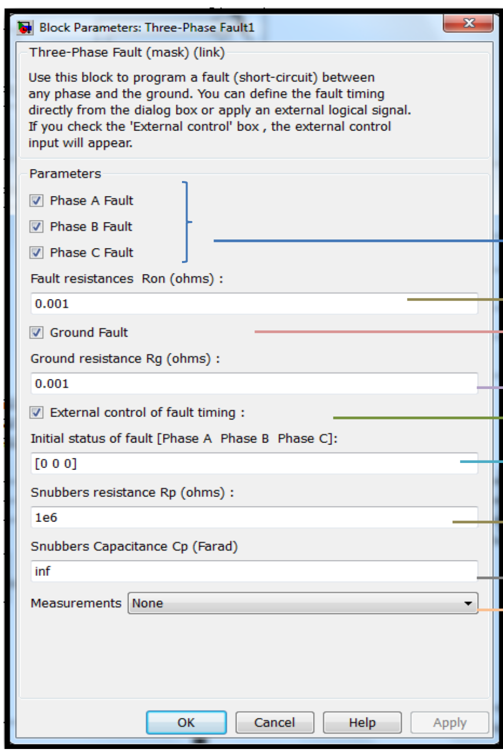


Fig. 4-18: Three Phase Fault Block

<u>Inputs & Outputs of Block</u>

The terminals A, B, C represent the three breakers inside the block which are connected to the ground through an internal ground resistance. We are also using this three phase fault block in an external control mode so that the user can apply fault whenever he wants to check the behavior of the system.

<u>Details of Parameters</u>



It provides option to either apply single phase, two phase or three phase faults. We are applying three phase to ground fault in our model i.e. symmetrical fault.

It specifies the internal fault resistance. It cannot be set to 0. We are setting the default value for this parameter.

This option allows applying ground faults. If this option is not connected then the ground resistance is kept to 1 Mega ohm. We are using three phase to ground fault so we have enabled this option.

The ground resistance has been set to a default value of 0.001 ohm.

This option is enabled as we are allowing the user to implement a three phase fault whenever he wants in order to analyze the behavior of the system.

0 represents fault is not connected and 1 represents fault is connected. Initially the three phase fault is not connected in this model.

Snubbers are required in case of serial connection of three phase fault with an inductive component or a current source. We are using the resistive snubbers with a default value. The resistive snubber can be eliminated by using inf (infinity) value for this parameter .

It provides option for a series Rs-Cs snubber circuit. It has been set to inf, i.e. we are ignoring the capacitive snubber.

This option can be used to measure the breaker voltage or currents etc. We are not using this option as we have used three phase VI measurement block to serve the same function.

The three phase fault block is provided to check dynamics of the system; it is not part of this study and is only provided in the system to allow the user to analyze dynamic behavior of system with any instability.

4.2.1.12. <u>Power GUI Block</u>

It is an environment block for SimPowerSystems models and provides multiple functions. It is available in the main library of SimPowerSystems as shown in Fig. 4-19

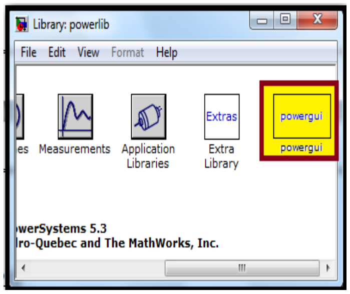
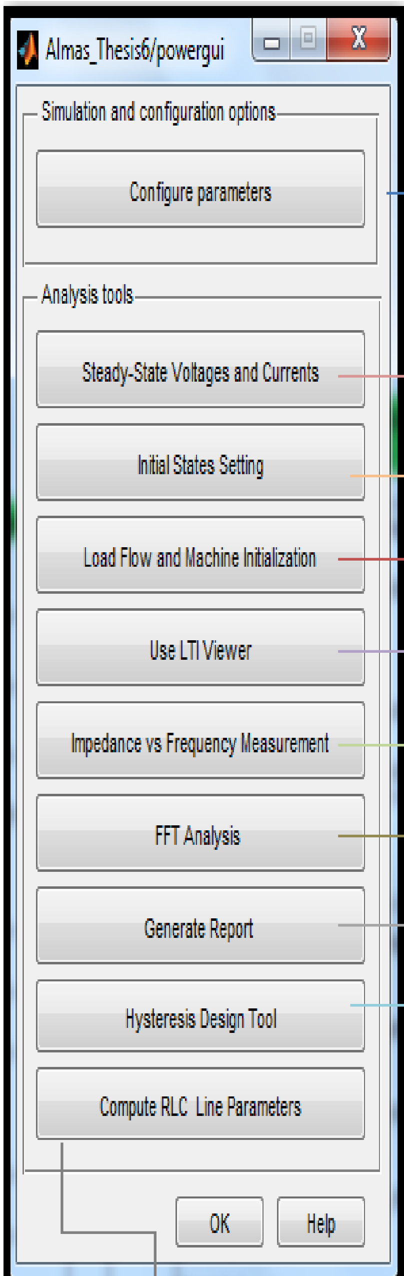
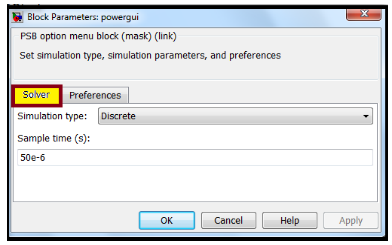
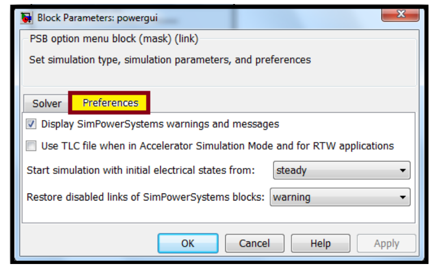


Fig. 4-19: Power GUI Block





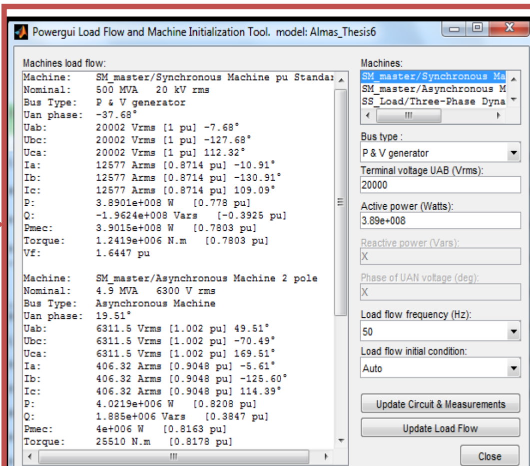


It allows to use either continuous, discrete or phasor mode for solving the model. As we are going to simulate our model in real-time simulator with a fixed time step, so we have chosen discrete mode with a sample time of 50 micro seconds.

The first option enables messages and warnings during the analysis and simulation of the model. Second is used to accelerate the simulation (not using this option as we are using the real-time simulator). Third option allows to start simulation with either steady state, zero or block parameters value. We are starting simulation with steady state values calculated by using initial state settings option of power GUI discussed below. Fourth option allows the user to see a warning in case of any disabled link for the blocks in the model

This tool displays the steady state voltages and currents of the model.

Initial state can be set to either zero or steady state by this tool.



This tool automatically configures the PV and PQ buses in the model and allows the user to set the values for terminal voltage and active power in case of PV bus and active and reactive power in case of PQ bus. In presence of induction motor, this tools automatically calculates the input mechanical torque required for the motor corresponding to the mechanical power output in Watts entered by the user (the mechanical power output which is desired by the motor). Update load flow button updates the load flow and sets the initial values for machines and loads.

To generate state space model.

Used in case of impedance measuring block.

Used to perform fourier analysis of the signals.

Allows to generate report of initial states, load flow and steady state values of the model.

Used in case of saturabale transformers which are not considered in this model

Can be used to determine R,L,C components of the transmission line if the type, number of bundle conductors and the spacing betwen them is known.

4.2.1.13. ***Metering Block***

In this model apart from monitoring the parameters of machines like speed, active power output, load angles etc. we are also monitoring the voltages and currents at the buses. This is done by using three phase VI measurement block which is available in the measurement category of SimPowerSystems library as shown in Fig. 4-20.

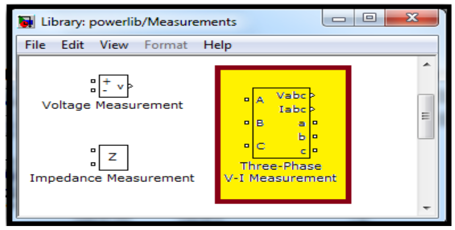


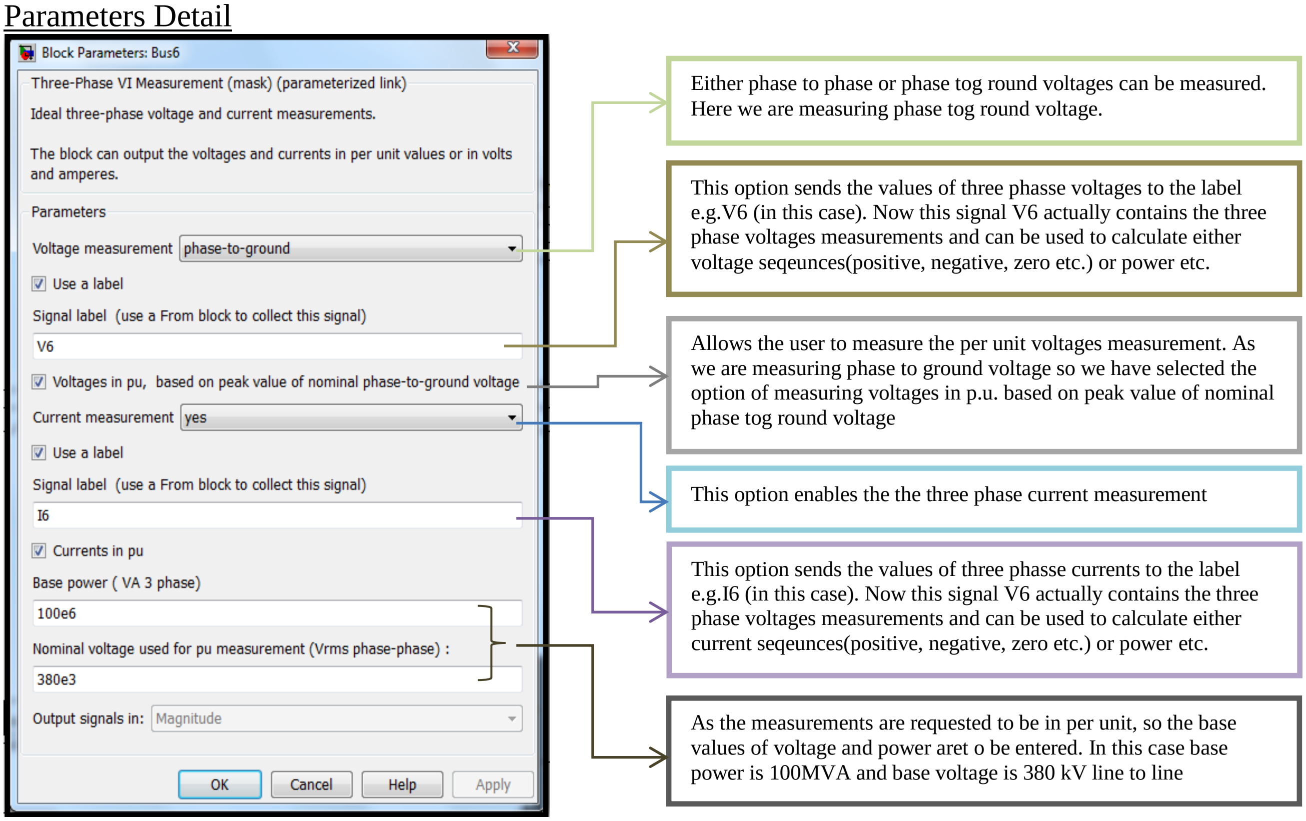
Fig. 4-20: Three Phase VI Measurement Block

This block measures the three phase instantaneous currents and voltages in a circuit. Either phase to phase or phase to ground voltages can be measured with the help of three phase VI measurement block.

Inputs & Outputs of Block

V_{abc} and I_{abc} are the outputs which contains the three phase voltages and current measurements. Terminals A B C are the input terminal and terminals a, b, c are the output terminals of this block. This block is often used to form a bus in the model as the output of the block is exactly the same as the input.

Parameters Detail



Another metering block used is discrete three phase sequence analyzer. As the signals from the three phase measurement blocks are the three phase voltages and currents in per unit, so these signals are fed to the discrete three phase sequence analyzer to get the positive sequence voltages and currents in per unit which are then monitored with the help of scope. The three phase discrete sequence analyzer is available in discrete measurement sub-category of the Measurements category in SimPowerSystems library as shown in Fig. 4-21.

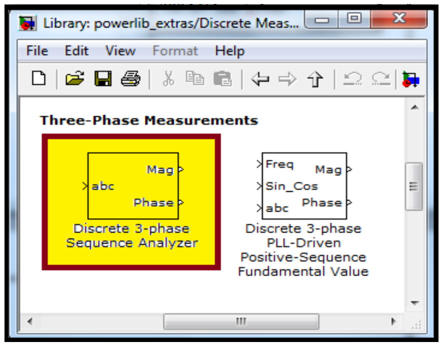
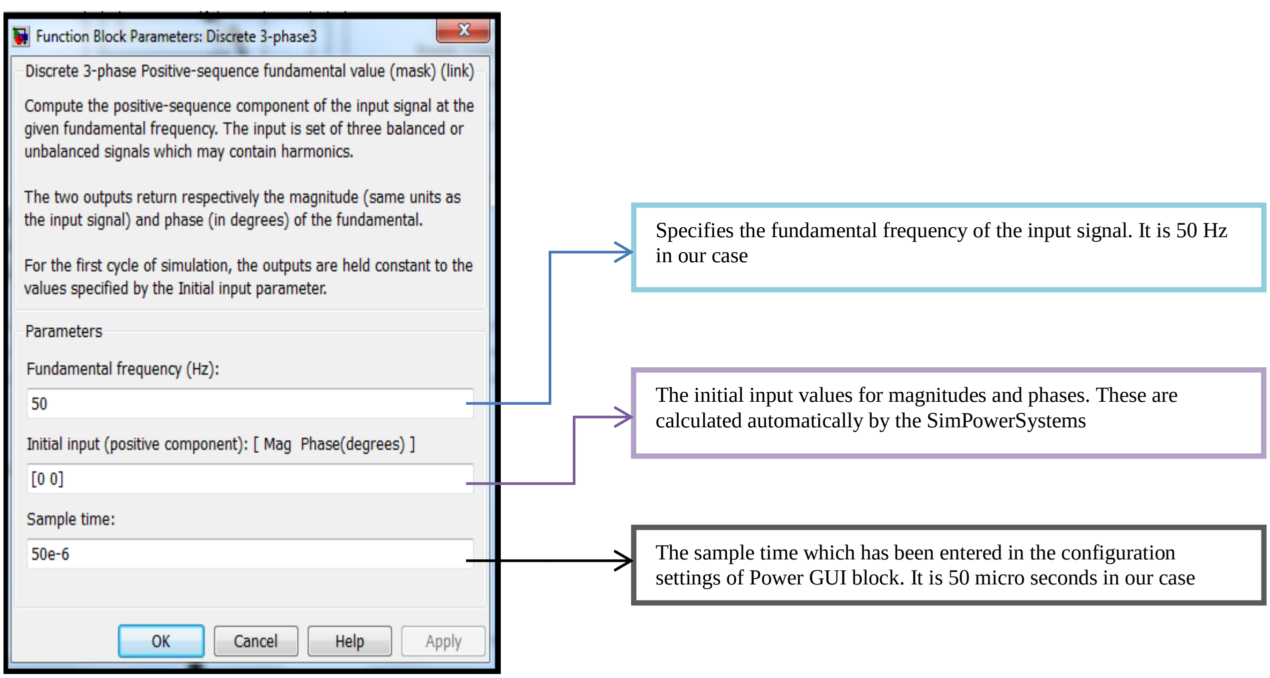


Fig. 4-21: Three Phase Discrete Sequence Analyzer Block

<u>Inputs & Outputs of Block</u>

a b c inputs can be either V_{abc} or I_{abc} generated by the three phase VI measurement block. The output mag and phase are the magnitude and phase of the positive sequence voltage/current.

<u>Details of Parameters</u>



4.3. Overall Power System Model

The single line diagram of all-in-one system including the circuit breakers and the provision for application of three phase fault is shown in Fig. 4-22.

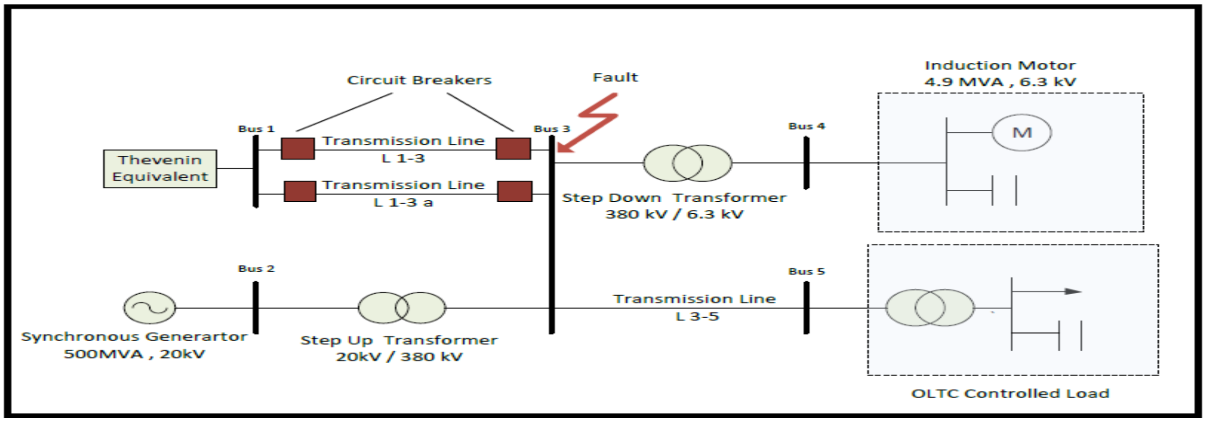
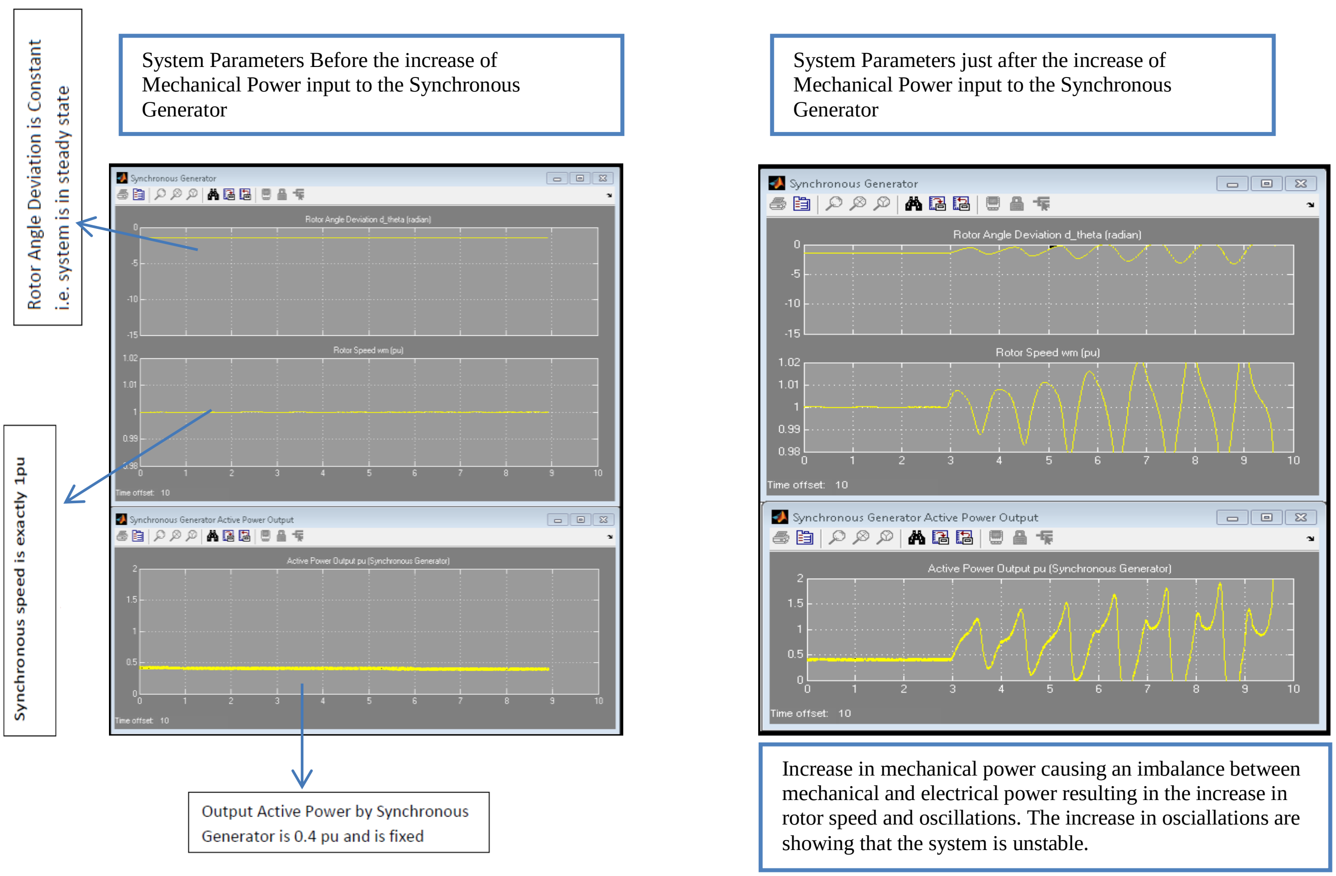


Fig. 4-22: Single Line Diagram of all-in-one System showing the breakers and the provision of applying faults

The all-in-one system has the provision to change the mechanical input of the synchronous generator in order to analyze the frequency instability scenarios. As this is not the part of the study, so we are just showing the effect of increasing the mechanical power input for showing the capability of the model.



This instability scenario is not part of the study. It is just shown to exhibit the capability of “all-in-one” test system. The project focuses on voltage instability, which is discussed in detail later in this section.
The overall system model in SimPowerSystems is shown in Fig. 4-23. The monitoring console where all the scopes are present and various parameters can be monitored is shown in Fig. 4-24. The console in Fig. 24 also contains the manual switches for manually operating breakers, applying faults, connecting loads, increasing mechanical power of the generator etc. in order to create different scenarios for stability studies. The system consists of the components which have been discussed in detail earlier.

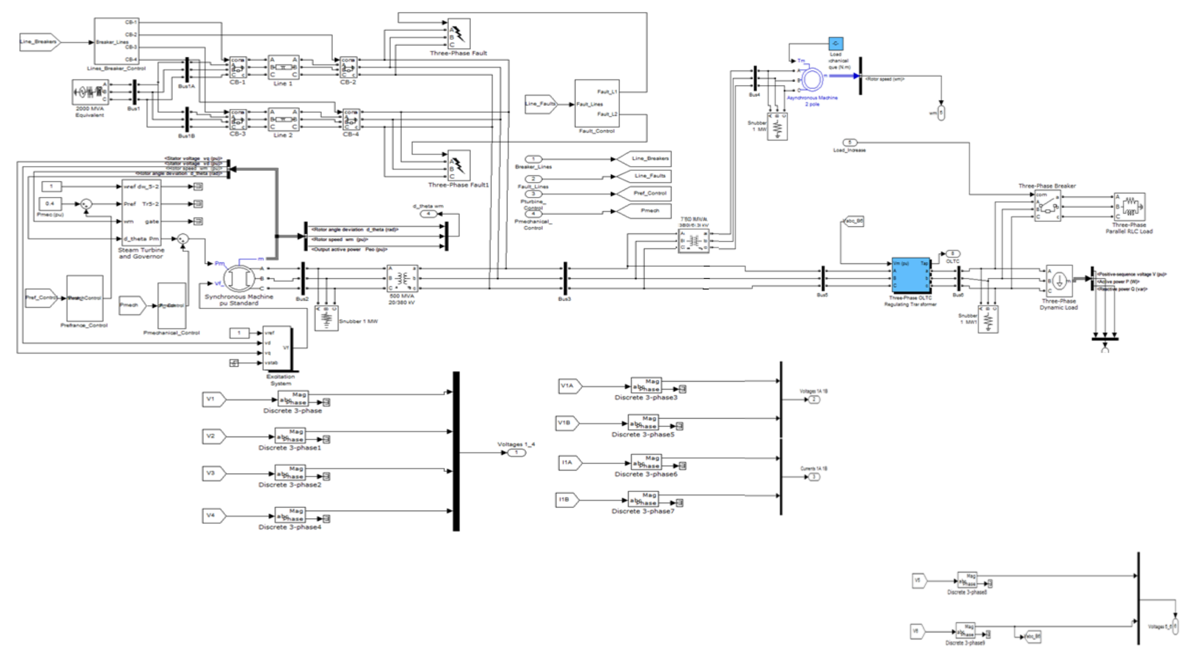


Fig. 4-23: SimPowerSystems Model of the “all-in-one” System

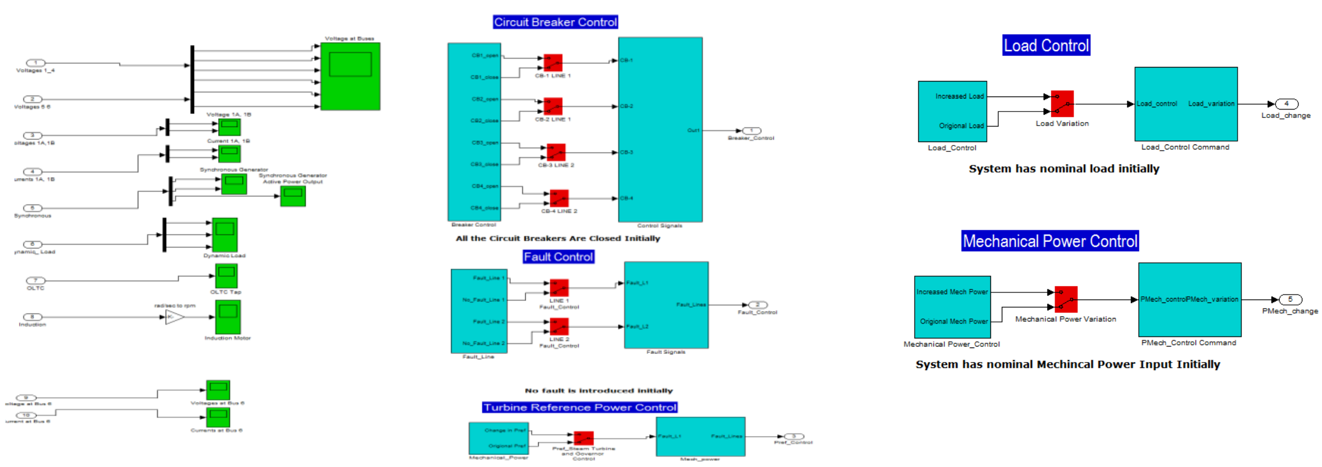


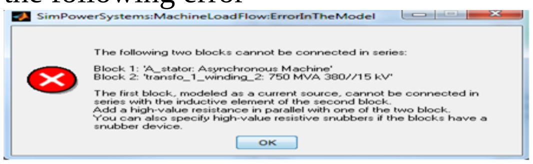
Fig .4-24: SimPowerSystems Model of the “all-in-one” System showing the console used for monitoring and controlling system parameters

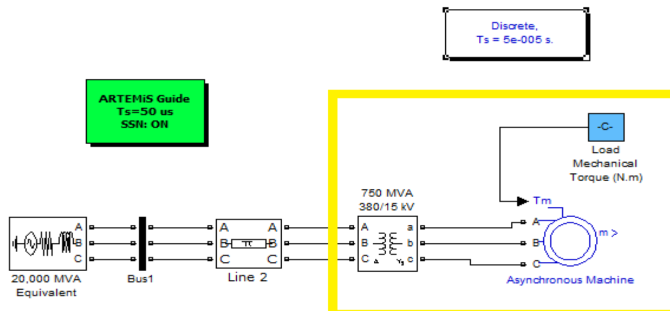
4.4. Complexities Involved in Modeling Power System with the SimPowerSystemsToolbox

During the modeling of the test system, there were some complexities involved which took some time to correct them. This section includes some of those major complexities, the error message received and the remedies used to correct them. These are being presented in order to save the time in modeling for future cases.

<u>Error 1</u>

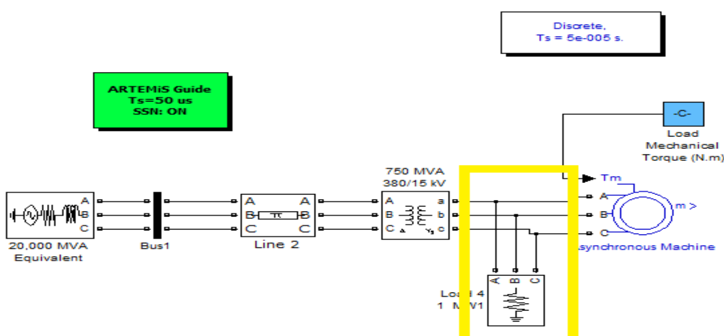
Connecting Machine with a Transformer directly. In this case Simpower system will give the following error





<u>Remedy</u>

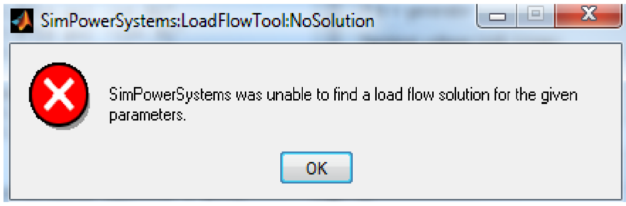
Add a high value resistance in parallel with the transformer and machine.



Same strategy should be used while connecting synchronous machine with the transformer. Generally the resistance of 1 Mega ohm is considered to rectify this error.

<u>Error 2</u>

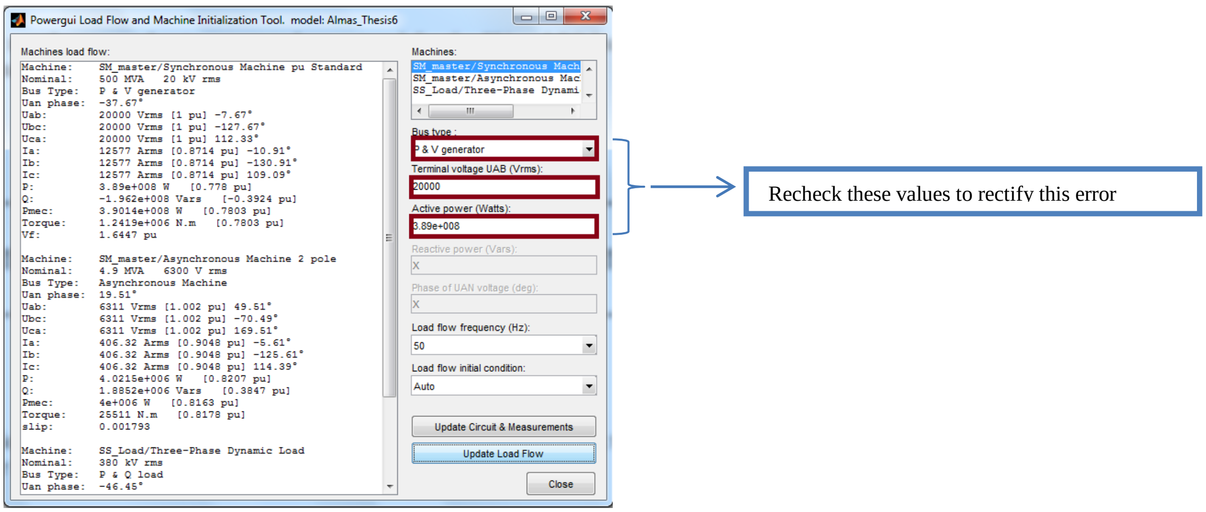
Most commonly the following error message is received while using the Load Flow and Machine initialization tool of the Power GUI Block.



This error mostly occurs due to wrong values entered for the PV and PQ buses in the Load flow and machine initialization tool of Power GUI block.

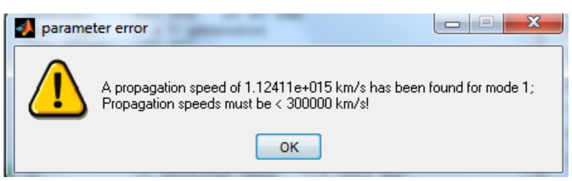
__Remedy__

Go to the load flow and machine initialization tool of Power GUI and recheck the values entered for the buses.



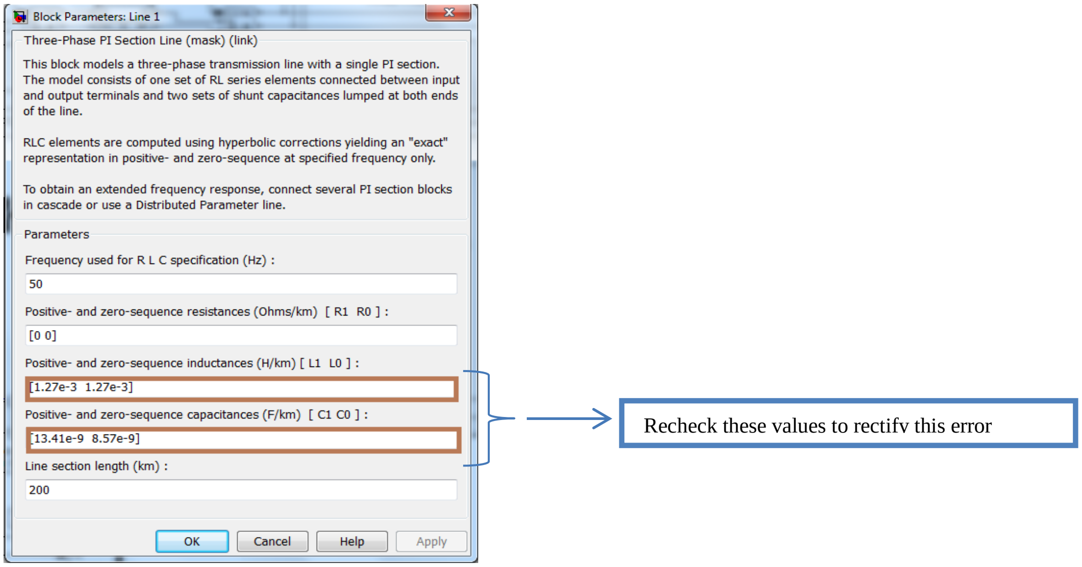
__Error 3__

Sometimes an error occurs due to wrong parameters settings for the transmission lines.



__Remedy__

Recheck all the parameters for all the transmission lines and use the appropriate (valid) values for the parameters to rectify this error.



Errors can also occur due to setting 0 value for some parameters which are not allowed by SimPowerSystems, e.g. the values for zero sequence capacitance and inductance in case of transmission lines, breaker resistance in case of circuit breakers, ground resistance in case of three phase fault block, etc.

4.5. Modifications Required to Make the Test System Model Compatible for Real Time Simulation

So far, we have modeled our system offline, i.e. not in the real-time. As we are using the Opal-RT Real Time simulator, modifications required for running the system in real-time are necessary. Here we are summarizing rules for these modifications, so that it becomes easier for the future studies to use the real time simulator.

4.5.1. Splitting System to Sub-System

The real-time simulator requires that the whole model should contain at least two sub-systems. One subsystem is called the Master subsystem and is denoted by SM_Master. This subsystem contains the model and its components. The other subsystem is the console subsystem denoted by SC_Console which contains all the metering scopes. When the model runs in the real-time simulator, only the subsystem SC_Console will be in front of the user. So the real time simulator will show all the metering scopes which the user has set in the SC_Console subsystem. As we are allowing the user to apply faults and different instabilities in the system, we have also placed some mechanical switches in the console, that when the system is running in real-time, the user can apply these changes to the system using the console. It is shown in Fig. 4-24.

4.5.2. Splitting System to Multiple Sub-Systems to Avoid Over-Runs

As discussed above, the real-time simulator demands that the system should be split to at least two subsystems. In the Opal-RT real-time simulator, each subsystem runs on one core of the simulator. At KTH we have a 24 core simulator. Each top level subsystem other than the console runs on one separate core of the simulator. If the system is divided into two subsystems i.e. SM_Master and SM_Console then SM_Master will run at one separate core of the simulator and SM_Console will run at the workstation connected to the simulator. So the limitation of at least two subsystems clearly specifies that there should be at least one subsystem running on the core of a simulator. However each core has a computation limitation depending on the step size used for simulation. In our case, when the step size of 50 micro seconds was used and the system was split to two subsystems i.e. running on a single core of simulator, then there were over-runs i.e. the simulator was unable to compute all tasks and come up with the solution (values of all parameters) within that step size (50 micro seconds). So we had to split SM_Master into two subsystems. In this case one system remains SM_Master and the other one is named SS_Slave. There can be only one SM_Master and one SC_Console in the model. All the rest of the subsystems are named as SS_Slave. The overruns depend on the number of switches in a subsystem. In our case, the OLTC transformer at bus 5 had the maximum number of switches which was causing overruns. So, we split our system at that point. The SC_Master and SS_Slave subsystems are shown in Fig. 28. The overall connection of theses subsystems with each other is shown in Fig. 29. The overruns result in long computation time and erroneous results.

4.5.3. Rules for Connecting Subsystems

If there are only two subsystems i.e. SM_Master and SC_Console then the rule is very simple. All the inputs to the SC_Console coming from SM_Master should first pass through a block named as OpComm shown in Fig 4-25. Similarly all the signals from SC_Console to SM_Master should pass through OpComm Block first:

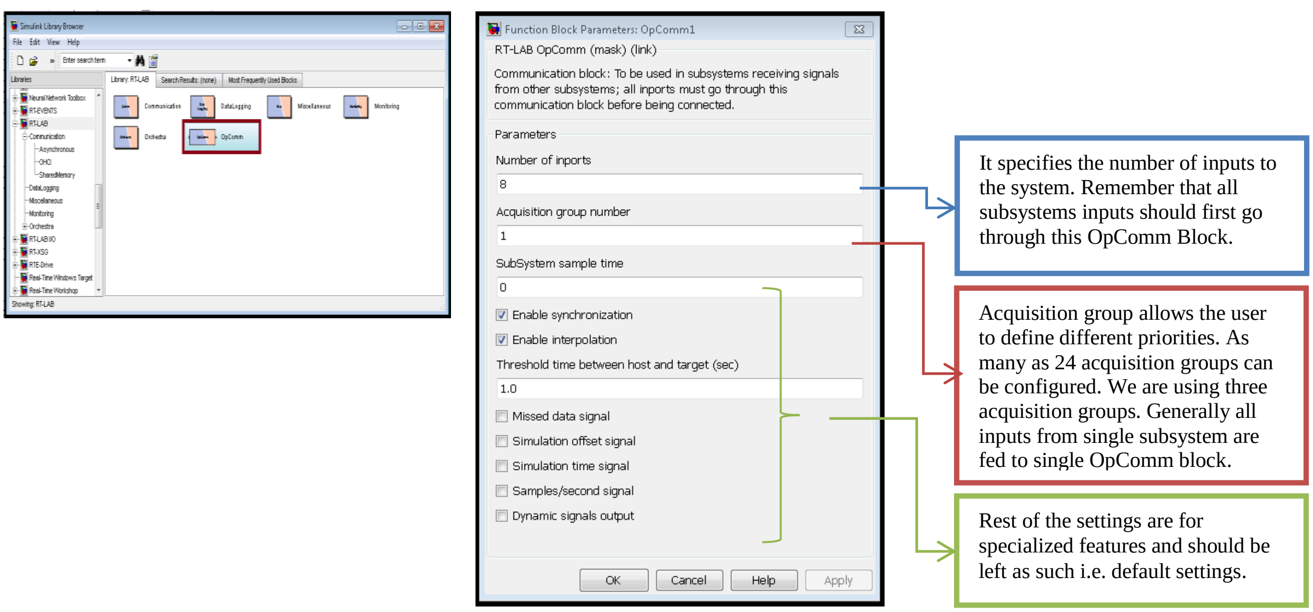


Fig. 4-25: OpComm Block and its parameters detail

- This is a specialized block provided by the Opal-RT and is present in the RT-LAB library.
- If there are multiple subsystems, the same rule exists. Remember that even the SS_Slave follows the same rules for OpComm block i.e. all the inputs from SC_Console to SS_Slave should first pass through the OpComm Block and all the signals from SS_Slave to SC_Console should pass through this block

Fig. 4-26 shows the implementation of OpComm block in the SC_Console. Fig. 4-28 and Fig. 4-29 show the implementation of OpComm block in the SM_Master and SS_Slave subsystems.

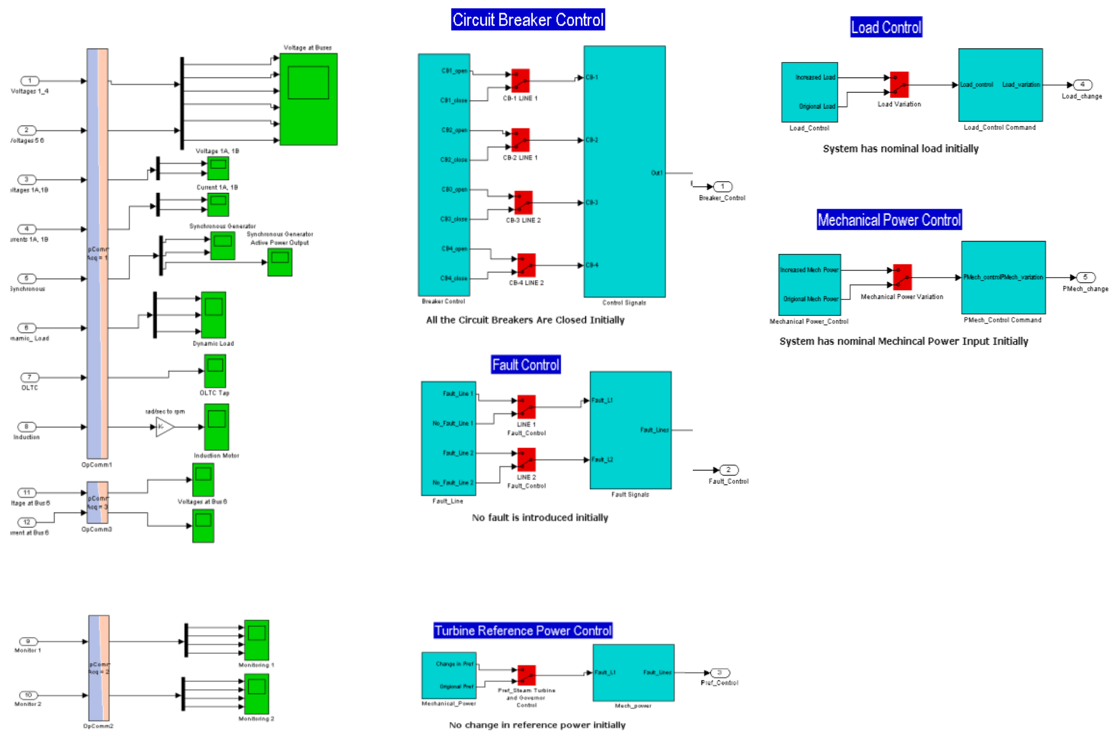
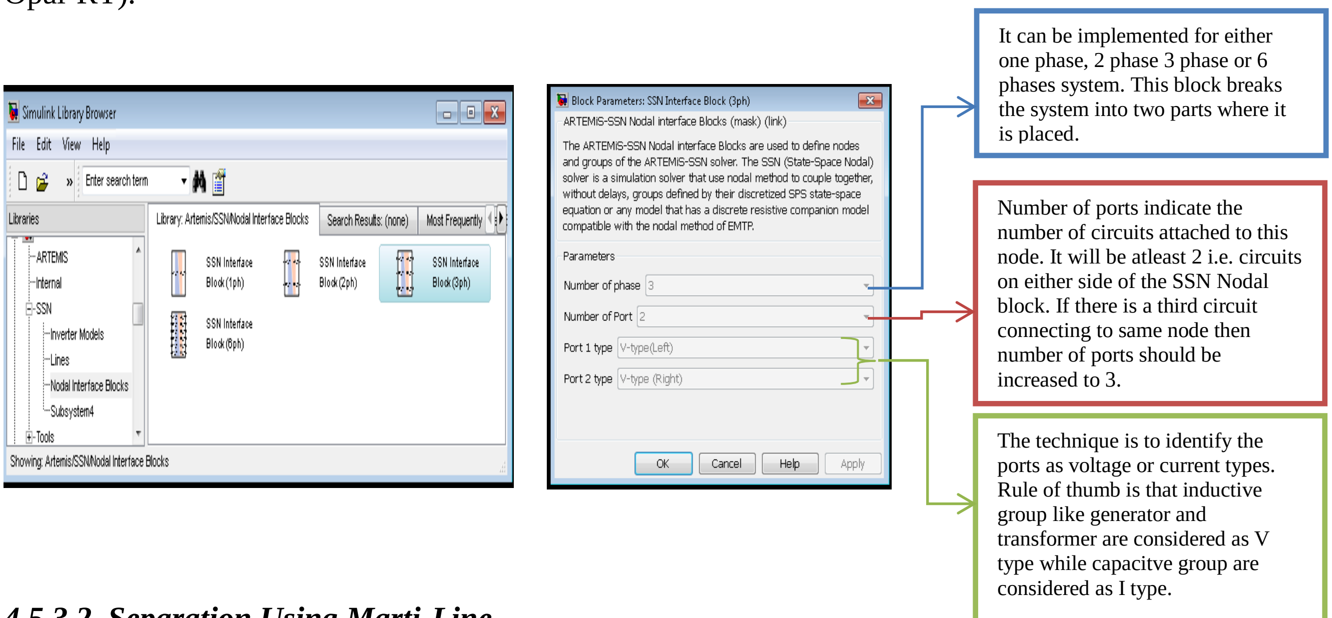


Fig. 4-26: SC_Console Subsystem modified by implementing OpComm block (Compare with Fig. 4-24)

If there are more than two subsystems (as in our case) i.e. SM_Master, SS_Slave and SC_Console, then there are several ways of connecting SM_Master and SS_Slave subsystems. There are some dedicated blocks provided by Opal-RT for connecting SM_Master and SS_Slave.

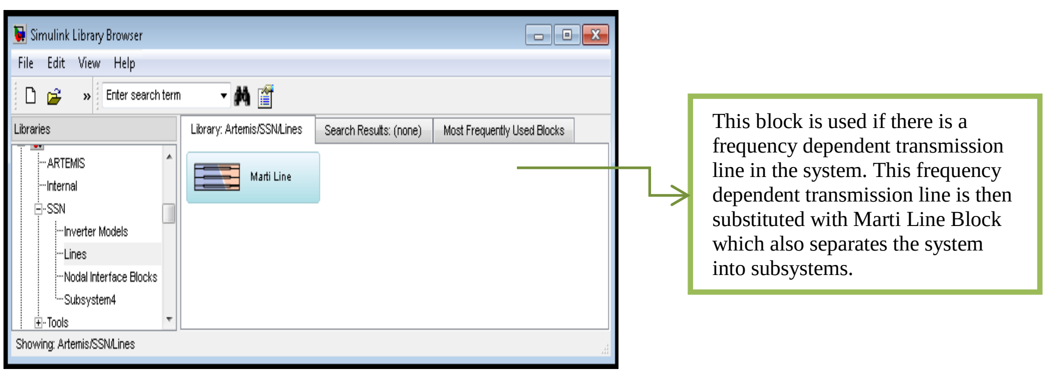
4.5.3.1. <u>State Space Nodal Block</u>

This block is available in the SSN category of the Artemis Library (dedicated library for Opal-RT).



4.5.3.2. <u>Separation Using Marti-Line</u>

This block is available in the SSN category of the Artemis Library. It is also a dedicated block which is present in Artemis library provided by Opal-RT.



4.5.3.3. <u>Separation Using ARTEMIS Line</u>

When physical modeling signals are transmitted between two subsystems at the root level i.e. from SS_Slave to SM_Master or from SM_Master to SS_Slave, then Artemis lines are used to separate the system. There are two ways of connecting subsystems using Artemis Lines;

a. *Using STUB Line*

Stub lines are used to decouple the system by separating the state space equations at both sides of the line. Stub lines are used when decoupling is required at DC link or the transformer winding. In case of stub line one only needs to enter the resistance and the inductance values corresponding to the place where it is separated.

b. *Using Distributed Parameters Line*

If there is a long transmission line (greater than 30000*sample time) then distributed parameters line can be used to simulate the transmission line and to connect the two subsystems. As in our case there is a transmission line between Bus 3 and Bus 5 (see Fig. 4-1), and the OLTC is connected at Bus 5, so we have used Distributed Parameters Line to separate the system into SS_Slave and SM_Master. A block representation of it is shown in Fig. 29 where SM_Master and SS_Slave are connected together by using Distributed parameters line which is actually representing the transmission line between Bus 3 and Bus 5.

As the requirement for using distributed parameters line is that the length of line should be greater than 30000*sample time i.e. for our case 30000*50 micro second = 1.5 km. So, we have taken this into account while setting parameters for the distributed parameters line. Fig. 4-27 shows the stub line and distributed parameters line.

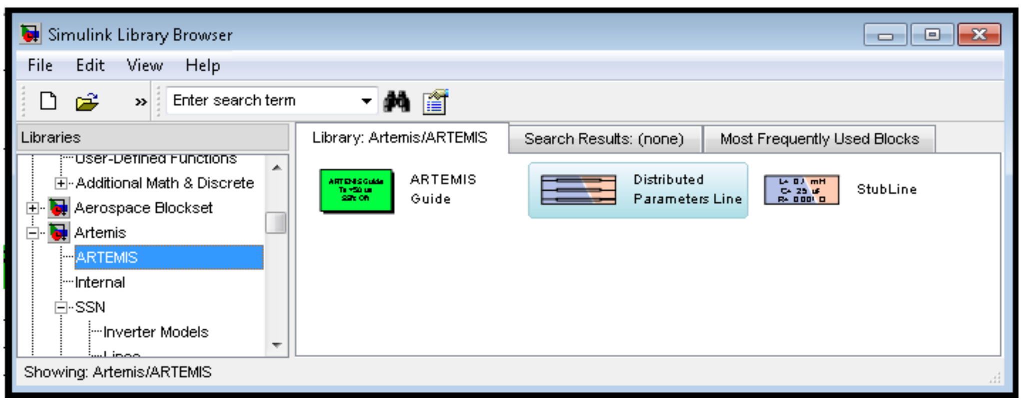
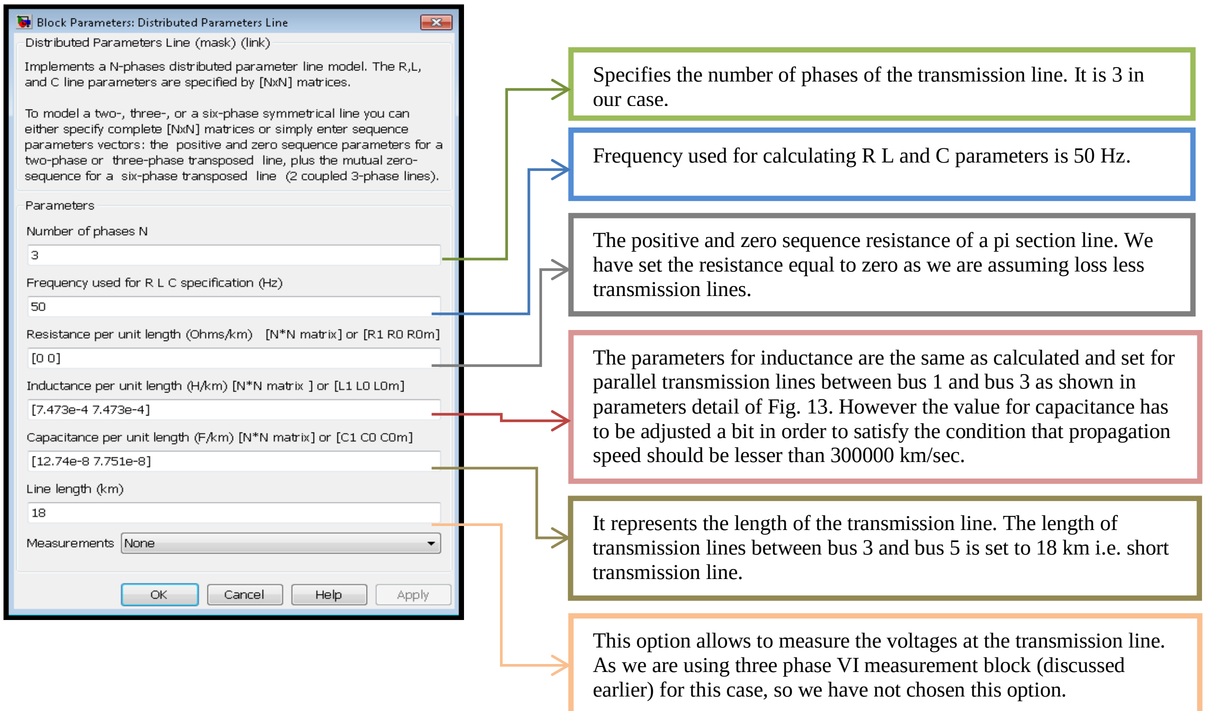


Fig. 4-27: The Distributed Parameters Line and Stub Line Blocks Available in Artemis Library



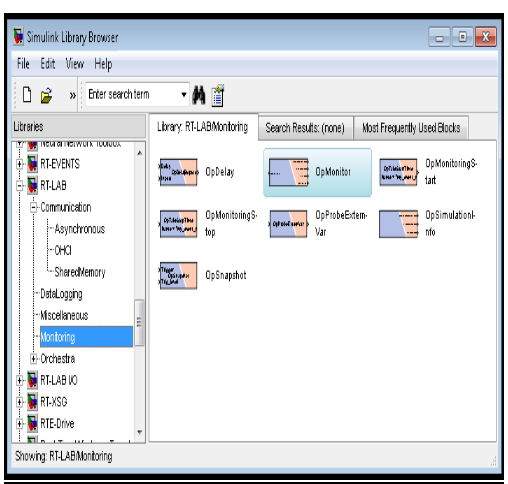
As we are using the Artemis block to separate the system into subsystems, therefore the Artemis Guide block should be used at the top level. This is shown in Fig 4-29.

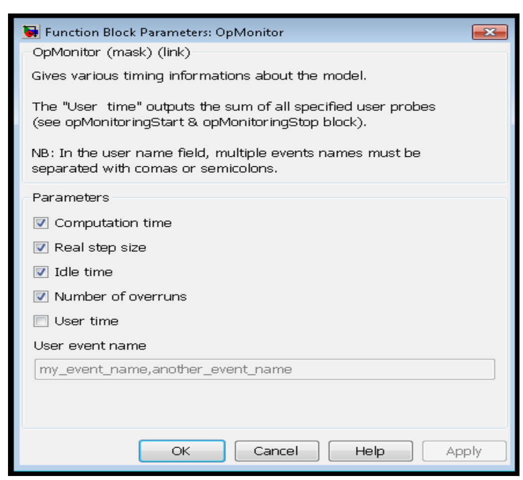
4.5.3.4. <u>Additional Blocks Used in the Model</u>

The two additional blocks used in the model other than the above mentioned requirements are;

a) *<u>OpMonitor Block</u>*

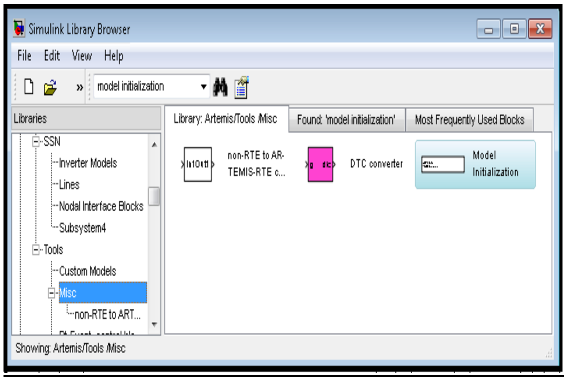
This block is available in the Monitoring category of RT-LAB library. It provides information regarding computation time, real step size, idle time, number of over-runs etc. of the subsystem. As each subsystem runs in a separate core in simulator, so this block is used in each subsystem i.e. SM_Master and SS_Slave.

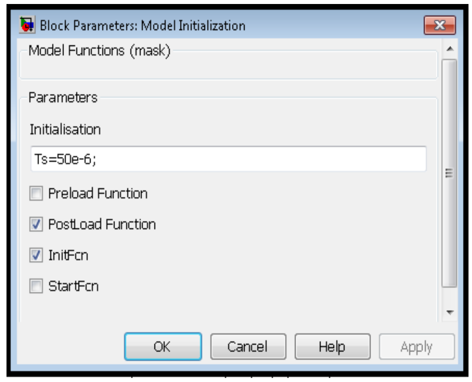


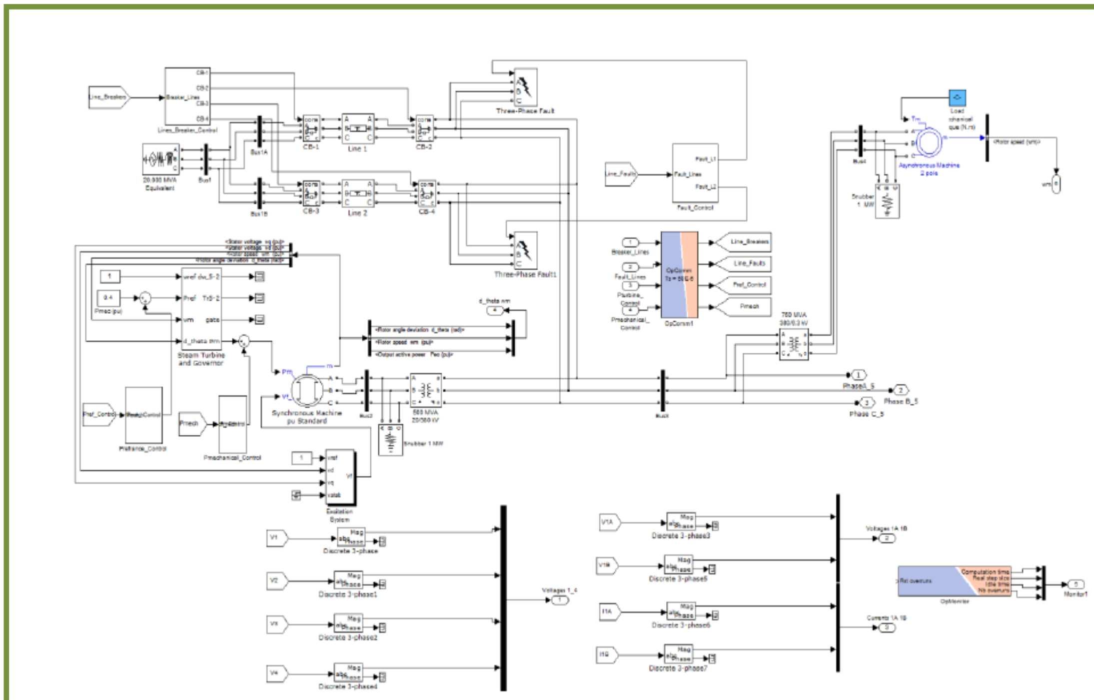


b) *Model Initialization Block*

This block is available in the Misc Category of the Artemis Library. It provides initialization for the Artemis blocks used in the model (distributed parameters line block in our case). The only important parameter needed to be configured in this block is the sample time. Other parameters should be left as default.







Master Sub-System: Containing Synchronous Generator, Transformers, Induction Motor, Thevenin Equivalent and Transmission Lines

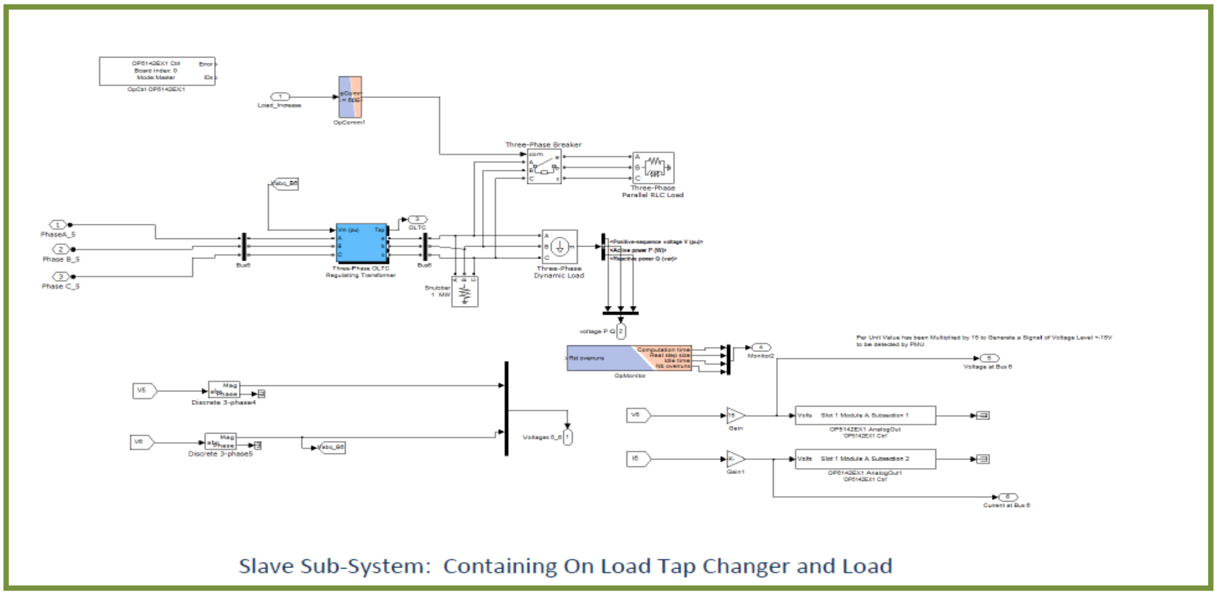


Fig. 4-28: SM_Master and SS_Slave Subsystems (Model is split to avoid overruns)

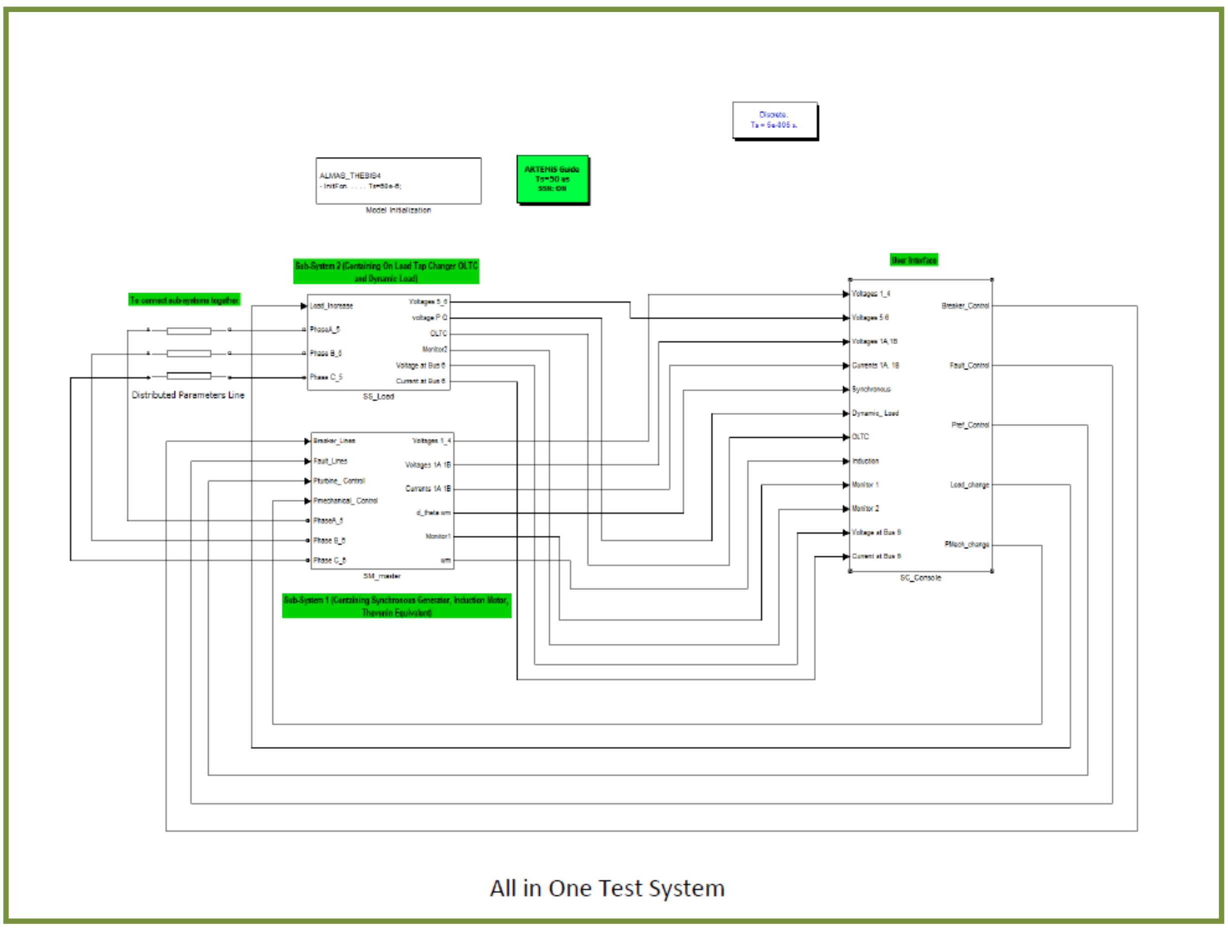


Fig. 4-29: The overall all-in-one system which is compatible with real time simulator

These are the required modifications which have to be implemented in order to simulate the power system in real time using Opal-RT simulator. In order to verify that the connections are made accurately and the correct blocks are used, one should run the simulation in offline mode first. If the system runs in offline mode with all these modifications, then it is ready to be run in the real time simulator.

4.5.4. Loading Model in the Real Time Simulator

Opal-RT simulator provides RT-LAB software which allows loading the model in the simulator. Once the required modifications (as discussed above) are implemented and the model is running in the offline mode, then RT-LAB software can be used to load the model in real-time Fig. 4-30 shows the screen shot of the software. Only those details of the software are provided which are used to load the model.

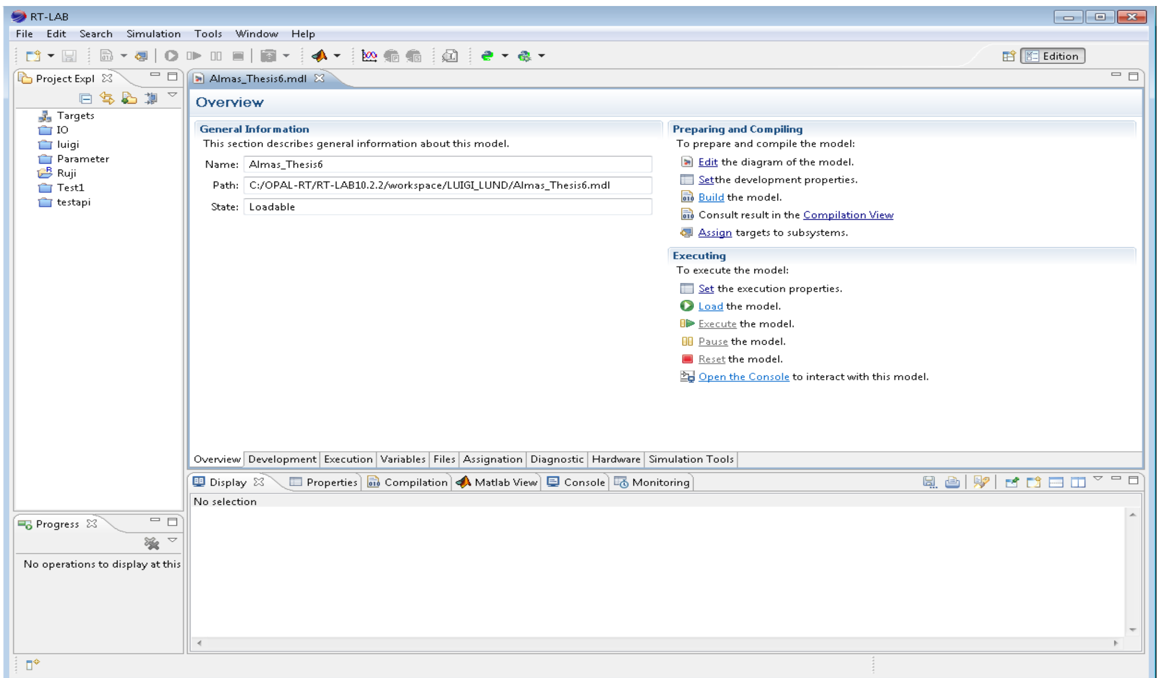
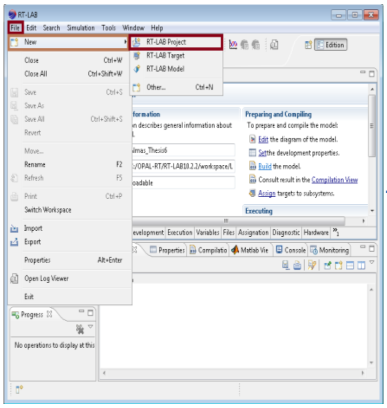


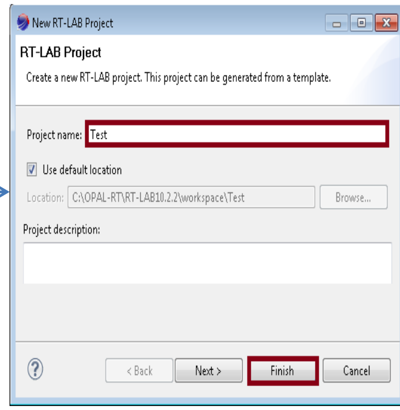
Fig. 4-30: Overview of RT-LAB software used to load model in the simulator

4.6. Steps Involved in Loading the Power System Model in the Real-Time Simulator

4.6.1. Step-1 (Creating RT-LAB Project)

The first step is to create an RT-LAB project. It can be done by selecting File→New→RT-LAB Project as shown in Fig. 4-31 (a). Clicking this option will open a new dialogue box which is shown in Fig.4-31 (b). Give the name of the project (e.g. Test) and click finish. This will create a new Project in the Project Explorer shown in Fig.4-31 (c).





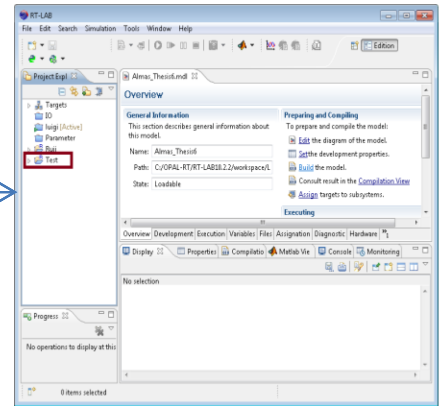


Fig.

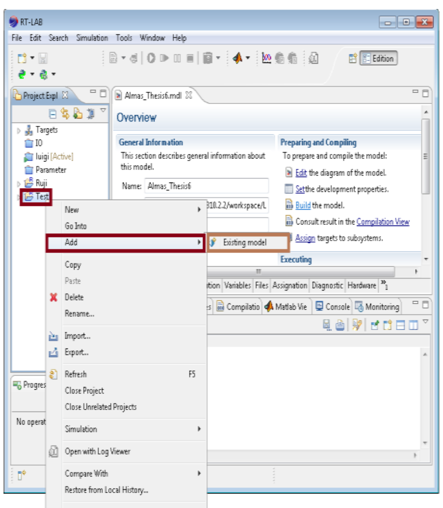
4-31 (a) Creating new project

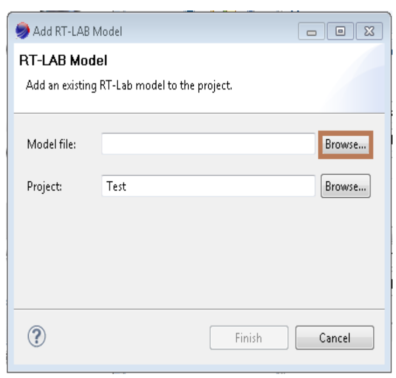
Fig. 4-31 (b) Naming new project

Fig. 4-31(c) New project completed

4.6.2. <u>Step-2 (Adding Model into the Project)</u>

The second step is to add the Simulink model into this new project. This can be done by right-clicking on the new project (test)→Add→Existing model as shown in Fig. 4-32(a). This will open a dialogue box to select the model. You can either write the name of the model file or select the browse option as shown in Fig. 4-32(b). Here you can browse the model which you created offline and you want to run in the real time simulator e.g. Phasor Signal Model as shown in Fig. 4-32(c) and click open to add the model into the new project.





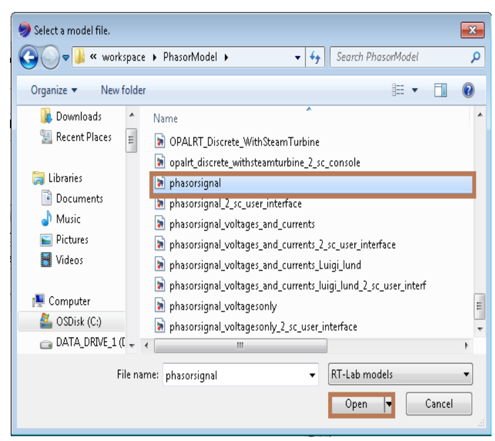


Fig. 4-32 (a) Adding model Added

Fig.4-32 (b) Browsing model Location

Fig. 4-32(c) Model

Once the model is added, it will appear in the tree of new project as shown in Fig. 4-33.

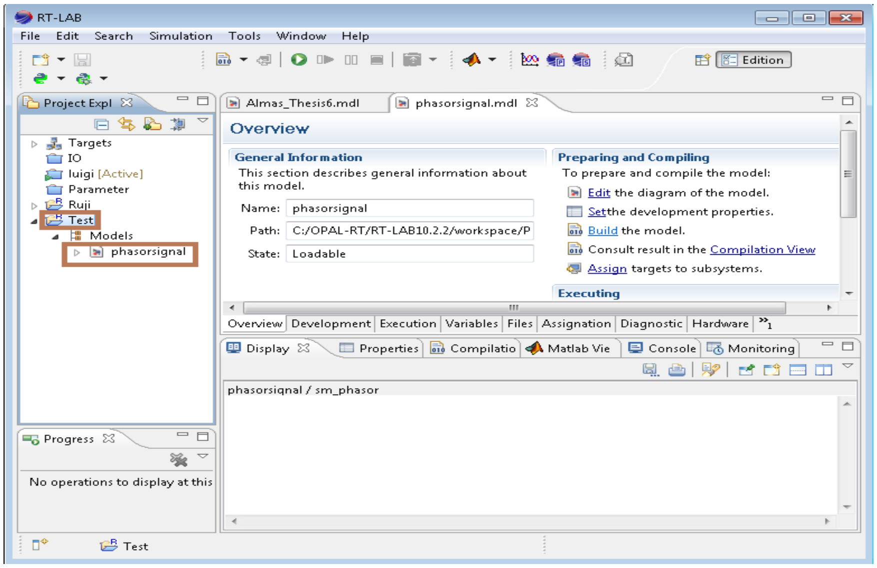


Fig. 4-33: Displaying the added model in the new project

4.6.3. Step-3 (Running the Model in Real Time)

Final step is to run this model in the real time. This procedure is shown in Fig. 4-34. By following this procedure, RT-LAB software automatically generates the SC_Console subsystem which is used for metering, monitoring and controlling (in our case e.g. manual control of breaker as discussed earlier etc.). The SC_Console block generated does not contain the input ports as shown in Fig. 4-35. Different signals can be monitored from the scopes in the SC_Console generated by RT-LAB.

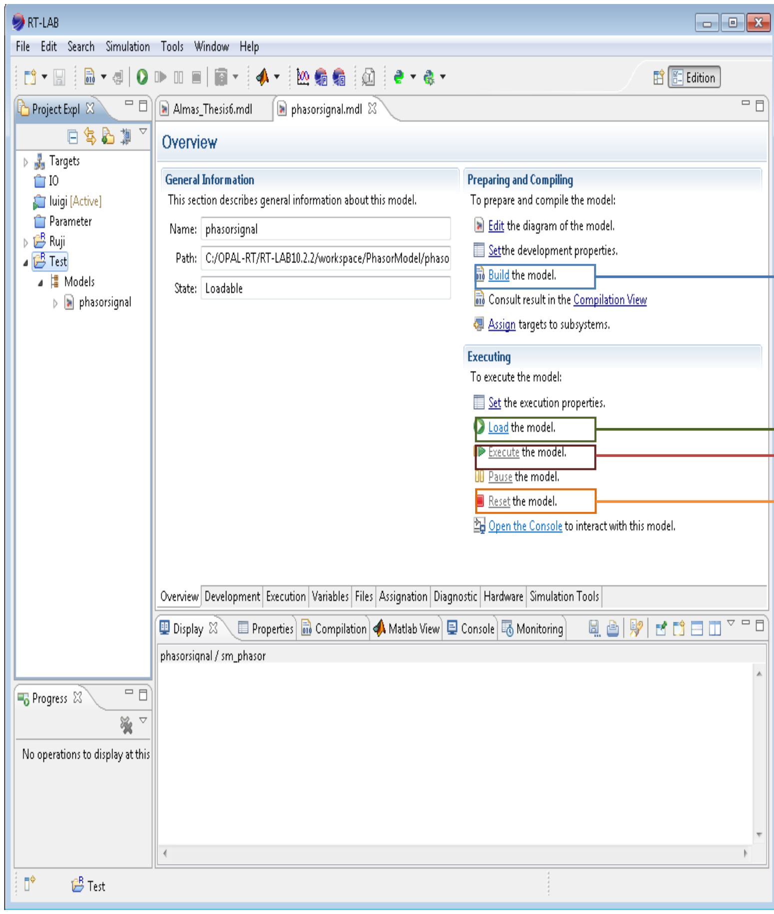


Fig. 4-34: Steps involved in running model in Real Time Simulator

Step 1: Build the model
This will result in preparing the origional model for code generation and model separation. The whole model is converted to C code. The final outcome of this step is that it provides an executable model which can be now loaded in the simulator. We just need to click the Build button, the rest of the things are done automatically.

Step 2: Load the Model
The next step is to load the model in the real time simulator. Clicking this option will load the model in the real time simulator and will automatically pop up the console window infront of the user.

Step 3: Execute the Model
Final step is to execute the model. Clicking this option will execute the model in the real time and the signals can be monitored from the scopes at the Console window which is generated automatically by the RT-LAB software

Stopping the Simulation
In order to stop the simulation in real time, press this option Reset the model. It will reset the model. The model can then be edited using the edit option

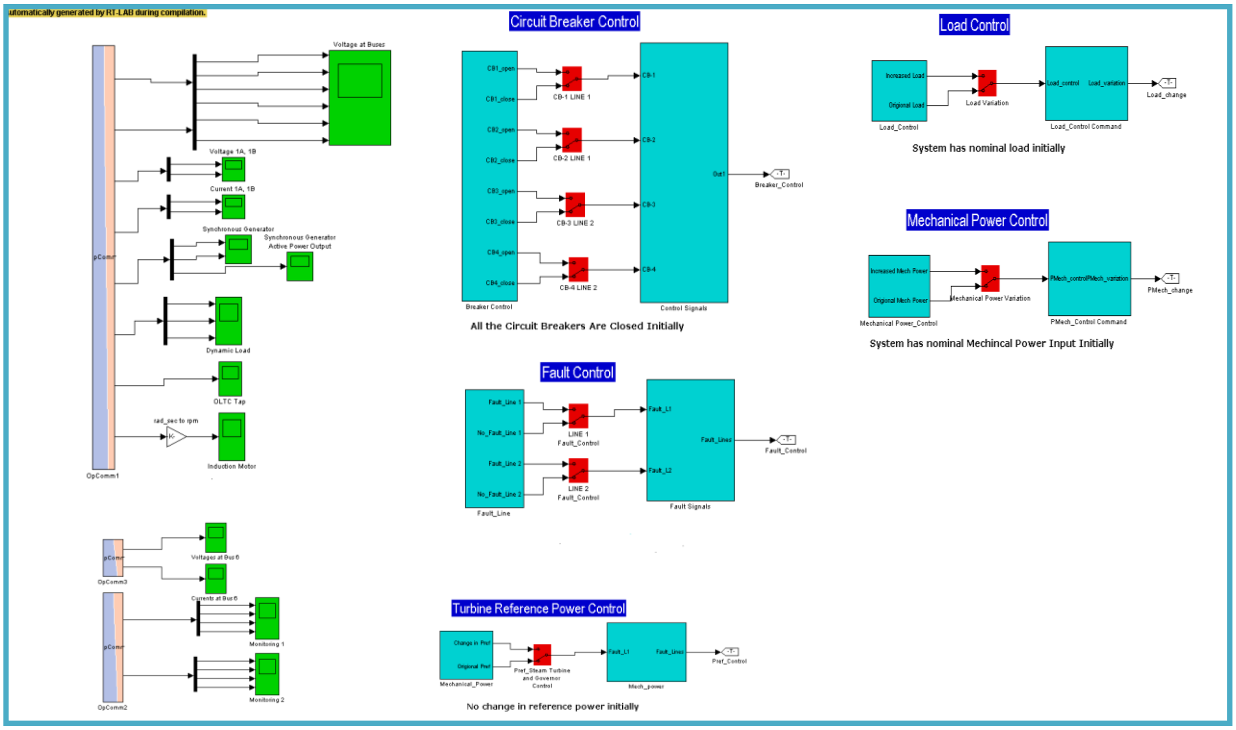


Fig. 4-35: SC_Console automatically generated by RT-LAB when model is loaded in the simulator (Compare with Fig. 4-26)

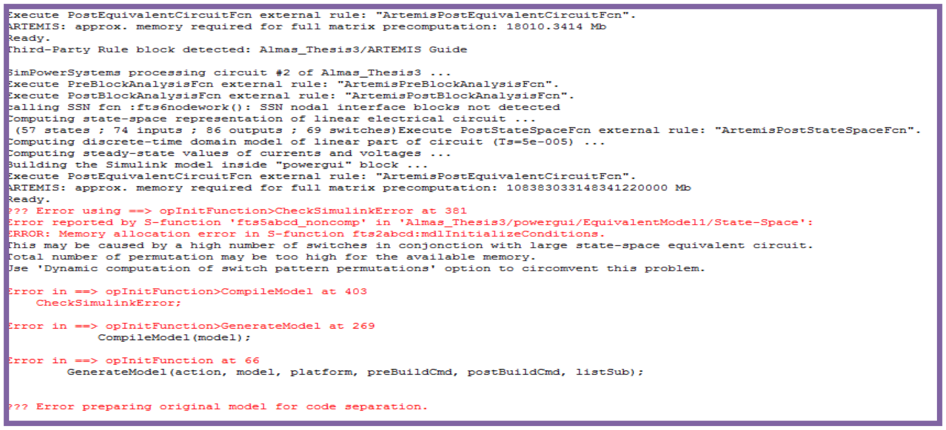
4.7. Complexities Involved in Simulating the Power System Model in the Real-Time Simulator

This section lists down some of the general errors which one encounters while building a model (See Step 1 in Fig. 34) to run it in real time simulator. The screen shots of the error along with the suggested remedies have been listed down for the benefit of future users.

<u>Error 1</u>

Due to large number of switches which results in a large state space equivalent matrix.

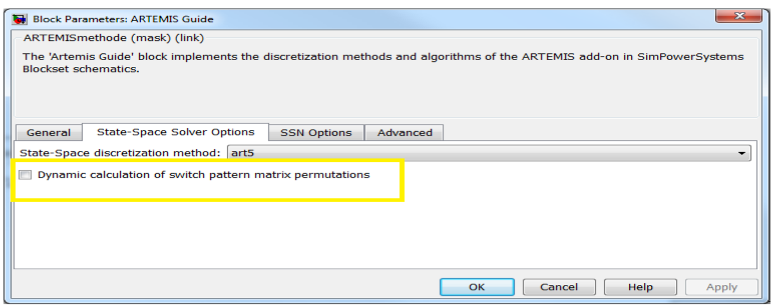
Screen Shot of Error



```
Execute PostEquivalentCircuitFcn external rule: "ArtemisPostEquivalentCircuitFcn".
ARTEMIS: approx. memory required for full matrix precomputation: 18010.3414 Mb
Ready.
Third-Party Rule block detected: Almas_Thesis3/ARTEMIS Guide

SimPowerSystems processing circuit #2 of Almas_Thesis3 ...
Execute PreBlockAnalysisFcn external rule: "ArtemisPreBlockAnalysisFcn".
Execute PostBlockAnalysisFcn external rule: "ArtemisPostBlockAnalysisFcn".
Calling SSN fcn :fts6nodework(): SSN nodal interface blocks not detected
Computing state-space representation of linear electrical circuit ...
 (57 states ; 74 inputs ; 86 outputs ; 69 switches)Execute PostStateSpaceFcn external rule: "ArtemisPostStateSpaceFcn".
Computing discrete-time domain model of linear part of circuit (Ts=5e-005) ...
Computing steady-state values of currents and voltages ...
Building the Simulink model inside "powergui" block ...
Execute PostEquivalentCircuitFcn external rule: "ArtemisPostEquivalentCircuitFcn".
ARTEMIS: approx. memory required for full matrix precomputation: 10838303314834122000 Mb
Ready.
??? Error using ==> opInitFunction>CheckSimulinkError at 381
Error reported by S-function 'fts5abcd_noncomp' in 'Almas_Thesis3/powergui/EquivalentModel1/State-Space':
ERROR: Memory allocation error in S-function fts2abcd:mdlInitializeConditions.
This may be caused by a high number of switches in conjonction with large state-space equivalent circuit.
Total number of permutation may be too high for the available memory.
Use 'Dynamic computation of switch pattern permutations' option to circomvent this problem.

Error in ==> opInitFunction>CompileModel at 403
    CheckSimulinkError;

Error in ==> opInitFunction>GenerateModel at 269
            CompileModel(model);

Error in ==> opInitFunction at 66
        GenerateModel(action, model, platform, preBuildCmd, postBuildCmd, listSub);


??? Error preparing original model for code separation.
```

Remedy

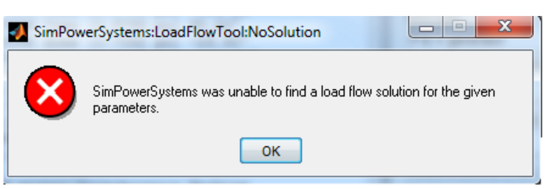
Use "*dynamic computation of switch pattern permutations*" in the "*Artemis*" Block Parameters

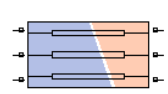


Error 2

Error in running load flow from GUI when Distributed Parameters Line (Artemis Model) is used.

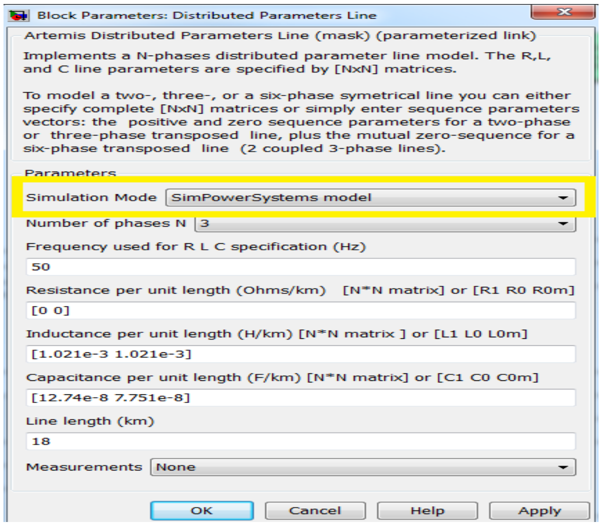
Screen Shot of Error





Remedy

Use “SimPowerSystems Model” in the “Simulation Mode” tab of block parameters of Artemis Distributed Parameters Line.



This concludes the modeling of the all-in-one system in SimPowerSystems and modifications required to run the system in the real-time. In case of RT-LAB software and the Matlab/Simulink blocks provided by the vendor (OPAL-RT), only those details are provided which are relevant to this study. The capabilities of RT-LAB software and OPAL-RT simulator are not just limited to the features discussed in these sections.

4.8. Creating a Long Term Voltage Instability Scenario

As discussed above, the “all-in-one” test system modeled has the provision to implement different kind of instabilities in the system i.e. transient instability (by applying three phase fault), frequency instability (by increasing the mechanical power input of the generator), voltage instability (by increasing the dynamic load connected at bus 6), etc. As we are particularly focusing on long-term voltage instability, so from here onwards, the discussion will be confined to long-term voltage instability.

The reason for selecting the voltage instability scenario is that voltage stability issues are of major concern worldwide. The significant numbers of blackouts have occurred in the recent pasts that were initiated due to voltage collapse [38]. These kinds of blackouts are most likely to happen in future as well. So it is important to accurately study these phenomena of voltage instability and to devise new ways of safeguarding the system against voltage instability or at least minimizing the effect of such instabilities. We will start our discussion with the definition of voltage stability.

4.8.1 **Definition of the Important Terms**

The definitions of the important terminologies are listed below:

Voltage Stability

In the literature, several definitions of voltage stability and voltage collapse are provided. Some of these are as follows:

Definitions according to Cigré

Cigré [39] defines voltage stability as:

• A power system at a given operating state and subject to a given disturbance is *voltage stable* if voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of attraction of the stable post-disturbance equilibrium.

• A power system undergoes *voltage collapse* if the post-disturbance equilibrium voltages are below acceptable limits.

Definitions According to Hill and Hiskens

According to Hill and Hiskens [40], the following definitions for the voltage stability terms are used:

• The voltages must be viable i.e. they must lie within an acceptable band.

• The power system must be in a voltage regular operating point. A regular operating point implies that if reactive power is injected into the system or a voltage source increases its voltage, a voltage increase is expected in the network.

Small disturbance voltage stability

A power system at a given operating state is small disturbance stable if following any small disturbance, its voltages are identical to or close to their pre-disturbance equilibrium values.

Large disturbance voltage stability

A power system at a given operating state and subject to a given large disturbance is large disturbance voltage stable if the voltages approach post-disturbance equilibrium values.

<u>Voltage collapse</u>

A power system at a given operating state and subject to a given large disturbance undergoes voltage collapse if it is voltage unstable or the post-disturbance equilibrium values are nonviable.

Definitions According to IEEE

According to IEEE [41], the following definitions of terms related to voltage stability are given;

Voltage Stability

It is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable.

Voltage Collapse

It is the process by which voltage instability leads to loss of voltage in a significant part of the system.

Voltage Security

It is the ability of a system, not only to operate stably, but also to remain stable (as far as the maintenance of system voltage is concerned) following any reasonably credible contingency or adverse system change.

A system is considered to be in a state of *voltage instability* when a disturbance (e.g. faults, line disconnection etc.) change in load (load increase or decrease), or system changes (set points of the generators, shunt reactors etc. which are compensating for the reactive power) causes a sudden or a progressive decay in voltage and operators and automatic system controls fail to halt the decay and bring the voltage back to the nominal value. The voltage decay may take just a few seconds or ten to twenty minutes. If the decay continues unabated, steady-state angular instability or *voltage collapse* will occur.

The increase in reactive power demands by a load connected a certain bus will cause the voltage at that bus to decrease. Similarly if a load consuming reactive power is disconnected at a bus, the voltage at that bus will increase. This means that there is a strong relation between reactive power and voltage. The main factor of causing voltage instability is the inability of the power system to meet demand for reactive power [64].

4.9. "All-in-one" System for Voltage Instability Analysis

In order to analyze long term voltage instability, the "all-in-one" system (discussed earlier) was used. The single line diagram in Fig. 4-36 shows how the long term voltage instability scenario is created by using this system. As shown in the figure, the reactive power consumption is increased at bus 5 which is being regulated by an OLTC transformer. The reactive power consumption can be increased by switching in an inductive load in the system as shown in the figure. However in the model, this approach is implemented by using an external control of the three phase dynamic load (see details of parameters of Fig.4-16)

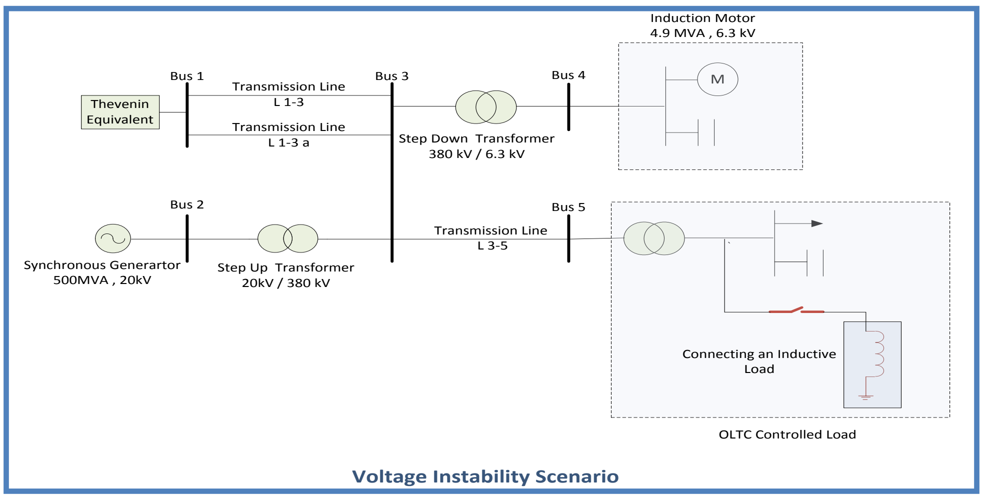


Fig. 4-36: Single Line Diagram for Conceptual Understanding of the way Long Term Voltage Instability is incorporated in the all-in-one system

and sending it the values of active and reactive power in the form of vector. It behaves in a similar way as connecting an additional inductive load at the bus.

The settings of the parameters of rest of the power system is exactly the same as discussed earlier except the fact that the three phase dynamic load is set in such a way that as soon as the manual switch (see Fig. 4-37) provided in the console, is activated, the load will continuously increase its active and reactive power demand till the system enters the state of voltage instability.

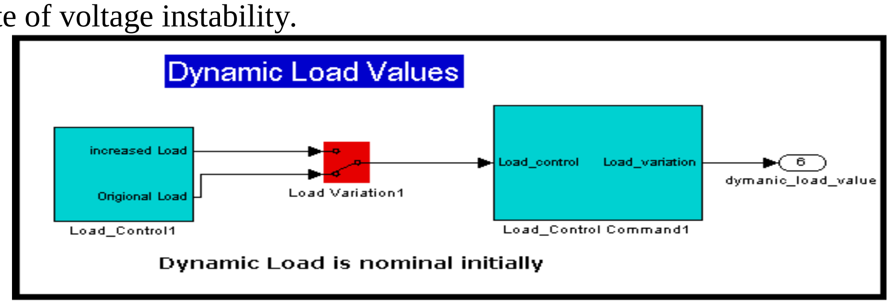


Fig. 4-37: The provision for starting a voltage instability scenario. When the mechanical switch is clicked, it will shift its contact to the increased load and the three phase dynamic load will start increasing its active and reactive power consumption.

The control strategy used to increase the load continuously is shown in Fig. 4-38.

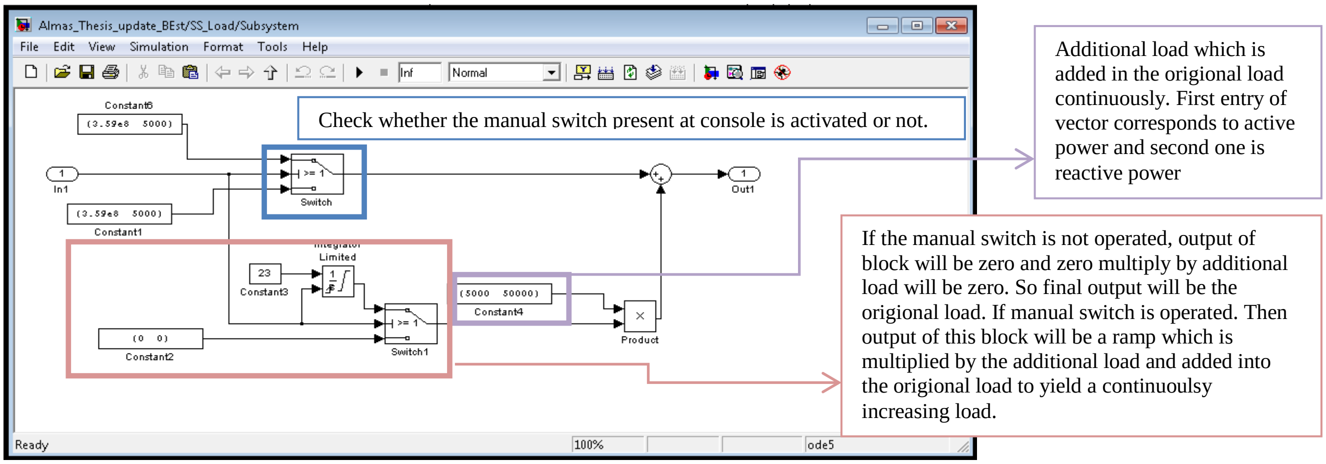


Fig. 4-38: The control strategy for increasing active and reactive power of the three phase dynamic load continuously.

The plots below show the voltages at all the buses when the load at bus 6 is increased continuously. In this case, the load increase is activated through mechanical switch at t=60 sec and the voltage collapses at t=300 sec. The plots clearly show a continuous voltage decrease which is less obvious in Bus 1 and Bus 2 because they both are attached to the voltage sources i.e. Bus 1 attached to voltage source representing thevenin equivalent and Bus 2 is attached to Generator which is meant to keep the voltage constant at that bus.

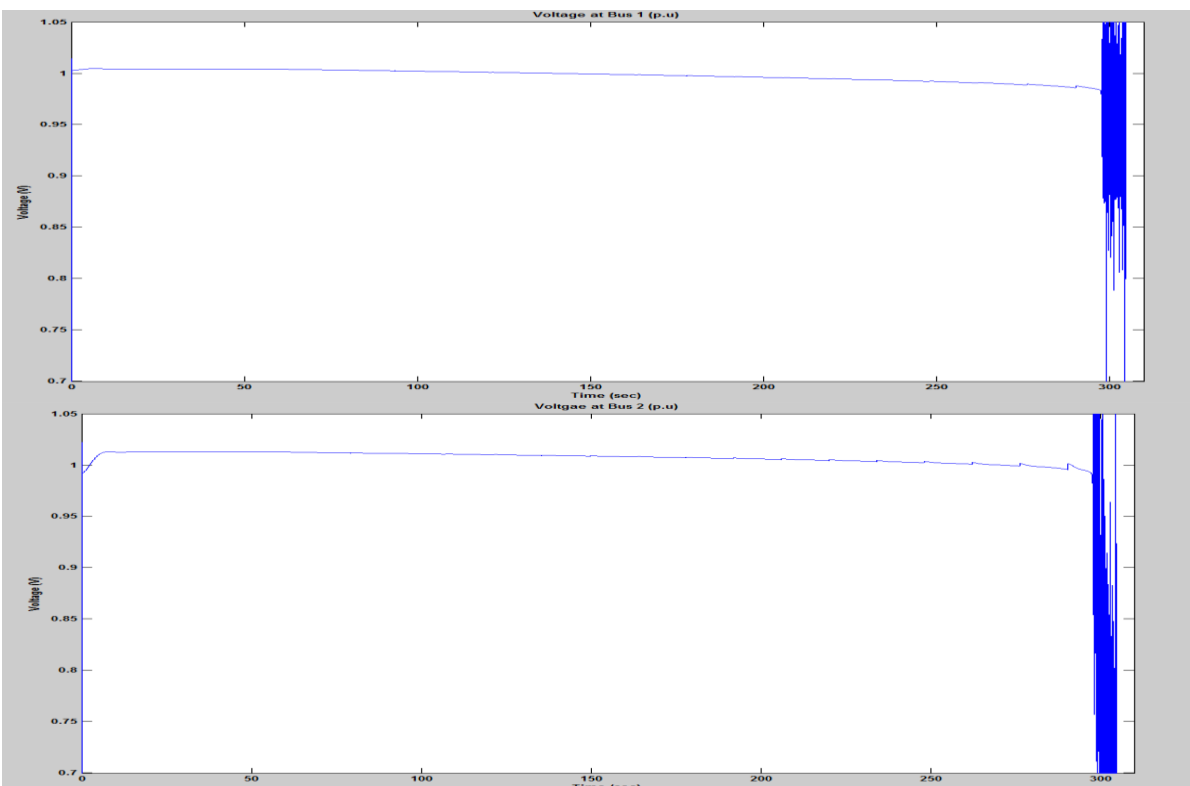


Fig. 4-39: Voltages at bus 1 and bus 2

As Bus 3 and Bus 4 are away from the sources, therefore the decay in voltage level is much obvious at these buses. Even the small notches obtained due to the OLTC operation to maintain voltage at Bus 6 can be observed in the voltages of these buses (Bus 3 and Bus 4)

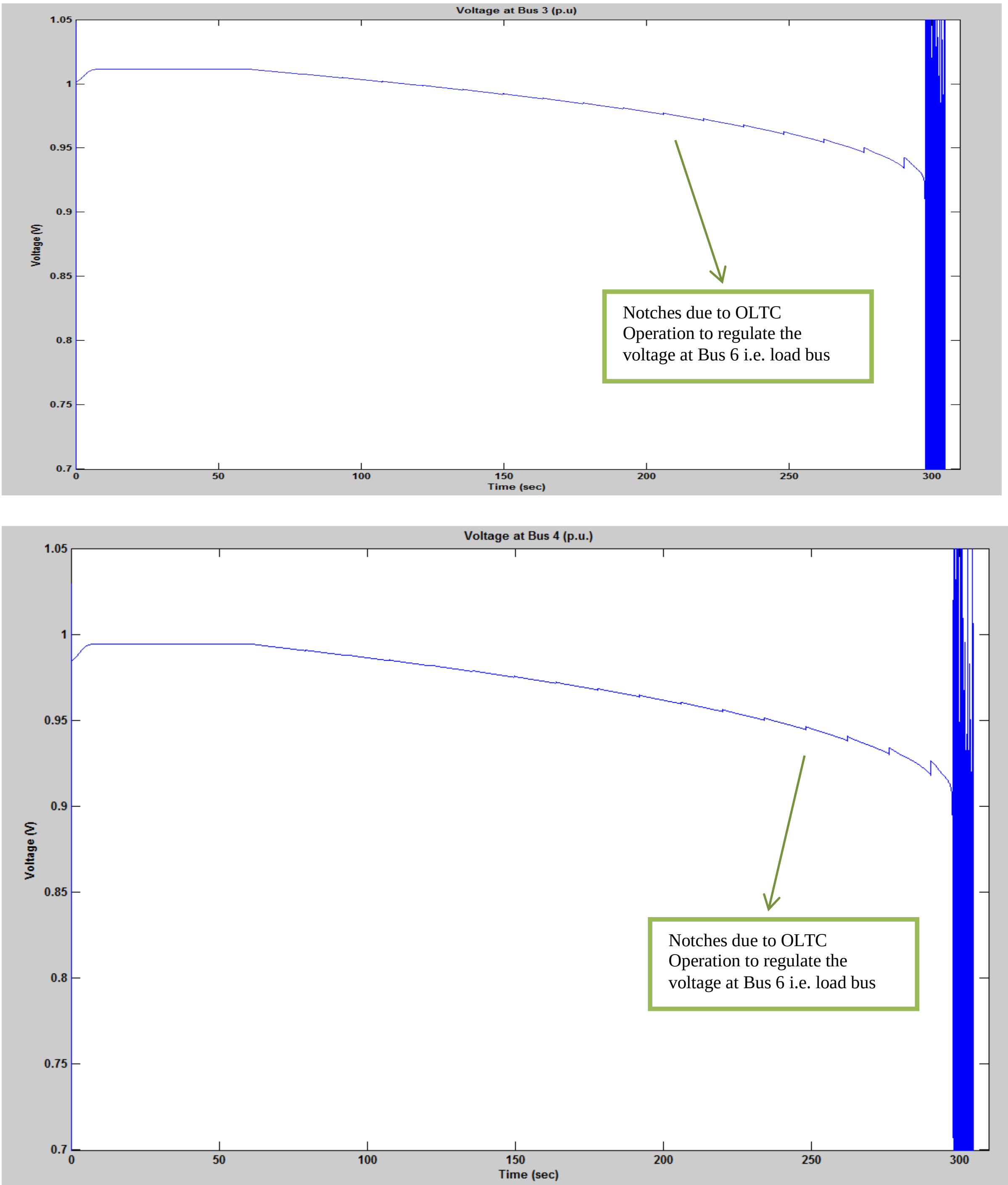
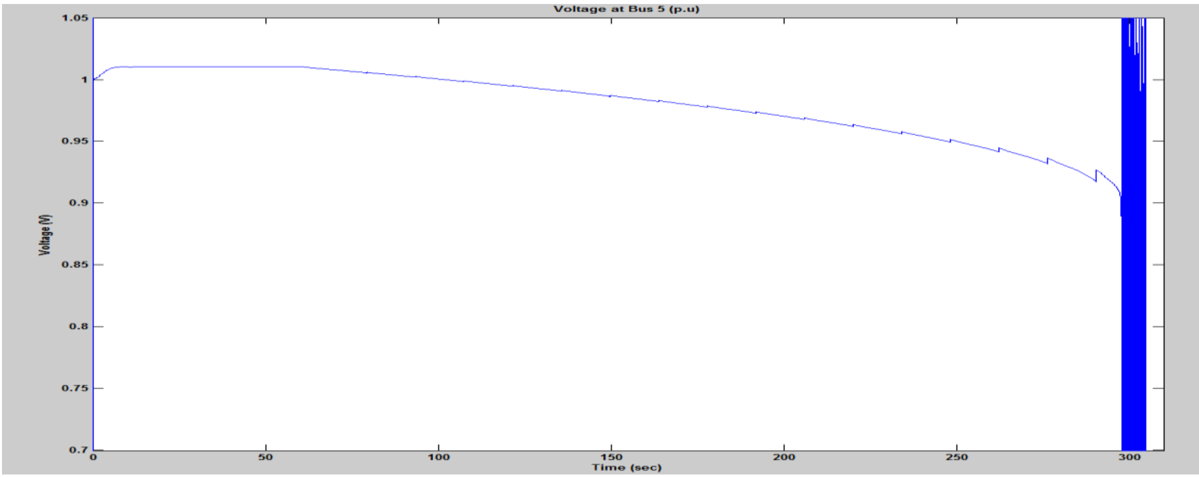


Fig. 4-40: Voltages at bus 3 and bus 4

As Bus 5 is the primary side of the OLTC transformer attached to the three phase equivalent load. As the reactive and active power consumption at Bus 6 increases, the voltage at the bus starts to decrease. The OLTC starts to restore the load voltage which results in decreasing of the tap (shown in next plot). As tap decreases, voltage increases but as the load is constantly being increased, so this results in decrement of voltage at bus 6. OLTC tries to bring the voltage to the nominal till it reaches its limit i.e. 16th position. As OLTC can no longer operate, the voltage collapses soon as shown in the plots below.



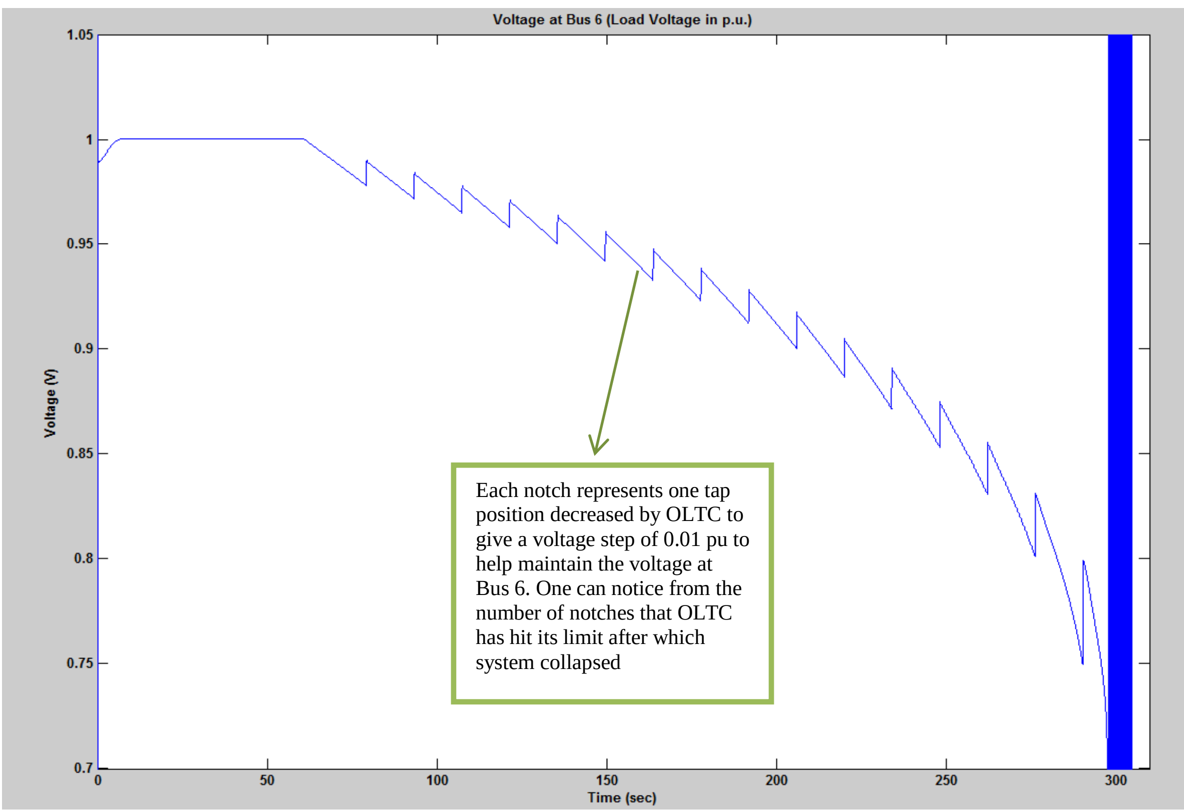


Fig. 4-41: Voltages at bus 5 and bus 6

As discussed earlier, the OLTC was configured in such a way that it provides a voltage step of 0.01 p.u. whenever the difference between the reference voltage (1 p.u.) and the bus voltage (voltage at Bus 6) increases 0.05 p.u. (half of the dead band. See Fig 4-16 for details). The plot below shows the OLTC operation of changing its taps to improve voltage at Bus 6.

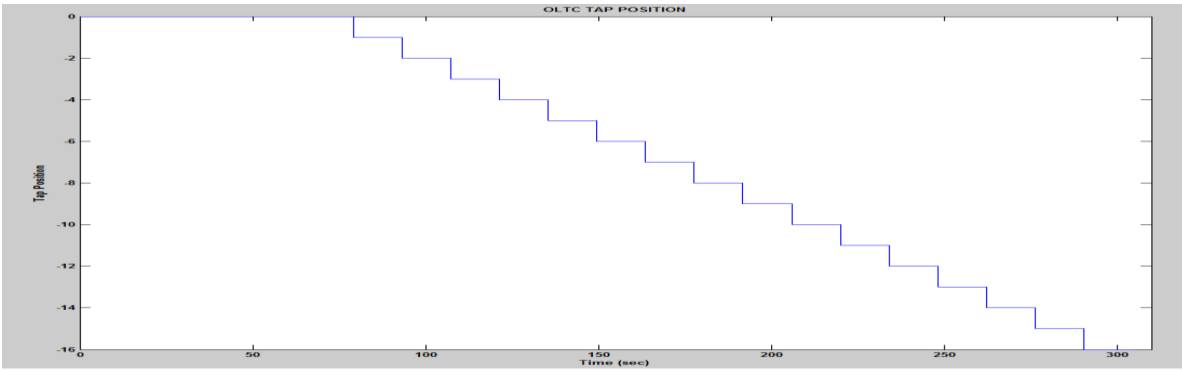


Fig. 4-42: OLTC Operation

The plot below shows the positive sequence voltage (which is actually voltage at Bus 6), the active power consumption and the reactive power consumption by the three phase dynamic load. There is a continuous small increment in the active power and there is a continuous increase in reactive power demand by the load (see Fig. 4-37) as soon as the manual switch is operated to initiate voltage instability scenario.

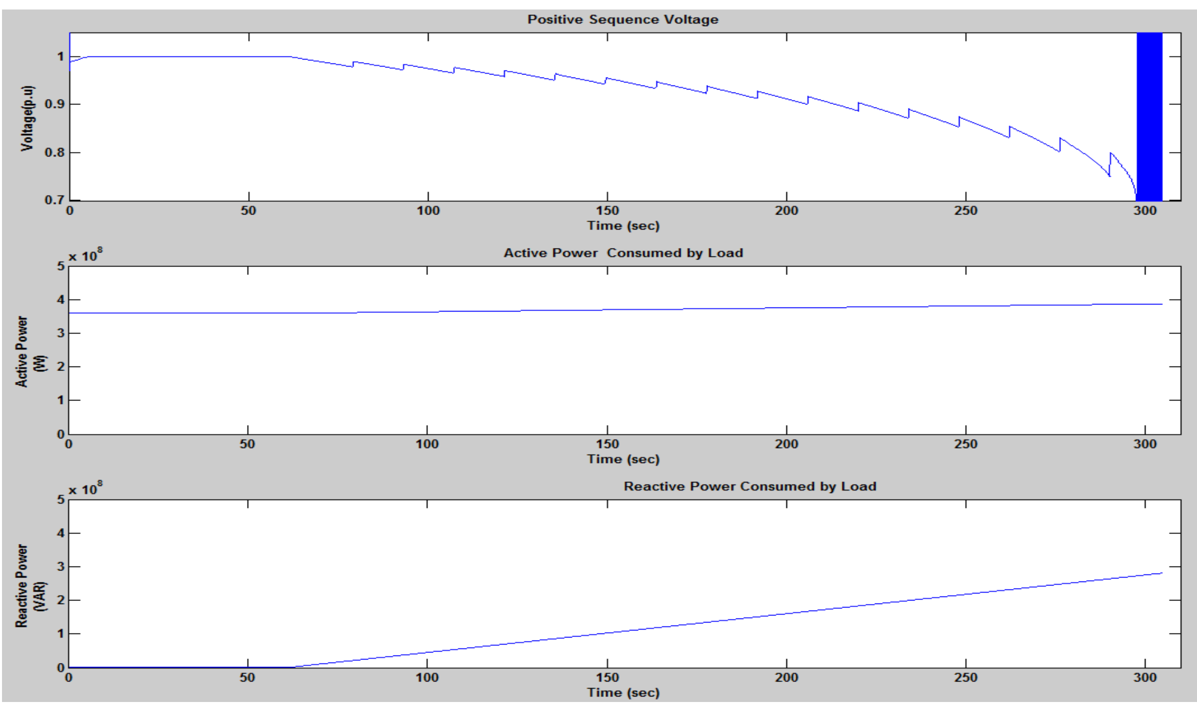


Fig. 4-43: Three phase dynamic equivalent load states

The plots below show the behavior of synchronous generator in the above discussed scenario of voltage instability. As can be seen, the increase in reactive power causes an increase in the reactive power output of the generator.

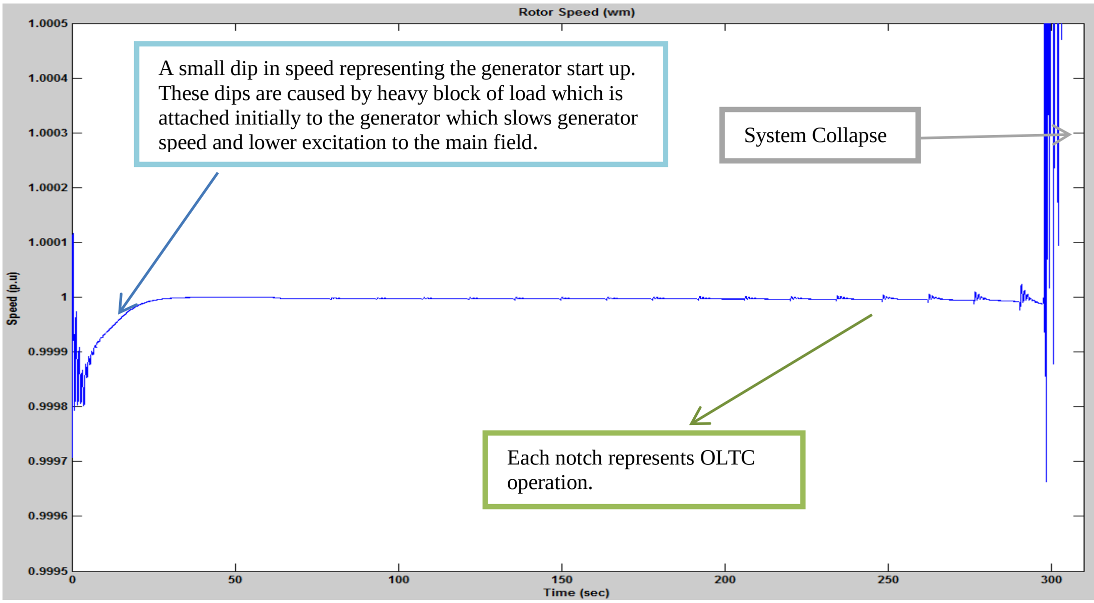


Fig. 4-44: Rotor Speed of the Generator

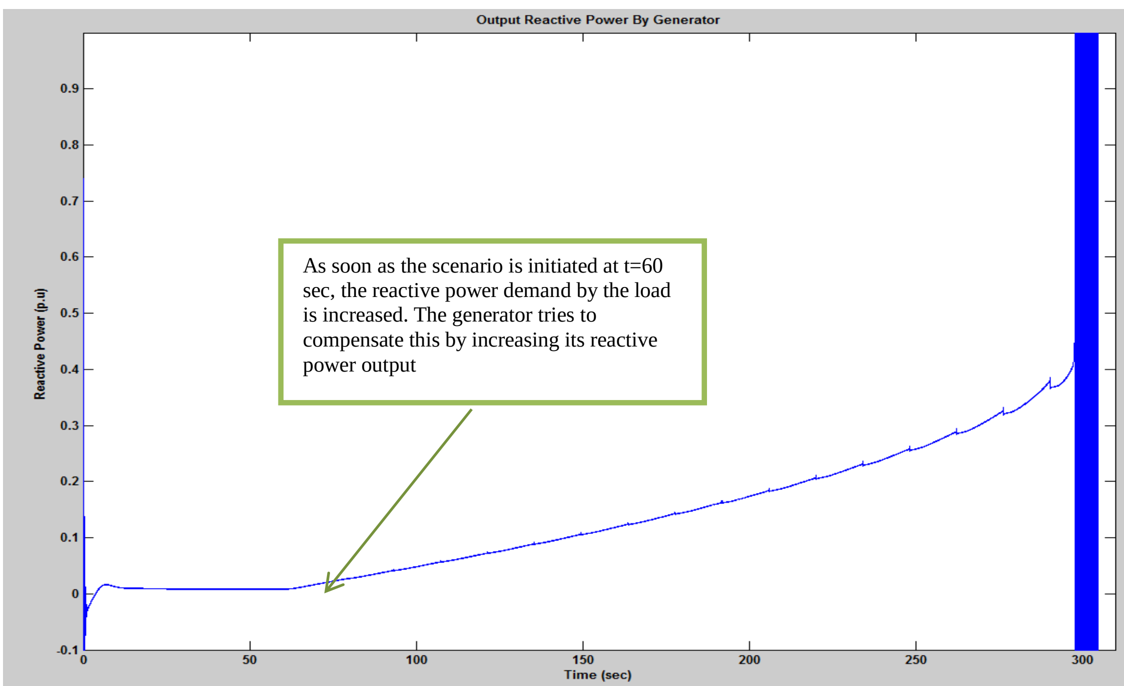


Fig. 4-45: Reactive Power Output by the Generator

As the load increases from t = 60 sec onwards, the reactive power output of the generator also increases. As the generator is synchronized to the external grid (Thevenin equivalent) and the power system. As the alternator matches the power supplied by the steam turbine, therefore the rotor angle deviation is constant. The load is increasing continuously, the generation is also increasing which is actually fed by the steam turbine (mechanical power input to the generator). The load is increasing rapidly with respect to the increase in generation, this causes the rotor to slow down a bit due to which the rotor angle deviation increases. However in the new balance condition, the rotor goes back to synchronous speed but at an increased angle. As the steam turbine mechanical power input to the synchronous generator is increasing continuously to handle the increasing load, therefore the system is finding a new operating time at each instance which results in the increasing rotor angle.

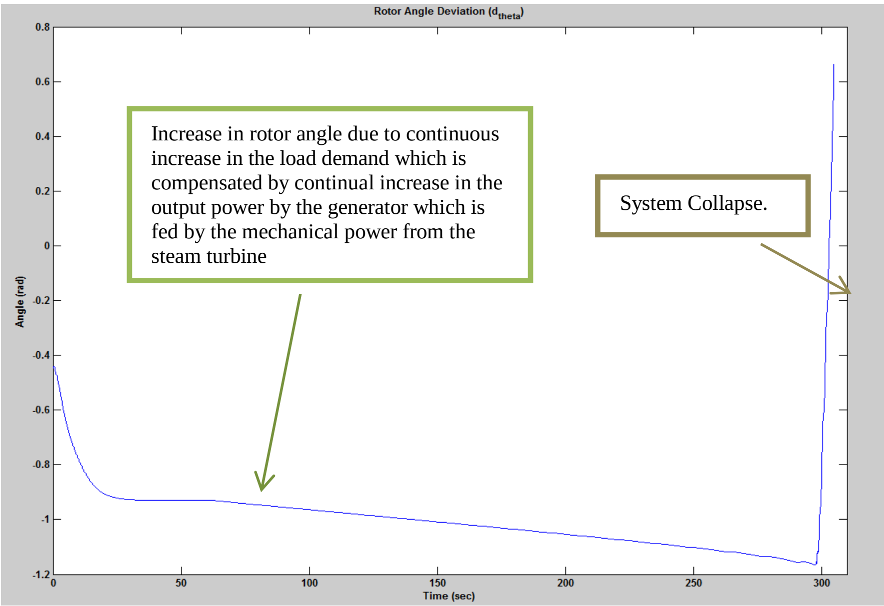


Fig. 4-46: Rotor Angle Deviation of the Generator

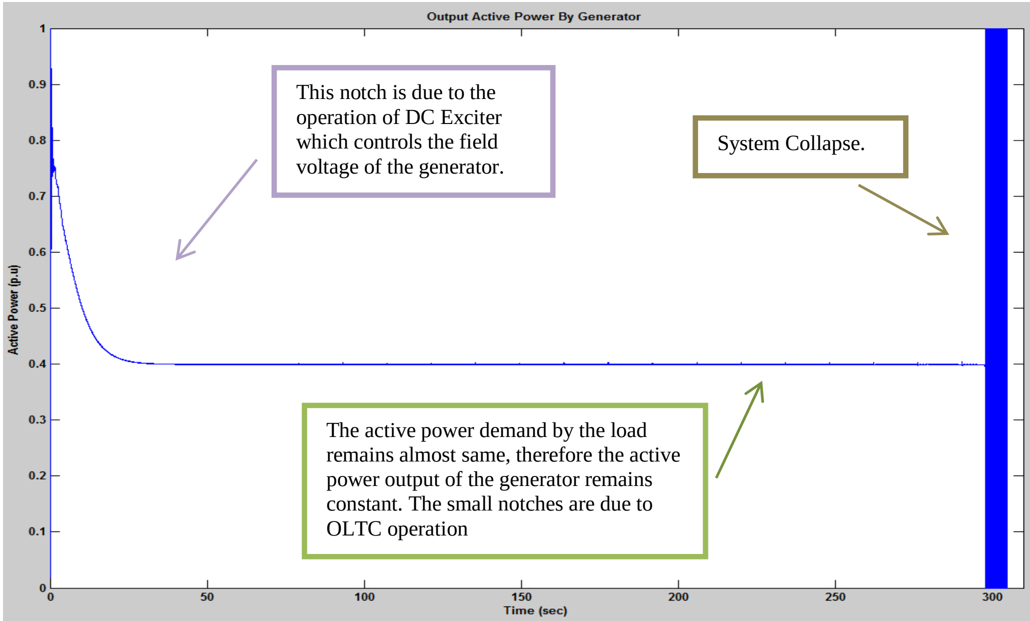


Fig. 4-47: Active Power Output by the Generator

The increase in load demand causes a dip in voltage at the generator bus which is sensed by the excitation system which increases the field voltage to maintain constant terminal voltage at the generator bus.

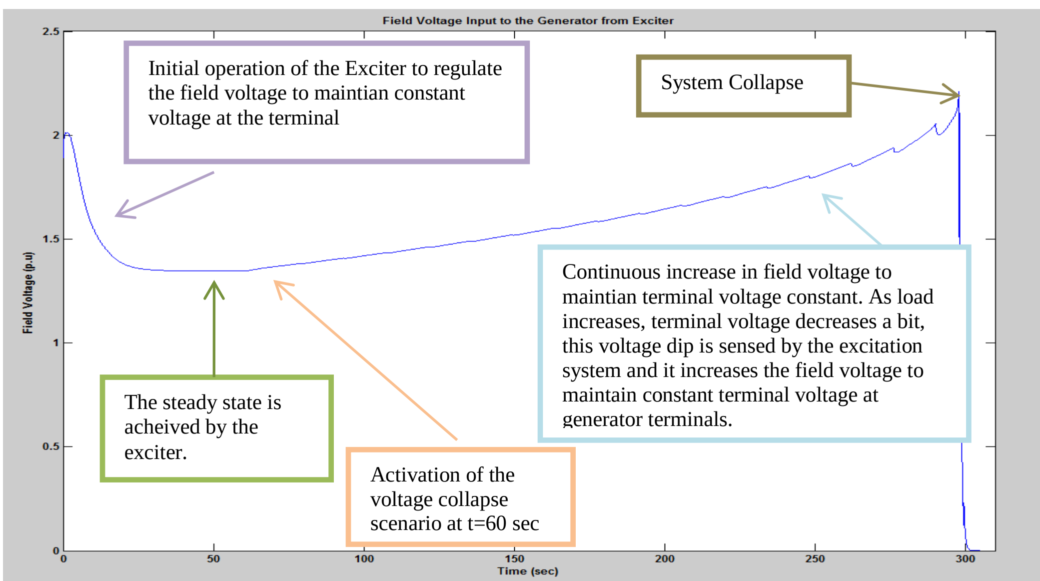


Fig. 4-48: Field Voltage Supplied by the Excitation System to the Synchronous generator

The induction motor is connected at Bus 4. As its load is constant therefore it only shows the dips in speed due to the decrease in the terminal voltage. As the load is constant, so the electromagnetic torque is also constant.

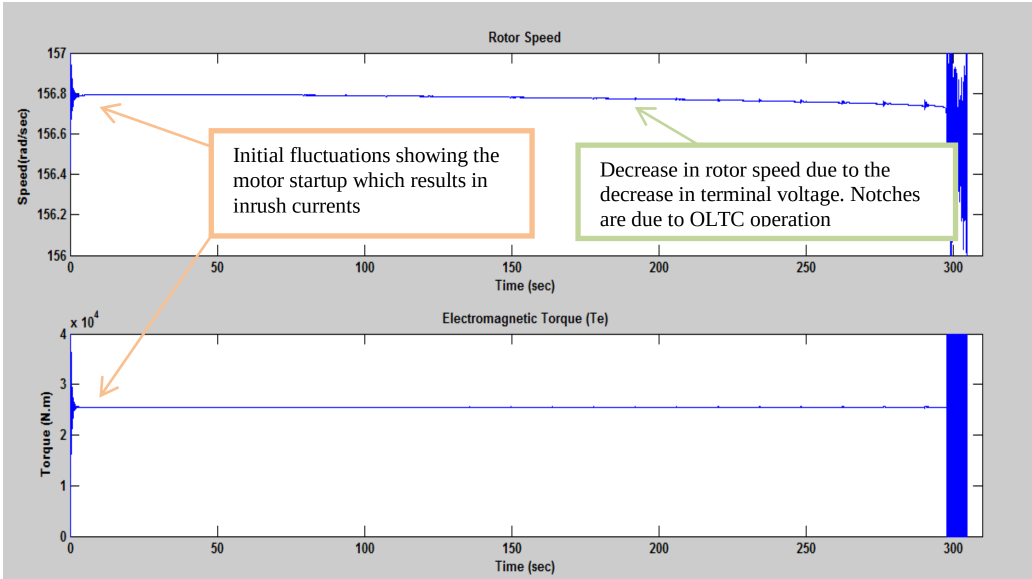


Fig. 4-49: Rotor Speed and Torque of the Induction Motor

This concludes our discussion for the long term voltage instability scenario analysis, done by using the all-in-one system modeled in SimPowerSystems and simulated in the OPAL-RT real-time simulator.

4.10. Chapter Summary

The chapter provides a detail insight of the modeling of a test system in SimPowerSystems (MATLAB/Simulink) and the simulation of the model in real-time. Various complexities and common errors that came across during real-time modeling and simulation have been discussed in detail along with their remedy. The chapter shows the procedure adopted for creating a voltage instability scenario. The detailed analysis is done in real-time and the simulation results are discussed in this chapter. This voltage instability scenario forms the basis of the rest of the tasks included in the report.

Chapter 5: Over-Current Relay Modeling, Implementation and Coordination in "All-in-One" Test System

5.1. Introduction

This chapter comprises the modeling of over-current relays in SimPowerSystems (MATLAB / Simulink) and their implementation and coordination in the "All-in-One" test system.

The chapter starts with an overview of power system protection and types of power protection relays used in the electrical power systems. A detailed description of the working, modeling, verification and implementation of an over-current relay model in the All-in-One system is presented. These relays are coordinated using a time grading and current grading approach for providing selectivity in case of faults. The over-current relay model is verified with different IEC/BS 142 curves standard inverse, very inverse, extremely inverse and long inverse characteristics.

Table of Figures

5.2. Power System Protection

In the earlier chapters, we have discussed the modeling of an All-in-One system which was used to analyze a voltage instability scenario. In this section we will primarily focus on the implementation of protection relays in the All-in-One system to minimize the effect of disturbances caused by any failure in the power system. This chapter includes the choice of protection relays, motivation behind choosing specific relay, Simulink implementation of the relay, testing of the relay in stand-alone mode, implementation of the relay in the all-in-one system and finally coordination of the relays to give maximum selectivity while minimizing the effect of disturbance and protecting the power system components.

5.2. 1. <u>Need for Power System Protection</u>

A power system is vulnerable to faults, either due to natural disasters that can cause damage to power apparatus or by mal-operation due to operator's negligence. The permanent damage of such components can bear a significant cost cost a lot and their replacement/procurement will result in a longer disconnection of power supply to customers which are highly undesirable. Hence, there is a need for a power system to sustain faults and protect important components from permanent damage and to minimize the effect of faults as much as possible. This is achieved by using power system protection techniques, methodologies and protective relays.

5.2. 2. <u>Types of Protection Relays</u>

Most of the modern day protection relays are the digital relays (or microprocessor based relays). They comprise of a microprocessor which has their own algorithms of monitoring the power system through current and voltage inputs from CTs and VTs respectively and detect fault and sends tripping signal to the circuit breaker to ensure safe and reliable operation of the power system. The figure below shows a general architecture of a protective relay.

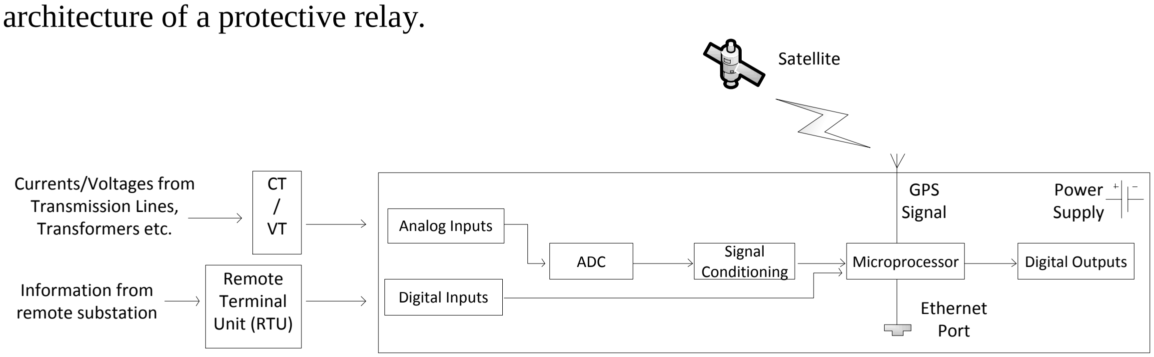


Fig.5-1: General Architecture of a digital relay

Fig. 5-1 shows the general architecture of a digital relay. The important components are discussed below:

- *Analog Inputs:* All the protection relays have analog input modules to measure the voltages and/or currents of the protected equipment. These voltages and currents are fed to the protection relays through VT and CT respectivily. These VT and CT steps down the voltages and current magnitudes respectivily to the level of 230 V and 5/1 A.
- *Analog to Digital Convertor:* ADC converts the continuous time analog signal to discrete time digital signal which could be fed to the microprocessor.
- *Signal Conditioning:* It consists of digital filtering and down sampling to avoid anti-aliasing effects.
- *Microprocessor:* It is a multi-purpose programmable device that takes in the digital signals, processes them by using an algorithim stored in its memory and generates the required outputs as results.
- *Digital Outputs:* These are the contacts of the relay which changes its position from Normal Open to Normal Close or vice versa, whenever the relay picks up the fault. These digital outputs are connected to the circuit breaker contacts to provide information to the circuit breaker that whether the relay has sent a trip signal or not.
- *GPS Time Synchronization:* In order to get an accurate time for synchronizing the applications in the overall substation, the relays are equipped with an IRIG-B input. This GPS signal provides time synchronization for synchrophasors.
- *Ethernet Ports:* The ethernet ports can be used to bring the relay on the network i.e. in order to access the relay through a digital network. Ethernet ports can also be configured to communicate to the relay and extract the information e.g. relay status, voltage and current measurements, synchrophasors etc.

The relay settings for ethernet ports, digital outputs, analog inputs, IRIG-B inputs can be done through vendor's specific softwares which are provided along with the relay

There are different protections schemes used to protect power systems. The choice of a protection scheme depends upon expected faults, budget, area, technical expertise of the protection scheme designer and other factors. Digital relays provide a wide range of protection functions [43] such as overcurrent, directional overcurrent, under voltage, over voltage, distance protection etc.

5.2. 3. Choice of Protection Relay for the All-in-One System

Overcurrent protection is one of the most important and basic protections applied for the power systems [44]. It is used as a main protection for medium and low voltage feeders [45] , main protection for medium size motors and other applications. Overcurrent relays are considered as a backbone for any protection scheme or strategy. They are often coordinated with other relays to provide backup protection for transmission lines. The primary protection for a transmission line is distance protection and backup protection is achieved through overcurrent relay. In the case of transformer where primary protection is differential relays but overcurrent relays provide protection for the HV and LV sides of the transformers in case of increased load.

As our main focus is to apply the protection scheme for a voltage instability scenario, so this means that an overcurrent relay can be effective and sufficient for this case (as we are increasing the load at bus 6 and this increased load means increased current demand which can be detected by the overcurrent relay). In order to make the protection strategy simple, we have considered overcurrent protection for the transmission lines, motor, loads etc. These overcurrent relays are then coordinated in such a way that the relay closest to the fault position detects the fault first and then send trip command to the respective breaker to minimize the effect of fault.

5.3. Basic Principle of Over-Current Protection

As the name states, an overcurrent relay provides protection against over currents. This relay only takes current inputs from the current transformer and compares this value of current with preset values. If the input current value exceeds the preset value, the relay detects an overcurrent and issues trip signal to the breaker which opens its contact to disconnect the protected equipment. As soon as the relay detects a fault, the condition is called fault pickup. The relay can send a trip signal instantaneously after picking up the fault (in the case of instantaneous over-current relay) or it can wait for a specific time before issuing a trip signal (in the case of time overcurrent relays). This time delay is also known as operation time of the relay and is computed by the relay on the basis of the protection algorithm incorporated in the microprocessor [46].

5.3.1. Classification of Over-Current Relays

Overcurrent relays are classified on the basis of their operation time, in the following three categories:

Instantaneous Overcurrent Relay

These relays instantaneously send a trip command to the breaker as soon as the fault is detected (input current greater than the preset value). They don't have any intentional time delay. They are usually implemented close to the source where the fault current level is very high and a small delay in operation of relay can cause heavy damage to the equipment. So an instantaneous relay is used there to detect and respond to a fault in few cycles.

Definite Time Overcurrent Relay

This type of overcurrent relay is used for backup protection for distance relays. If the distance relay does not detect a line fault and does not trips the breaker, then after a specific time delay, the overcurrent relay will send a trip command to the breaker. In this case, the overcurrent relay is time delayed by a specific time which is just greater than the normal operating time of the distance relay.

Inverse Definite Minimum Time (IDMT) Overcurrent Relay

This relay has an inverse time characteristic. This means that the relay operating time is inversely proportional to the fault current. If fault current is higher, operating time will be lesser [47]. It can be graded for a very large range of operating times and fault currents.

We have selected IDMT overcurrent relays for the all-in-one system. The disadvantage with the definite time overcurrent relays is that if there are several such relays in the system, then the coordination is done in a way that the time of operation increases as fault location becomes closer to the source. The major advantage of IDMT relays is that the operation time will be much lesser if the fault current is higher [48].

5.3.2. Logic Diagram for Over-Current Relays

The logic diagram of an overcurrent relay is shown in Fig.5-2. The comparator actually compares the values of the input signal with the preset value and generates a trip signal (either instantaneous or time delayed)

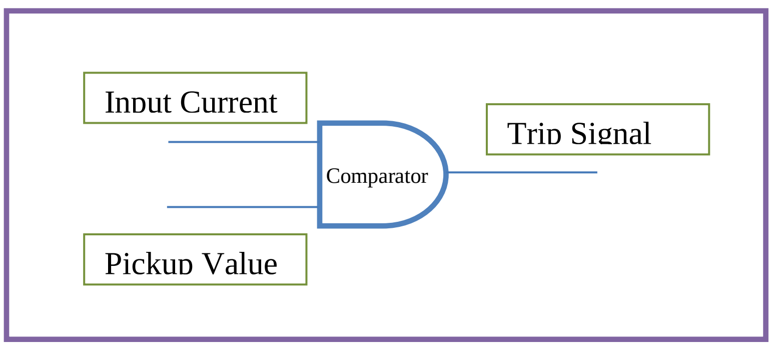


Fig.5-2: Logical Diagram of Overcurrent Relay

5.3.3. Characteristics of IDMT Overcurrent Relays

The characteristics of an overcurrent relay depend on the type of standard selected for the relay operation. These standards can be ANSI, IEEE, IAC or user defined. The relay calculates the operation time by using the curves and the corresponding parameters [49]. Any of the above mentioned standards can be used to implement a characteristic curve for an overcurrent relay. The overcurrent relay will then calculate the operation time corresponding to that particular characteristic curve.
In accordance with IEC 60255 or BS142, the characteristics of IDMT relays are represented with the following equation:

$$T = \frac{C}{\left(\frac{I}{I_s}\right)^{\alpha} - 1} \times TMS \qquad \text{(Eq. 1)}$$

Where T – Relay operation time
C – Constant for relay characteristic
I_s – Current Set point
I – Current Input to the relay
α – Constant Representing Inverse Time Type ($\alpha > 0$)
TMS – Time Multiplier setting controls the relay tripping time. By using appropriate TMS settings, the grading of a protection network system can be achieved [51]. The range of TMS is normally 0.1 to 1.0.

Different types of curves can be obtained by varying α and C. These different curves are: (i) Standard Inverse, (ii) Very Inverse, (iii) Extremely Inverse and (iv) Long Inverse

Table 1 below shows values for α and C corresponding to each curve:

Different Types of Inverse Characteristics		
Relay Characteristic Type	**α**	**C**
Standard Inverse	0.02	0.14
Very Inverse	1	13.5
Extremely Inverse	2	80
Long Inverse	1	120

Table.1: Different Types of Inverse Characteristics Curves

5.3.4. Flowchart For Overcurrent Relay Operation

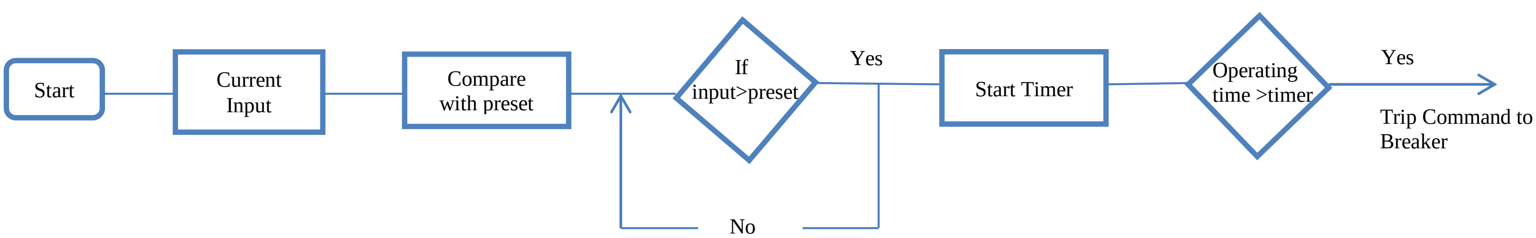


Fig.5-3: Flow Chart for Over-Current Relay Operation

The flow chart shows that the relay will send a trip signal if the input value of the current is greater than the preset value and the intended time delay has elapsed. This flowchart can be used to implement a simple algorithm for either single phase or three phase tripping. For this thesis we are focusing on an overcurrent relay which allows three phase tripping of the breaker. So we are not considering the single phase tripping of the breaker. However the same strategy of comparing the input currents for individual phases can be done to trip individual phase of the breaker. In this project in case of either single phase or three phase overcurrent, the relay will give a three phase tripping command to the breaker

5.4. Modeling of Overcurrent Relay in MATLAB/Simulink

This section provides details about the modeling of overcurrent relay in Simulink. This is a basic model [52] based on IEC standards. The block diagram of the relay is shown in Fig.5-4.

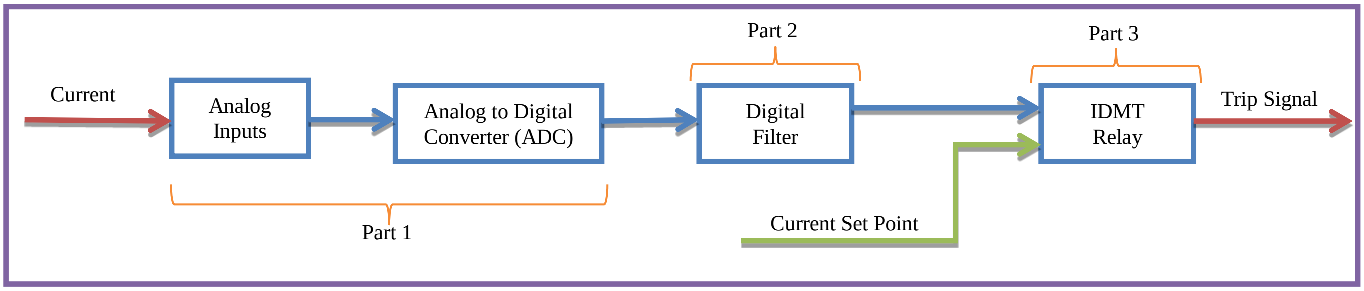


Fig.5-4: Block Diagram of Overcurrent Relay

5.4.1. *Detail of Model*

The block diagram shown above represents the Overcurrent Relay. For a clear understanding, the whole block diagram will be explained in three parts;

Part 1

In order to present an accurate model of the microprocessor based overcurrent relay, the current inputs which are analog signals are converted to digital signals by Analog to Digital Conversion. In Simulink this can be achieved by using Zero Order Hold Block. This ZOH block is present in the Discrete Library of Simulink as shown in Fig. 5-5.

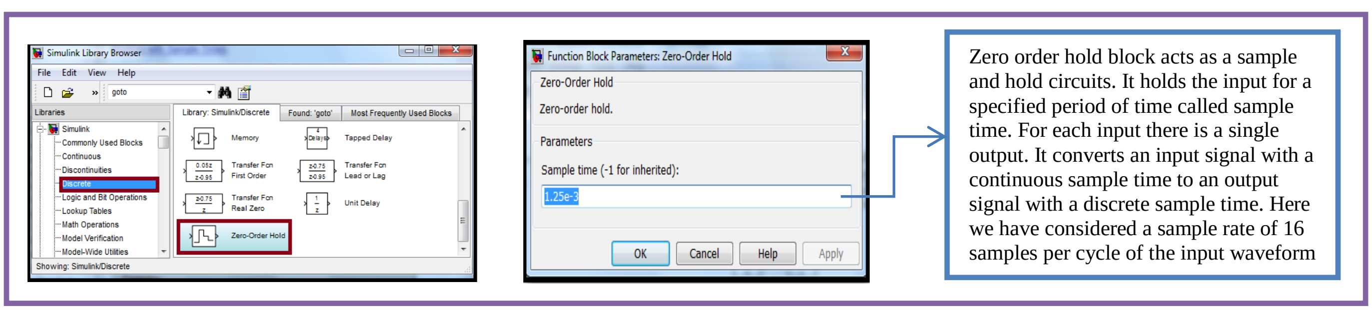


Fig.5-5: Block Diagram of Zero Order Hold

Part 2

A digital filter is used to extract the fundamental signal. A down sampler is used in order to reduce the sampling rate. Down sampling helps avoiding anti-aliasing [53] effects. The digital filter used here is a low pass digital FIR filter [54]. Fig. 5-6 shows these blocks and their setting details.

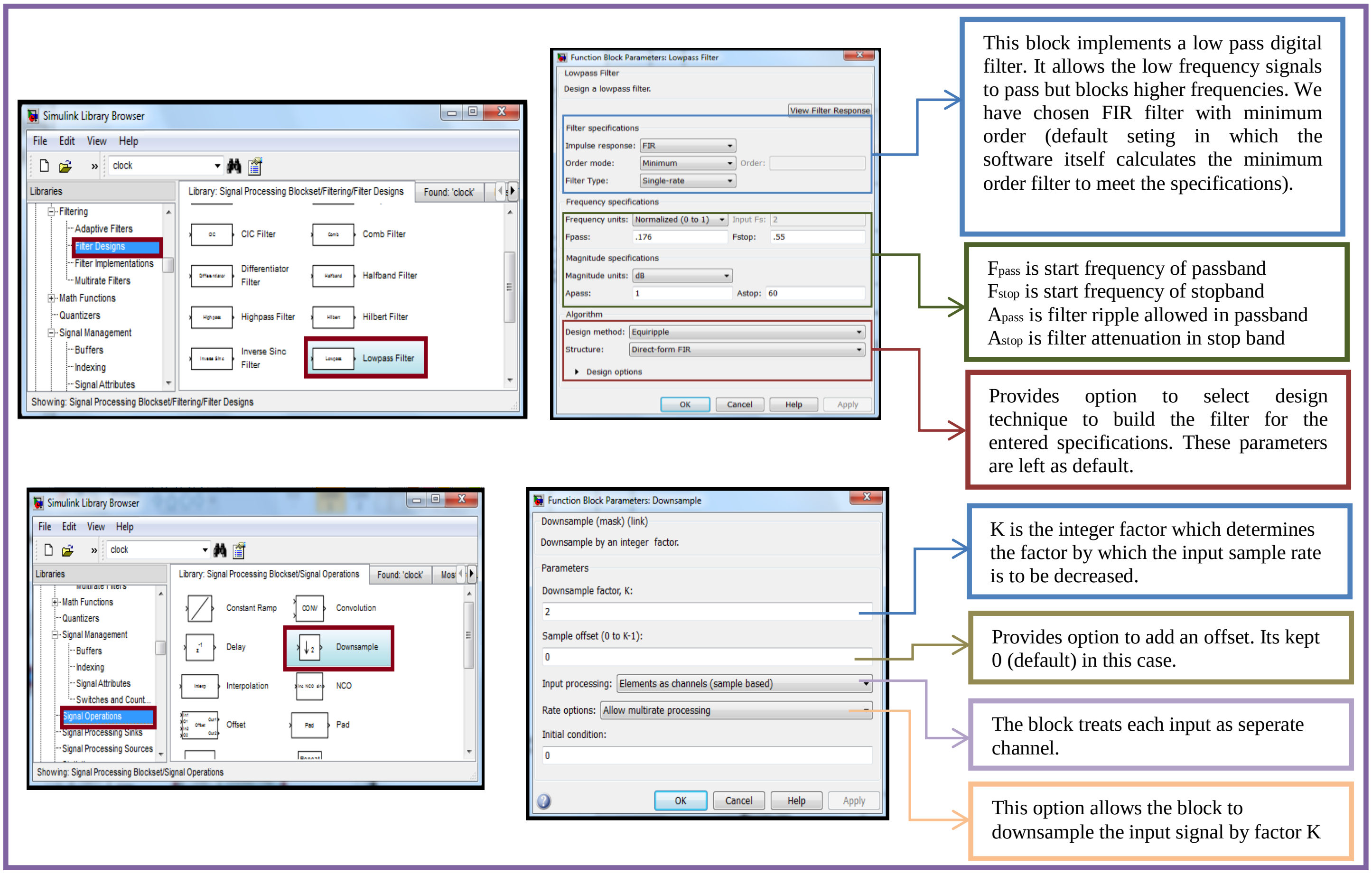


Fig.5-6: Block Diagram of Low Pass Filter and Down-sample with their parameters settings

In order to extract the fundamental signal out of the digital signal, the output of the down-sampler is fed to the Fourier block. This block performs Fourier analysis of the signal and can be configured to calculate the magnitude and phase of the fundamental, harmonics or DC Component of the input signal. As we are interested only in the fundamental component, we have configured this block accordingly. In addition the output of the block was divided by $\sqrt{2}$ to get the rms value of the fundamental. This rms value is then fed into the relay logic block (discussed below) to compute the operation time and give trip signal if the input exceeds the pickup. Fig. 5-7 shows the Fourier block which is present in the Discrete Measurement Category of the SimPowerSystems Library.

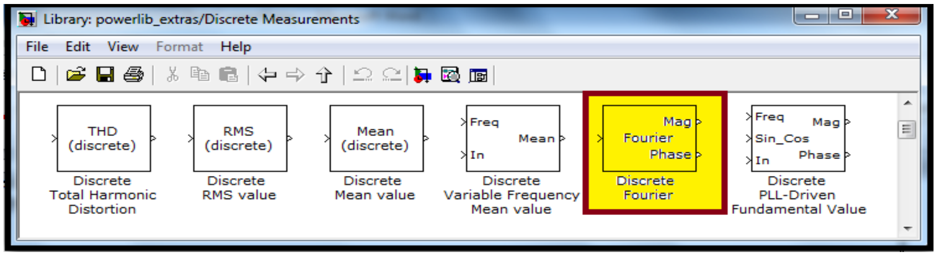
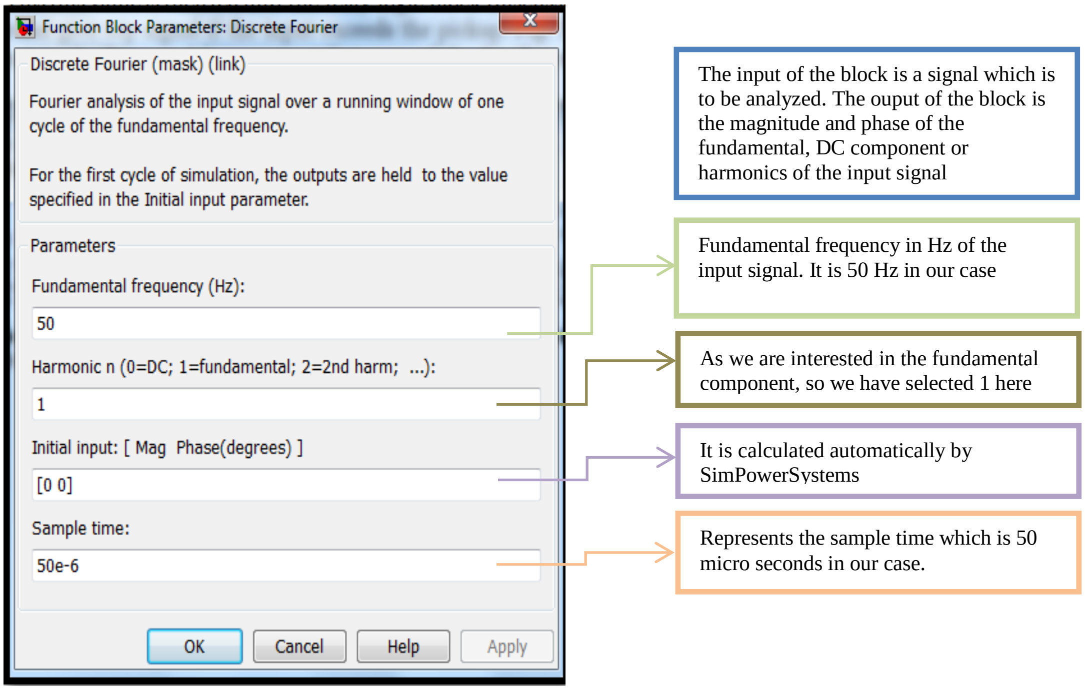
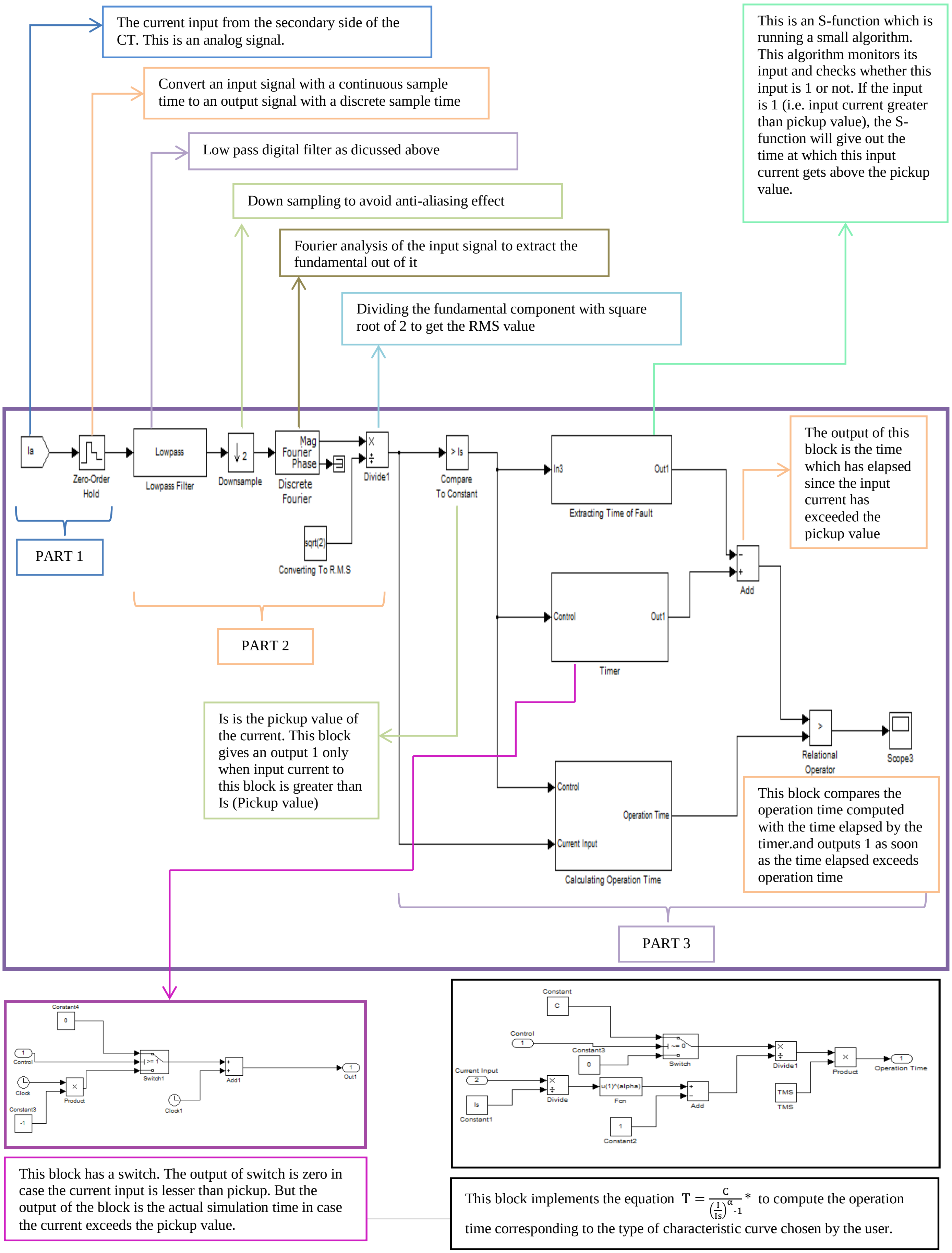


Fig.5-7: Fourier Block available in SimPowerSystems Library



Part 3

Once the RMS value of the current is obtained, this current is fed into the IDMT Relay Block. This block compares the current value with the pickup value. If the input current exceeds the pickup value, then the relay will compute the operation time for this scenario taking into consideration the characteristic curve (Standard Inverse, Very Inverse, Extremely Inverse or Long Inverse) and sends a trip signal once the operation time is elapsed. Fig. 5-8 shows the overall model of the IDMT relay showing all the three parts discussed above. The logics used for the relay is also explained.


The current input from the secondary side of the CT. This is an analog signal.
Convert an input signal with a continuous sample time to an output signal with a discrete sample time
Low pass digital filter as dicussed above
Down sampling to avoid anti-aliasing effect
Fourier analysis of the input signal to extract the fundamental out of it
Dividing the fundamental component with square root of 2 to get the RMS value
This is an S-function which is running a small algorithm. This algorithm monitors its input and checks whether this input is 1 or not. If the input is 1 (i.e. input current greater than pickup value), the S-function will give out the time at which this input current gets above the pickup value.
Ia
Zero-Order Hold
Lowpass
Lowpass Filter
Downsample
Mag
Fourier
Phase
Discrete Fourier
Divide1
sqrt(2)
Converting To R.M.S
> Is
Compare To Constant
In3
Out1
Extracting Time of Fault
Control
Out1
Timer
Add
The output of this block is the time which has elapsed since the input current has exceeded the pickup value
PART 1
PART 2
Is is the pickup value of the current. This block gives an output 1 only when input current to this block is greater than Is (Pickup value)
Control
Operation Time
Current Input
Calculating Operation Time
Relational Operator
Scope3
This block compares the operation time computed with the time elapsed by the timer.and outputs 1 as soon as the time elapsed exceeds operation time
PART 3
Constant4
Control
Clock
Product
Constant3
Switch1
Clock1
Add1
Out1
Constant
Control
Constant3
Switch
Current Input
Divide
u(1)^(alpha)
Fcn
Constant1
Add
Constant2
Divide1
TMS
Product
Operation Time
This block has a switch. The output of switch is zero in case the current input is lesser than pickup. But the output of the block is the actual simulation time in case the current exceeds the pickup value.
This block implements the equation $T = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} *$ to compute the operation time corresponding to the type of characteristic curve chosen by the user.

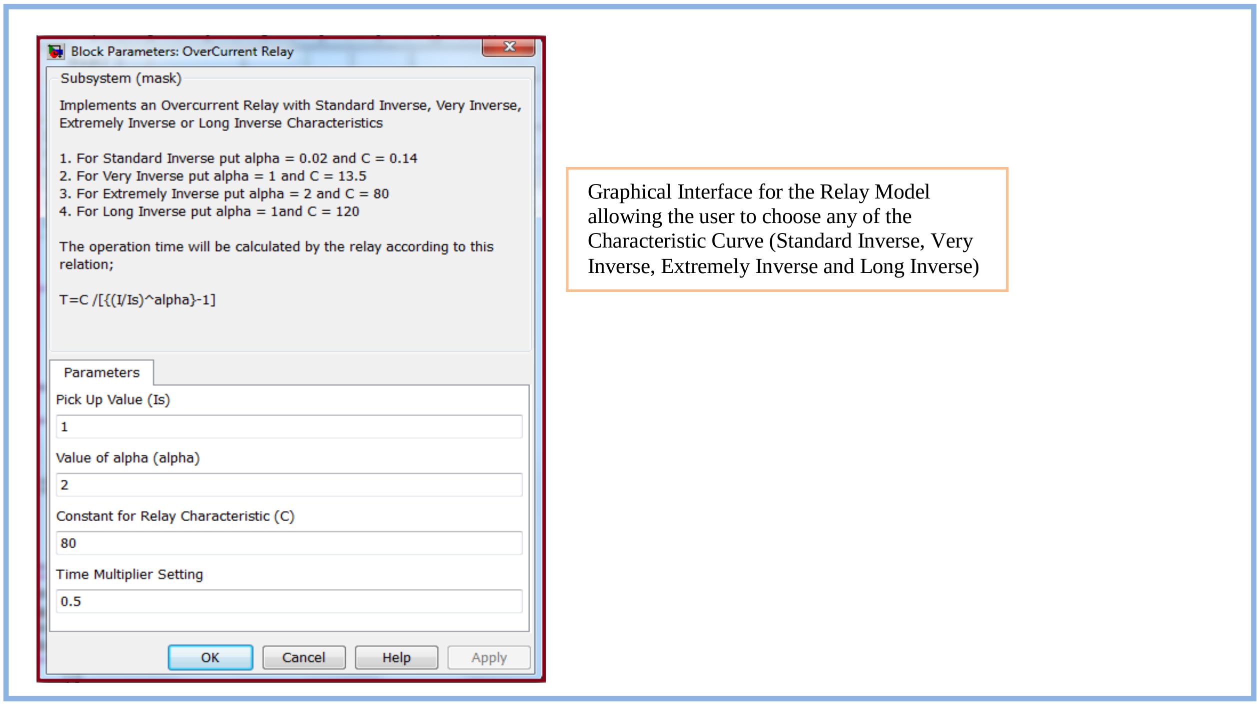


Fig.5-8: Graphical Interface for the Relay Model

5.5. Test System for Overcurrent Relay Model Validation

In order to validate the result of the model implementation, a small test system was developed and the tripping time of the overcurrent relay was analyzed with different characteristic curves. These were checked by the numerical results given in IEC/BS142 curves. The test system is shown in Fig.5-9.

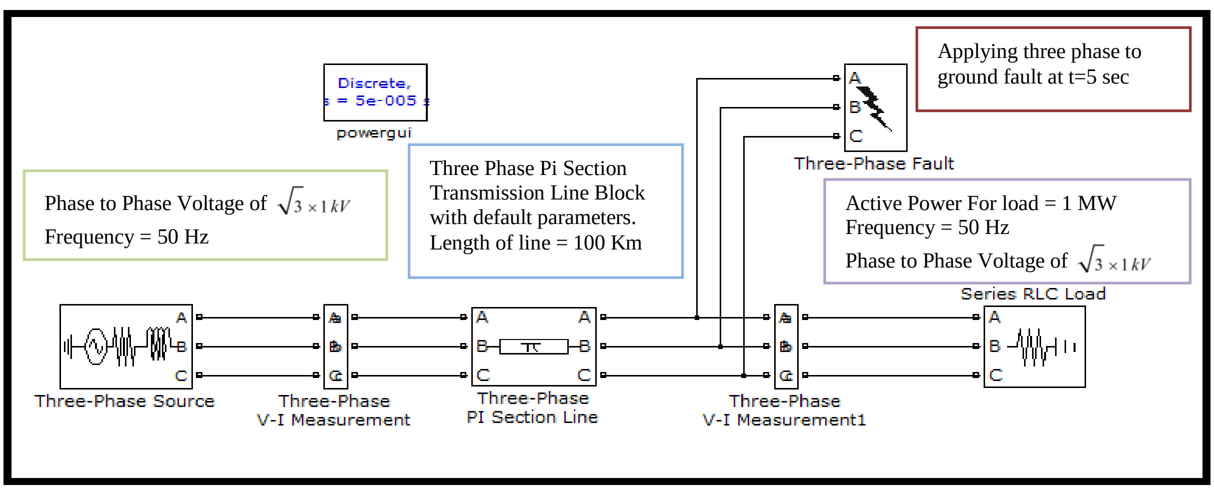


Fig.5-9: Test System for Relay Model Validation

We are considering that the Overcurrent relay is connected at Bus 1. In order to set the parameters for the relay, the full load current was measured for the system and also the maximum and minimum fault currents. These details are provided in Table 2.

Analysis of Test System	
Measurements	**Value (RMS-Amperes)**
Full Load Current	330
Minimum Fault Current (Phase to Ground Fault)	1777
Maximum Fault Current (Three Phase to Ground Fault)	3088

Table 2: Analysis of the Test System for Relay Parameters Settings

Here we are considering a CT with the ratio 400:1 i.e. if the primary side of the CT is 400A then it will give 1 A at its secondary. Most of the relays are configured for either 5 A or 1 A CT secondary. The pickup value for the overcurrent relay is set to be 1 A. This means that the relay will operate if the current input exceeds 1 A (depending on the characteristic curve chosen to compute operating time). A common practise for setting the pickup value for the relay is

$$1.2 * Max\ Load\ Current \ \leq Pickup\ Value \ \leq 0.9 * Minimum\ Fault\ Current$$

According to our setting, the maximum load current is 330 A. This current will be fed to the CT. The turn ratio for CT is 400:1. So the full load current at the secondary side of the CT will be $330 * \frac{1}{400} = 0.825\ A$. According to rule of thumb:

$$1.2 * Max\ Load\ Current = 1.2 * 0.825 = 0.99A.$$

So we have selected a pickup value of 1 A which satisfies the criteria is selected. As the minimum fault current is 1777 A, so the minimum fault current at secondary side of CT will be $1777 * \frac{1}{400} = 4.4425\ A$ which is sufficiently above the pickup value of 1 A.The plots in Fig. 5-10 show the full load and fault currents for the test system.

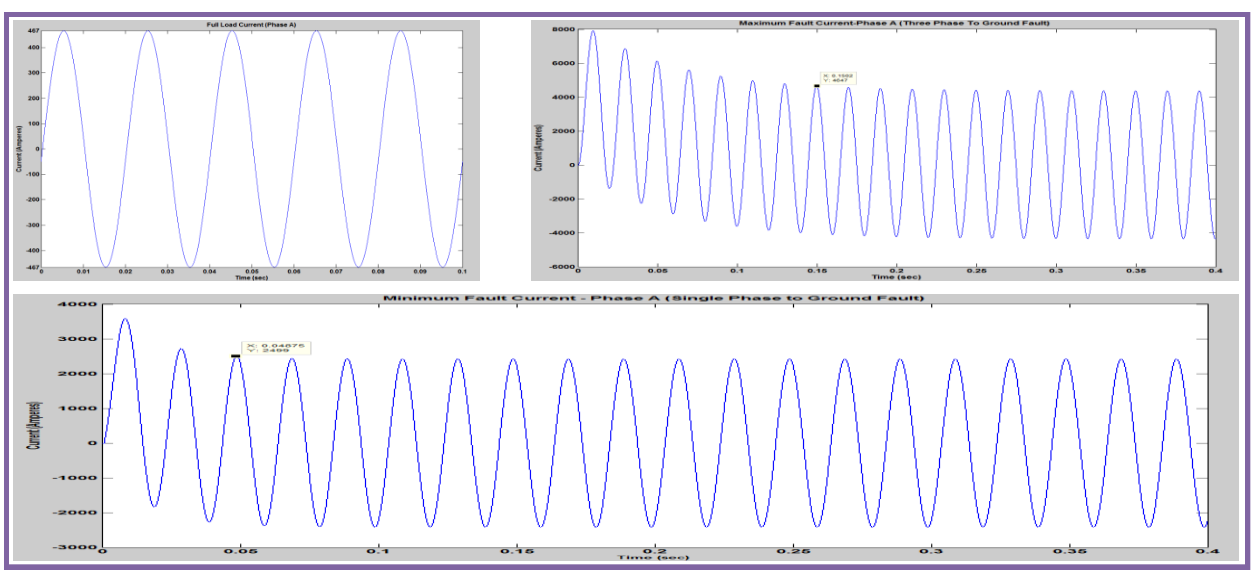
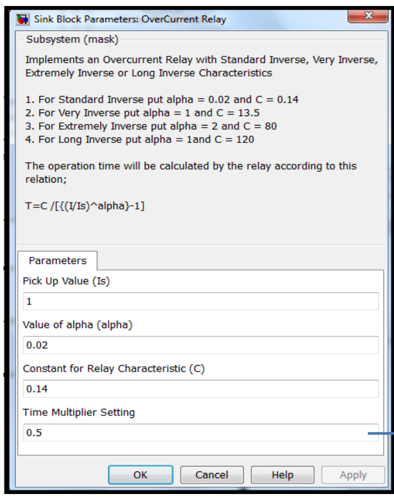


Fig.5-10: The full load, minimum fault and maximum fault currents for the test system (only phase A is shown as it is a symmetrical system so other two phases are just phase shifted by 120 degrees)

For the test system we are using Time Multiplier Setting of 0.5 (can be any number between 0 and 1). This TMS can be set from the Overcurrent Relay Block (see Fig. 5-6). The three phase to ground fault is applied at t=2 sec and the simulation is run for 5 sec. The relay is checked for different characteristic curves and the trip signal is observed. These are discussed sequentially.

5.5.1. Standard Inverse Curve

For Standard Inverse Characteristic, the relay parameters were configured as shown in Fig. 5-11



TMS is set to 0.5 (only for testing and validating the relay model)

As Maximum fault current is 3088A which means secondary side of CT will be 3088 $* \frac{1}{400} = 7.72$. So $\frac{I_{Fmax}}{I_{Pickup}} = 7.72$
Using the analytical formula for calculating the operating time of the relay with these settings (see Table 1)

$$T = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} * TMS$$

$$T = \frac{0.14}{\left(\frac{7.72}{1}\right)^{0.02} - 1} * 0.5$$

$$T = 1.6777\ sec$$

Fig.5-11: Overcurrent Relay setting for standard inverse curve and analytical calculation for tripping time computation.

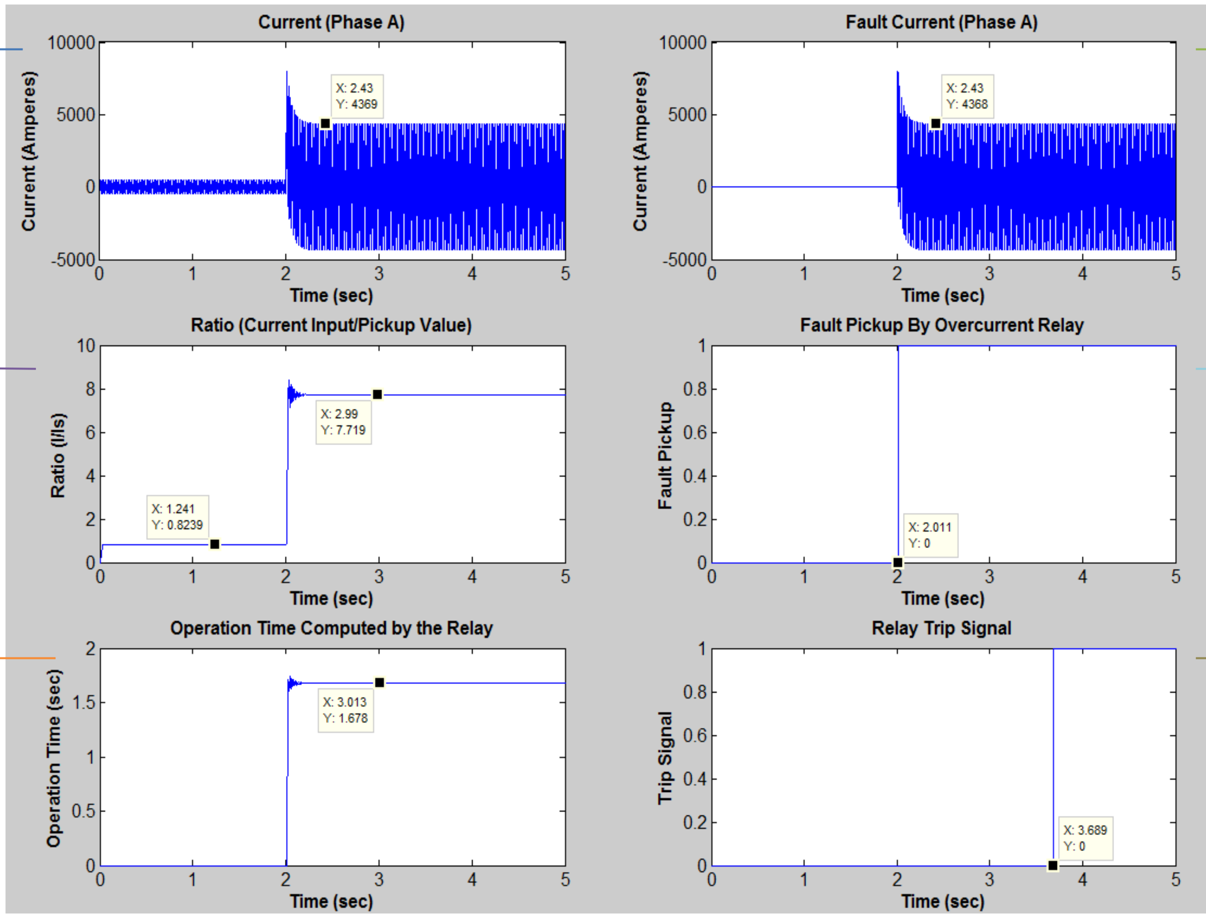
Plots in Fig. 5-12 show the fault currents, relay fault pickup, operating time computed by the relay, trip signal generated by the relay. The plots show that as soon as the fault is applied at t= 2 sec, the relay picks up the fault at 2.011 sec. The operating time calculated by the relay is 1.678 sec which is pretty close to the analytically computed operating time of 1.6777 sec. Finally the relay sends a trip signal at t=3.689 sec. The fault is applied at t=2 sec and the operating time calculated is 1.678 sec. So trip signal should be at $T_{Trip} = T_{Fault} + T_{Operation\ Time} = 2 + 1.678 = 3.678\ sec$. This model has sent a trip signal at T= 3.689 sec. This difference of 0.011 sec is due to the time the relay has taken to sense the fault (see fault pickup plot in Fig. 5-12). This difference is negligible and thus we can say that the model is in accordance with the Standard Inverse Characteristic Curve (IEC/BS 142). Table 3 shows the comparison of characteristics of the relay model with the calculated one in tabular form.

Characteristics	From Relay Model	From Calculations
Operating Time	1.6780	1.6777
Trip Signal	3.689	3.678

Table.3: Characteristic Comparison of the Model with Calculated Values (Standard Inverse)

The current measurements for phase A. The fault is applied at t=2sec. The data cursor shows that the peak value of the fault current is 4369 A which means $\frac{4369}{\sqrt{2}} = 3089A$ (RMS)

The fault current at Phase A which clearly shows that fault current is 0 till t=2 sec and then increases to 3089 A (RMS) as soon as the fault is applied.



The operating time computed by the relay is 1.678 sec which is similar to the calculated value (1.6777sec)

Initially I/Is = 0.824 (calculated value of 0.825) and once the fault is implemented, this value increases to 7.719 (7.72 calculated). The relay picks it up as fault because I/Is >1 and starts the timer and computes the operating time.

As the relay has picked up the fault at t=2.011 sec. So the final tripping time of the relay is

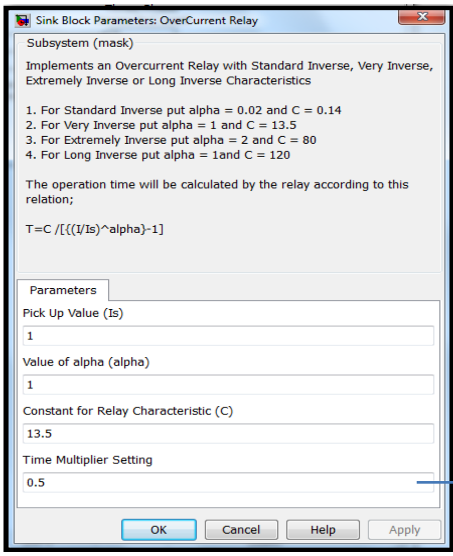
$$T_{Trip} = T_{Fault} + T_{Operation\ Time}$$
$$= 2.011 + 1.678$$
$$= 3.689\ sec$$

The plot shows that the relay has picked up fault at 2.011 sec (as soon as I/Is >1)

Fig.5-12: Response of Overcurrent Relay with Standard Inverse Characteristic Curve

5.5.2. ***Very Inverse Curve***

For Very Inverse Characteristic, the relay parameters were configured as shown in Fig. 5-13



TMS is set to 0.5 (only for testing and validating the relay model)

As Maximum fault current is 3088A which means secondary side of CT will be $3088 * \frac{1}{400} = 7.72$. So $\frac{I_{Fmax}}{I_{Pickup}} = 7.72$
Using the analytical formula for calculating the operating time of the relay with these settings (see Table 1)

$$T = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} * TMS$$

$$T = \frac{13.5}{\left(\frac{7.72}{1}\right)^{1} - 1} * 0.5$$

$$T = 1.0045\ sec$$

Fig.5-13: Overcurrent Relay setting for very inverse curve and analytical calculation for tripping time computation.

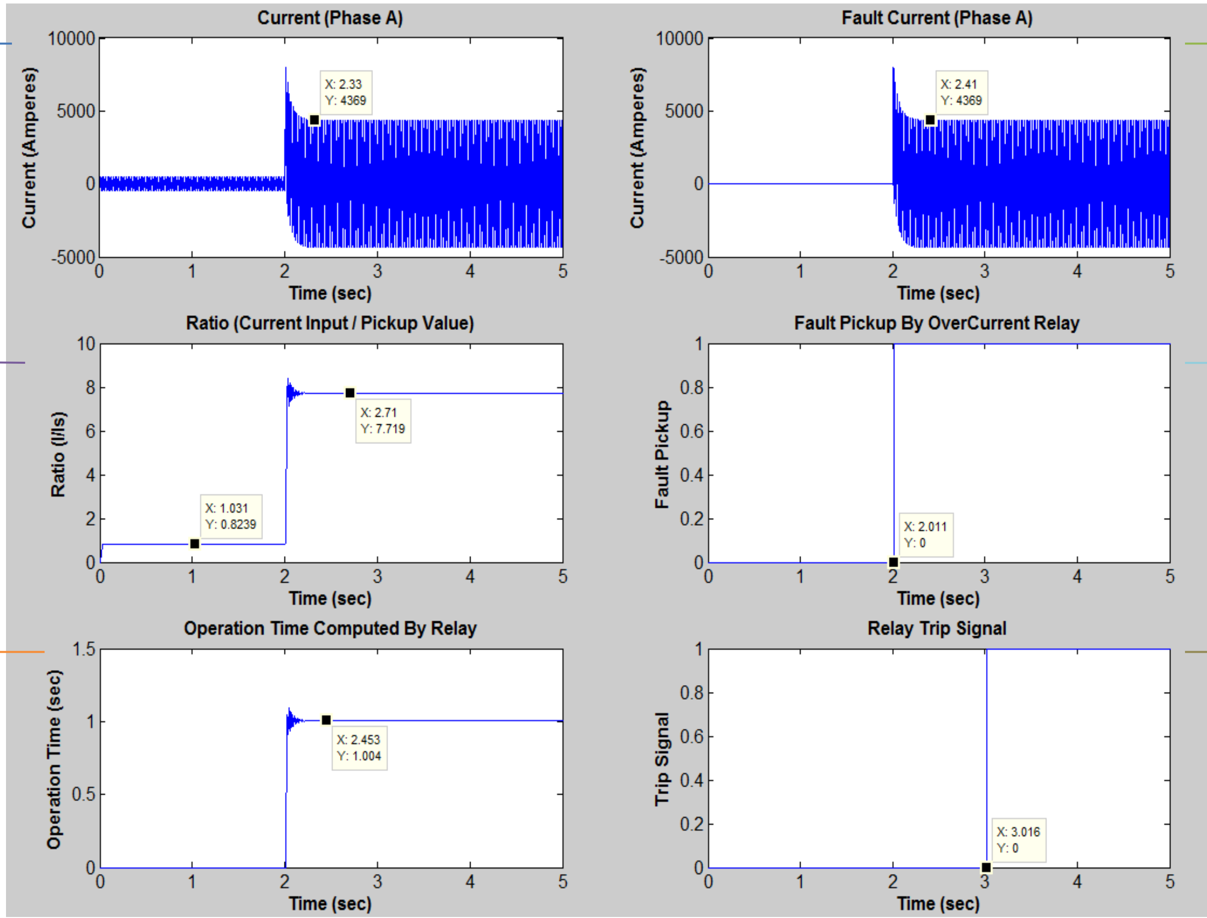
Plots in Fig. 5-14 show the fault currents, relay fault pickup, operating time computed by the relay, trip signal generated by the relay. The plots show that as soon as the fault is applied at t= 2 sec, the relay picks up the fault at 2.011 sec. The operating time calculated by the relay is 1.0040 sec which is pretty close to the analytically computed operating time of 1.0045 sec. Finally the relay sends a trip signal at t=3.016 sec. The fault is applied at t=2 sec and the operating time calculated is 1.0040 sec. So trip signal should be at $T_{Trip} = T_{Fault} + T_{Operation\,Time} = 2 + 1.0040 = 3.0040\ sec$. This model has sent a trip signal at T= 3.016 sec. This difference of 0.011 sec is due to the time the relay has taken to sense the fault (see fault pickup plot in Fig. 5-14). This difference is negligible and thus we can say that the model is in accordance with the Very Inverse Characteristic Curve (IEC/BS 142). Table 4 shows the comparison of characteristics of the relay model with the calculated one in tabular form.

Characteristics	From Relay Model	From Calculations
Operating Time	1.0040	1.0045
Trip Signal	3.0160	3.0040

Table.4: Characteristic Comparison of the Model with Calculated Values (Very Inverse)

The current measurements for phase A. The fault is applied at t=2sec. The data cursor shows that the peak value of the fault current is 4369 A which means $\frac{4369}{\sqrt{2}} = 3089A$ (RMS)

The fault current at Phase A which clearly shows that fault current is 0 till t=2 sec and then increases to 3089 A (RMS) as soon as the fault is applied.



The operating time computed by the relay is 1.004 sec which is similar to the calculated value (1.0045sec)

As the relay has picked up the fault at t=2.011 sec. So the final tripping time of the relay is

$$T_{Trip} = T_{Fault} + T_{Operation\,Time}$$
$$= 2.011 + 1.004$$
$$= 3.015\ sec$$

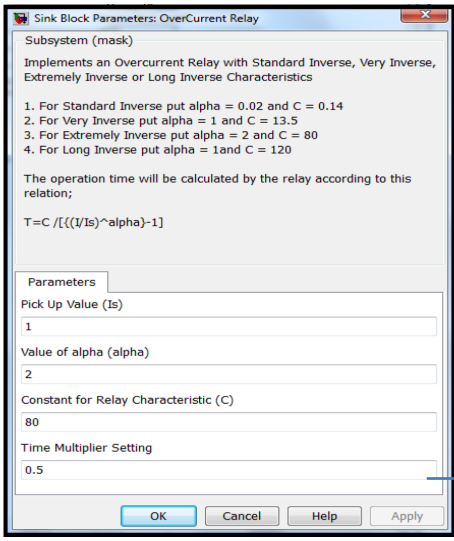
Initially I/Is = 0.824 (calculated value of 0.825) and once the fault is implemented, this value increases to 7.719 (7.72 calculated). The relay picks it up as fault because I/Is >1 and starts the timer and computes the operating time.

The plot shows that the relay has picked up fault at 2.011 sec (as soon as I/Is >1)

Fig.5-14: Response of Overcurrent Relay with Very Inverse Characteristic Curve

5.5.3. ***Extremely Inverse Curve***

For Extremely Inverse Characteristic, the relay parameters were configured as shown in Fig. 5-15



TMS is set to 0.5 (only for testing and validating the relay model)

As Maximum fault current is 3088A which means secondary side of CT will be $3088 * \frac{1}{400} = 7.72$. So $\frac{I_{Fmax}}{I_{Pickup}} = 7.72$
Using the analytical formula for calculating the operating time of the relay with these settings (see Table 1)

$$T = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} * TMS$$

$$T = \frac{80}{\left(\frac{7.72}{1}\right)^{2} - 1} * 0.5$$

$$T = 0.6826\ sec$$

Fig.5-15: Overcurrent Relay setting for extremely inverse curve and analytical calculation for tripping time computation.

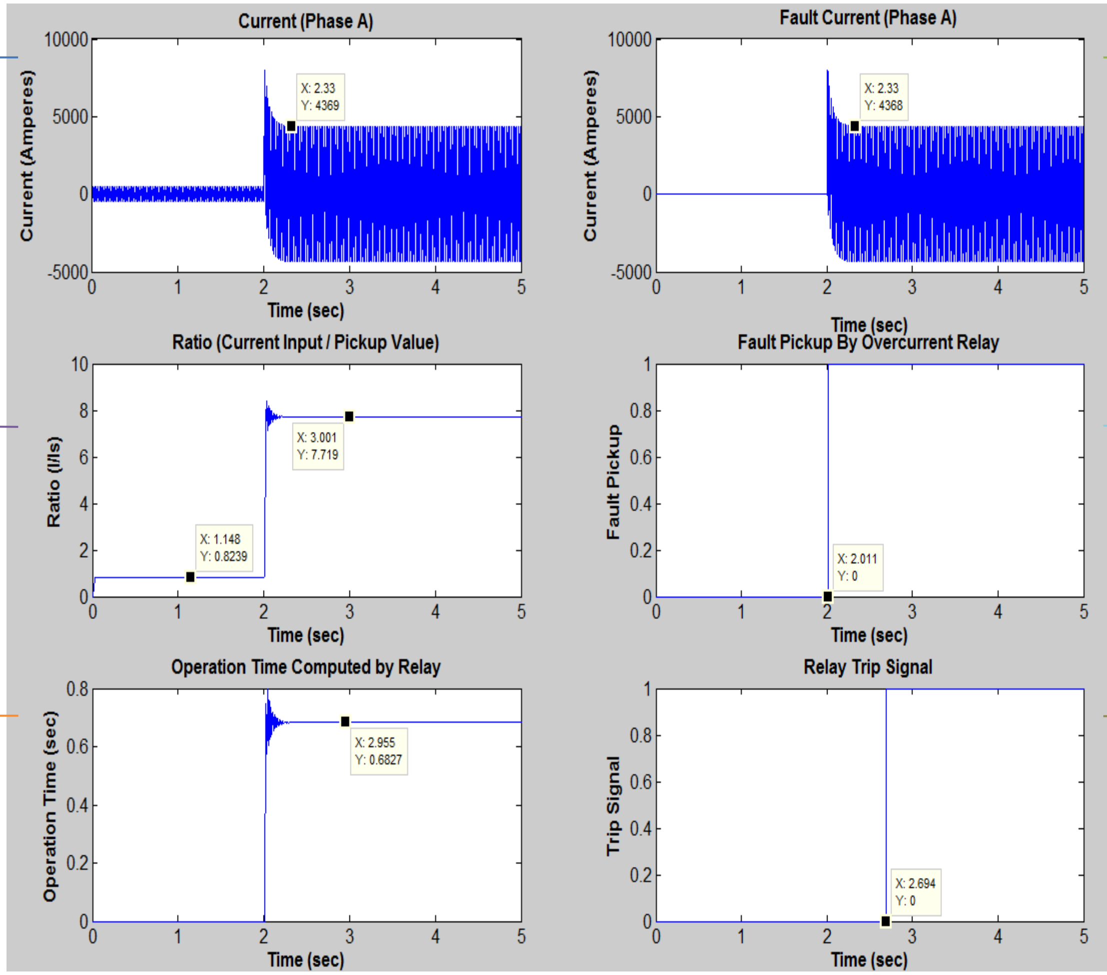
Plots in Fig. 5-16 show the fault currents, relay fault pickup, operating time computed by the relay, trip signal generated by the relay. The plots show that as soon as the fault is applied at t= 2 sec, the relay picks up the fault at 2.011 sec. The operating time calculated by the relay is 0.6827 sec which is pretty close to the analytically computed operating time of 0.6826 sec. Finally the relay sends a trip signal at t=2.694 sec. The fault is applied at t=2 sec and the operating time calculated is 0.6827 sec. So trip signal should be at $T_{Trip} = T_{Fault} + T_{Operation\,Time} = 2 + 0.6827 = 2.6827\ sec$. This model has sent a trip signal at T= 2.694 sec. This difference of 0.011 sec is due to the time the relay has taken to sense the fault (see fault pickup plot in Fig. 5-16). This difference is negligible and thus we can say that the model is in accordance with the Extremely Inverse Characteristic Curve (IEC/BS 142). Table 5 shows the comparison of characteristics of the relay model with the calculated one in tabular form.

Characteristics	From Relay Model	From Calculations
Operating Time	0.6827	0.6826
Trip Signal	2.694	2.6826

Table.5: Characteristic Comparison of the Model with Calculated Values (Extremely Inverse)

The current measurements for phase A. The fault is applied at t=2sec. The data cursor shows that the peak value of the fault current is 4369 A which means $\frac{4369}{\sqrt{2}} = 3089A$ (RMS)

The fault current at Phase A which clearly shows that fault current is 0 till t=2 sec and then increases to 3089 A (RMS) as soon as the fault is applied.



The operating time computed by the relay is 0.6827 sec which is similar to the calculated value (0.6826sec)

As the relay has picked up the fault at t=2.011 sec. So the final tripping time of the relay is

$$T_{Trip} = T_{Fault} + T_{Operation\,Time}$$
$$= 2.011 + 0.6827$$
$$= 2.6937\ sec$$

Initially I/Is = 0.824 (calculated value of 0.825) and once the fault is implemented, this value increases to 7.719 (7.72 calculated). The relay picks it up as fault because I/Is >1 and starts the timer and computes the operating time.

The plot shows that the relay has picked up fault at 2.011 sec (as soon as I/Is >1)

Fig.5-16: Response of Overcurrent Relay with Extremely Inverse Characteristic Curve

5.6. Implementation of Over-Current Relays in All-in-One System

As discussed earlier, the over-current relay provides the most basic and fundamental protection for power system equipment. Fig. 5-17 shows the single line diagram of the all-in-one system. The red circles show the current transformers whose secondary side is connected to over-current relays. As there are three transmission lines, three over current relays for each transmission line are needed. One over-current relay is used for the dynamic load[1]. One over-current relay is implemented between Bus 2 and bus 3. The motivation behind using an over-current relay here is to protect the step up transformer connected between the generator (Bus 2) and Bus 3. In the voltage collapse scenario, we are increasing the load at bus 5, this results in more power generation at Bus 2 in order to compensate for the extra load. The over current relay between Bus 2 and Bus 3 will protect the transformer against over loading and transformer damage.

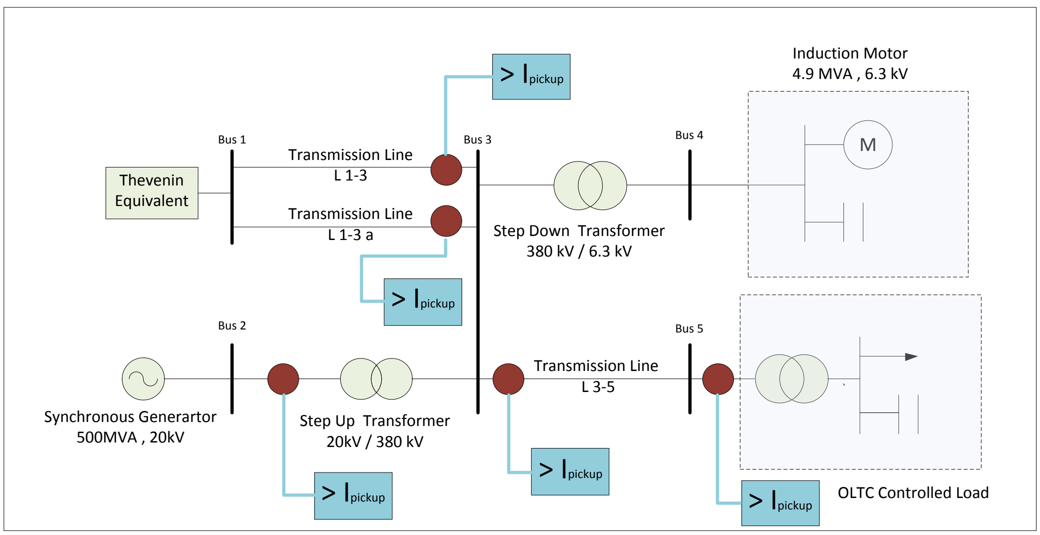


Fig.5-17: All-in-one System with Implementation of Over-Current Relays

5.6.1. Over-Current Relay Settings

As we have considered five overcurrent relays. So the first step towards implementation of relays is to calculate the CT ratios and the pickup values for the relays. As discussed earlier, the pickup value depends on the full load currents and the minimum fault currents. According to the rule of thumb:

$$1.2 * Max\ Load\ Current \leq Pickup\ Value \leq 0.9 * Minimum\ Fault\ Current$$

Fig. 5-16 shows the full load steady state currents at all the buses. The same information is provided in Table. 6

[1] when the load is increased to reproduce a voltage instability scenario, the load current will increase well above the nominal full load value and an over-current relay is necessary to cut off the load when the current goes above a certain value

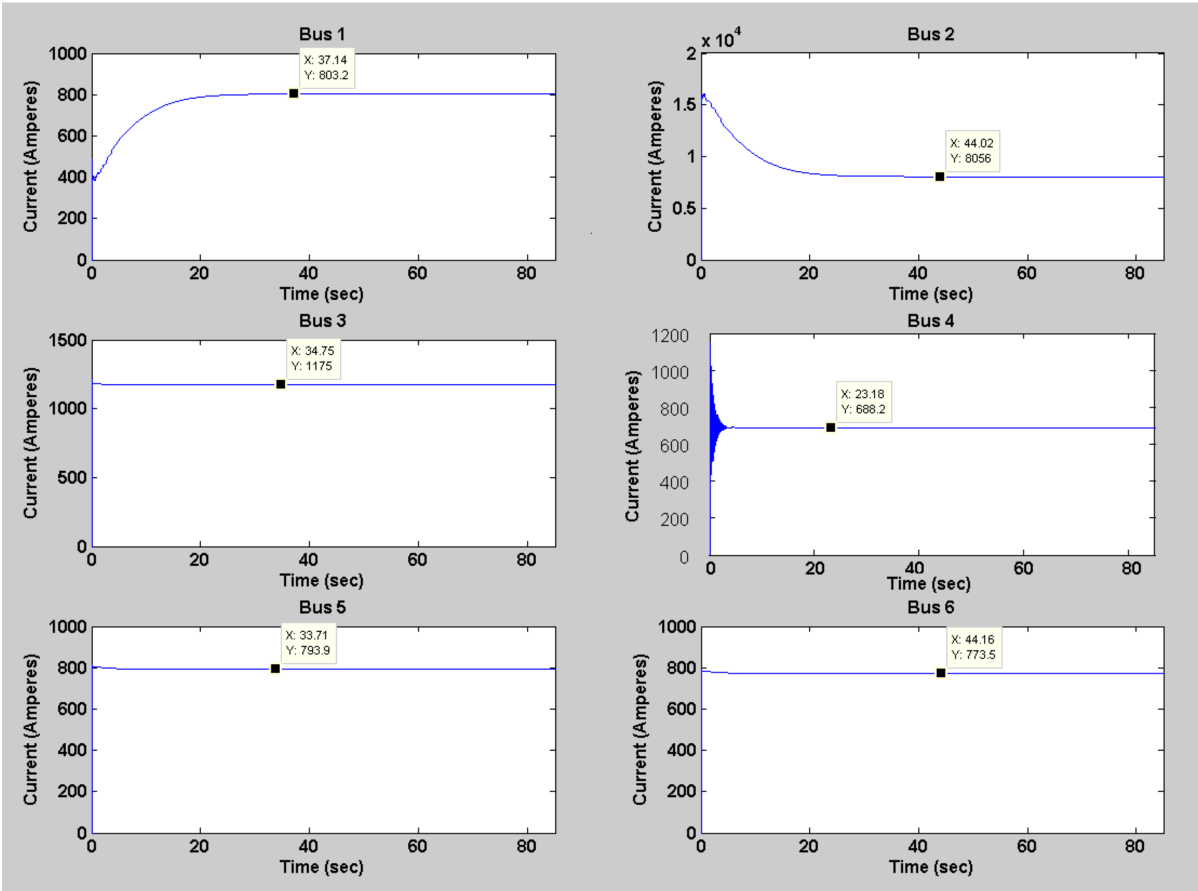


Fig.5-18: Steady State Currents at the Buses in All-in-One Test system

Bus Number	Steady State Current (Amperes)
1	804
2	8056
3	1175
4	690
5	794
6	774

Table.6: Steady State Currents at the Buses in All-in-One Test system

The fault currents were obtained by applying three phase to ground faults at the buses. The faults were applied for 0.1 sec. The fault current at Bus 1 was calculated analytically[2] the fault current at bus 1 was calculated from the short circuit capacity of the thevenin equivalent and the nominal voltage at bus 1. As stated earlier, the short circuit capacity for the thevenin equivalent was set to 20000MVA and the nominal voltage is 380kV. So the fault current can be calculated as;

$$I_{fault} = \frac{Short\ Circuit\ Capacity\ (Three\ Phase)}{\sqrt{3} * Nominal\ Voltage}$$

$$I_{fault} = \frac{20000 * 10^6}{\sqrt{3}\ * 380 * 10^3}\ \frac{VA}{V}\ = 30387\ A$$

Fig. 5-19 shows the fault currents when the three phase to ground faults are applied at the buses. The same information is provided in Table. 7

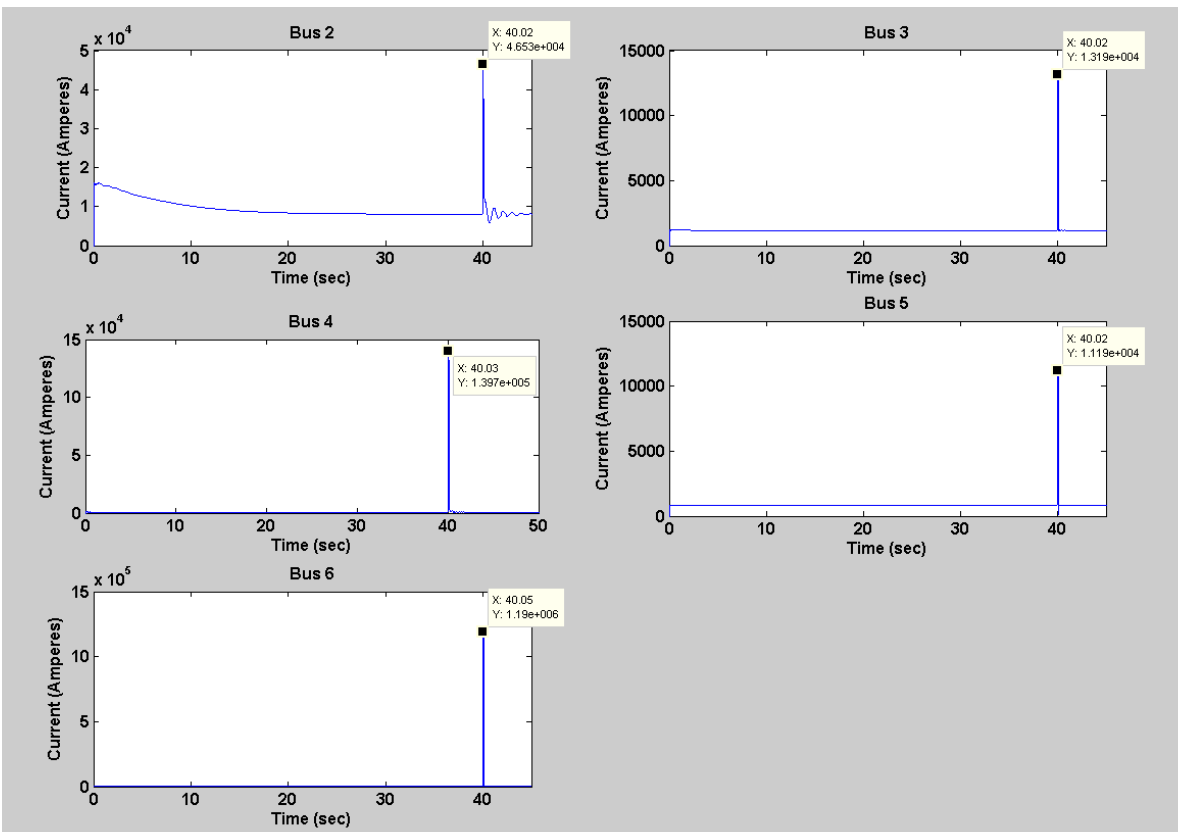


Fig.5-19: Fault Currents at the Buses in All-in-One Test system

[2] applying the fault at this bus actually disconnects the thevenin equivalent (Swing Bus) from rest of the system and the program crashes

Bus Number	Fault Currents (Amperes)
1	30387
2	46500
3	13200
4	139700
5	11190
6	1190000

Table.6: Steady State Currents at the Buses in All-in-One Test system

For the settings of the overcurrent relays in all-in-one system, the following rule of thumb is taken into consideration;

$$1.4 * Max\ Load\ Current\ \leq Pickup\ Value\ \leq 0.9 * Minimum\ Fault\ Current$$

As we are dealing with only three phase to ground faults i.e. symmetrical faults in the system, so the minimum fault current is actually the three phase to ground fault current which has been listen in Table. 6.

The settings of various overcurrent relays are explained sequentially;

5.6.2. <u>Over-Current Relay at Bus-6 (Load Bus)</u>

The maximum load current is 774 Amperes (from Table. 5). So $1.4 * Max\ Load\ Current = 1084\ A$. Normally the closest turn ratio available for this scenario is 1000:1 or 1200:1. However as we are modeling the CT, so we have the provision to choose any turn ratio for the CT. For this relay we have chosen turn ratio of 1100:1. This means that at $1.4 * Max\ Load\ Current = 1084\ A$, the CT secondary would be $1084 * \frac{1}{1100} = 0.985\ A$. So the pickup value for this relay is set to be 1 A i.e. as the secondary side of the CT will exceed this value of 1 A, the relay will generate a trip signal. In addition this relay has been configured to provide an instantaneous trip without any time delay (i.e. we are not considering the IEEE or BS-142 curves for this relay). The fault current at this bus is 1190000 Amperes (from Table.6). So at this fault current, the CT secondary will measure $1190000 * \frac{1}{1100} = 1081\ A$ which is much greater than the pickup value of 1 A.

Parameters of Over-Current Relay at Bus 6 (Load Bus)	
Characteristic	**Value**
Maximum Load Current	774 A
1.4 x Maximum Load Current	1084 A
Fault Current	1190000A
0.9 x Fault Current	1071000A
CT Ratio	1100:1
Pickup Value	1 A

Characteristic Curve	Instantaneous (No Time Delay)

Table.7: Over-Current Relay Setting at Bus 6

5.6.3. Over-Current Relay between Bus 3-5

The maximum load current is 794 Amperes (from Table. 5). So $1.4 * Max\ Load\ Current = 1111.6\ A$. Normally the closest turn ratio available for this scenario is 1000:1 or 1200:1. However as we are modeling the CT, so we have the provision to choose any turn ratio for the CT. For this relay we have chosen turn ratio of 1150:1. This means that at $1.4 * Max\ Load\ Current = 1111.6\ A$, the CT secondary would be $1112 * \frac{1}{1150} = 0.967\ A$. So the pickup value for this relay is set to be 1 A. However this relay is configured as a time overcurrent relay with very inverse characteristic curve (see Fig. 5-11). As the secondary side of the CT will exceed this value of 1 A, the relay will generate a trip signal after a certain time delay (depending upon the ratio of Isec/Ipickup). The TMS setting for this relay is set to 0.16 . The fault current at this bus is 11190Amperes (from Table.6). So at this fault current, the CT secondary will measure $11190 * \frac{1}{1150} = 9.7304\ A$ which is much greater than the pickup value of 1 A. Calculating the operating time for the relay at this fault current using Equation (1),

$$T = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} * TMS$$

For very inverse characteristic curve, C= 13.5 and α = 1, hence

$$T = \frac{13.5}{\left(\frac{9.7304}{1}\right)^{1} - 1} * 0.16 \ = 0.247\ sec$$

By running simulations and acquiring data for the current at Bus 5 under the voltage collapse scenario, it is noticed that when the relay at Bus 6 gives a trip signal, the current at Bus 5 is 1248 A (Fig.5-36). In addition the current at Bus 5 exceeds 1150 A at t= 216.3 sec. So at t=216.3 sec, the secondary side of CT feeding the relay will be 1150/1150 = 1A which is also the pickup value for this relay. The relay can pick up the fault and start its timer. As the maximum current seen by this relay is 1248/1150 = 1.0852 A. At this ratio the operating time will be:

$$T = \frac{13.5}{\left(\frac{1.0852}{1}\right)^{1} - 1} * 0.16 = 25.352\ sec$$

But as the timer has already started at t=216.3 sec (time at which Isec becomes equal to 1A, see Fig. 5-36). With a current of 1248 A, the relay will give a trip signal at

$$T_{Trip} = T_{Fault\ Pickup} + T_{Operation\ Time} \ = 216.3 + 25.352 = 241.652\ sec$$

However the relay at Bus 6, gives an instantaneous trip at t=241.2 sec (see Fig. 5-38) and brings the system back to the nominal initial state. So this relay not only behaves as a primary protection for the transmission line between Bus 3 and Bus 5 but also behaves as a back-up protection for the load at Bus 6. In case if the relay at Bus 6 malfunctions and does not send a trip signal, then the relay at Bus 5 will operate. The trip command from this relay can be used to open the circuit breaker for the Line 3-5 and thus disconnecting the whole transmission line and load from the rest of the system[3].

Parameters of Over-Current Relay Between Bus 3 and 5 (Transmission Line)	
Characteristic	**Value**
Maximum Load Current	794 A
1.4 x Maximum Load Current	1112 A
Fault Current	11190A
0.9 x Fault Current	10071A
CT Ratio	1150:1
Pickup Value	1 A
Characteristic Curve	Inverse Characteristic Curve

Table.8: Over-Current Relay Setting between Bus 3-5 (transmission line)

5.6.4. <u>Over-Current Relays For Parallel Transmission Lines Between Bus 1-3</u>

The full load current at bus 1 is 804A (see Table.5). The full load current of 804 A is divided equally in two transmission lines, 402 A each and their pick up values are set to $1.4 * Max\ Load\ Current = 1.4 * 402 = 562.8\ A$. Normally the closest turn ratio available for this scenario is 500:1 or 600:1. However as we are modeling the CT, it is possible to choose any turn ratio for the CT. We have considered the CT ratio of 580:1. This means that at $1.4 * Max\ Load\ Current = 562.8\ A$, the CT secondary would be $562.8 * \frac{1}{580} = 0.97\ A$. So the pickup value for this relay is set to be 1 A. This relay is configured as an instantaneous overcurrent relay as the secondary side of the CT will exceed this value of 1 A, the relay will generate a trip signal instantaneously. The fault current at this bus is 13200Amperes (from Table.6). So at this fault current, the CT secondary will measure $13200 * \frac{1}{580} = 22.758\ A$ which is much greater than the pickup value of 1A.

Parameters of Over-Current Relays Between Bus 1 and 3 (Parallel Transmission Lines)	
Characteristic	**Value**
Maximum Load Current	402 A
1.4 x Maximum Load Current	562.8 A
Fault Current	13200A
0.9 x Fault Current	11880A
CT Ratio	580:1
Pickup Value	1 A
Characteristic Curve	Instantaneous (No Time Delay)

Table.9: Over-Current Relay Setting between Bus 1-3 (parallel transmission lines)

[3] this is not the case in our model as in our case, the relay at bus 6 operates and sheds the load to avoid voltage collapse

5.6.5. <u>Over-Current Relays Between Bus 2-3</u>

The full load current at Bus 2 is 8056A (see Table.5). So $1.4 * Max\ Load\ Current = 1.4 * 8056 = 11279\ A$. Normally the closest turn ratio available for this scenario is 3000:1 or. However as we are modeling the CT, it is possible to choose any turn ratio for the CT. We have considered the CT ratio of 3760:1 This means that at $1.4 * Max\ Load\ Current = 11279A$, the CT secondary would be $11279 * \frac{1}{3760} = 3\ A$. The pickup value for this relay is set to be 3 A. This relay is configured as an instantaneous overcurrent relay as the secondary side of the CT will exceed this value of 3 A, the relay will generate a trip signal instantaneously. The fault current at this bus is 46500A (from Table.6). So at this fault current, the CT secondary will measure $46500 * \frac{1}{3760} = 12.36\ A$ which is much greater than the pickup value of 3A.

Parameters of Over-Current Relays Between Bus 1 and 3 (Parallel Transmission Lines)	
Characteristic	**Value**
Maximum Load Current	8056 A
1.4 x Maximum Load Current	11279 A
Fault Current	46500A
0.9 x Fault Current	41850A
CT Ratio	3760:1
Pickup Value	3 A
Characteristic Curve	Instantaneous (No Time Delay)

Table.10: Over-Current Relay Setting between Bus 2-3

5.7. Real Time Simulation of All-in-One Test System with the Implementation of Protection Relays

By using the settings for the protection relays as discussed earlier in the section, the all-in-one test system was simulated in real-time. The voltage collapse scenario was reproduced by increasing the load continuously, and finally the response of the system was analyzed considering the presence of the protection relays.

As discussed earlier, the over-current relay at bus-6 was configured as an instantaneous over-current relay. Furthermore, two different protection schemes were implemented which are discussed below.

5.7.1. Protection Scheme 1

In the first protection scheme, the trip command from the relay is generated upon fulfillment of the criteria of $I_{secondary} > I_{Pickup}$ where $I_{secondary}$ is the current at the secondary side of the CT which is connected to the over-current relay. This trip command is used to shed the continuously increasing load. This protects the system from voltage collapse and brings the system back to a steady state condition. As discussed earlier, the voltage collapse scenario was reproduced by continuously increasing the reactive load at Bus 6 which results in the continuous degradation of the voltage at Bus 6 and the continuous increase in the load current[4]. The overcurrent relay tracks the load current and generates the trip command as soon as the condition of $I_{secondary} > I_{Pickup}$ is satisfied. This trip signal is used to shed the continuously increasing load which was meant to produce the voltage instability scenario. As a result the system gets back to its steady state.

The plots in Fig 5-20 to 5-26 below show the voltages at all the buses when the load at Bus 6 is increased continuously. In this case, the load increase is activated through a mechanical switch at t=60sec and the overcurrent relay pickups the fault at t=241.2 sec at which $I_{secondary} > I_{Pickup}$. The plots clearly show a continuous voltage decrease which is less obvious in Bus 1 and Bus 2 because they both are attached to stiff voltage sources. Bus 1 is attached to a voltage source (Thevenin equivalent) and Bus 2 is attached to a generator which is meant to keep the voltage constant at that bus. However at t=241.2 sec, the protection scheme activates and shed downs the incremental load which was bringing the system towards voltage collapse. The tripping of load brings the system back to steady state.

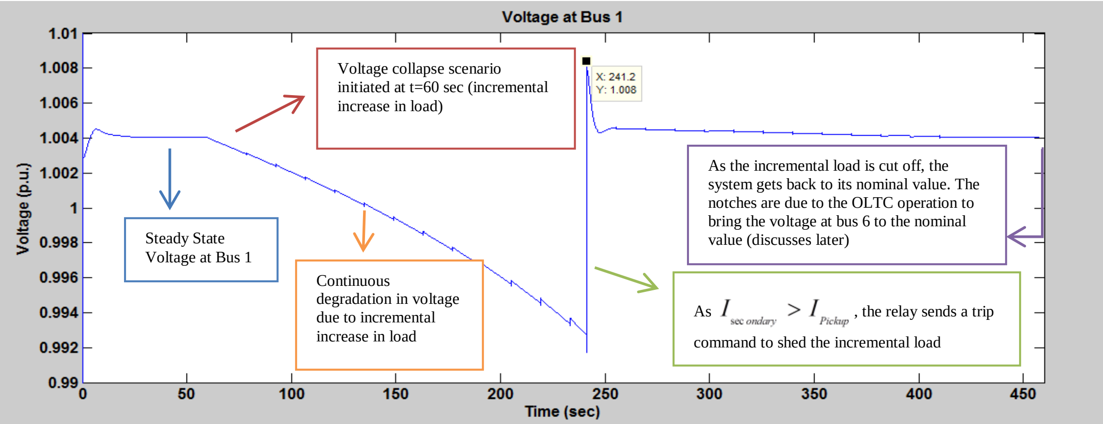


Fig.5-20: Voltage at Bus 1 (Protection Scheme 1)

[4] as the load is constant power

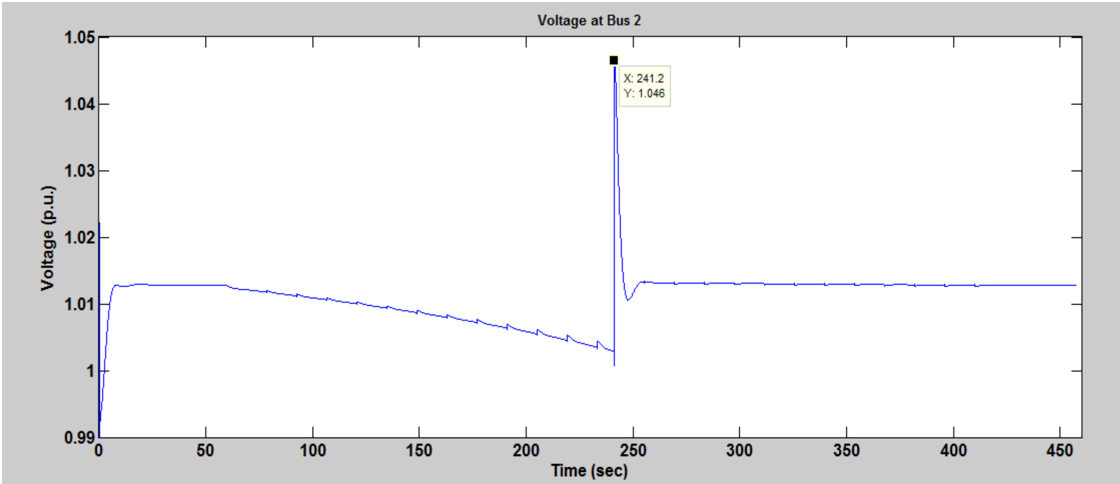


Fig.5-21: Voltage at Bus 2 (Protection Scheme 1)

As Bus 3 and Bus 4 are away from the sources, the decay in voltage level is much obvious at these buses. Even the small notches obtained due to the OLTC operation to maintain voltage at Bus 6 can be observed in the voltages of these buses (see Fig 5-22 and 5-23). The same explanation applies here, at t=241.2 sec, the protection scheme activates and disconnects the incremental load from rest of the system and brings the system back to steady state.

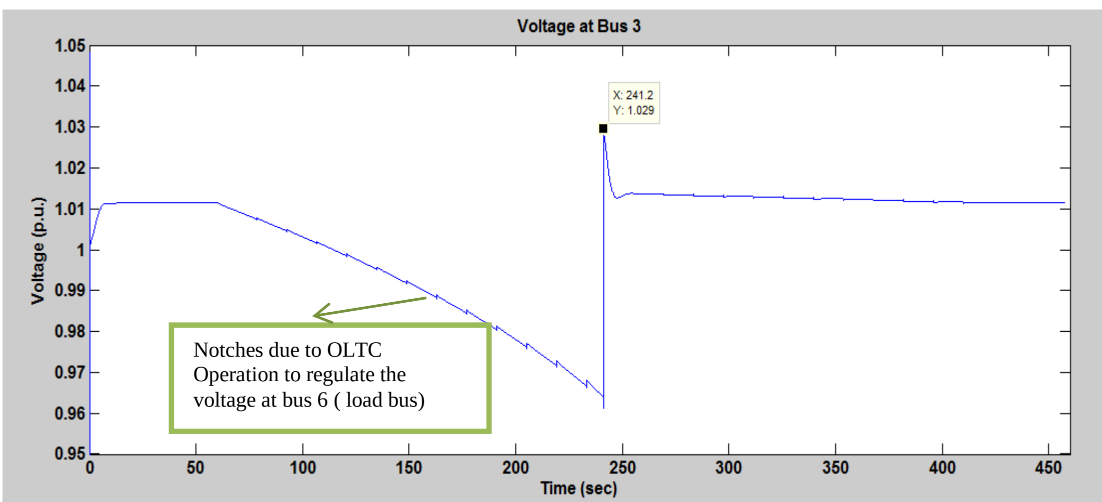


Fig.5-22: Voltage at Bus 3 (Protection Scheme 1)

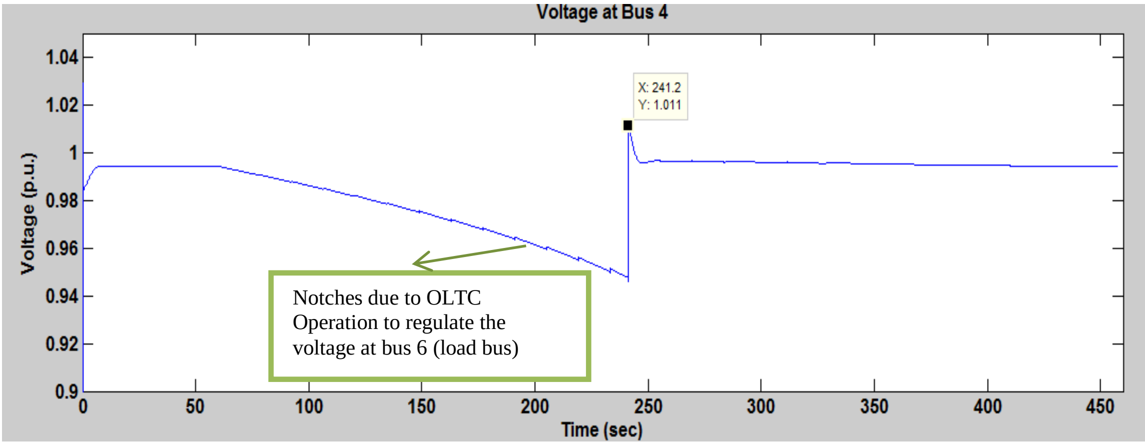


Fig.5-23: Voltage at Bus 4 (Protection Scheme 1)

Bus 5 is the primary side of the OLTC transformer attached to the three phase equivalent load. As shown in Fig. 5-24, the power consumption at Bus 6 increases, the voltage at the bus starts to decrease. The OLTC starts to restore the load voltage which results in decreasing of the tap (shown in Fig. 5-27). As shown in Fig. 5-25, when the tap is lowered, the voltage increases but as the load is constantly being increased, this results in decrement of voltage. The OLTC tries to bring the voltage to its nominal value. When the OLTC is at tap position 12, the protection scheme activates due to the fulfillment of the condition $I_{secondary} > I_{Pickup}$. As a result the incremental load is disconnected and the voltages become nominal again. It is important to note that OLTC has not hit its limit (tap position 16).

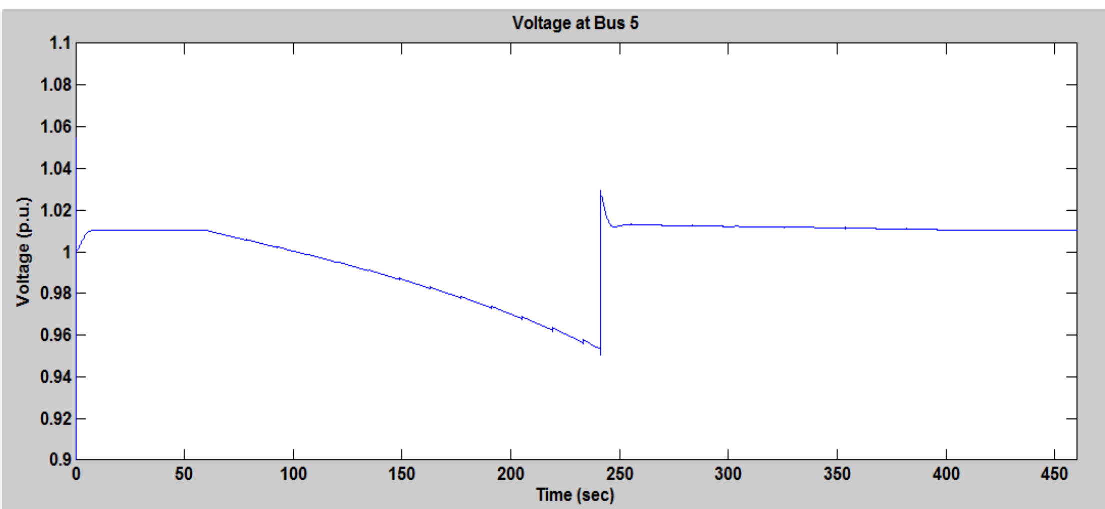


Fig.5-24: Voltage at Bus 5 (Protection Scheme 1)

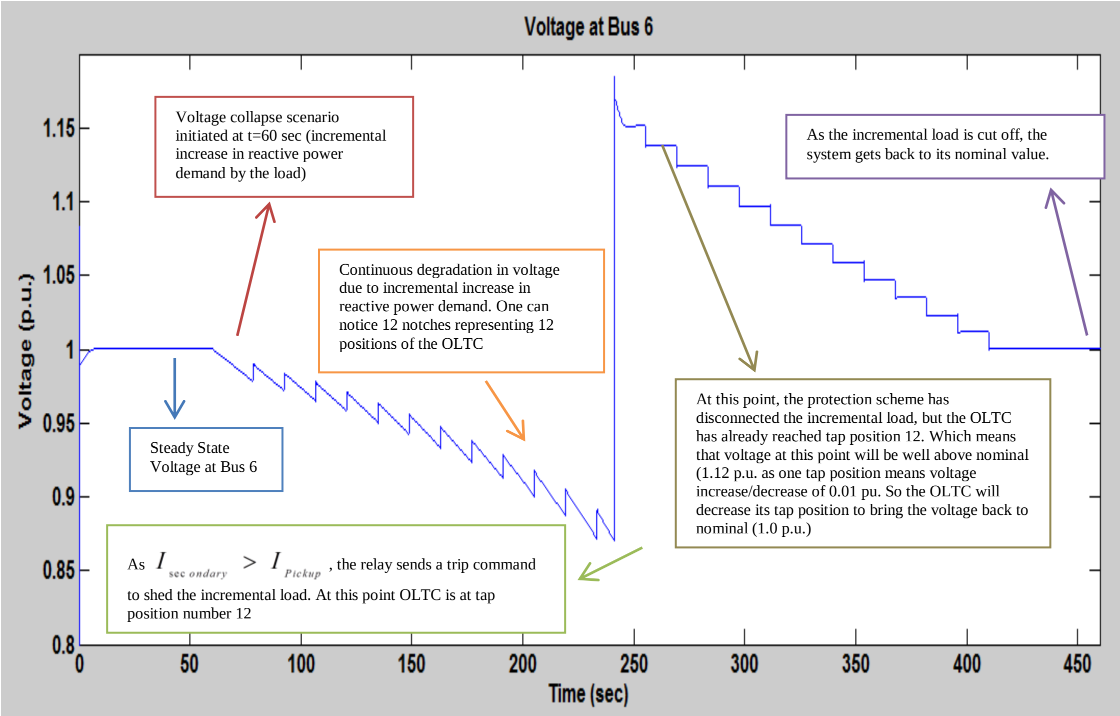


Fig.5-25: Voltage at Bus 6 (Protection Scheme 1)

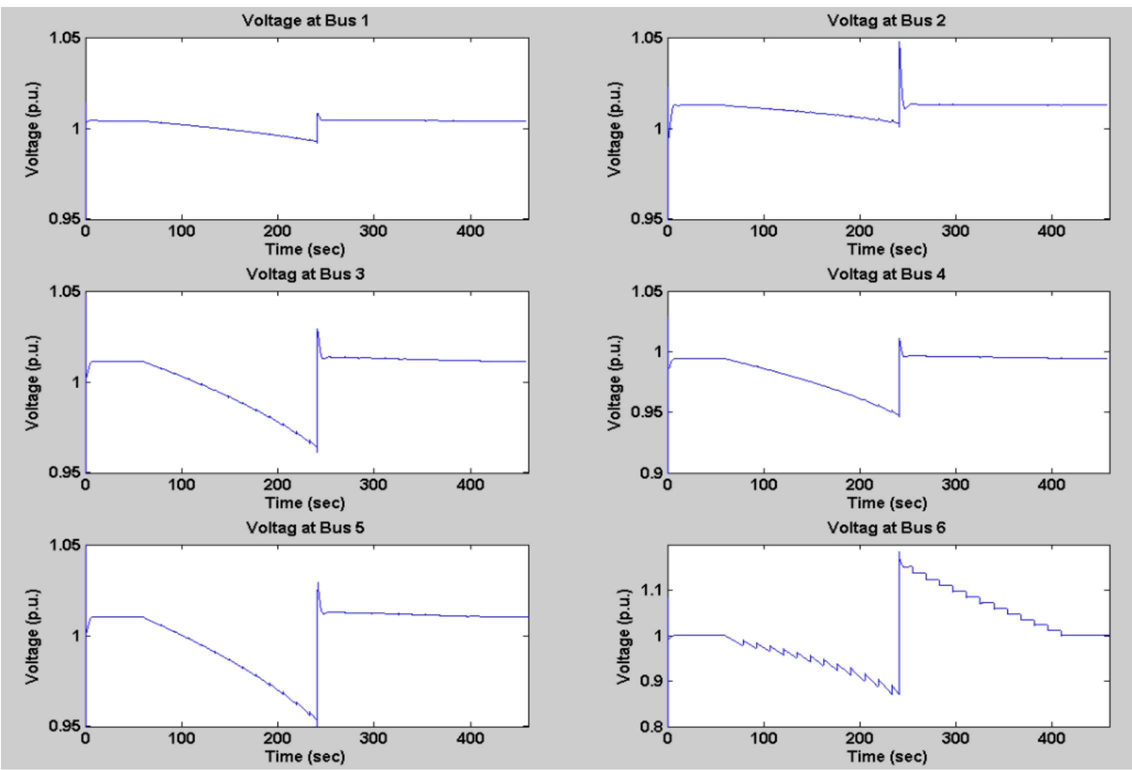


Fig.5-26: Voltage at Buses in presence of protection relays (Protection Scheme 1)

As discussed earlier, the OLTC was configured in such a way that it provides a voltage step of 0.01 p.u. whenever the difference between the reference voltage (1 p.u.) and the bus voltage (voltage at bus 6) increases 0.05 p.u. (half of the dead band). The plot in Fig. 5-27 shows the OLTC operation. At t= 241.2 sec, the OLTC is at tap position 12 when the protection scheme activates and disconnects the incremental load. The disconnection of load results in surplus reactive power which appears as an increased voltage at Bus 6. The OLTC brings the voltage back to nominal 1.0 (p.u.) by decreasing its tap. It can be noticed that the tap position of OLTC at steady state after the activation of protection scheme is at the nominal position (Tap position =0).

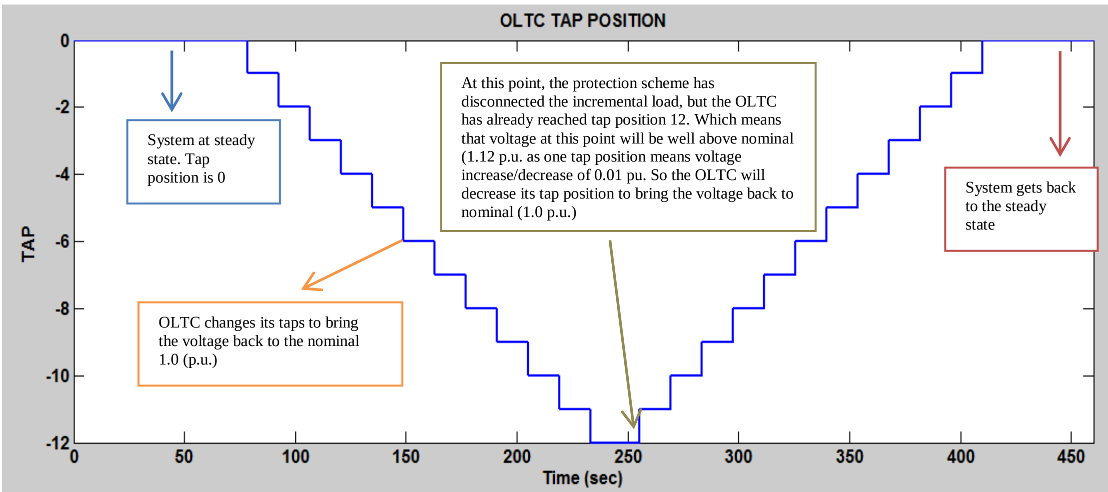


Fig.5-27: OLTC Tap Positions (Protection Scheme 1)

Fig. 5-28 shows the positive sequence voltage (which is actually voltage at Bus 6), the active power consumption and the reactive power consumption by the three phase dynamic load. There is a continuous small increment in the active power and there is a continuous increase in reactive power demand by the load as soon as the manual switch is operated to initiate voltage instability scenario. However at t=241.2 sec, the protection scheme activates and disconnects the incremental load causing a voltage drop.

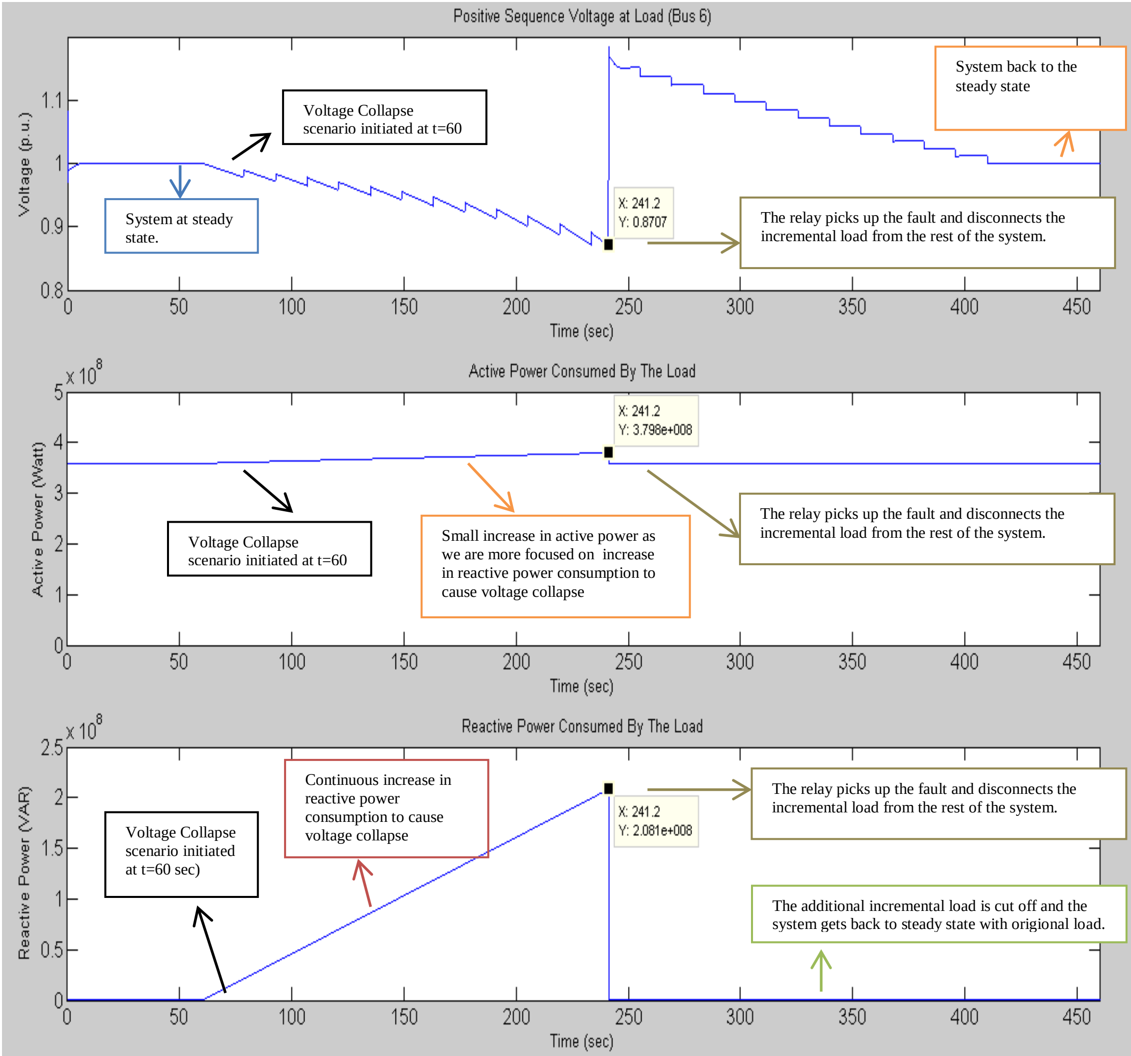


Fig.5-28: States of three phase dynamic equivalent load at bus 6 (Protection Scheme 1)

Fig. 5-29 shows the behavior of synchronous generator in the above discussed scenario of voltage instability and in presence of the protection relays. As can be seen, the increase in reactive power causes an increase in the reactive power output of the generator.

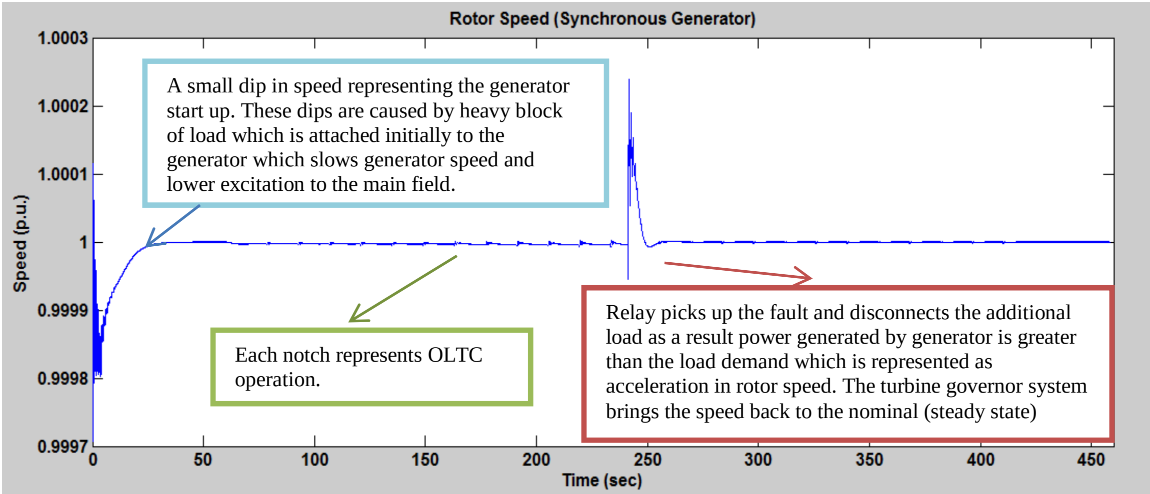


Fig.5-29: Rotor Speed of Synchronous Generator (Protection Scheme 1)

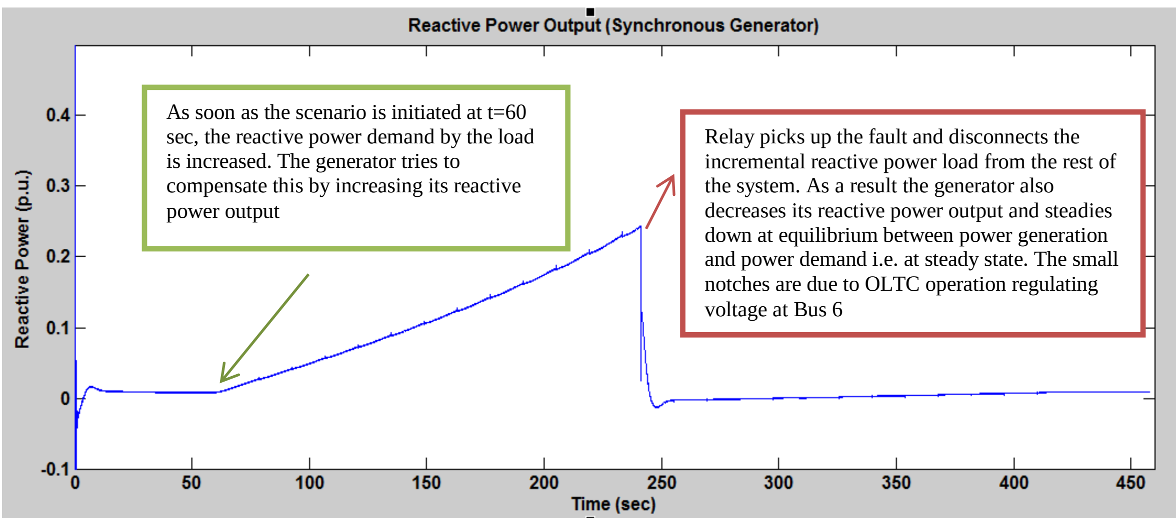


Fig.5-30: Reactive Power Output by Synchronous Generator (Protection Scheme 1)

As the load increases from t=60 sec onwards, the reactive power output of the generator also increases. The generator is synchronized to the external grid (Thevenin equivalent) and the power system. As the alternator matches the power supplied by the steam turbine, therefore the rotor angle deviation is constant. As the load is increasing continuously, the generation is also increasing which is actually fed by the steam turbine (mechanical power input to the generator). As the load is increasing rapidly with respect to the increase in generation, this causes the rotor to slow down a bit due to which the rotor angle deviation increases. However in the new balanced condition, the rotor goes back to synchronous speed but at an increased angle. As the steam turbine mechanical power input to the synchronous generator is increasing continuously to handle the increasing load, the system is finding a new operating point at each instant which results in the increasing rotor angle. At t=241.2 sec, the relay picks up the fault and sends a trip signal to shed the incremental load which results in bringing the system back to steady state.

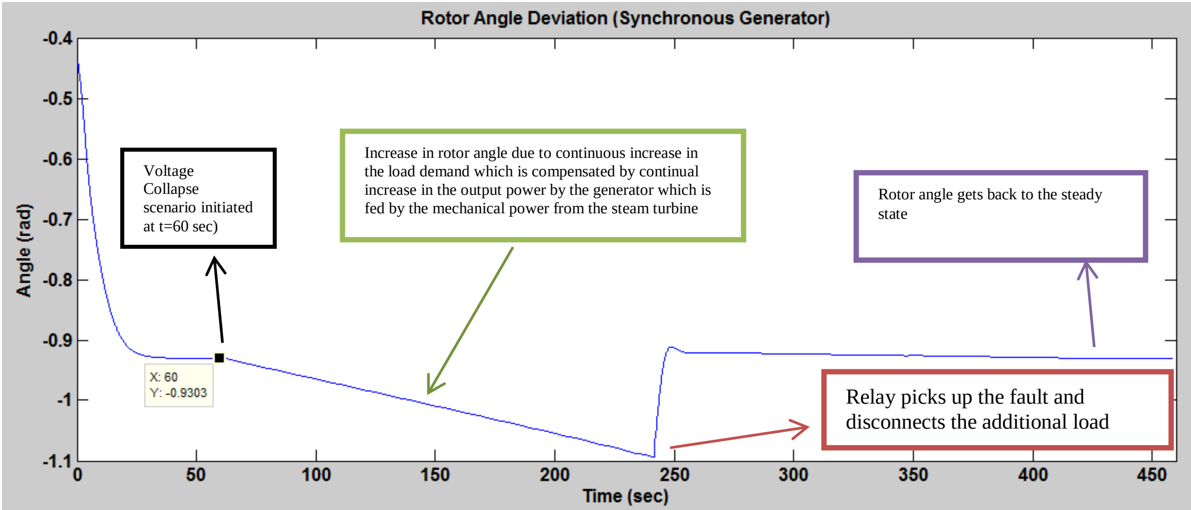


Fig.5-31: Rotor Angle Deviation of the Generator (Protection Scheme 1)

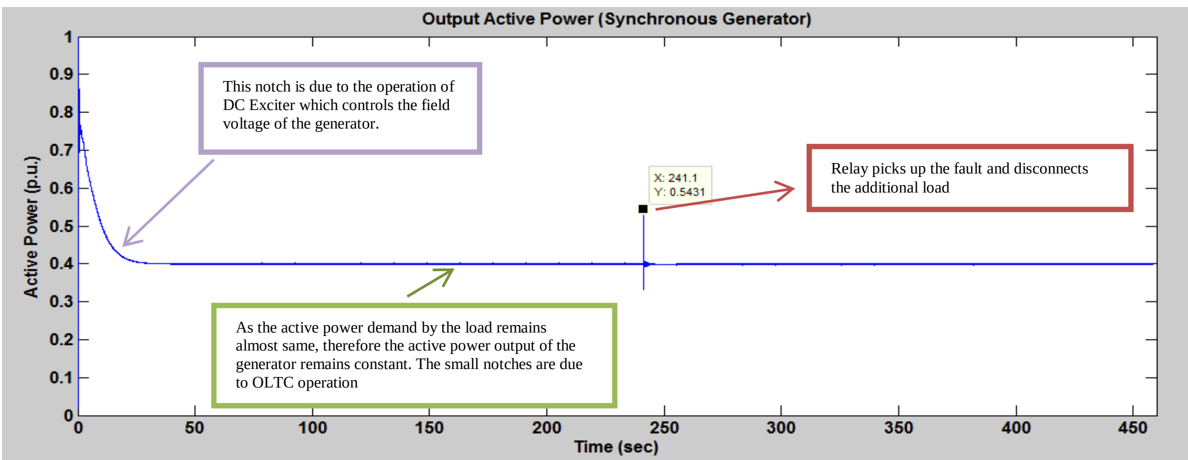


Fig. 5-32: Active Power Output by the Generator (Protection Scheme 1)

The increase in load demand causes a dip in voltage at the generator bus which is sensed by the excitation system which increases the field voltage to maintain constant terminal voltage at the generator bus. Once the protection scheme activates at t=241.2 sec, the incremental load is tripped and the system gets back to initial states.

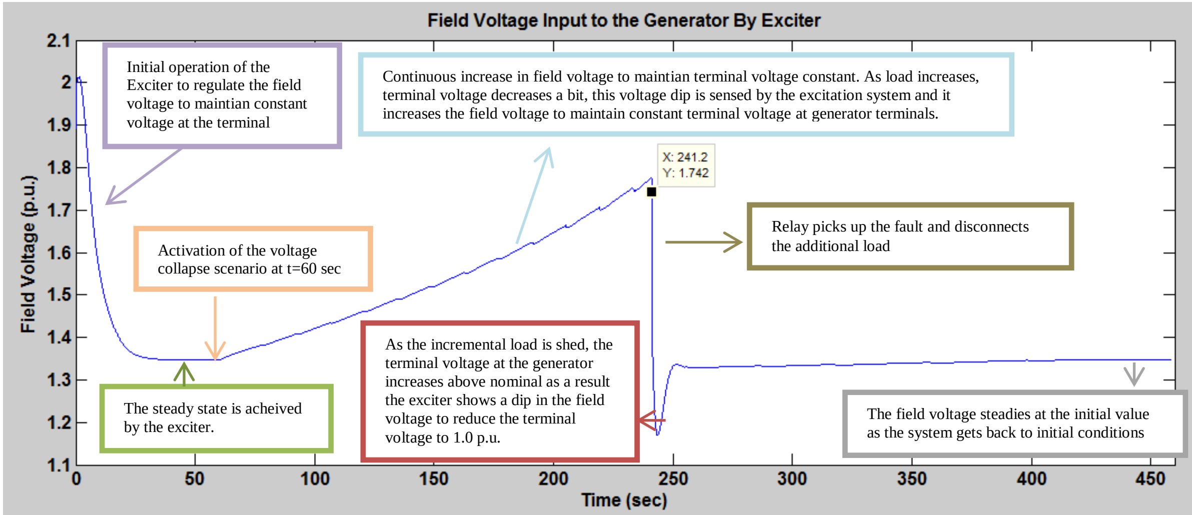


Fig.5-33: Field Voltage Supplied by the Excitation System to the Synchronous Generator (Protection Scheme 1)

The induction motor is connected at Bus 4. As shown in Fig. 5-34, its load is constant therefore it only shows the dips in speed due to the decrease in the terminal voltage. As the load is constant, so the electromagnetic torque is also constant.

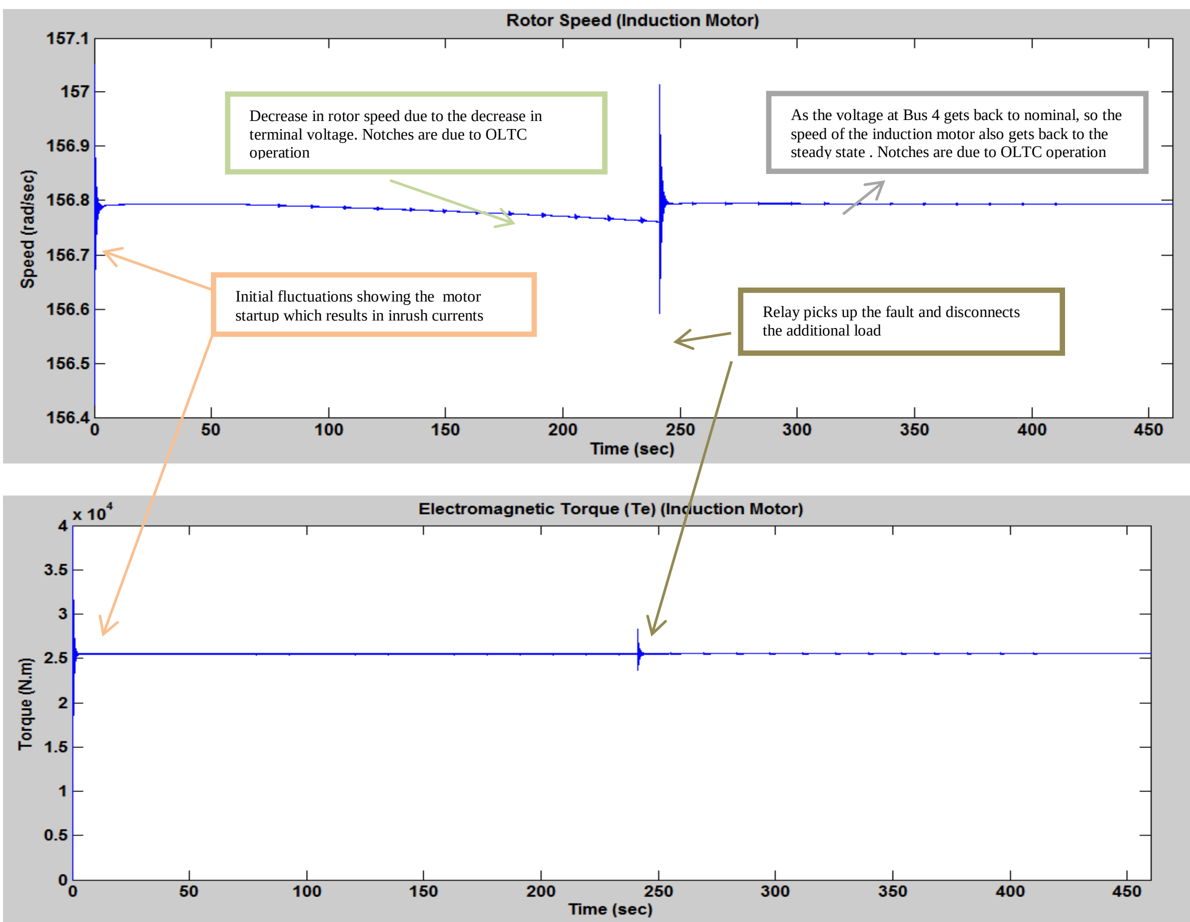


Fig. 5-34: Rotor Speed and Torque of the Induction Motor (Protection Scheme 1)

The currents at the buses increases as soon as the voltage collapse scenario is initiated at t=60sec. The plots in Fig. 5-35 to Fig. 5-38 show the currents through each bus. It is important to mention that only the protection relay at Bus 6 picks up the fault (due to the coordination of relays) and trips the incremental load.

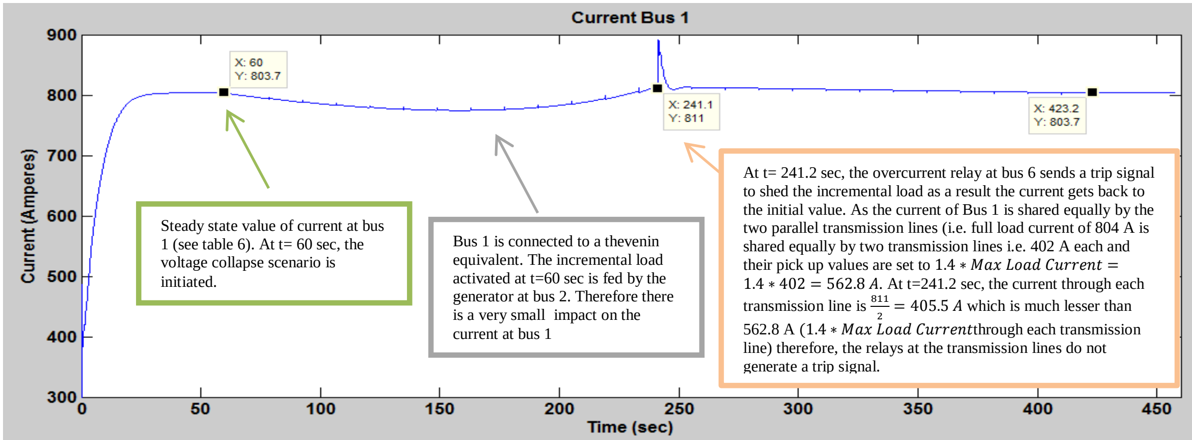


Fig. 5-35: Current through Bus 1 (Protection Scheme 1)

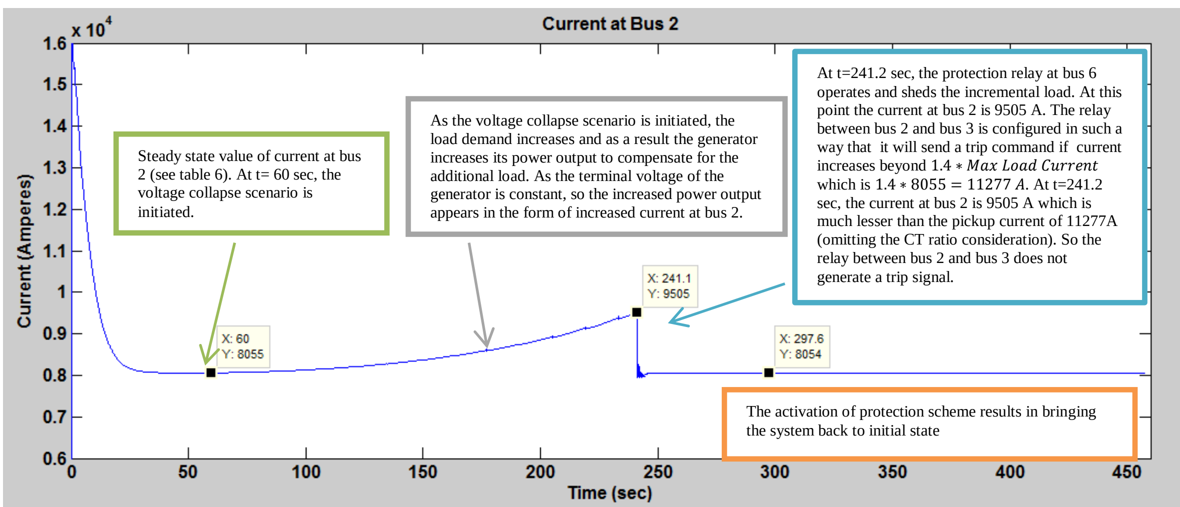


Fig. 5-36: Current through Bus 2 (Protection Scheme 1)

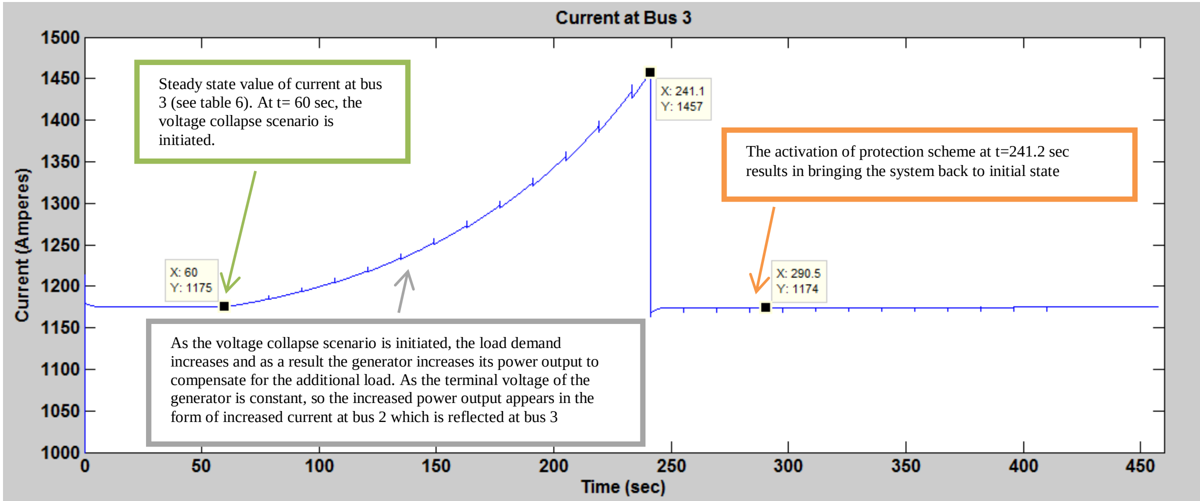


Fig. 5-37: Current through Bus 3 (Protection Scheme 1)

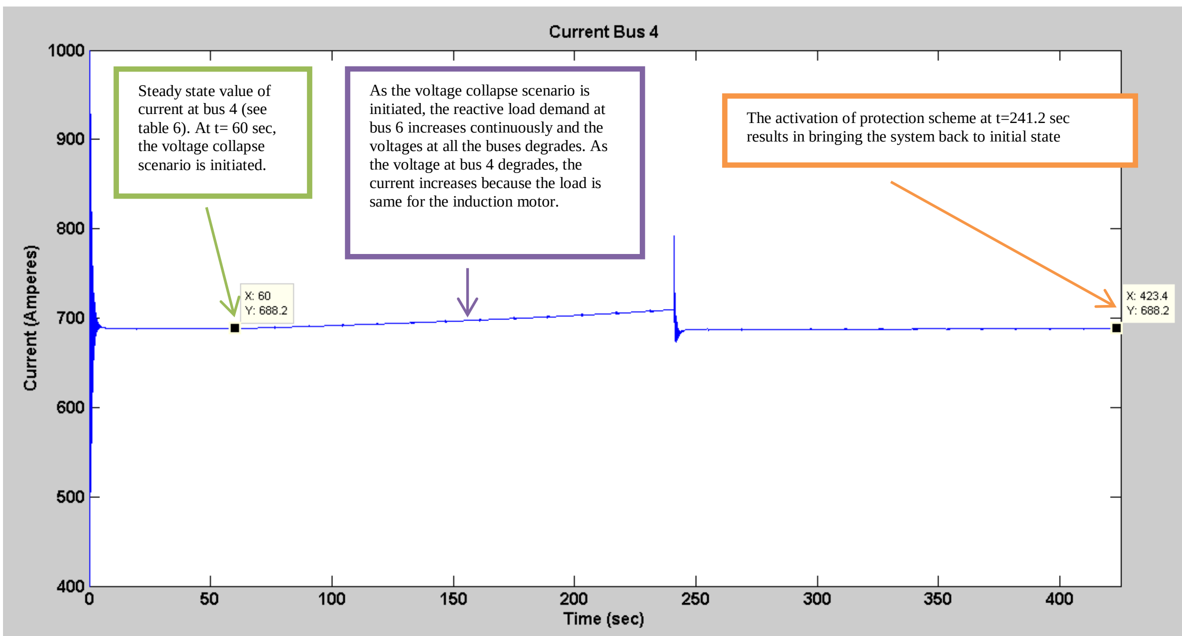


Fig. 5-38: Current through Bus 4 (Protection Scheme 1)

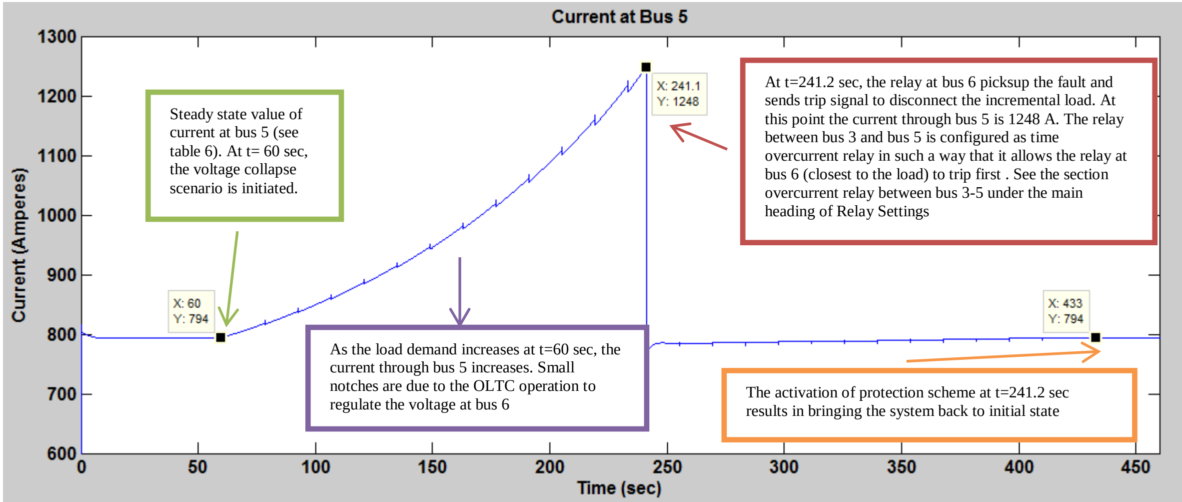


Fig. 5-39: Current through Bus 5(Protection Scheme 1)

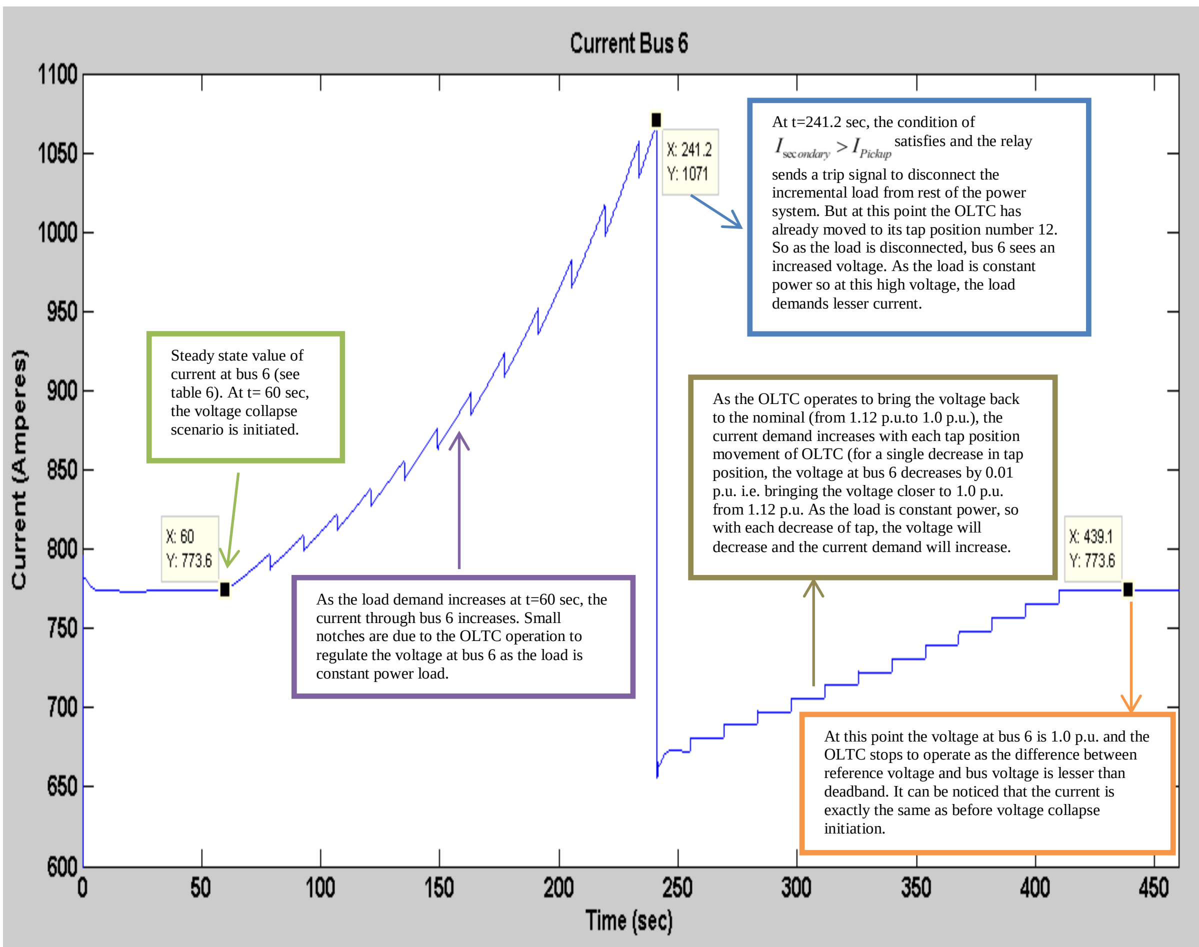


Fig. 5-40: Current through Bus 6 (Protection Scheme 1)

As only the relay at Bus 6 operates, therefore only the plots for this relay are shown in Fig. 5-41. For all the other relays, the ratio will be lesser than 1 and the pickup and trip signals are 0.

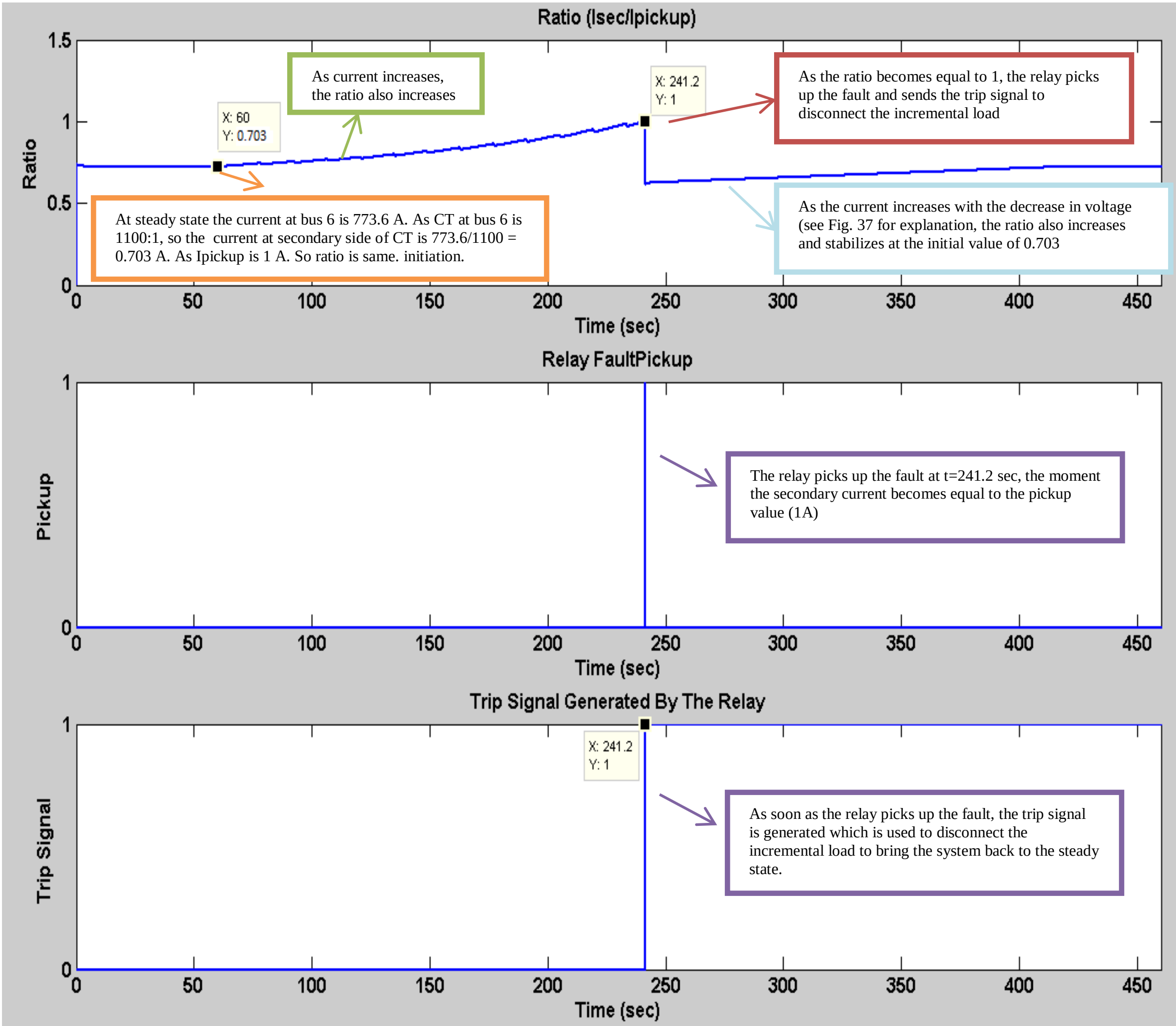


Fig. 5-41:Over- current relay at bus 6 (Protection Scheme 1)

5.7.2. __Summary of Protection Scheme 1__

In this protection scheme, the relay at Bus 6 picks up the fault and generates at trip command instantaneously. This trip command is used to disconnect the continuously incremental load and thus it avoids the voltage collapse. The system gets back to the pre-disturbance state.

__Advantage:__

This scheme is very easy to apply and needs a single circuit breaker to trip the additional load.

Disadvantage:

One of the disadvantages of this protection scheme is that it has shed the whole additional load. As a result the voltage at Bus 6 goes well above the nominal value and the OLTC operates again to regulate the voltage at Bus 6. The OLTC is a mechanical device and such a large movement of taps causes wear and tear of the OLTC and reduces its life which is highly discouraged. In addition it makes the system quite rigid and simply brings the system back to pre-disturbance state in case the protection system activates (due to increased load at Bus 6).

5.7.3. Protection Scheme 2

In the second protection scheme, the trip command from the relay is generated upon fulfillment of the criteria of $I_{secondary} > I_{Pickup}$ where $I_{secondary}$ is the current at the secondary side of the CT which is connected to the over-current relay. The trip command is used to stop the continuous increment in the load and block the OLTC operation. This avoids the system from voltage collapse and brings the system to a new equilibrium point with reduced voltage levels at the buses. The OLTC is blocked because the further operation of OLTC beyond this point will require more reactive power and will ultimately cause a voltage collapse. So the OLTC is blocked as soon as the trip command is received by the relay.

The plots in Fig. 5-42 to Fig. 5-48 show the voltages at all the buses when the load at bus 6 is increased continuously. In this case, the load increase is activated through mechanical switch at around t=60sec and the overcurrent relay pickups the fault at t=243 sec at which $I_{secondary} > I_{Pickup}$. The explanation for the response of different parameters of the system is exactly the same as discussed in protection scheme 1, with an exception that the system gets stable at new operating point with additional load instead of coming back to the initial conditions.

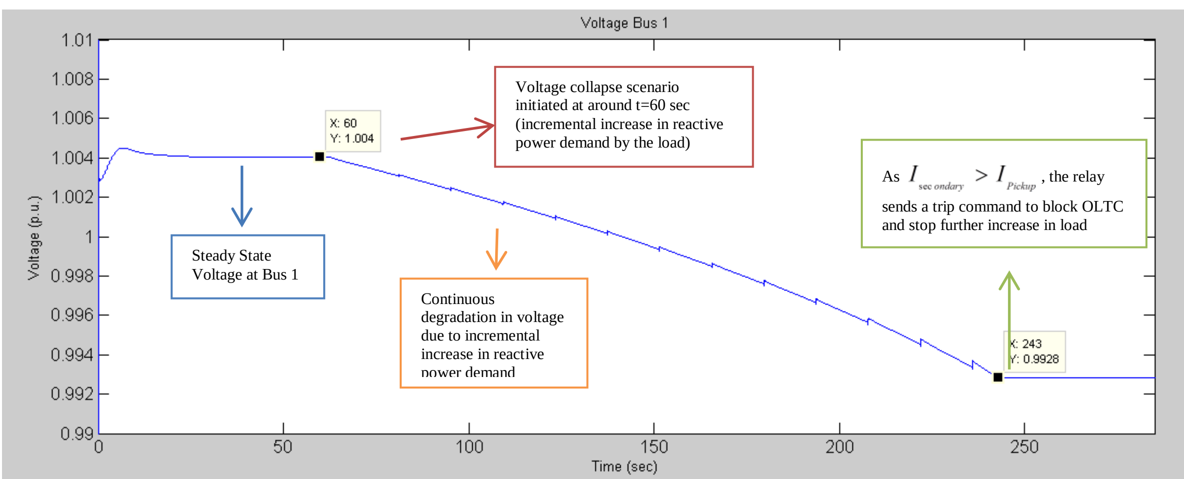


Fig.5-42: Voltage at Bus 1 (Protection Scheme 2)

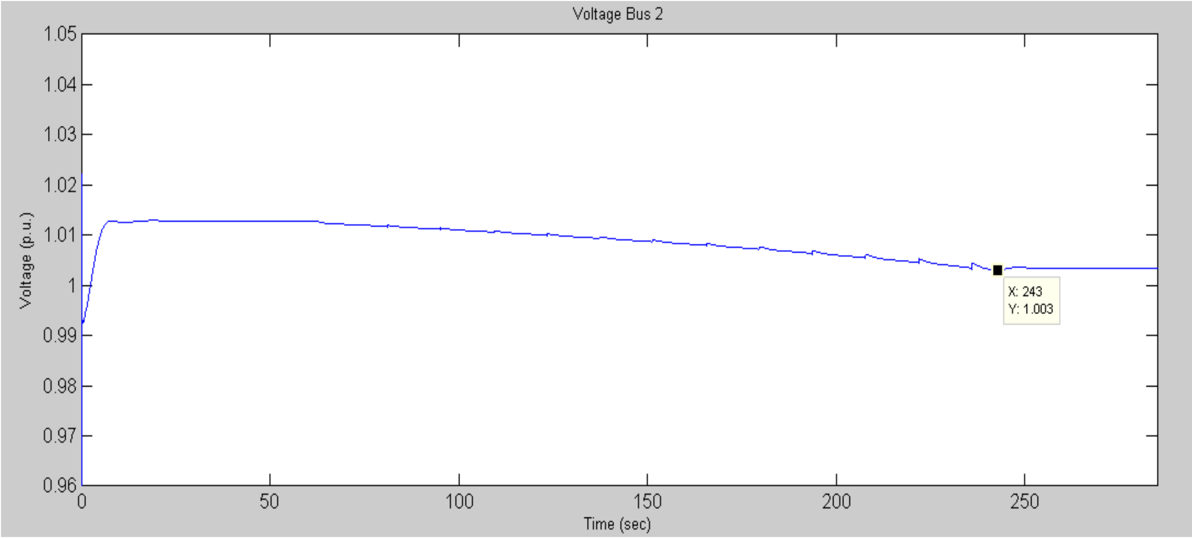


Fig.5-43: Voltage at Bus 2 (Protection Scheme 2)

As Bus 3 and Bus 4 are away from the sources, therefore the decay in voltage level is much obvious at these buses. Even the small notches obtained due to the OLTC operation to maintain voltage at Bus 6 can be observed in the voltages of these buses (Bus 3 and Bus 4). The same explanation applies here that at t=243 sec, the protection scheme activates and stops the incremental load from further increasing its load demand.

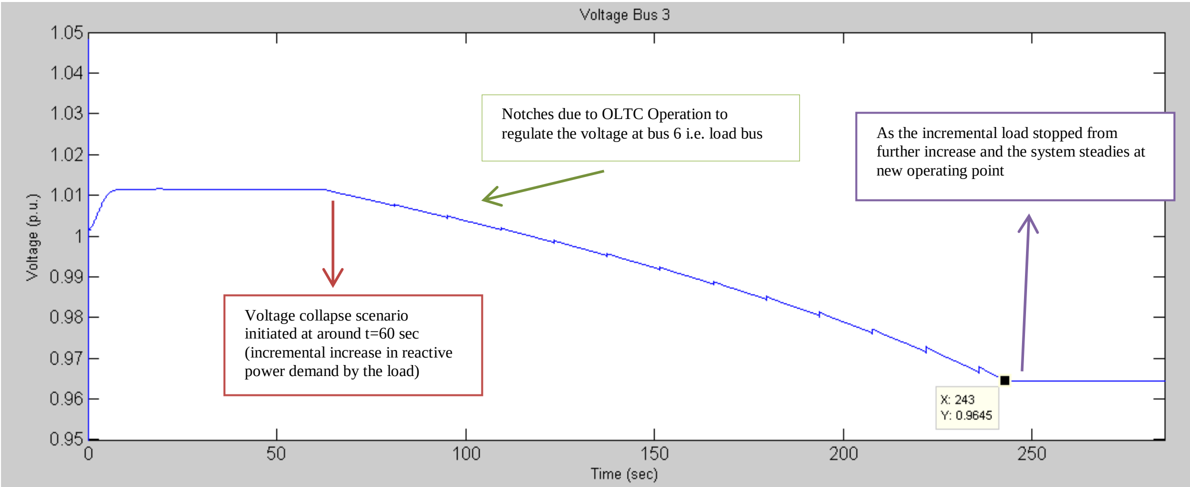


Fig.5-44: Voltage at Bus 3 (Protection Scheme 2)

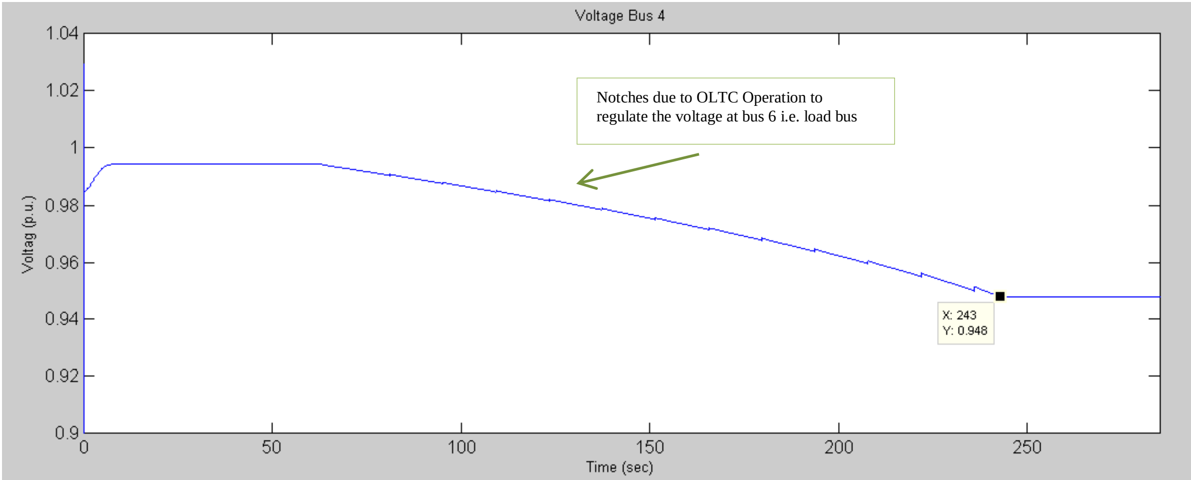


Fig.5-45: Voltage at Bus 4 (Protection Scheme 2)

As Bus 5 is the primary side of the OLTC transformer attached to the three phase equivalent load. The voltage profile at this bus is shown in Fig. 5-46

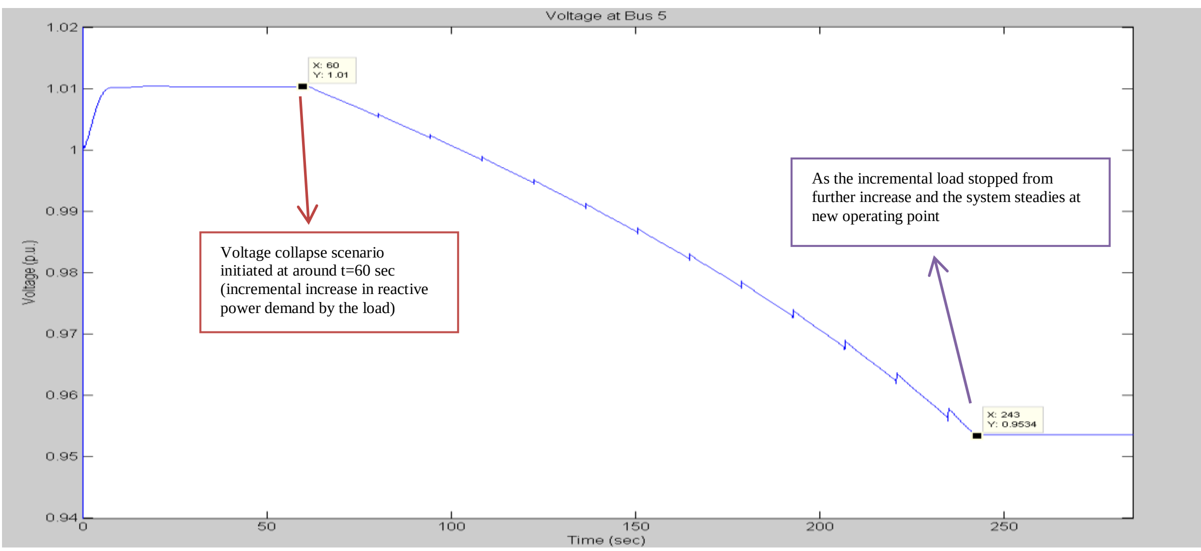


Fig.5-46: Voltage at Bus 5(Protection Scheme 2)

Fig. 5-47 shows the voltage profile at Bus 6.

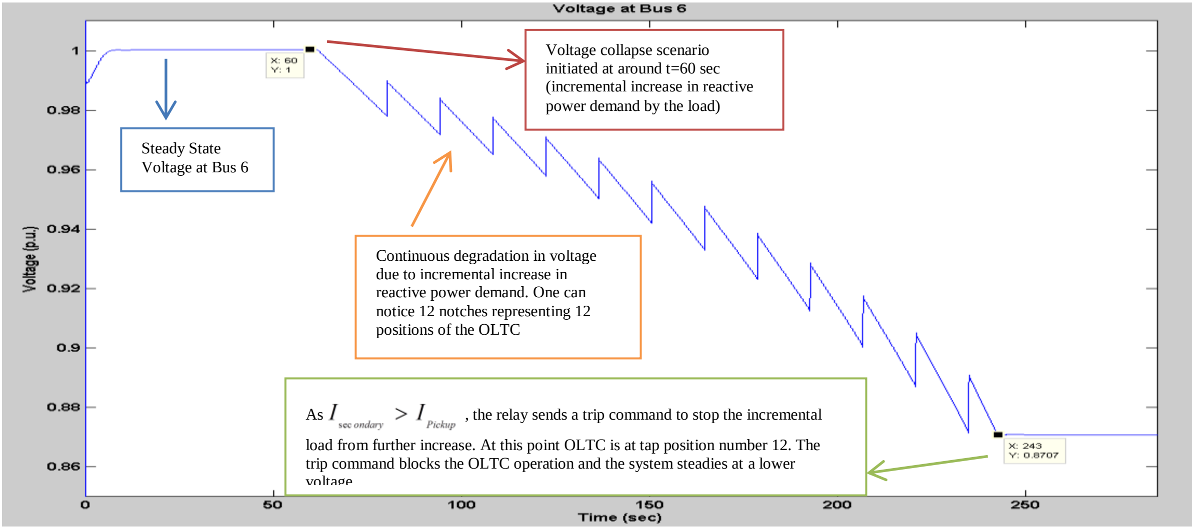


Fig.5-47: Voltage at Bus 6 (Protection Scheme 2)

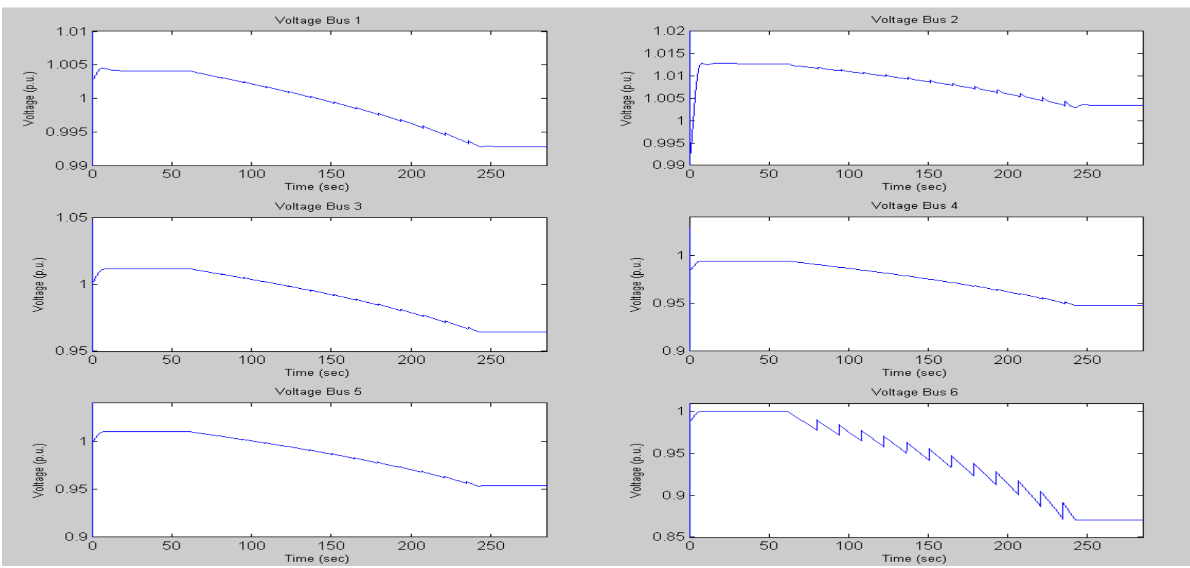


Fig.5-48: Voltages at Bus 1-6 (Protection Scheme 2)

Fig. 5-49 shows the OLTC operation of changing its taps to improve voltage at Bus 6. At t= 243sec, the OLTC is at tap position 12 when the protection scheme activates and stops the incremental load from further increasing its load. The trip signal also blocks the OLTC. It can be noticed that the tap position of OLTC at steady state after the activation of protection scheme is at (Tap position =12).

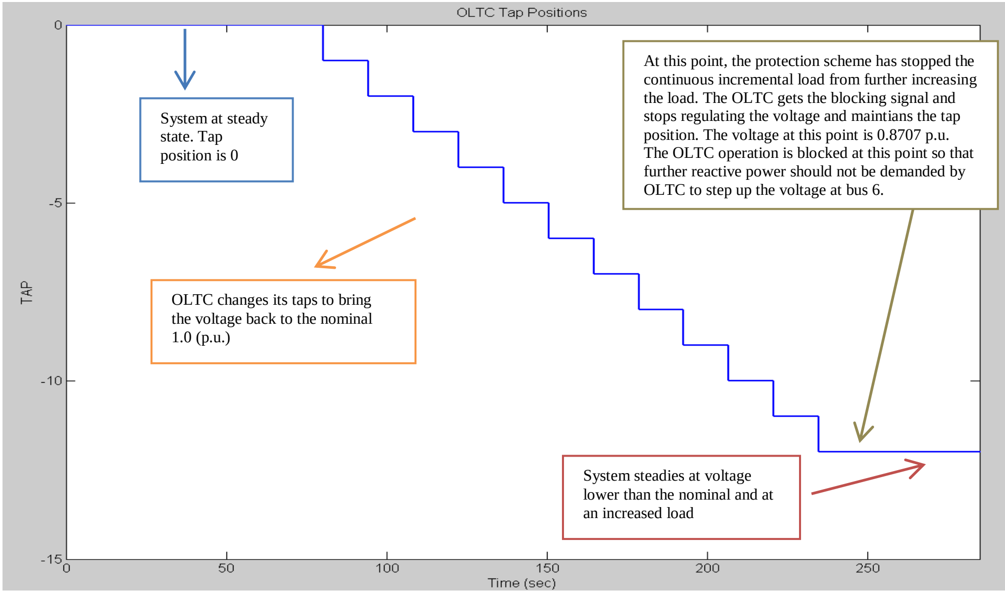


Fig. 5-49: OLTC Tap Position (Protection Scheme 2)

Fig. 5-50 shows the positive sequence voltage Bus 6, the active power consumption and the reactive power consumption by the three phase dynamic load. There is a continuous small increment in the active power and there is a continuous increase in reactive power demand by the load as soon as the manual switch is operated to initiate voltage instability scenario. However at t=243 sec, the protection scheme activates and stops the incremental load from increasing further.

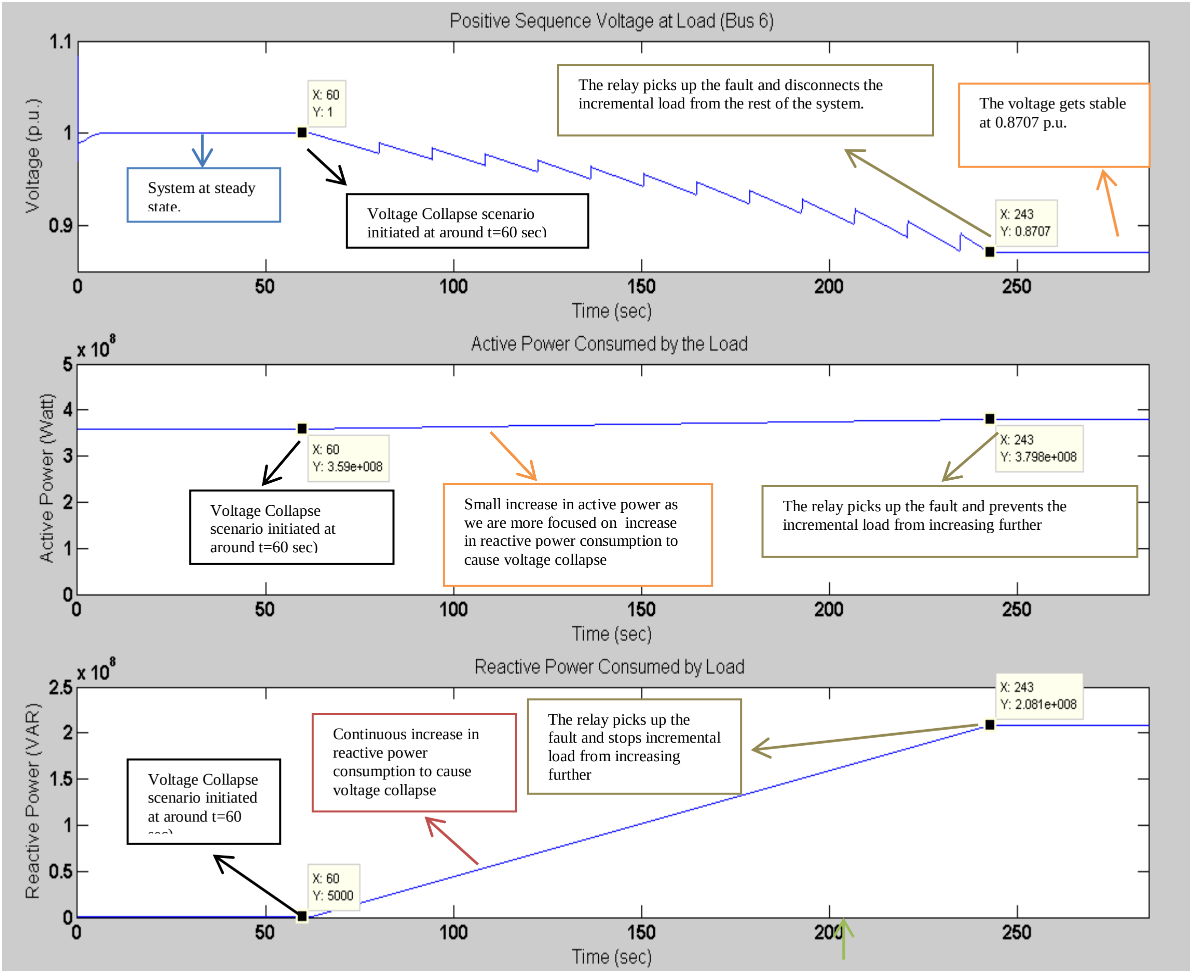


Fig. 5-50: States of Three Phase Dynamic Equivalent Load at Bus 6 (Protection Scheme 2)

Fig. 5-51 and Fig. 5-52 show the behavior of synchronous generator in the above discussed scenario of voltage instability and in presence of the protection relays. As can be seen, the increase in reactive power causes an increase in the reactive power output of the generator.

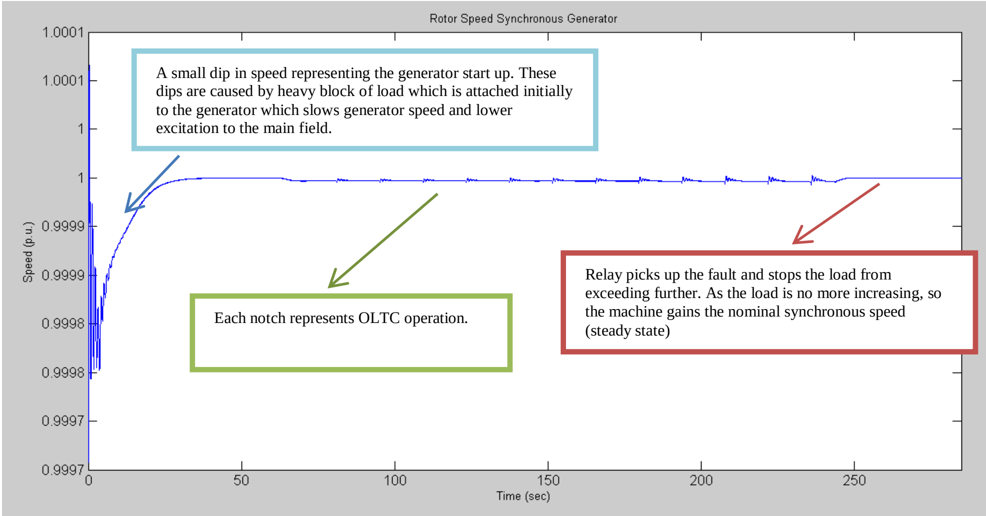


Fig.5-51: Rotor Speed of Synchronous Generator (Protection Scheme 2)

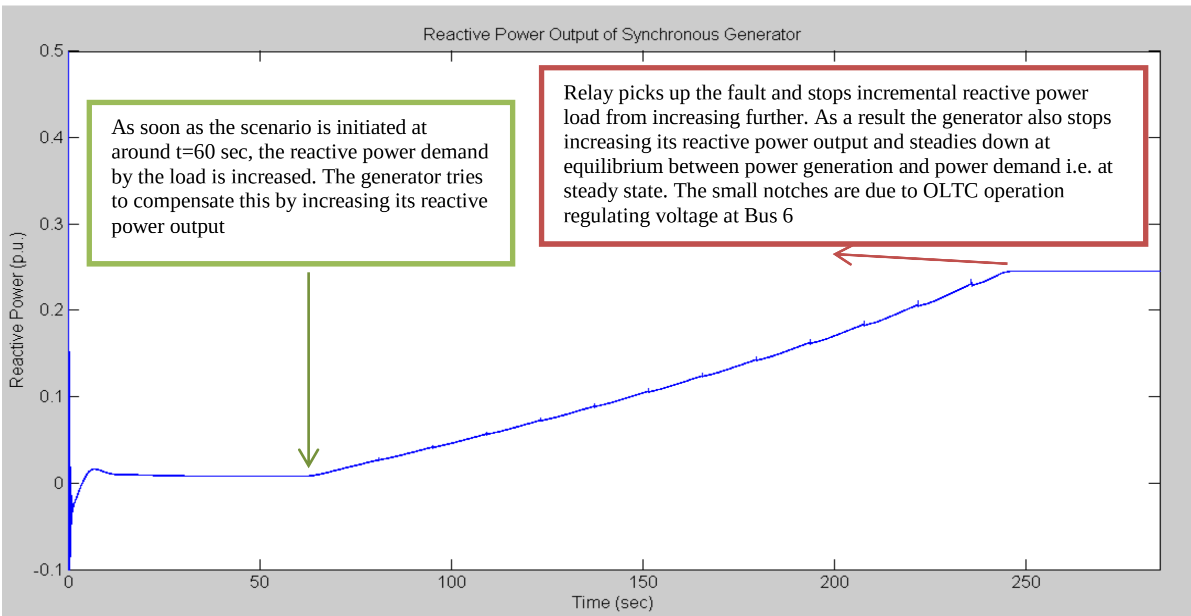


Fig.5-52: Reactive Power Output by Synchronous Generator (Protection Scheme 2)

As the load increases from t=60 sec onwards, the reactive power output of the generator also increases. In the new balance condition, the rotor goes back to synchronous speed but at an increased angle. As the steam turbine mechanical power input to the synchronous generator is increasing continuously to handle the increasing load, therefore the system is finding a new operating point at each instant which results in the increasing rotor angle deviation. At t=243sec, the relay picks up the fault and sends a trip signal to stop further increment in load. As a result the rotor angle also reaches steady state.

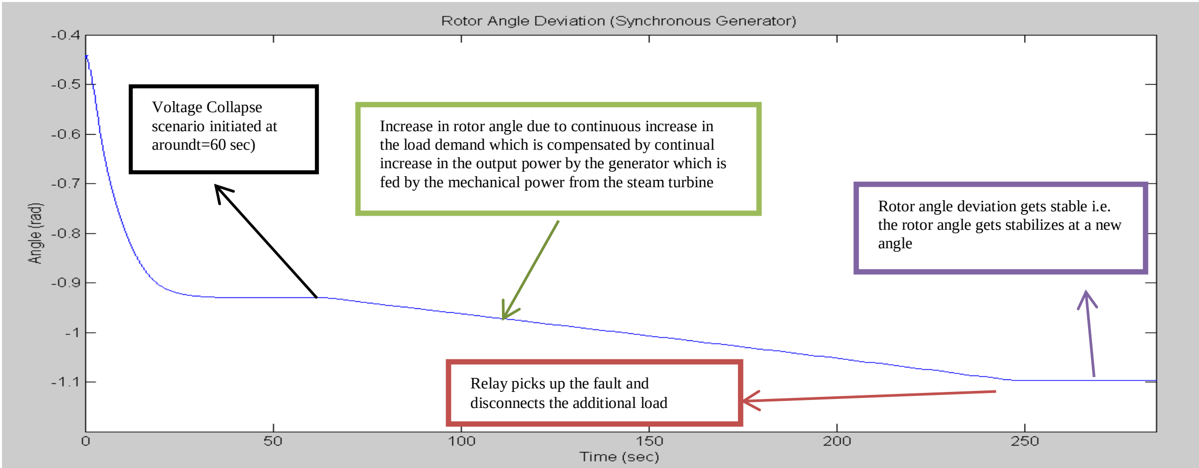


Fig.5-53: Rotor Angle Deviation of the Generator (Protection Scheme 2)

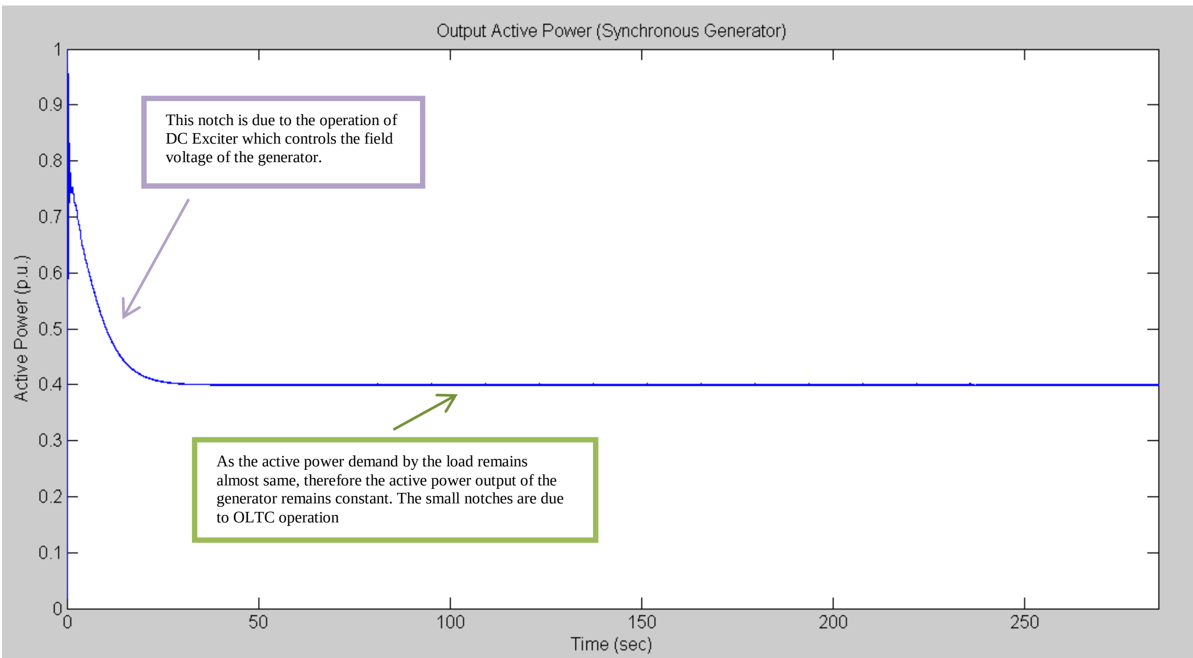


Fig. 5-54: Active Power Output by the Generator (Protection Scheme 2)

The increase in load demand causes a dip in voltage at the generator bus which is sensed by the excitation system which increases the field voltage to maintain constant terminal voltage at the generator bus. Once the protection scheme activates at t=243sec, the incremental load does not increase further and the system reaches steady state.

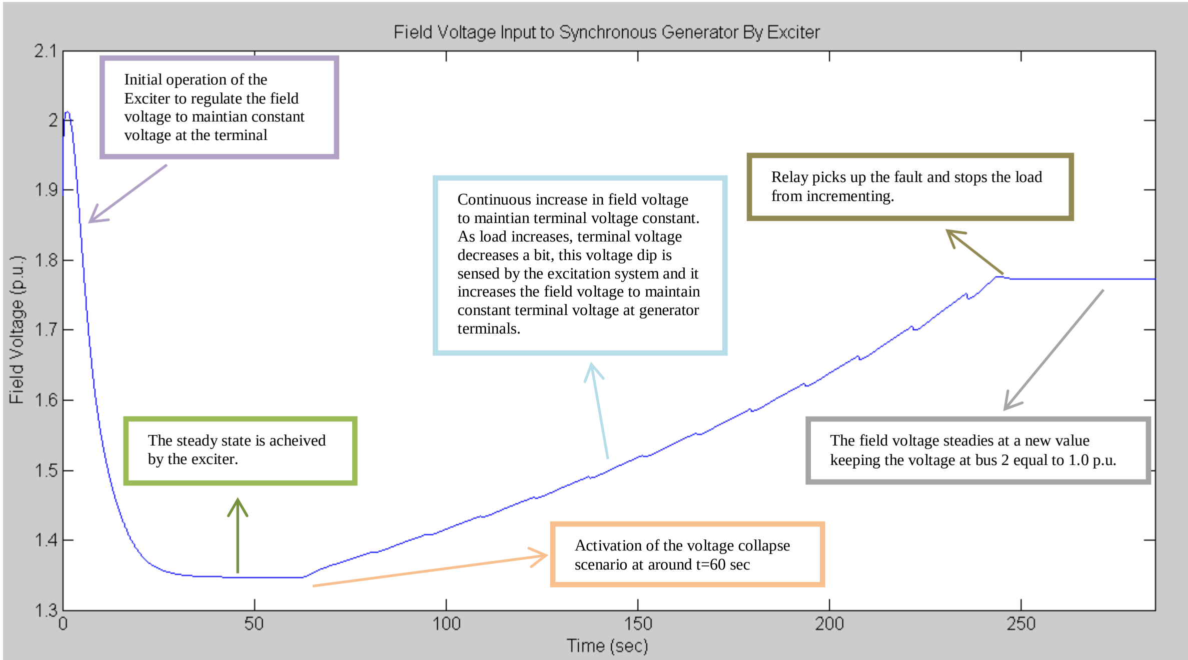


Fig. 5-55: Field Voltage Supplied by the Excitation System to the Synchronous Generator (Protection Scheme 2)

Fig. 5-56 shows the charactersistic of induction motor which is connected at bus 4.

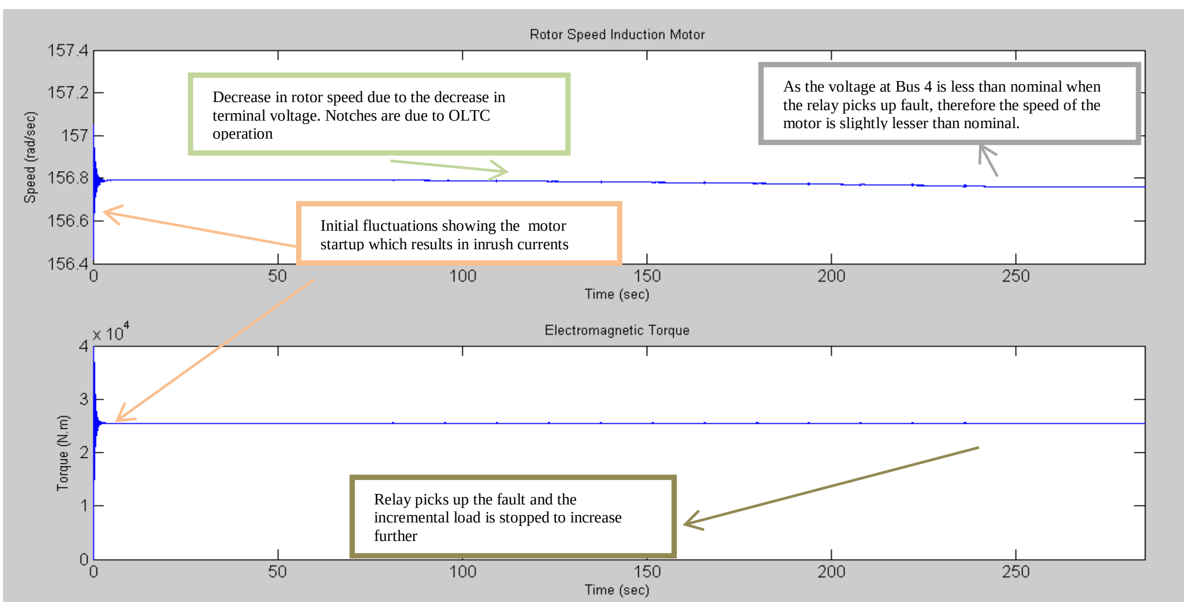


Fig. 5-56: Rotor Speed and Torque of the Induction Motor (Protection Scheme 2)

The currents at the buses increases as soon as the voltage collapse scenario is initiated at around t=60sec. Fig. 5-57 to Fig. 5-62 show the currents through each bus. It is important to mention that only the protection relay at Bus 6 picks up the fault (due to the coordination of relays) and trips the incremental load.

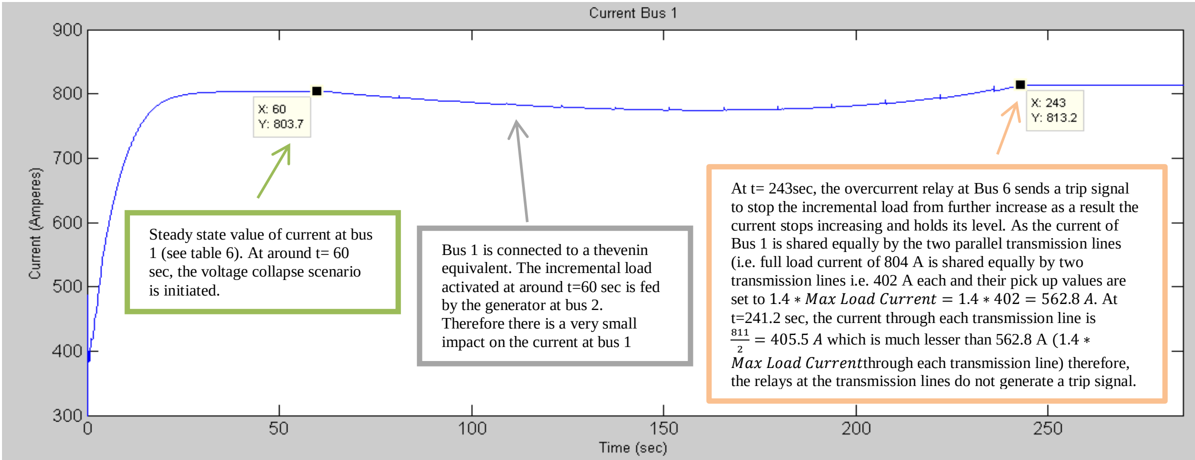


Fig. 5-57: Current at Bus 1(Protection Scheme 2)

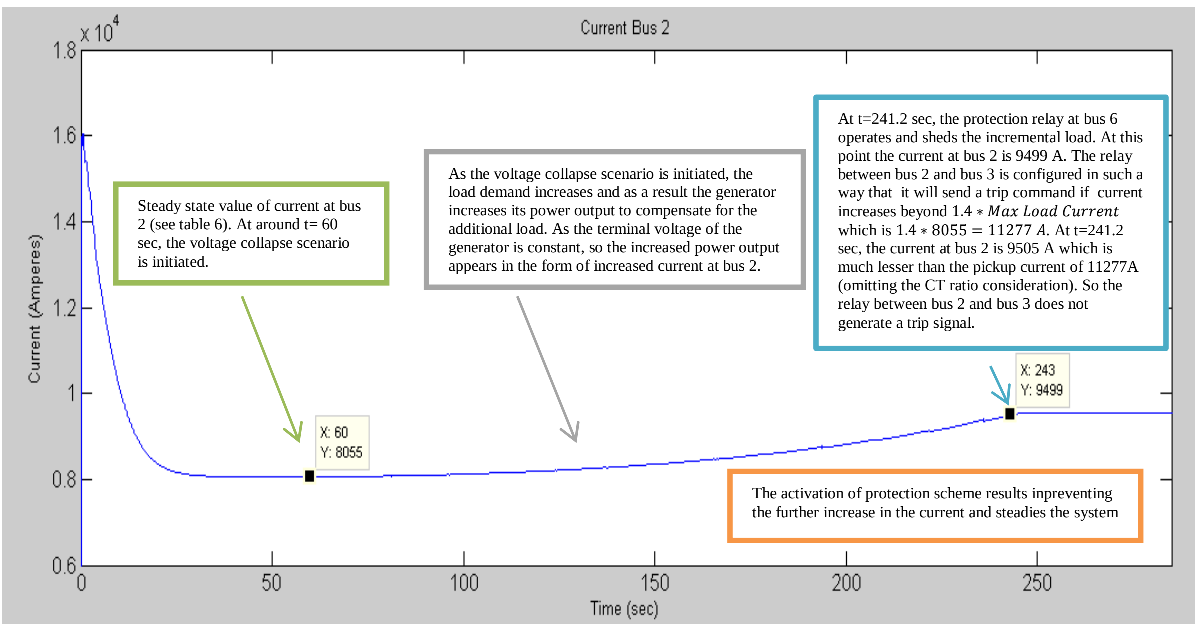


Fig. 5-58: Current at Bus 2 (Protection Scheme 2)

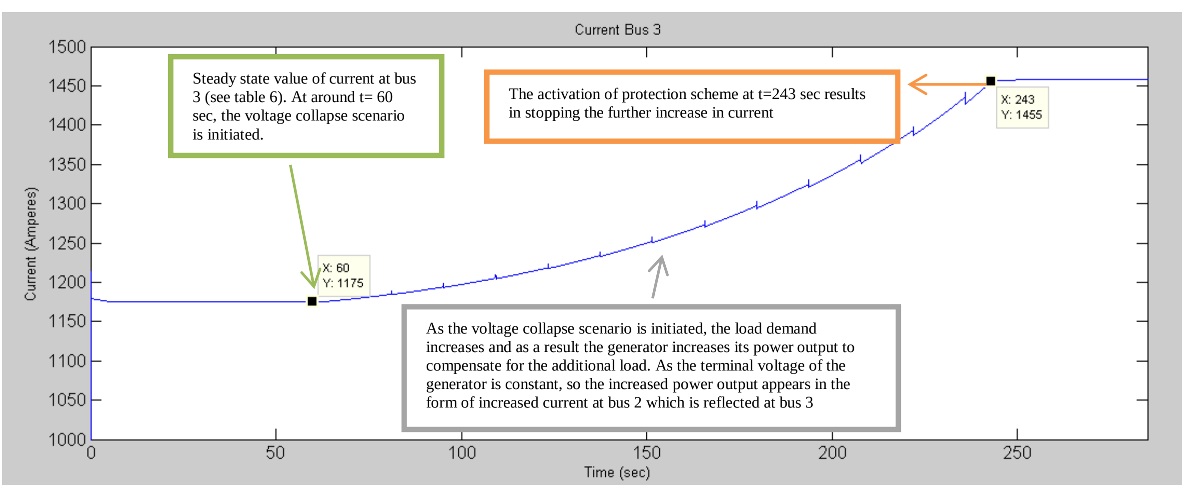


Fig. 5-59: Current at Bus 3(Protection Scheme 2)

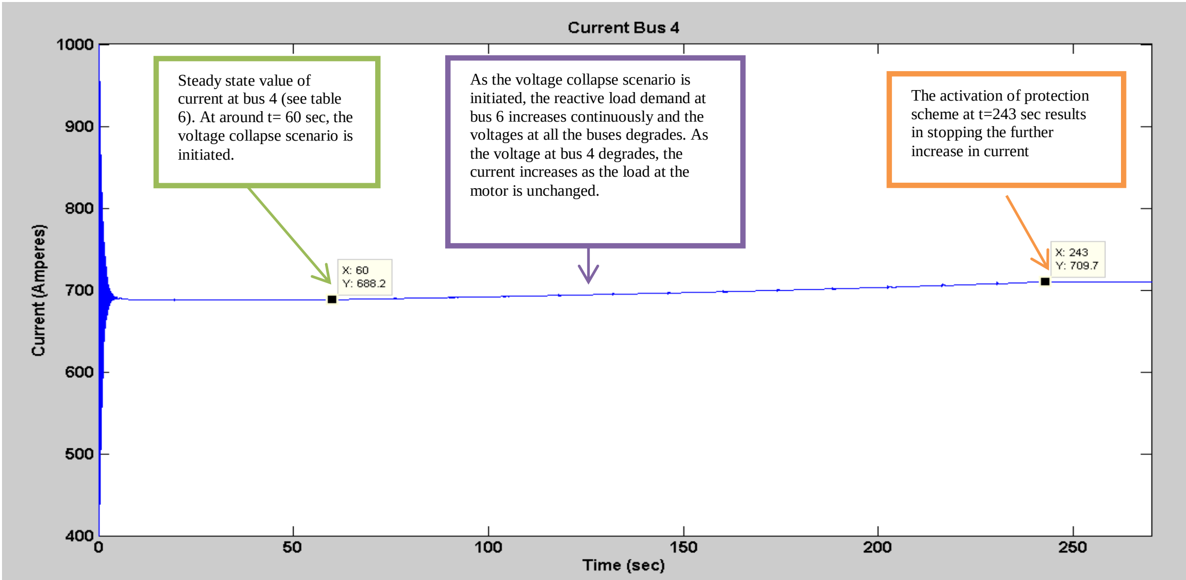


Fig. 5-60: Current at Bus 4(Protection Scheme 2)

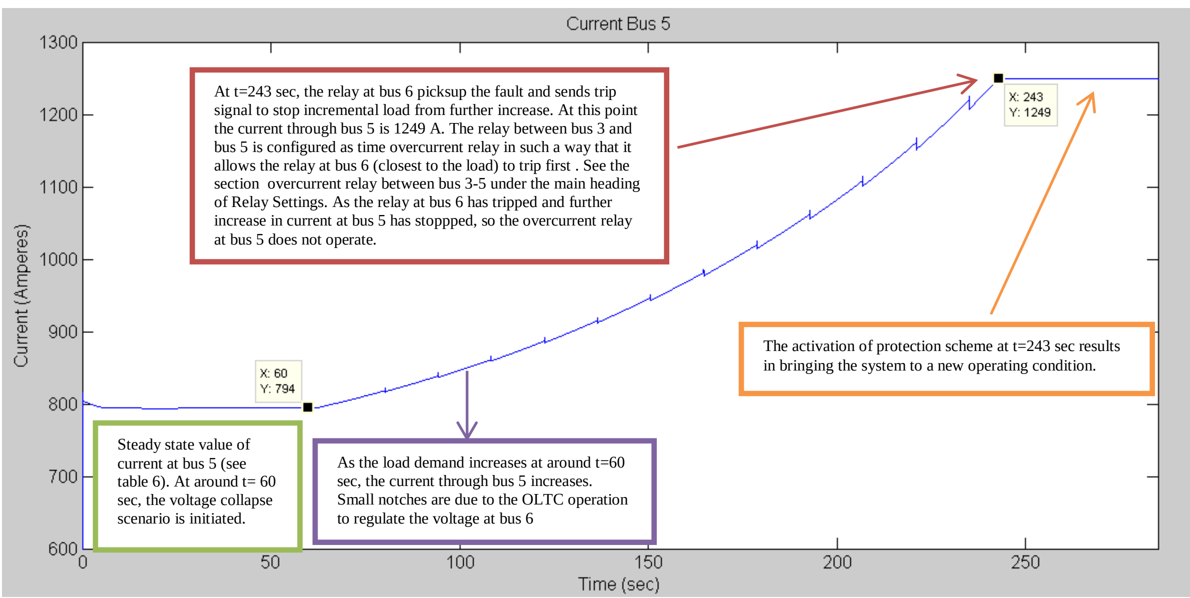


Fig. 5-61: Current at Bus 5 (Protection Scheme 2)

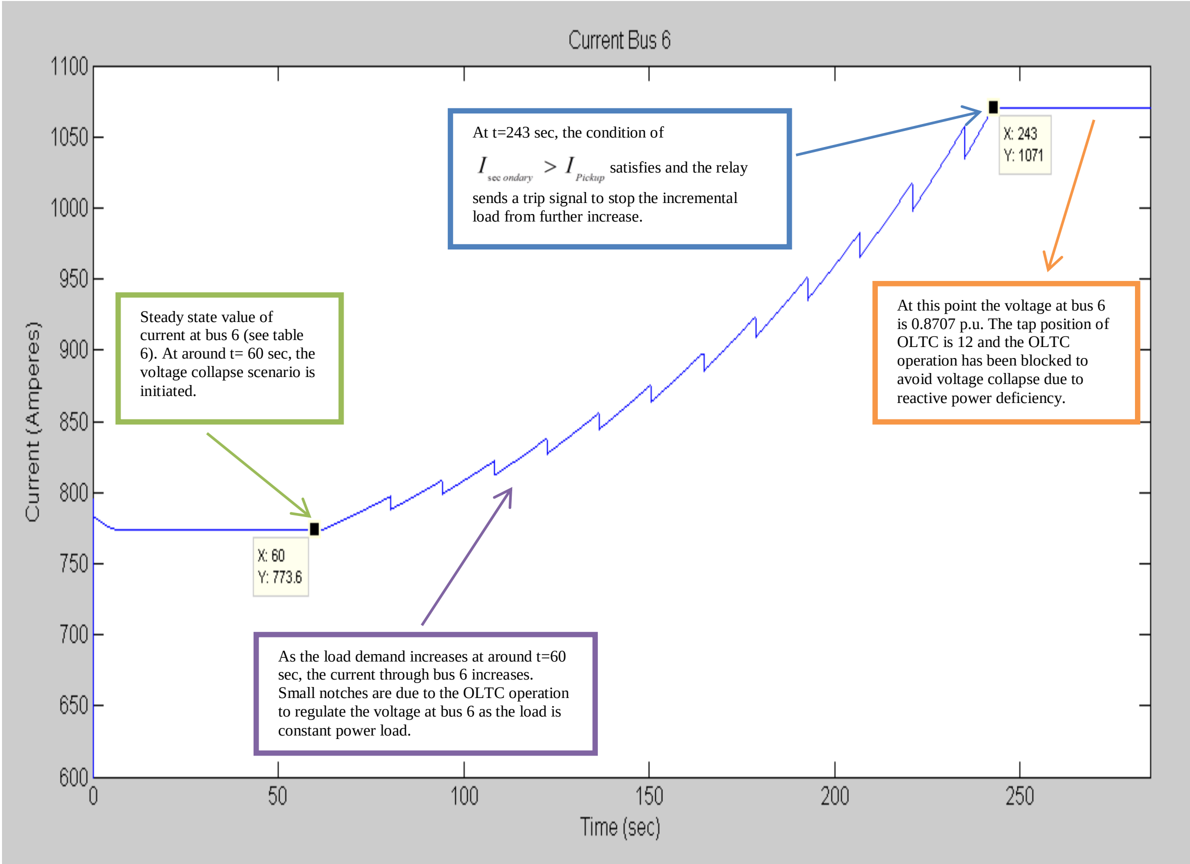


Fig. 5-62: Current at Bus 6 (Protection Scheme 2)

As only the relay at Bus 6 operates, therefore only the plots for this relay are shown in Fig. 5-63. For all the other relays, the ratio will be lesser than 1 and the pickup and trip signals are 0.

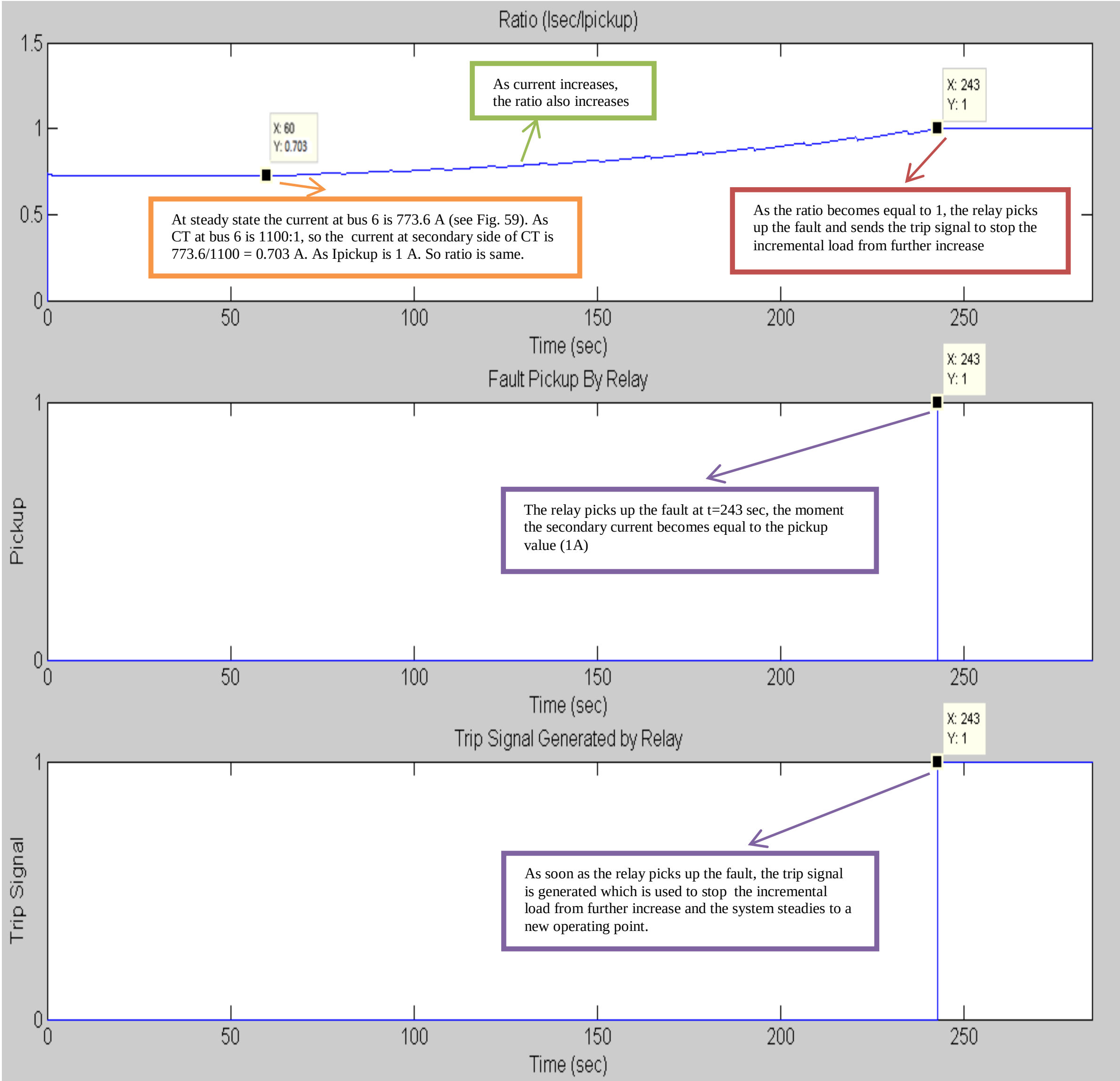


Fig. 5-63: Over- current relay at bus 6 (Protection Scheme 2)

5.7.4. <u>Summary of Protection Scheme 2</u>

In this protection scheme, the relay at bus 6 picks up the fault and generates at trip command instantaneously. This trip command is used to block the OLTC operation from further change in tap position. Also the trip command is used to stop further increment in load demand.

<u>Advantage:</u>

This scheme provides flexibility that even a much higher load is sustained by the system and still it’s stable enough and not collapsing. In addition it avoids OLTC operation for bringing the voltage back to nominal value (protection scheme 1). Thus it ensures longer life of OLTC.

Disadvantage:

One of the disadvantages of this protection scheme is that the voltages at the buses are below the nominal value. However this protection scheme can be used in coordination with FACTS or HVDC devices. Coordinating these devices with relays could provide the reactive power compensation to keep the voltages within acceptable limits while the protective relays allow additional loading of the system.

5.8. A Note on Modeling Issues

The transformers damage curves are not considered for setting relay parameters. The reason is that for the scenario at which we were focusing, the current at the buses where transformers present (Bus 2-3 and Bus 3-4) does not become extremely large. The current at Bus 2 increases only 1.18 times which is considered normal generally. The general rule of thumb, that states that the pickup value should be set such that it is higher than at least 1.2 times the full load current. In addition the transformer between Buses 2-3 is being fed by a single synchronous generator. The rating of transformer is exactly same as the rating of the generator. So the overloading of transformer is unlikely.

5.9. Chapter Summary

Overcurrent relay modeling in SimPowerSystems (MATLAB/Simulink) is discussed in detail. Analysis of a test system for the verification of the relay model implementation with respect to the different IEC characteristic curves (IEC/BS 142) standard inverse, very inverse, long inverse, was performed. The operating time of the relay was compared with the analytical operating time of the overcurrent relay calculated by IEC/BS 142 curves. Once the relay model was validated, it was then implemented in All-in-One system and the coordination of the relays was done by using a time grading and current grading approach. The voltage instability scenario was utilized, and two protection schemes were designed to safeguard the system from the voltage collapse. The protection schemes were discussed in detail and their relative advantages and disadvantages were listed.

Chapter 6: Modeling of Reactive Power Compensation Devices for Real-Time Simulation and their Implementation for Real-Time Voltage Instability Simulations

6.1. Introduction

This chapter focuses on modeling of reactive power compensation devices for real-time simulation and implementing these devices in the "All-in-One" system to analyze their effect on long term voltage instability.

A brief description of HVDC systems is provided first. Then the detail modeling of VSC-HVDC in SimPowerSystems (MATLAB/Simulink) is thoroughly described along with the required alterations in the model to simulate it in real time. The behavior of the "All-in-One" system in presence of VSC-HVDC is analyzed. The chapter concludes with the modeling issues of VSC-HVDC and proposing an alternative reactive power compensation device instead of VSC-HVDC. Analysis of power system dynamic performance is carried out when reactive power compensation devices are present in the system.

Table of Figures

As discussed in earlier sections, the "All-in-One" system was modeled to investigate the behavior of the power system when subjected to faults, disturbances and outages. The overall model was then equipped with protection relays (over-current relays) to analyze how the protection relays can limit the faults (voltage instability). In the previous section, two protection schemes were discussed along with their advantages and drawbacks. This section will conclude with the modeling of reactive power compensation devices for real-time simulation. The effects of the disturbances on the "All-in-One" system in presence of protection relays and reactive power compensation devices will be investigated. For this particular thesis, different controllable devices[5] were studied. However, in this report we will limit our discussion to the VSC-HVDC modeling for the real-time simulation.

6.2. Description of HVDC Apparatus

In order to interconnect power systems where conventional AC transmission lines face technical or economical implementation challenges, HVDC transmission provide an alternative solution. Some examples of HVDC applications are connecting two power systems with different operating frequencies, connecting generation sites with load centers which are geographically at long distances, etc.

The two major types of HVDC transmission are;

6.2.1. Line Current Commutated – High Voltage Direct Current (LCC-HVDC)

HVDC systems based on thyristor technology are called Line Current Commutated (LCC-HVDC) or simply "Classical HVDC". They are dedicated for bulk power transmission. The thyristors can only conduct in one particular direction (i.e. they are unidirectional). By changing the firing angle of the thyristors, the magnitude and polarity of DC voltage can be changed from maximum positive to a minimum negative. LCC-HVDC requires reactive power support to compensate for reactive power generated by the filters[6] and to balance out the reactive power consumed by the converters. Fig. 6-1 shows the simplified single line diagram for the LCC-HVDC.

[5] like SVC, STATCOM, TCSC, SSSC, UPFC and HVDC
[6] to limit the harmonics generated by converters from entering the grid

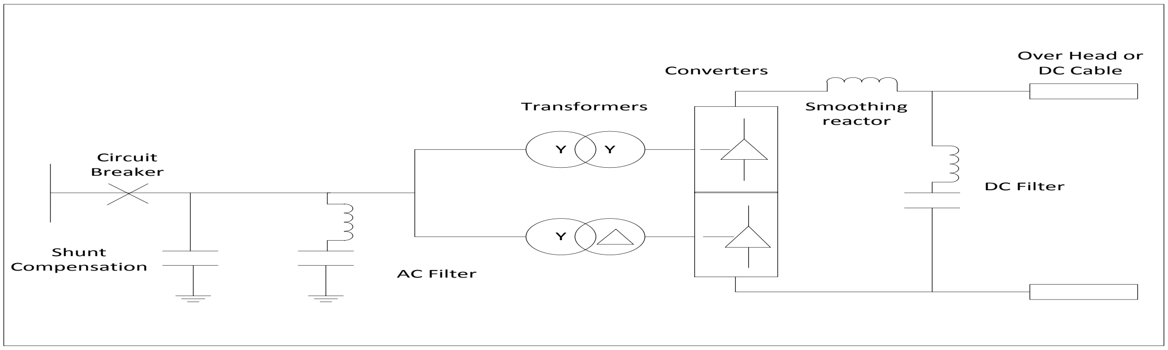


Fig. 6-1: Single Line Diagram of LCC-HVDC

The detail of the important components in Fig. 1 is given below;

i. <u>Shunt Compensation</u>
It is required to compensate for the reactive power generated by the filters and the reactive power consumed by the thyristor converter.

ii. <u>AC Filter</u>
Blocks the harmonics generated by the converters from entering into the AC grid.

iii. <u>Transformers</u>
The transformers are used to change the voltage level to the one compatible with the converter withstand voltage.

iv. <u>Converters</u>
A single block of converter in Fig. 1 represents a 6-pulse converter assembled in such a way that each phase (leg) is equipped with 2 thyristors. The topology in Fig. 1 thus shows a 12-pulse converter fed with a Y-Δ configuration from the transformer.

v. <u>Smoothing Reactors</u>
They are at the DC side and their purpose is to reduce the ripples of the direct current.

vi. <u>DC Over Head Transmission Line or Cable</u>
They are used to transmit the DC power from one converter (rectifier) to the other converter (inverter).

6.2.2. <u>*Voltage Source Converter – High Voltage Direct Current (VSC-HVDC)*</u>

In case of LCC-HVDC systems, the reactive power cannot be independently controlled. In addition the thyristors always consume reactive power, hence, reactive power compensation is required. These drawbacks are minimized by the advent of Voltage Source Converter-based (VSC) technology. VSC-HVDC can rapidly control active and reactive power independently of one another. This flexibility allows the designer to place the HVDC anywhere in the AC-network as there is no restriction on minimum network short circuit capacity. In VSC-HVDC, converters based on IGBT or GTO are used instead of thyristors.

6.2.3. Advantages of VSC-HVDC over LCC-HVDC

- It is possible to control their reactive power to regulate the AC system voltage (virtual generator)
- Provides black start capability i.e. it doesn't require grid connection to power up the HVDC system
- Improves voltage stability by supporting AC voltages at both converter terminals.

Fig. 6-2 shows the simplified single line diagram for the VSC-HVDC.

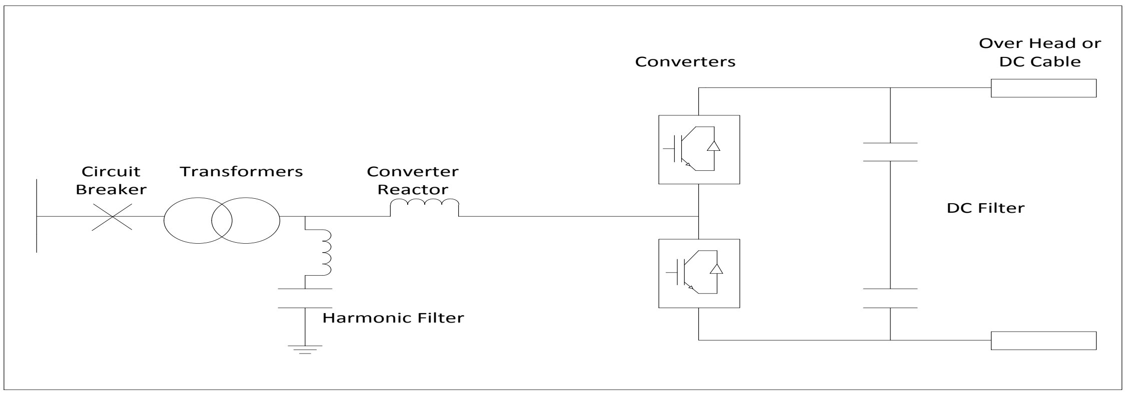


Fig. 6-2: Single Line Diagram of VSC-HVDC

The detail of the important components in Fig. 6-2 is given below;

i. Harmonic Filter
It is used to block the harmonics from entering the AC network.

ii. Transformers
It is used to transform the voltage level so that it matches with the AC voltage system.

iii. Converter Reactor
It extracts the AC fundamental frequency from the raw PWM (Pulse Width Modulated) waveform.

iv. <u>Converters</u>

A single block of converter in Fig. 2 represents a 6-pulse converter assembled in such a way that each phase (leg) is equipped with 2 IGBTs. The topology in Fig. 2 thus shows a 12-pulse converter.

v. <u>DC Capacitor</u>

It serves as a DC filter to smooth the DC voltage

vi. <u>DC Over Head or Cable</u>

They are used to transmit the DC power from one station (rectifier) to the other station (inverter).

6.2.4. Applications of HVDC Technology

The most common applications of HVDC technology are described in the tabular form below;

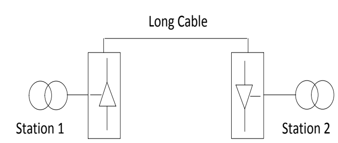
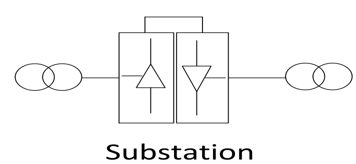
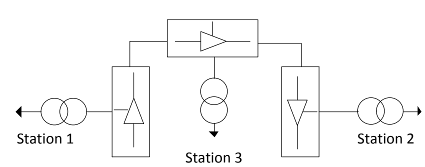
Topology	Description	Application	Connection Diagram
Point to Point Transmission	To connect two nodes in a power system or interconnect two separate power systems	When distance between two nodes is very large	
Back to Back Station	For connecting two asynchronous power systems without the need of transmission line	Connecting two power systems with different frequencies (e.g. 50Hz and 60 Hz). Both converters are located in the same substation	
Multi-Terminal Systems	For connecting more than two terminals.	In order to form a multi terminal HVDC system (potential application for offshore wind projects)	

Fig. 6-3: Applications of HVDC

For this particular thesis, focus is placed to VSC-HVDC systems. The point to point topology is considered for the system. Fig. 6-3 shows the single line diagram of all in one system with VSC-HVDC.

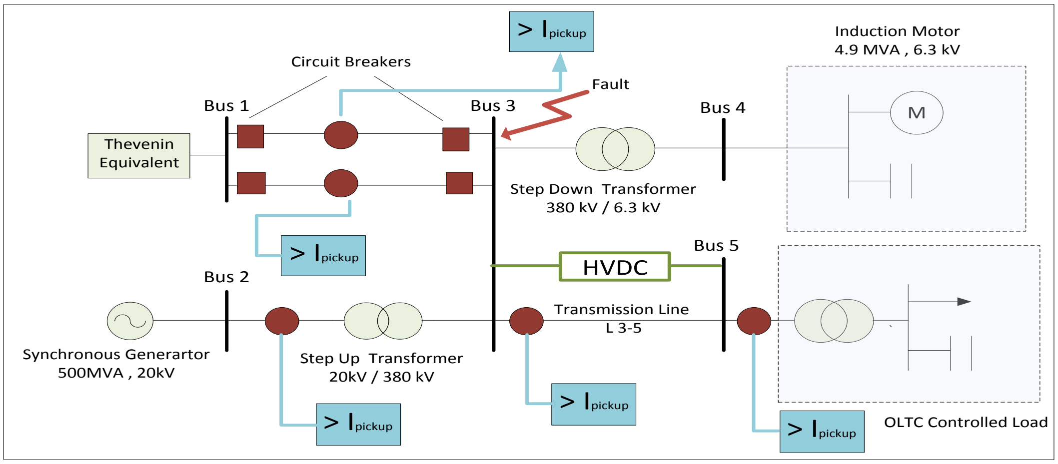


Fig. 6-4: All-in-One System with VSC-HVDC connected between Transmission Line 3-5

6.3. Modeling of VSC-HVDC for Real-Time Simulation

In this section, modeling of VSC-HVDC for real time simulation is explained. The SimPowerSystems library does not contain VSC-HVDC discrete controller blocks. Hence, a demo in Simulink for VSC-HVDC was modified[7]. The purpose of this study is to use HVDC in the “All-in-One” model and repeat the voltage instability scenario to observe the resulting dynamic behavior under the presence of this device. This section will explain the overall HVDC model and its implementation in real-time. The results of simulations are furnished.

6.3.1. Description of the Model

Fig. 6-5 shows the demo model available in the SimPowerSystems library. To run the model in offline mode, voltage levels at AC side were changed from 230 kV to 380 kV. This change in voltage level was made to make this model compatible with the all-in-one system. As the HVDC is supposed to be connected between Bus 3 and Bus 5 where the voltage level is 380 kV, this change in voltage level was important.

[7] The demo can be found by writing power_hvdc_vsc.mdl in the command window.

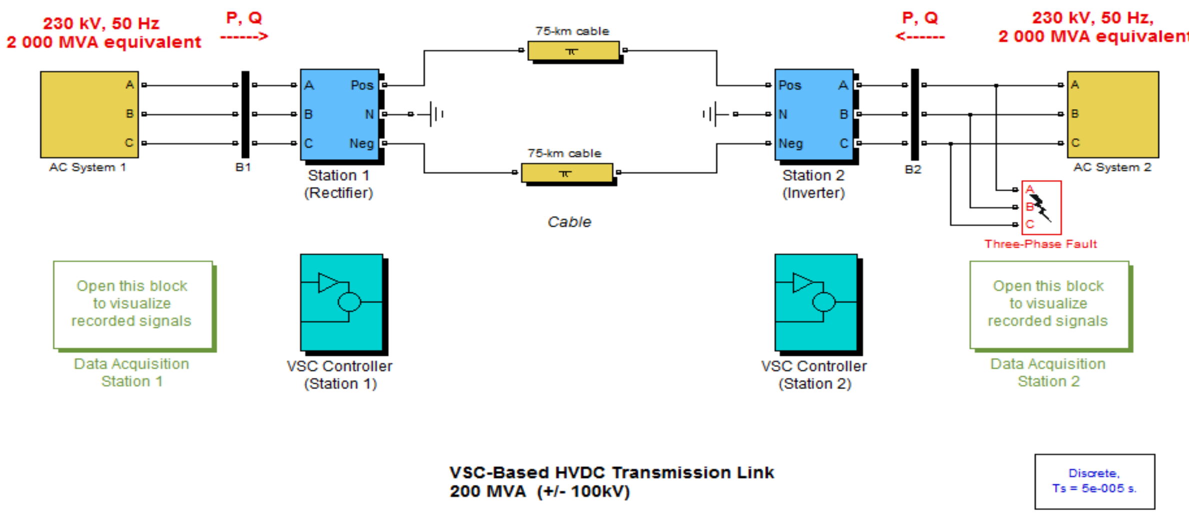


Fig. 6-5: VSC-HVDC Demo Model available in SimPowerSystems

Figure 6-5 shows 380kV, 2000MVA AC systems (AC System 1 and AC System 2). The subsystem AC System 1 is shown in Fig. 6-6. It contains a three phase voltage source (380 kV) and RL circuit to provide a phase angle between voltage and current equal to 80 degrees.

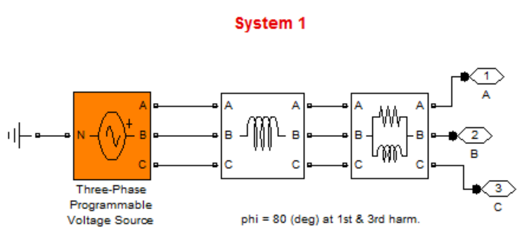


Fig. 6-6: Subsystem AC-System 1

The next subsystem Station 1 (Rectifier) is shown in Fig. 6-7. A transformer is used to step down the voltage from 380kV to 100kV which can be fed to the converters. The Y Grounded/Delta arrangement of the transformer blocks the tripplen harmonics generated by the converters. In order to have a modulation index of 0.85, the transformer ratios of 0.915 and 1.015 are used on the rectifier and inverter sides respectively. The converter reactor and transformer leakage reactance permit the VSC output voltage to shift in phase and amplitude with respect to the AC system, and allows control of converter active and reactive power output. Three level bridge converters are designed by using IGBT and diodes. The AC filters are tuned for 27th and 54th harmonic.

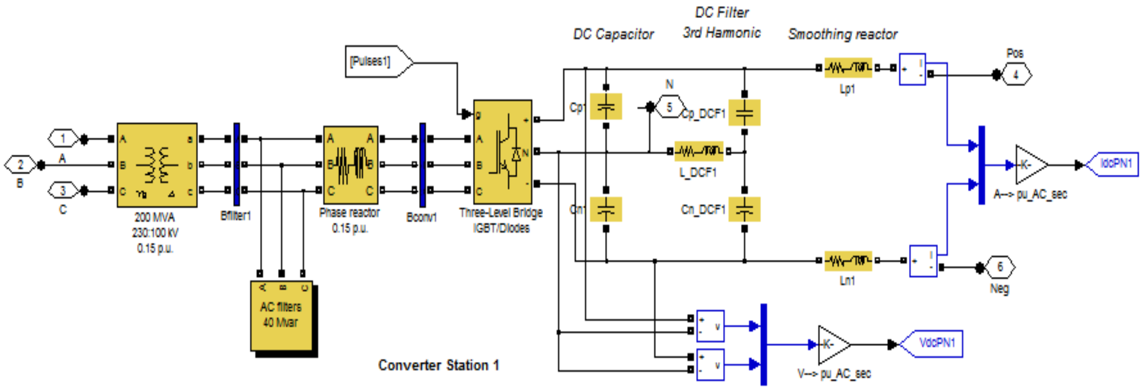


Fig. 6-7: Subsystem (Station 1-Rectifier)

In order to reduce the ripple on the DC side, the DC capacitors are used. The DC side filters are tuned to block the third harmonic. Smoothing reactor is connected in series at each pole terminal. The rectifier and inverter are connected through a 75 km cable.

In this model, Converter 1 is used for active and reactive power control while converter 2 is used for DC voltage and reactive power control. The two controllers are independent and there is no communication between them.

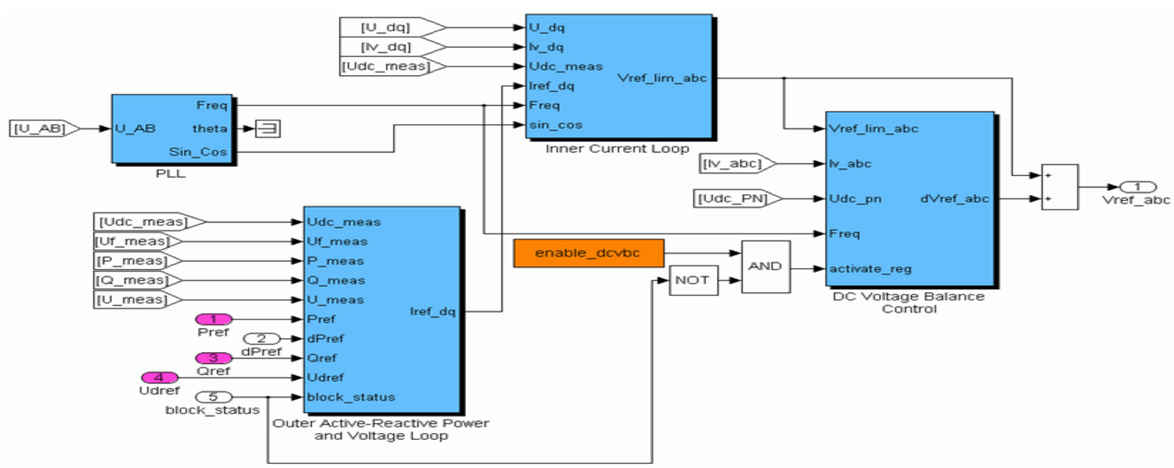


Fig. 6-8: High Level Block Diagram of Discrete VSC-Controller

A Clark Transformation block transforms the three phase quantities to space vector components α and β (real and imaginary part). The dq Transformation block computes the d and q quantities from α and β quantities. A signal calculation block calculates and filters quantities used by the controller (e.g. active and reactive power, modulation index, DC current and voltage etc.)

Figure 6-8 shows the discrete VSC-Controller. A Phase Locked Loop (PLL) block measures the system frequency and provides the phase synchronous angle for dq Transformation blocks.

Figure 6-9 shows the Outer Active and Reactive Power Control. It contains the following elements:

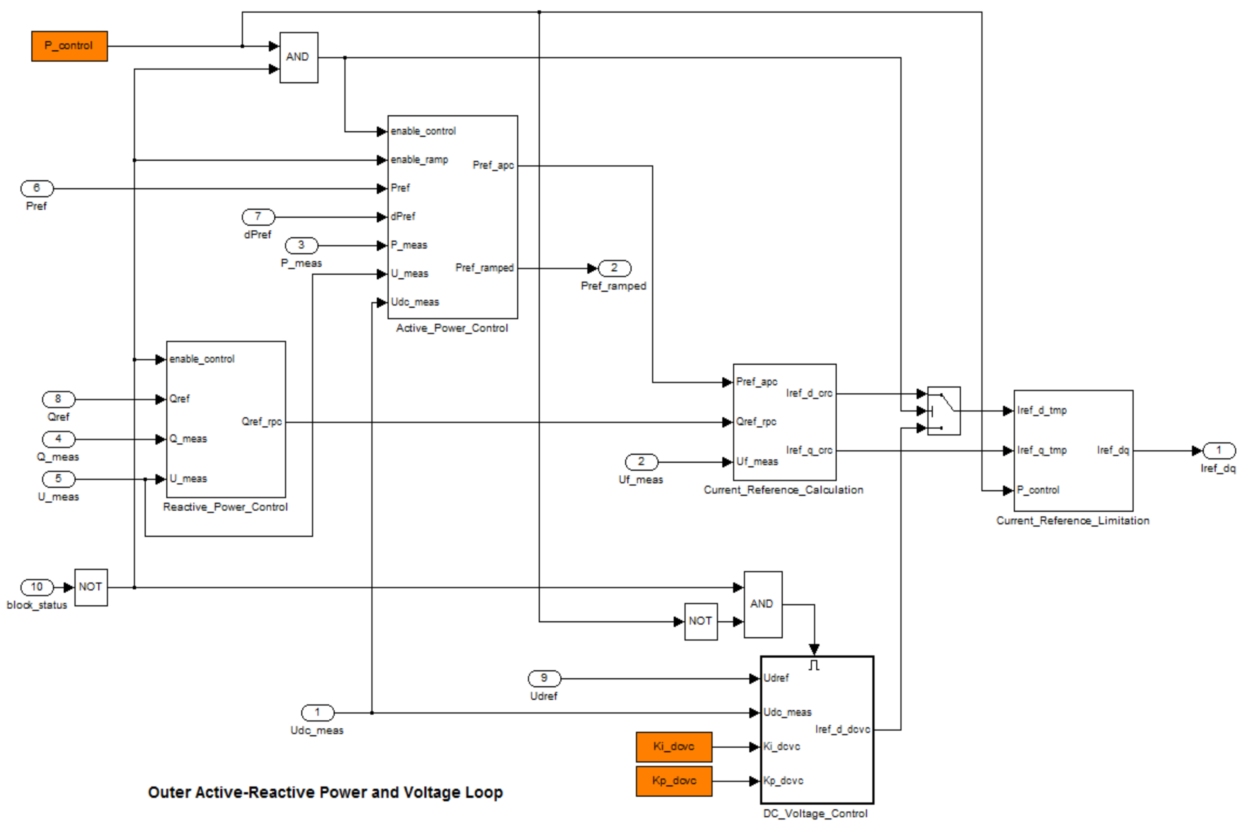


Fig. 6-9: Outer Active and Reactive Power Control Subsystem

- A Reactive Power Control Regulator block which consists of a PI controller with a feed forward control to increase speed response.
- An Active Power Control block (similar to reactive power control block).
- A DC Voltage Control block which uses PI regulator. This block is enabled when active power control block is disabled. The block output is a reference value for the “d” component of converter current vector for Current Reference Limitation block.
- A Current Reference Calculation block which transforms active and reactive power references, calculated by P and Q controllers to current references according to measured voltage at filter bus.
- A Current Reference Limitation block which limits the maximum acceptable value by the current reference block.

Figure 6-10 shows the Inner Current Loop. It consists of following elements:

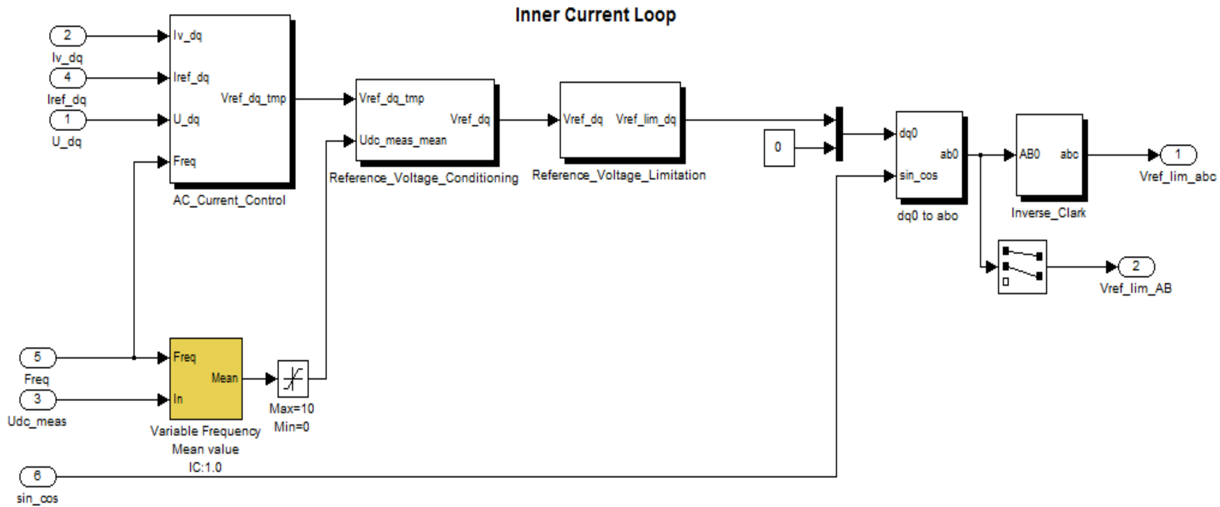


Fig. 6-10: Inner Current Control Loop Subsystem

- An AC Current Control block which tracks the current reference vector.
- A Reference Voltage Conditioning block which provides the new optimized reference voltage vector.
- A Reference Voltage Limitation block which limits the reference voltage vector amplitude to 1.0 p.u since over modulation is not desired.
- Inverse Transformation blocks are required to generate three phase voltage references to the PWM.

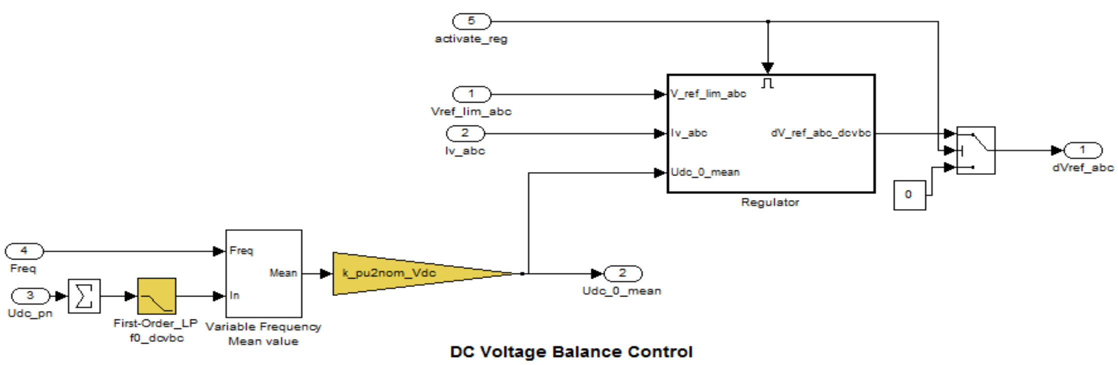


Fig. 6-11: DC Voltage Balance Control Subsystem

Fig. 6-11 shows the DC Voltage Balance Control which balances the voltages at the DC sides of three level bridges. Small deviations between the pole voltages may occur at changes of active/reactive converter current or due to nonlinearity on lack of precision in the execution of the pulse width modulated bridge voltage. Furthermore, deviations between the pole voltages may be due to inherent unbalance in the circuit components impedance.

6.3.2. Model Modification for Real Time Simulation

As this model was already available in the SimPowerSystems library, the next task was to modify this model to run it in real-time. The first step is to convert the model into subsystems. As the time step for the simulation is 50 micro seconds, this model was divided into three subsystems Master subsystem, slave subsystem and console subsystem. The master and the slave subsystem contain the rectifier and the inverter station along with their controllers respectively. Fig. 6-12 shows the high level block diagram of the modified model.

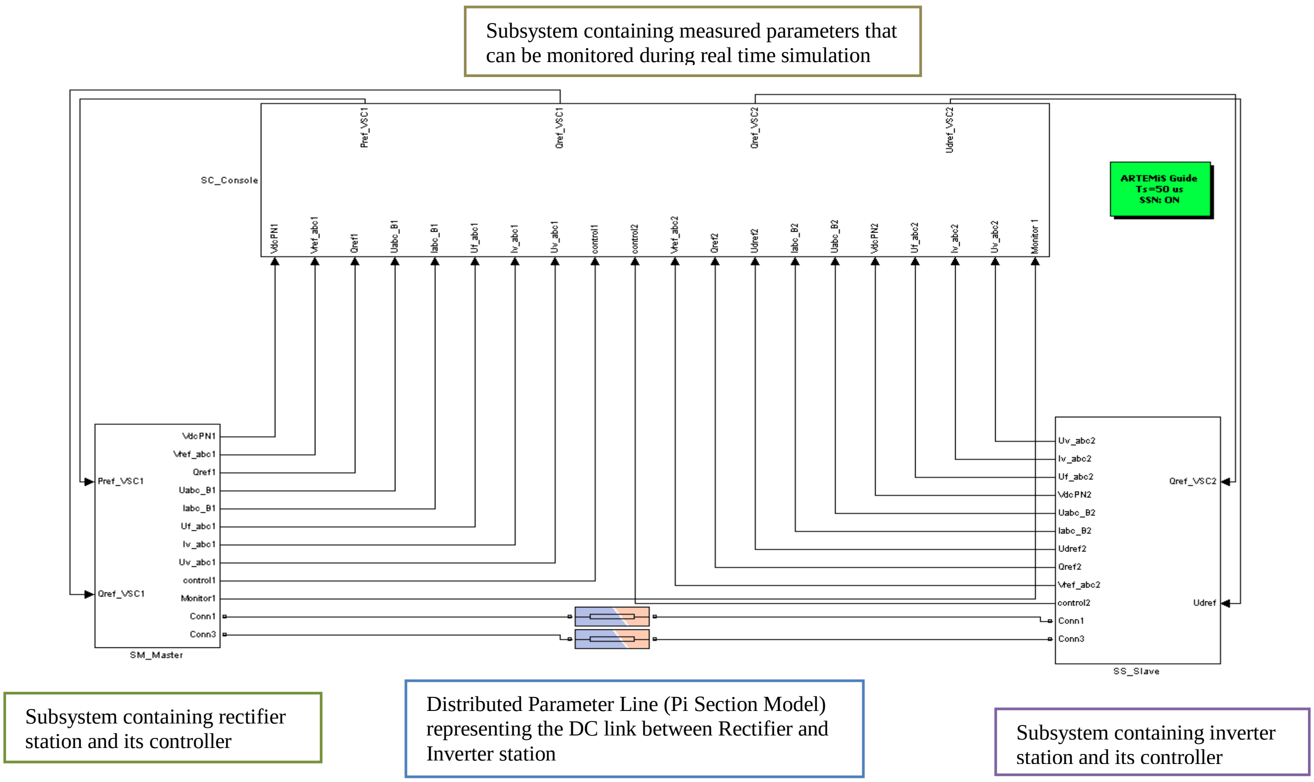


Fig. 6-12: High Level Block Diagram of Modified VSC-HVDC Model

As we were using the State Space Nodal (SSN) [67] solution technique in our model, State Space Nodal Interface Blocks (from the Artemis Library)[8] were used to separate voltage sources from current sources. For the sake of clarity, SSN blocks consider inductors as voltage sources and capacitors as the current sources. Fig. 6-13 below shows this implementation. In addition the same rule applies here that all the signals entering a subsystem from another subsystem should first pass through an OPCOM block. The same changes are made on the inverter station i.e. subsystem SS_Slave.

[8] Artemis Library is provided by Opal-RT.

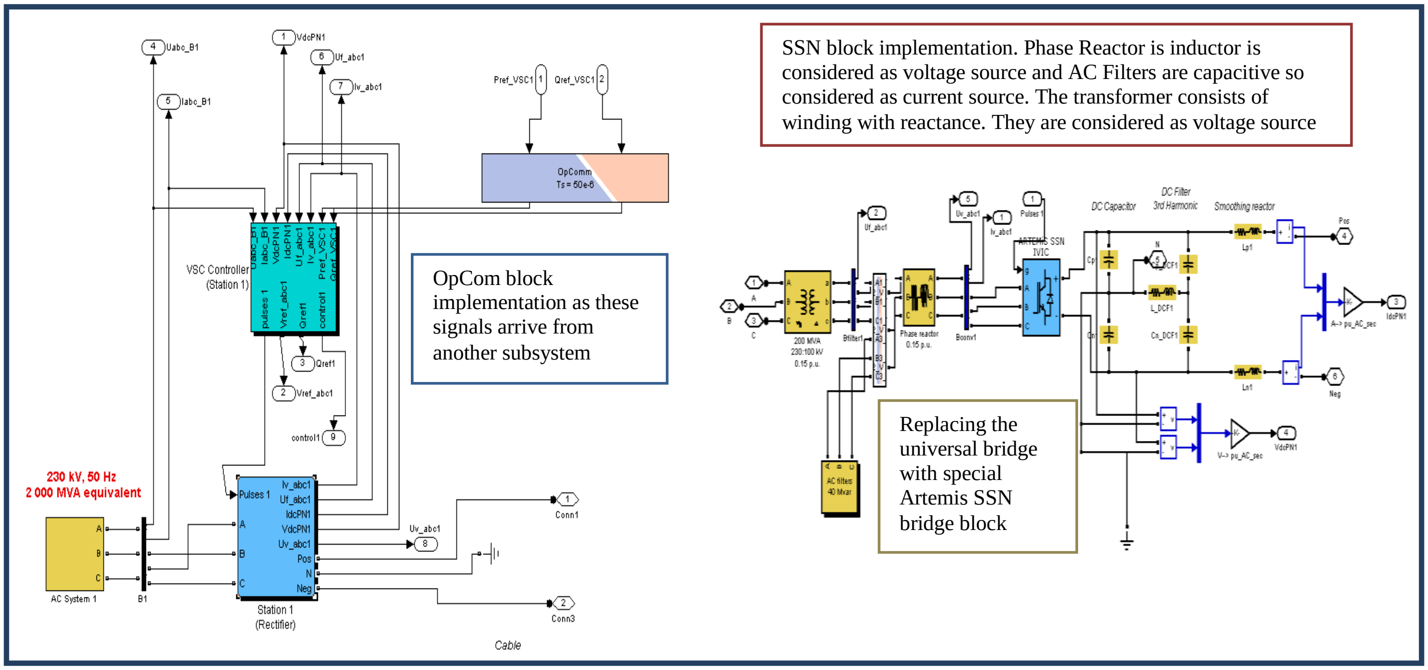


Fig. 6-13: SM_Master Subsystem showing the OpCom block, SSN block and Artemis SSN Bridge block

All the signals which are required to be monitored are sent to the console block. Fig. 6-14 shows the SC_Console subsystem.

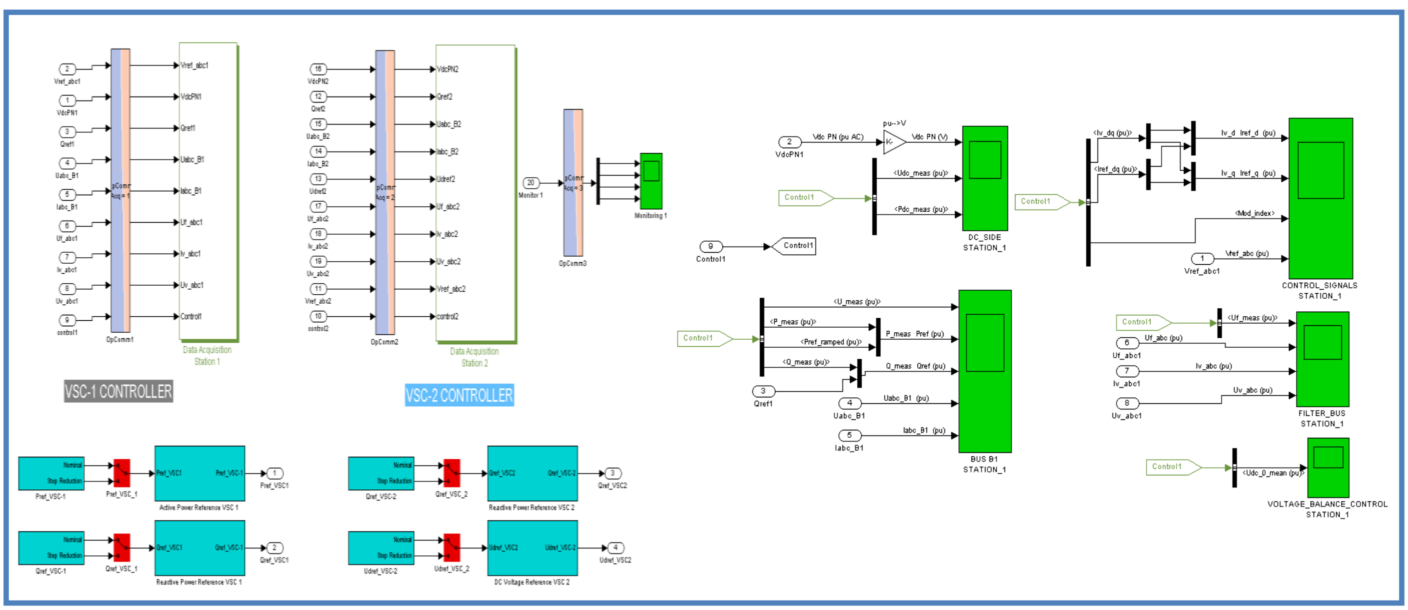


Fig. 6-14: SC_Console Subsystem

6.3.3. Dynamic Performance Evaluation of the VSC-HVDC Model in Real-Time

In order to analyze the VSC-HVDC model, some disturbances were incorporated in the model. Station 1 controls the active and reactive power while station 2 controls the DC voltage and reactive power. The following sequences of disturbances were incorporated in the model:

i. Station 2 converter which controls the DC voltage is first de-blocked at t=1 sec
ii. The active power converter at Station 1 which is de-blocked at t=2 sec to slowly ramp up the power to 1 pu
iii. A step of -0.1 pu is applied to the reference active power at t=5 sec.
iv. A step of -0.1 pu is applied to the reference reactive power at t=10.0 sec
v. In Station 2, a -0.05 pu step is applied to DC Voltage reference at t=7.5 sec

The waveforms in Fig. 6-15 show the response of the controller to these perturbations.

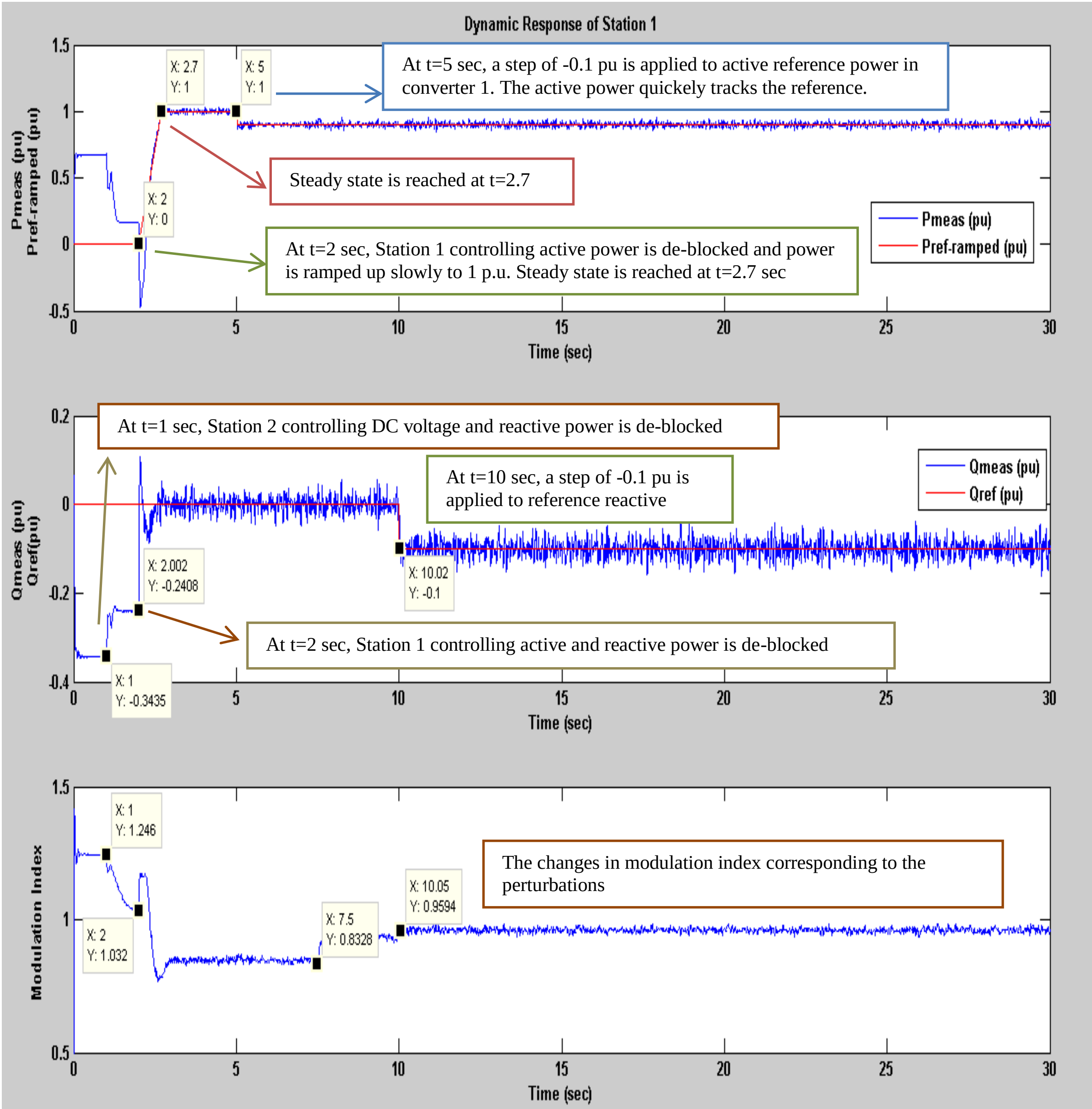


Fig. 6-15: Dynamic Behavior of Station 1 when subjected to perturbations

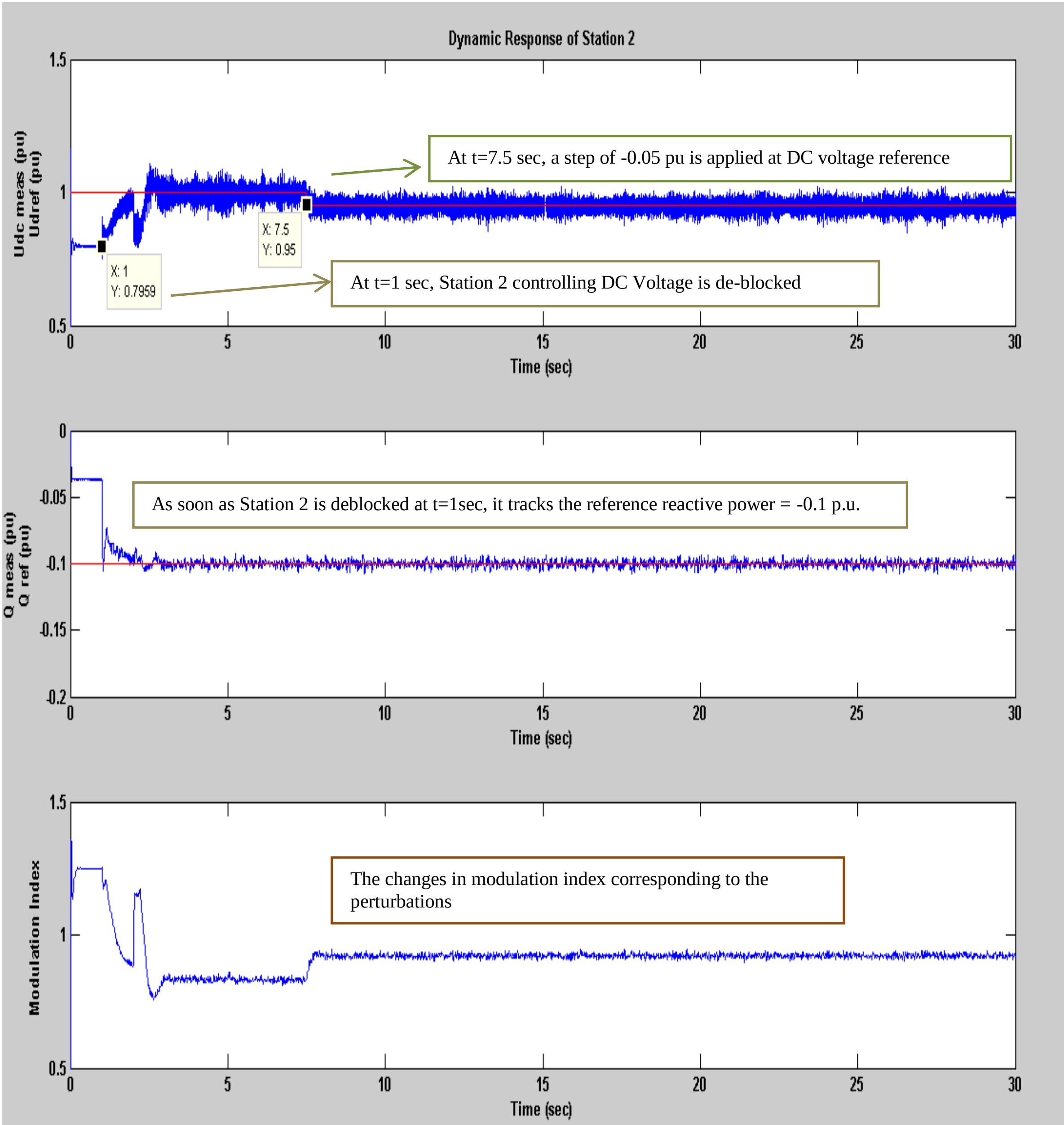


Fig. 6-16: Dynamic Behavior of Station 2 when subjected to perturbations

It is worth noticing that the control design actually decouples the active and reactive power responses. The active and reactive powers are controlled independently. But the regulators are more or less mutually affected as can be noticed by the modulation index of the two stations.

6.3.3.1. AC Side Perturbations

When the system is in a steady state, a minor and a severe perturbation is executed at Station 1 and Station 2. In case of Station 1, a three phase voltage sag is applied (at t=15sec for 0.14 sec, 7 cycles) which is followed by a three phase to ground fault at station 2 bus (at t=20 sec for 0.12 sec, 6 cycles). The aim is to check the response of the controller which should be prompt and stable.

The main waveforms from the scopes are reproduced in the following figures;

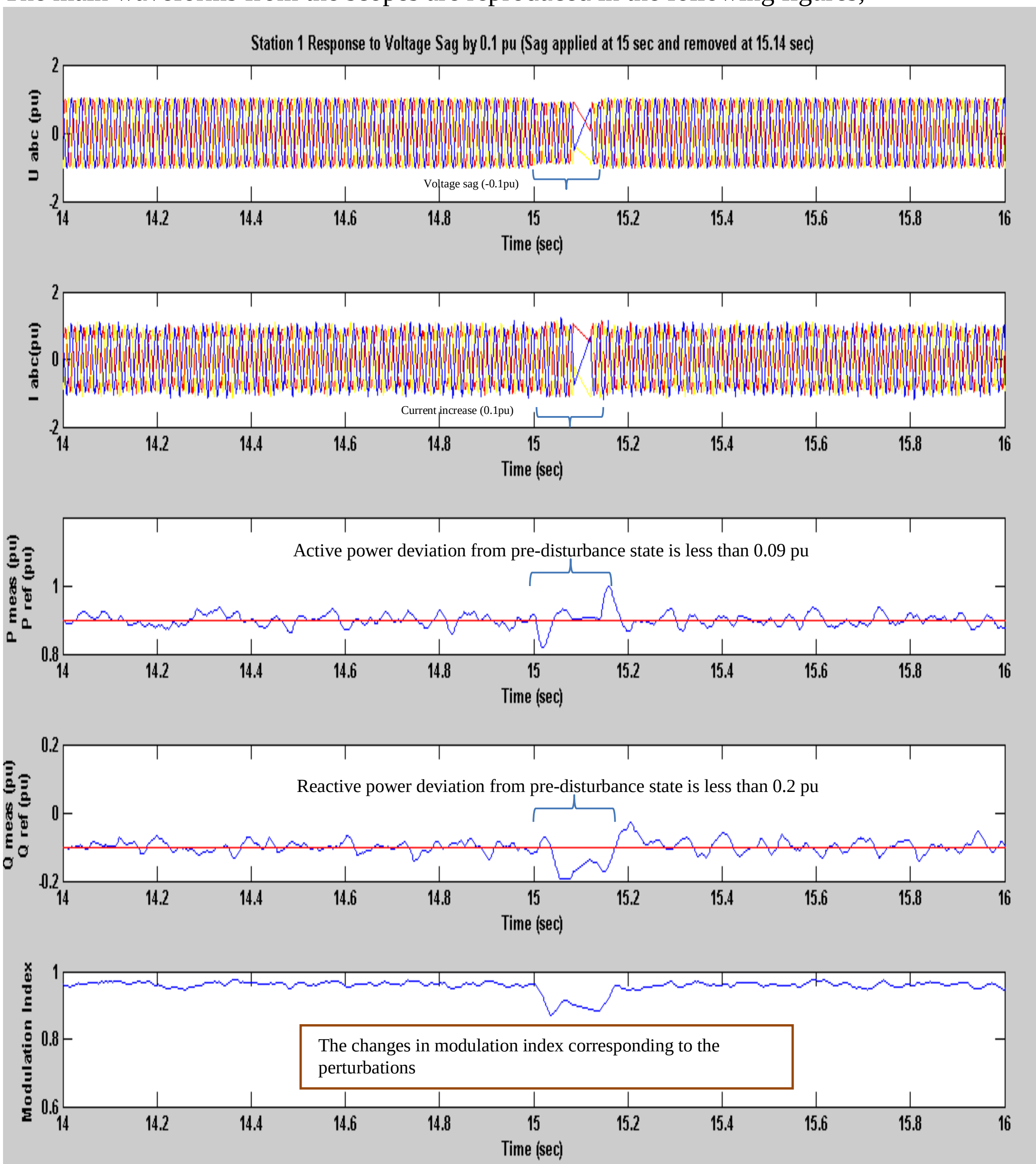


Fig. 6-17: Dynamic Behavior of Station 1 when subjected to Voltage Sag on AC System 1

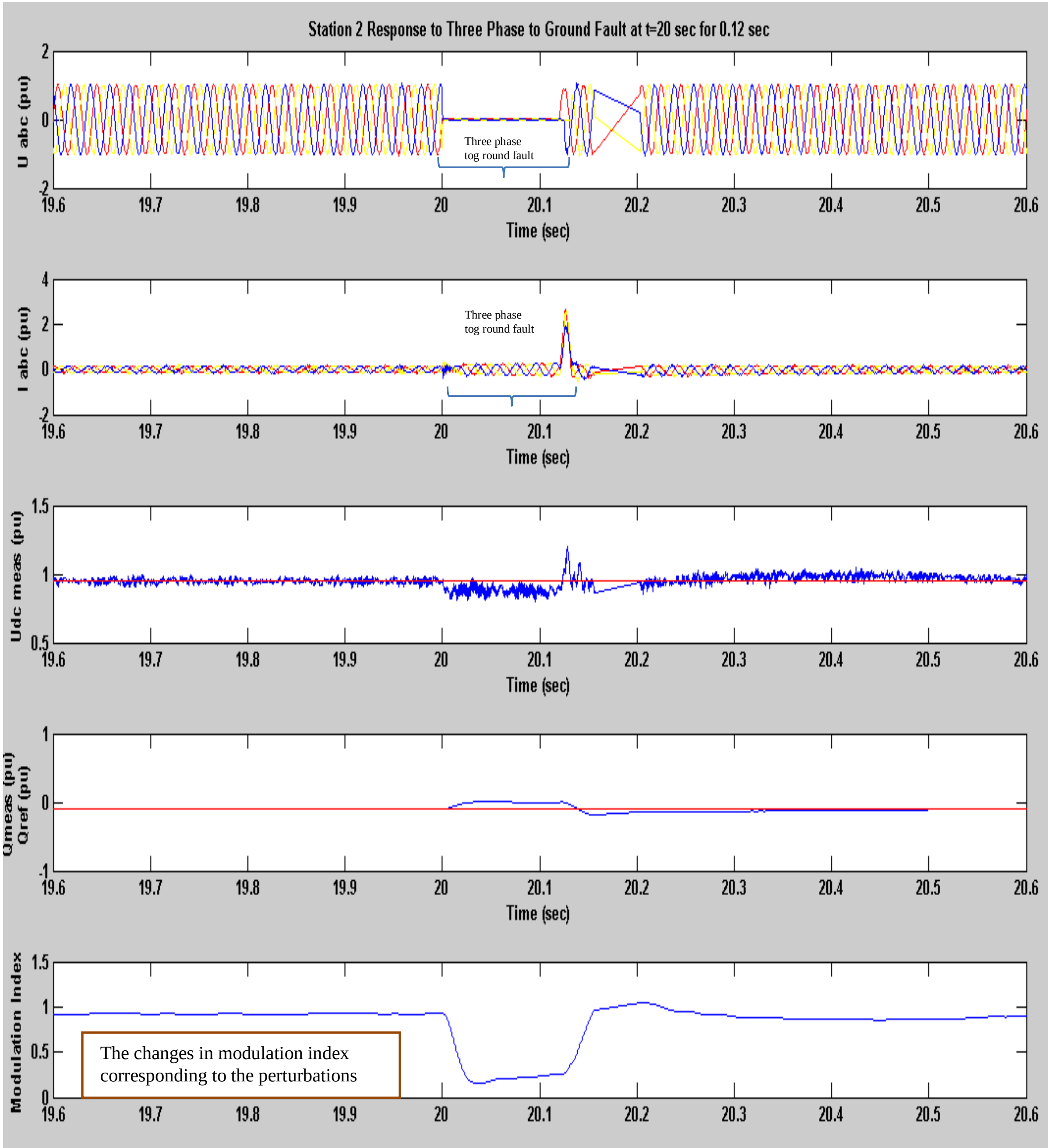


Fig. 6-18: Dynamic Behavior of Station 2 when subjected to Three Phase to Ground Fault at AC System 2

This concludes that HVDC model responds rapidly to changes in reference active, reactive power and DC voltage. When subjected to AC side perturbations (AC voltage sag and three phase faults), the HVDC controllers respond adequately. Hence, this model can be used in all-in-one system between Bus 3-5 parallel to the transmission Line 3-5 (see Fig. 6-4).

6.4. Implementation of VSC-HVDC in All-in-One System

The VSC-HVDC model proposed in the previous section was implemented in all-in-one system between Bus3 and Bus 5 i.e. parallel to transmission line 3-5 (see Fig. 6-4). The overall high level block diagram of the all-in-one system with implementation of VSC-HVDC is shown in Fig. 6-19

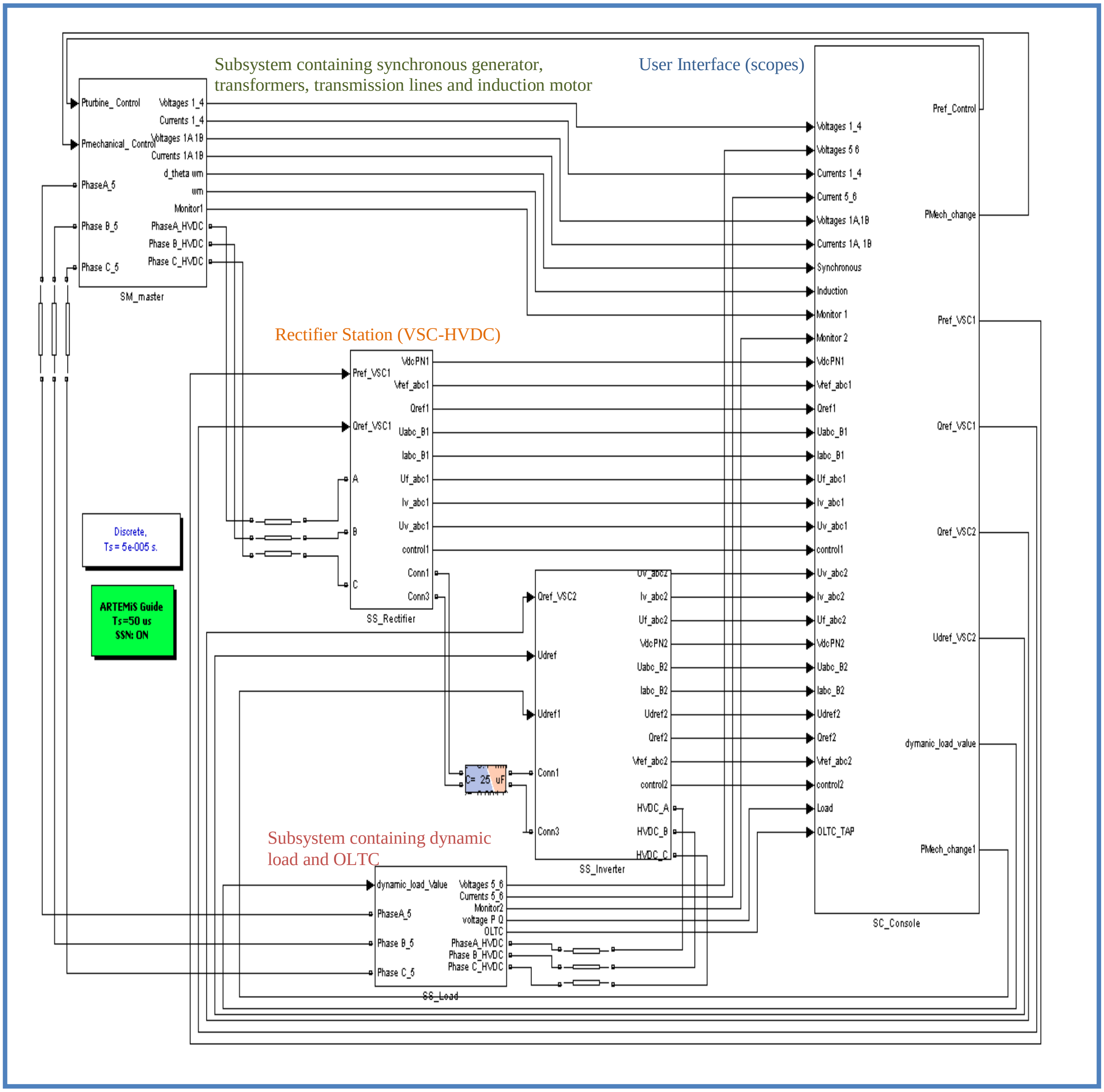


Fig. 6-19: High Level Block diagram showing different subsystems in all-in-one model after implementation of VSC-HVDC

Due to the addition of VSC-HVDC model, there were large numbers of switches in the network as a result the State Space Nodal (SSN) technique gave errors. So in order to decrease the number of switches, the taps of the OLTC are reduced from (+-16) to (+-2). We repeated the whole simulations with and without HVDC for this case in presence of protection relays, HVDC and lower tap OLTC. These cases are discussed in detail in the next section.

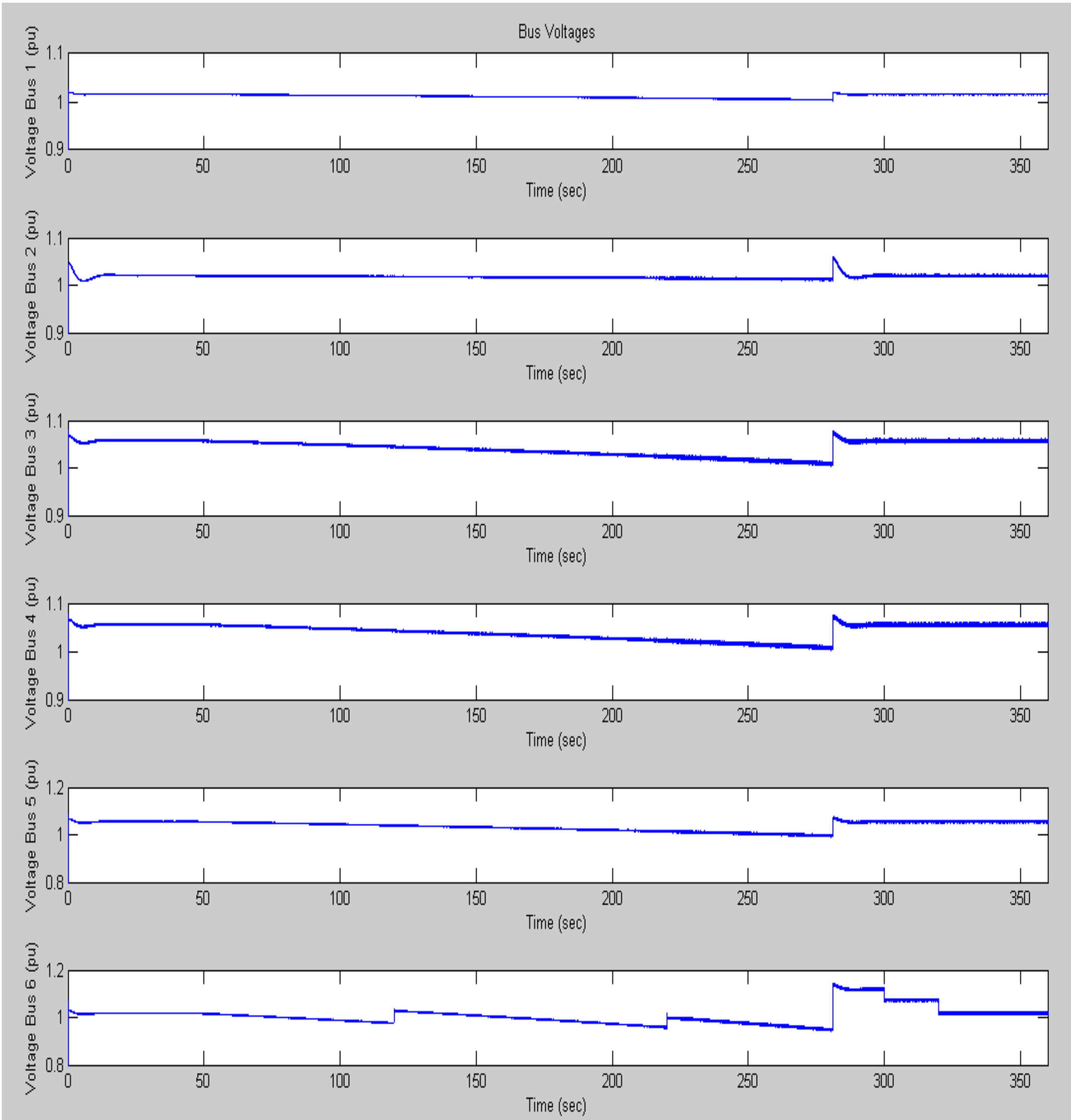


Fig. 6-20: Bus Voltages

The plots of the bus voltages show that the voltage collapse scenario (i.e. continuous increment of the reactive power consumption of load) is initiated at t=60 sec. This increase in reactive power demand degrades the voltage at Bus 6. The OLTC changes its tap at t= 120sec and then at t=220 sec to maintain the bus voltage equal to the pre-disturbance state. But as the reactive power demand further increases, the constant load power increases its current demand which causes the overcurrent relay to pick up the fault and trip the incremental load at t=280 sec. As the incremental load is disconnected at this stage, the voltage goes above reference voltage (because the OLTC is at tap = - 2). The OLTC detects that the Voltage is above reference voltage and shifts its tap at t = 300sec and then again at t = 320 sec to bring the voltage back to the reference level.

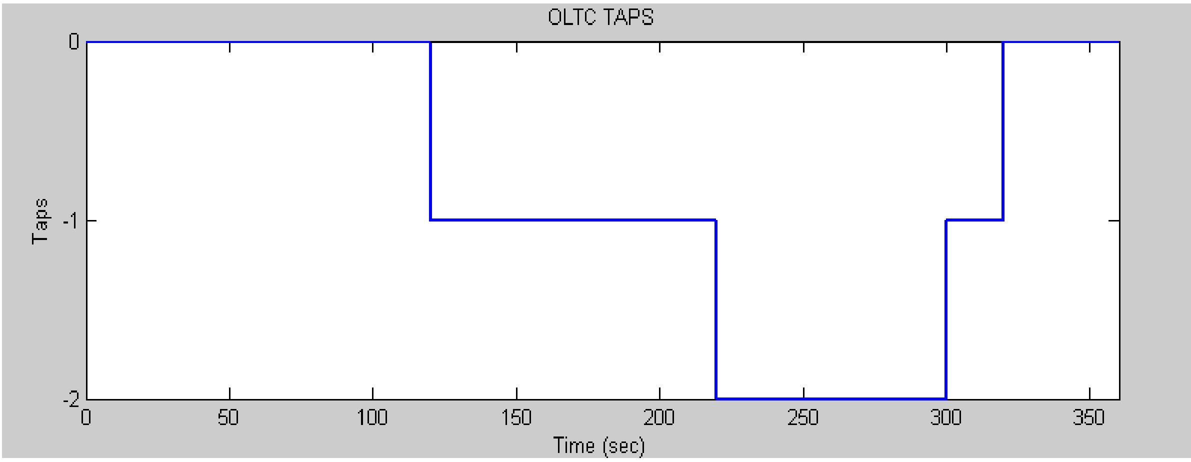


Fig. 6-21: OLTC Tap Positions

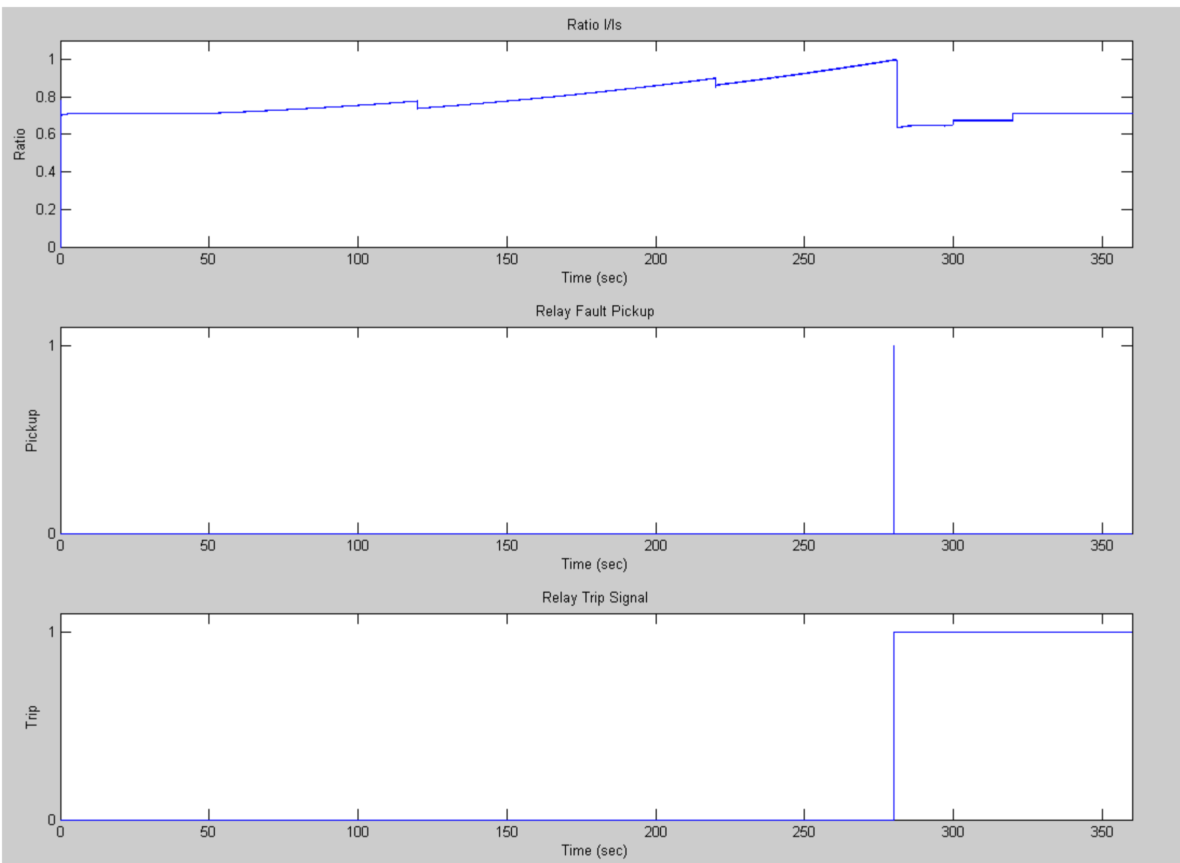


Fig. 6-22: Over-Current Relay Plots

It can be noticed that the waveforms of the voltages are not perfectly smooth. This is because of the presence of the power electronic switching devices. At this very moment the HVDC is blocked. But as soon as the HVDC is de-blocked, the waveforms get distorted. It may be due to the case of over-runs in the system or due to the tuning of the filters. In stand-alone, the HVDC was connected between two strong grids, however in this case the HVDC is connected in the middle of the single generator system. Another case which can be checked is to increase the step size from 50 micro to 100 micro seconds and check whether the distortions are still there or not. It was the same case even with the STATCOM and the SVC. To complete the main study in this report, a simple approach for reactive power compensation was applied. This is discussed in next section.

6.5. Reactive Power Compensation Devices as Alternative of VSC-HVDC

As discussed earlier, this study considered the implementation of a VSC-HVDC in All-in-One system and to simulate it within the voltage collapse scenario. The aim was to analyze how the HVDC responds to provide reactive power support to minimize voltage collapse. However, due to issues with switching frequency and the filtering, the HVDC was creating severe disturbances (see Fig. 6-22) in the whole system. The VSC-HVDC is actually a combination of Static Synchronous Series Capacitor (SSSC, used to control the power flow and provides damping) and Static Synchronous Compensator (STATCOM). This scenario of voltage collapse initiates by increasing the reactive power demand and the active power demand remains almost constant throughout the scenario. So in order to simplify the model, an alternative to the VSC-HVDC was considered in the form of a simple STATCOM[9].

With this purpose, a simplified reactive power support source was modeled using capacitors. As the capacitors actually inject reactive power into the system and provide voltage support, a controllable capacitor was modeled using the series connected load block available in SimPowerSystems Library (see Fig. 6-23)

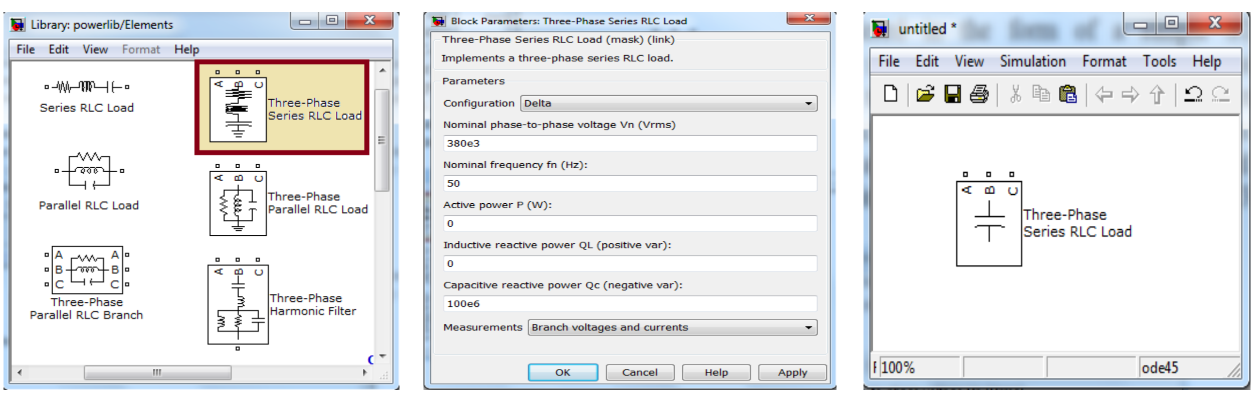


Fig. 6-23: Three phase series RLC load block available in SimPowerSystems library. The figure to the right shows only a capacitor as we have considered the active and inductive load equal to null.

[9] A controllable device which could provide reactive power compensation (i.e. voltage control).

Reactive power compensation can be supplied by adding such capacitors in series with different ratings (Mvar) and switch on the capacitors when the voltage degrades. These capacitors will inject capacitive current (reactive power) and will try to regulate the voltage at the bus. Fig. 6-24 shows the series of capacitors which are connected with three phase breakers to couple or decouple the capacitors in the power system model.

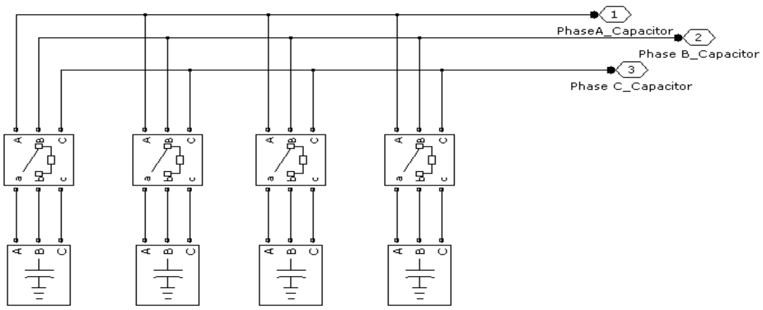


Fig. 6-24: Capacitors connected together to provide reactive power support

The overall model of all-in-one system after the addition of capacitors is shown in Fig. 6-25

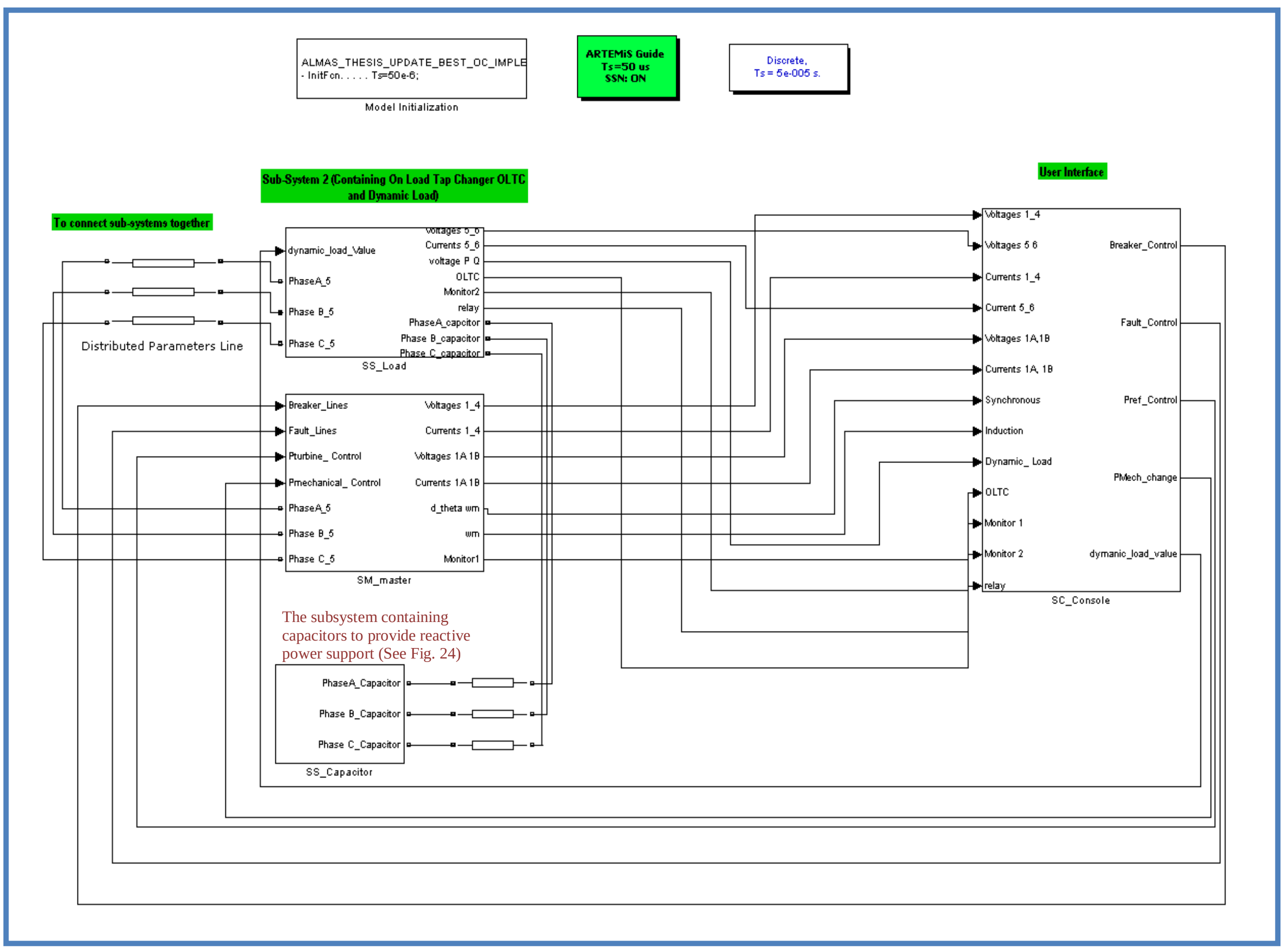


Fig. 6-25: All-in-one System with the addition of Controllable Capacitors as Reactive Power Support

6.5.1. All-in-One Model Analysis In Presence of Reactive Power Compensation Device (Block Mode)

As the topology of the system is changed, also the connection between new subsystem SS_Capacitor and SS_Load is made through a distributed parameters transmission line, therefore it will have a small effect on the overall power system. So we carry out the simulations again. These simulations result will then be compared with the results from switching the capacitors into the network to provide the reactive power support.

As these simulations are replica of the case described in the precious sections, so only waveforms are shown in Figure 6-26 to Figure 6-33. The voltage collapse scenario is initiated at t=60 sec.

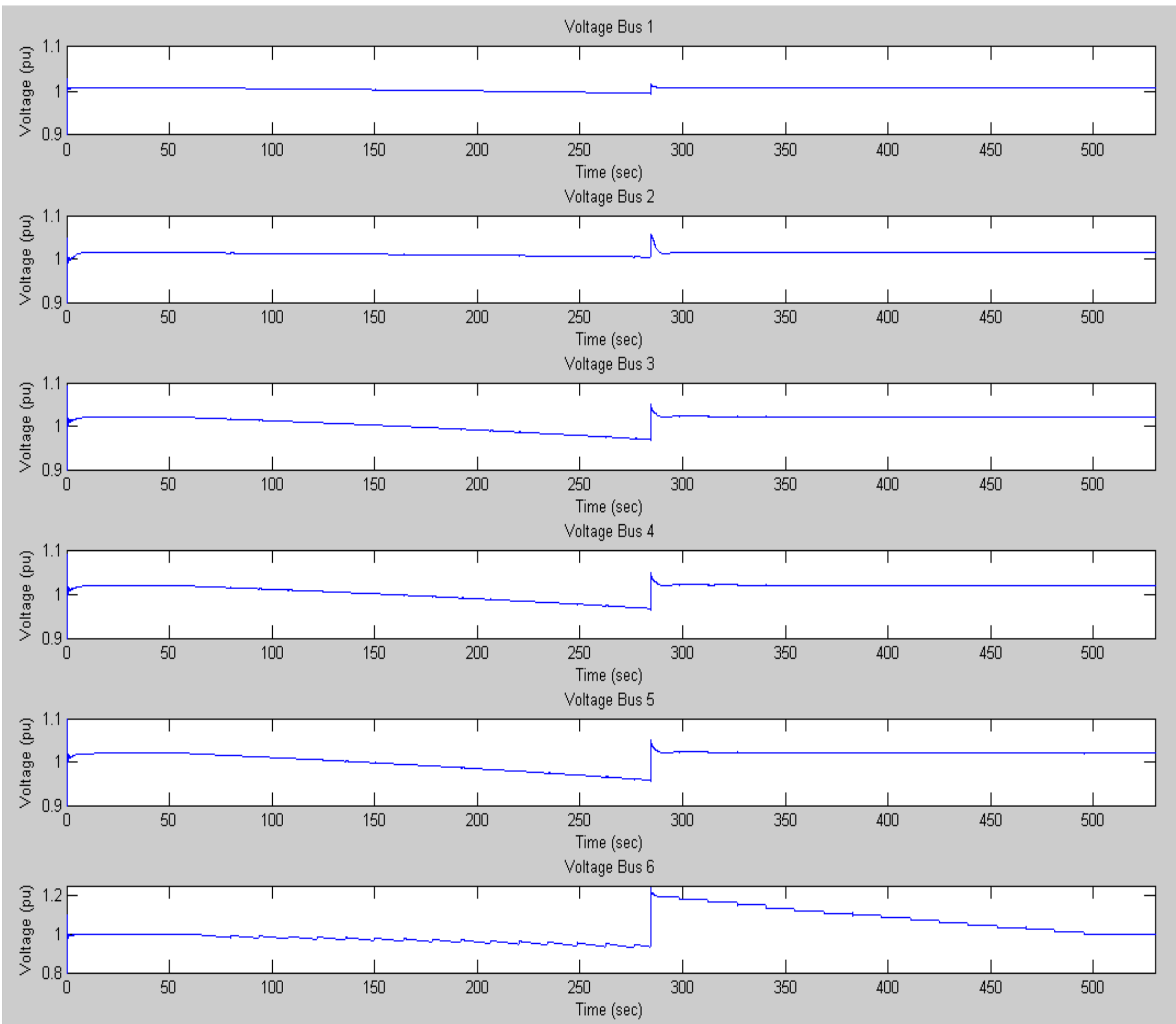


Fig. 6-26: Voltages at the Buses

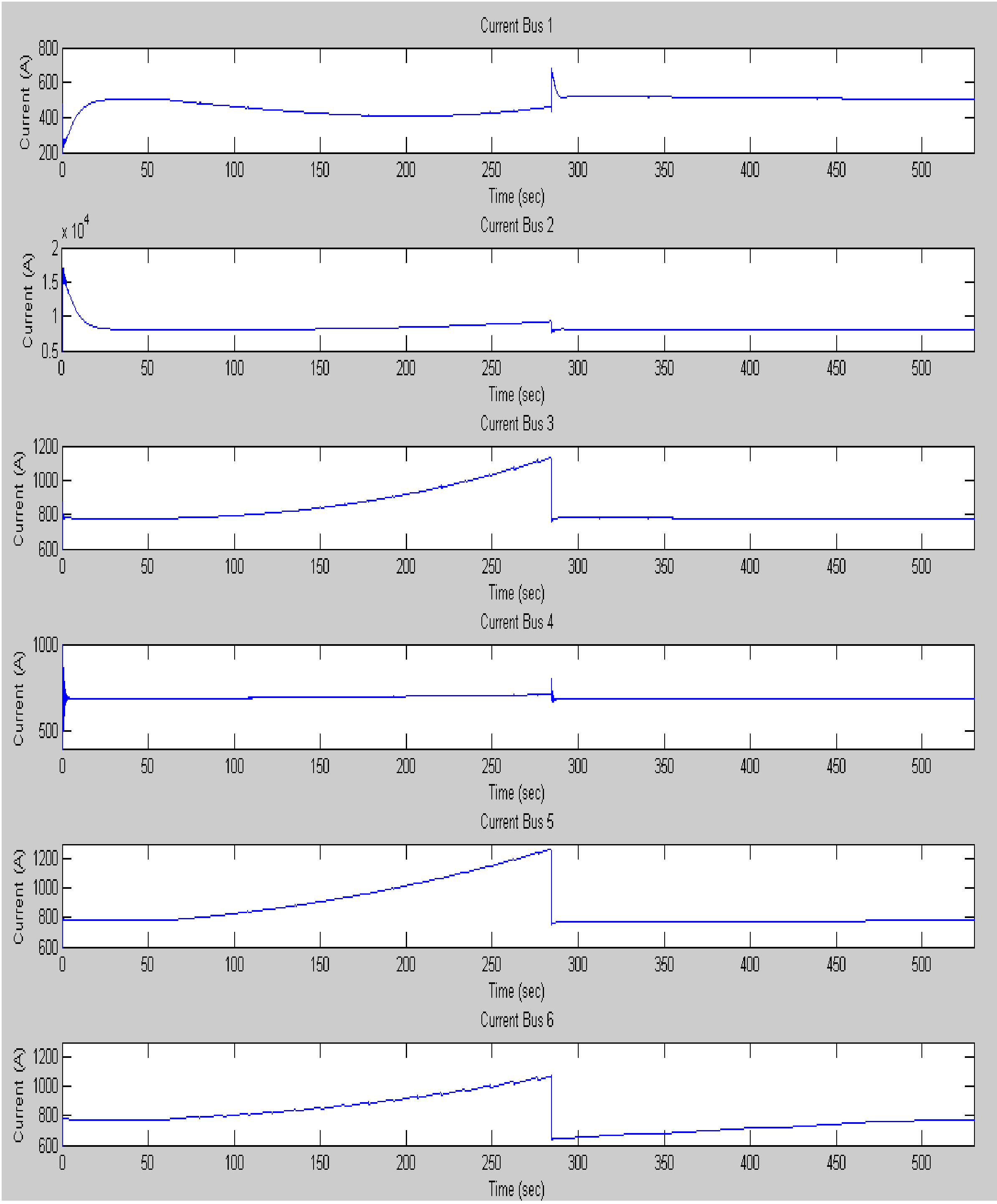


Fig. 6-27: Currents at the Buses

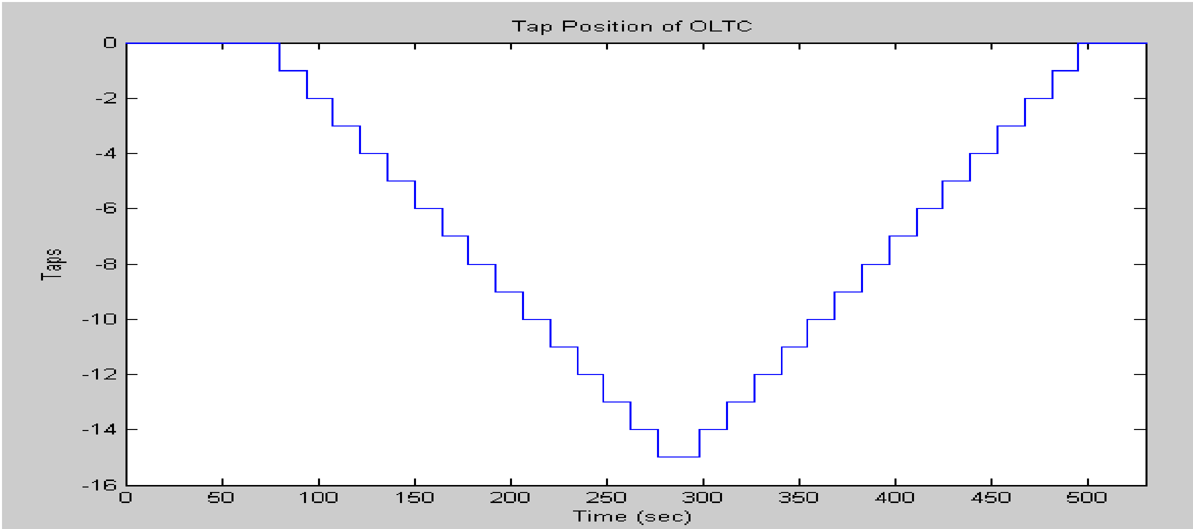


Fig. 6-28: Tap Position of the OLTC

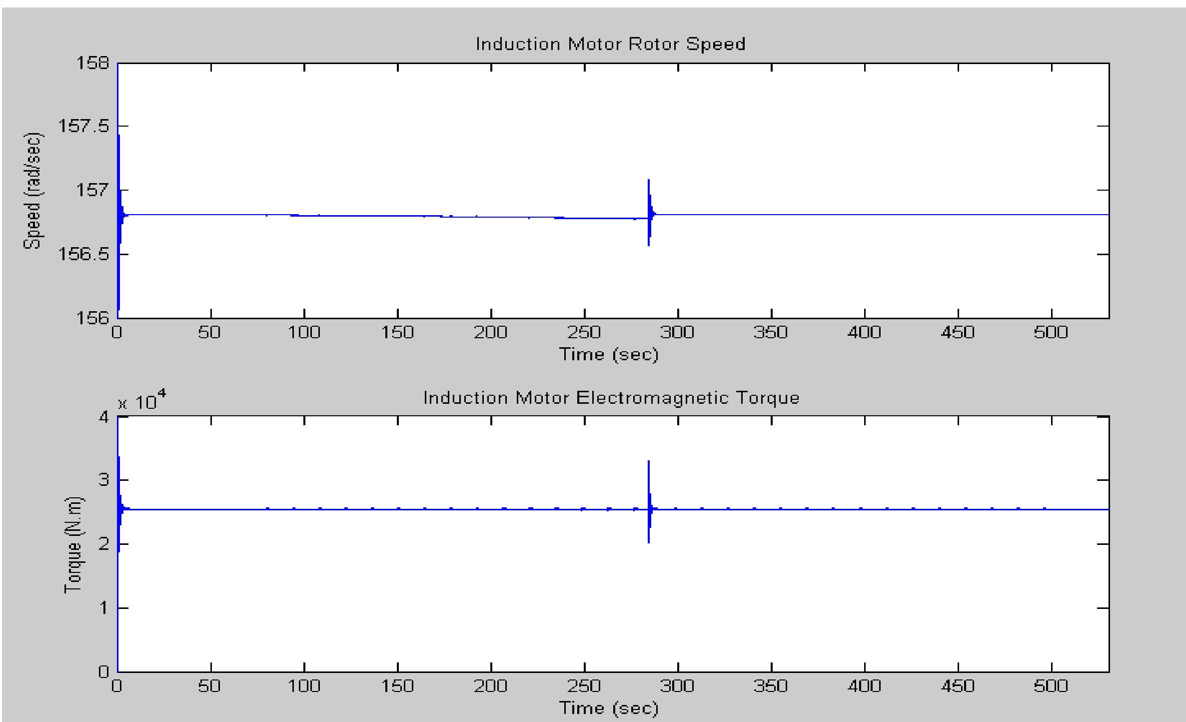


Fig. 6-29: Induction Motor

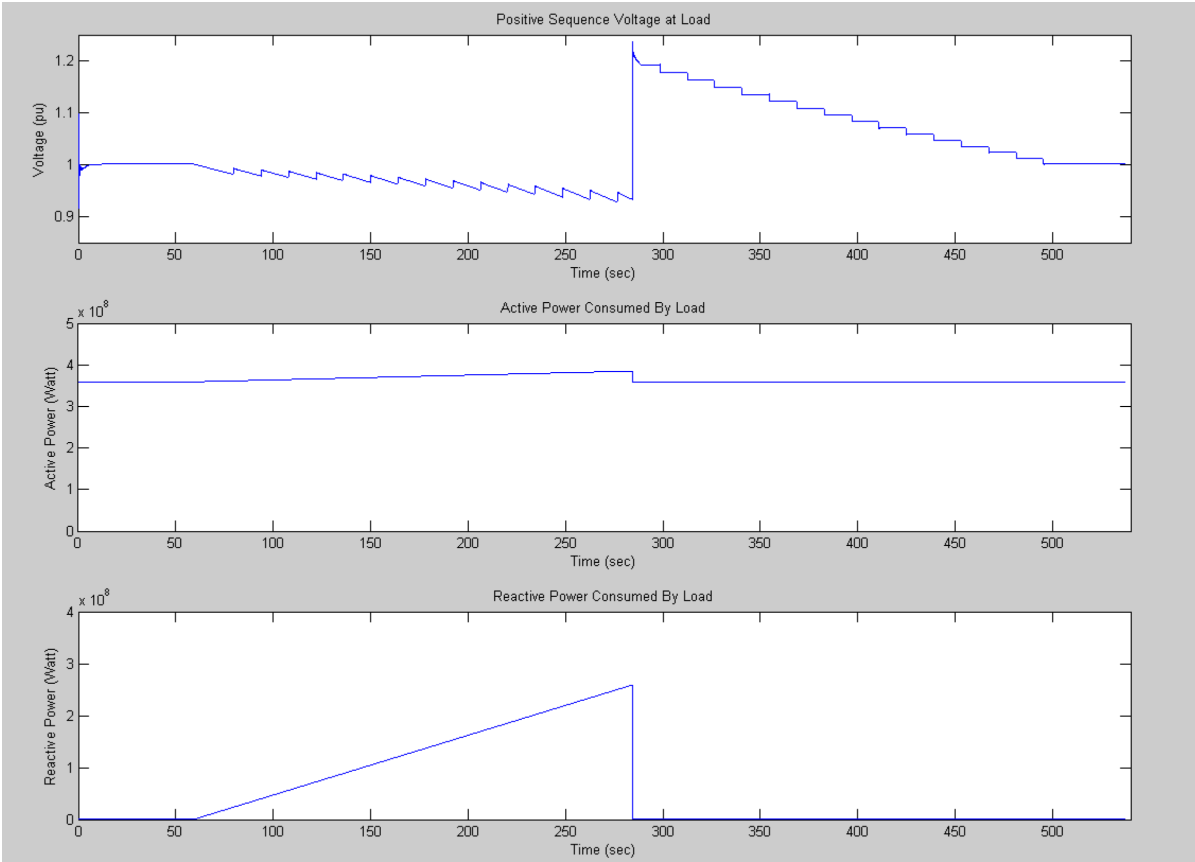


Fig. 6-30: Three phase dynamic equivalent load states

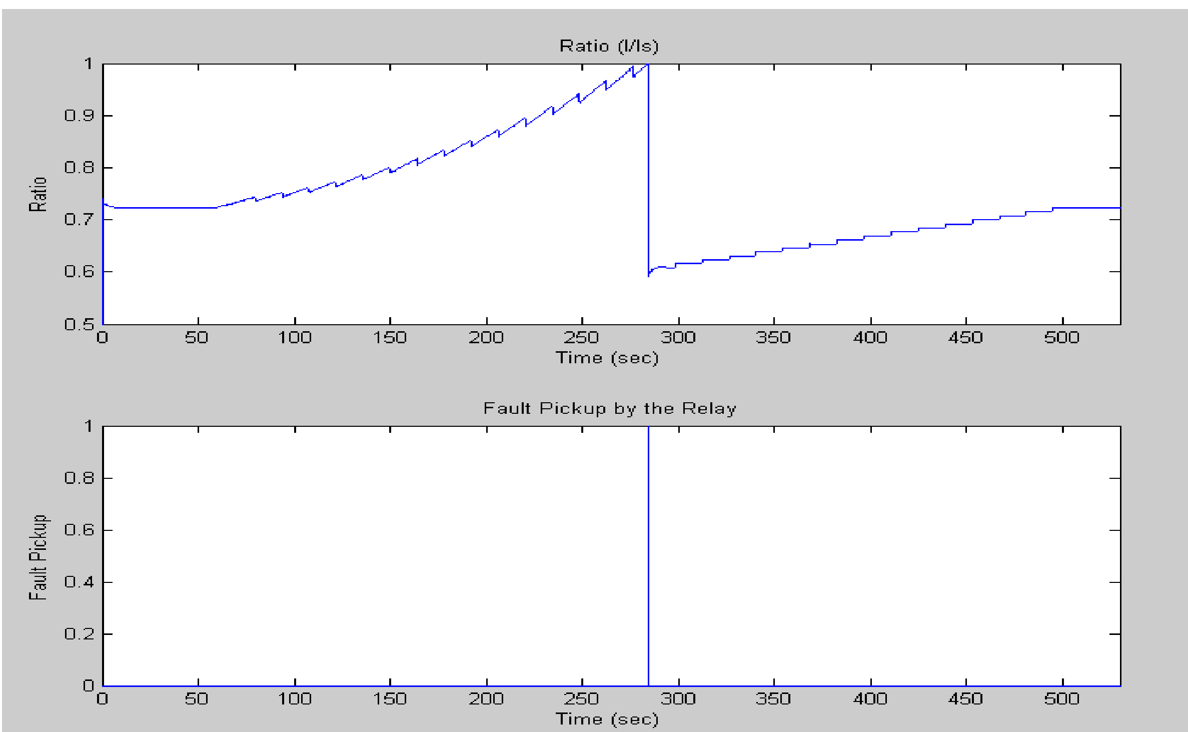


Fig. 6-31: Over Current Relay

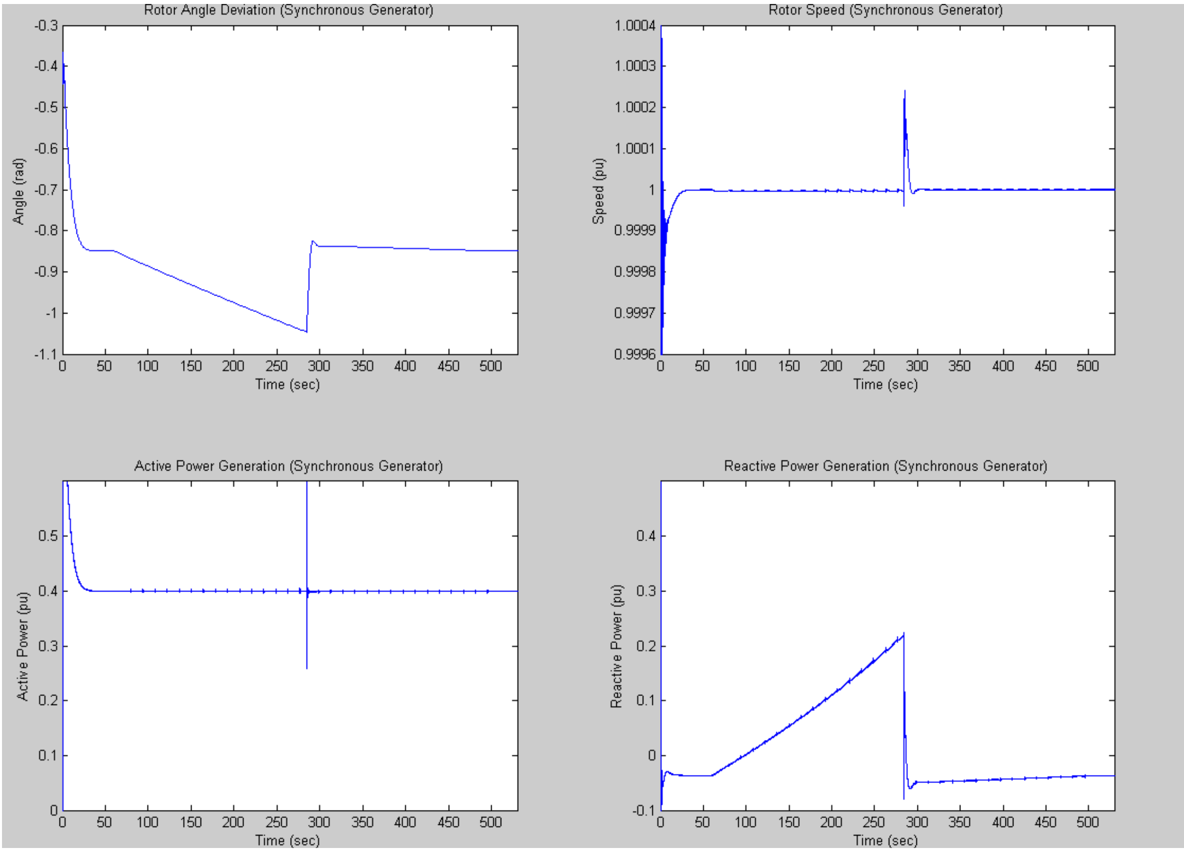


Fig. 6-32: Synchronous Generator

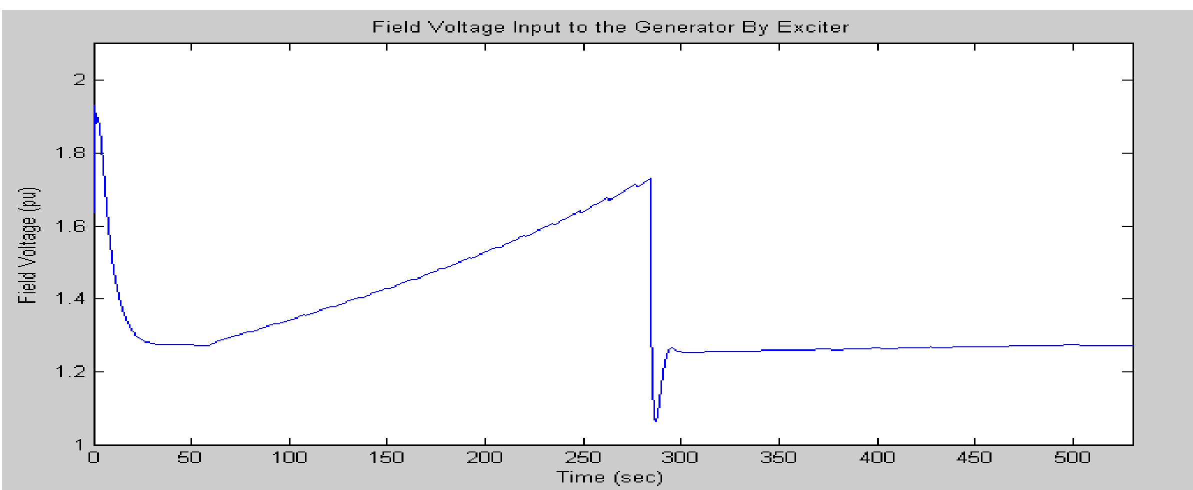


Fig. 6-33: Field Voltage Supplied by the Excitation System to the Synchronous Generator

The relay at Bus 6 picks up the fault and generates a trip command instantaneously at t=284.5 sec. This trip command is used to disconnect the continuously incremental load and thus it avoids the voltage collapse. The system gets back to the pre-disturbance state.

6.5.2. <u>All-in-One Model Analysis In Presence of Reactive Power Compensation Device (Active Mode)</u>

Now that we have the whole voltage collapse scenario in which the trip signal is generated at t= 284.5 sec, we will implement a 2 MVar Capacitor (Reactive Power Support) to this model at Bus 6 and evaluate if the tripping time increases. Hence, the aim is to determine if we can have an extra time which can be used to carry out System Integrity Protection Scheme (SIPS). As soon as the voltage reaches 0.95 p.u. at the load bus (Bus 6), the capacitor is connected, injecting reactive power to stabilize the voltage. The aim is to stretch the limits of the system without losing the load and delay the system collapse. This is only test case, thus a capacitor of 2 MVar is used. In the later section, during optimization of the model, the capacitor with different MVar will be used to provide a perfect solution to this particular voltage collapse.

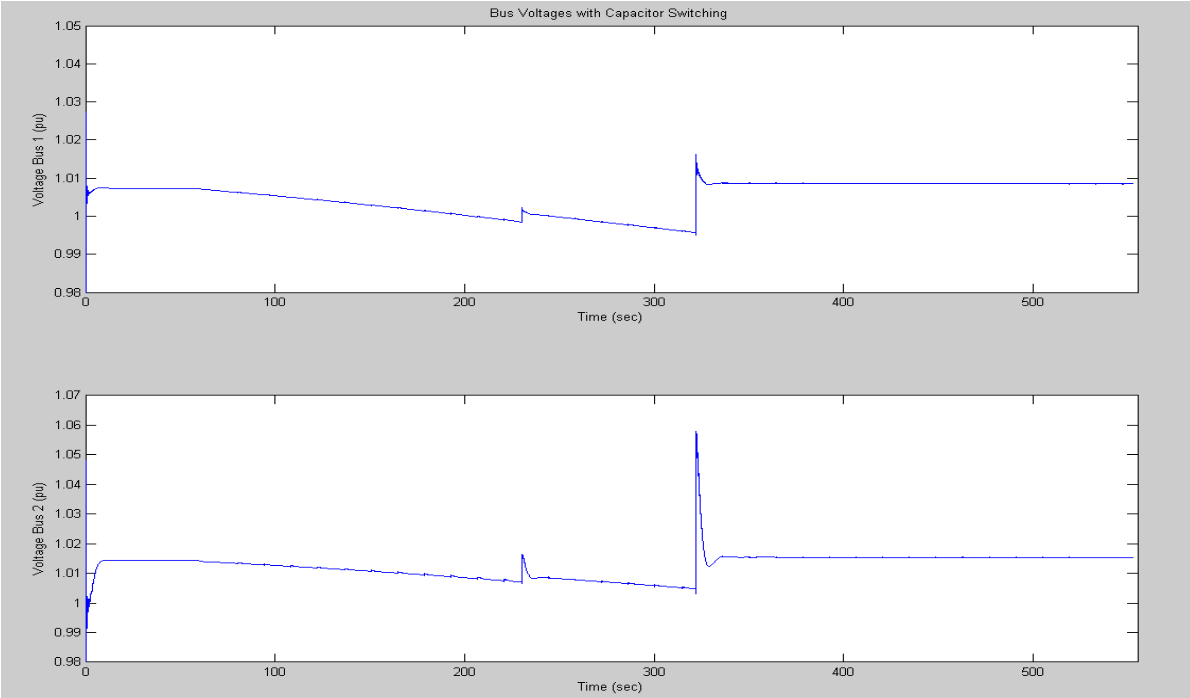


Fig. 6-34: Voltages at Bus 1 and Bus 2 (Capacitor Switching at t=230sec)

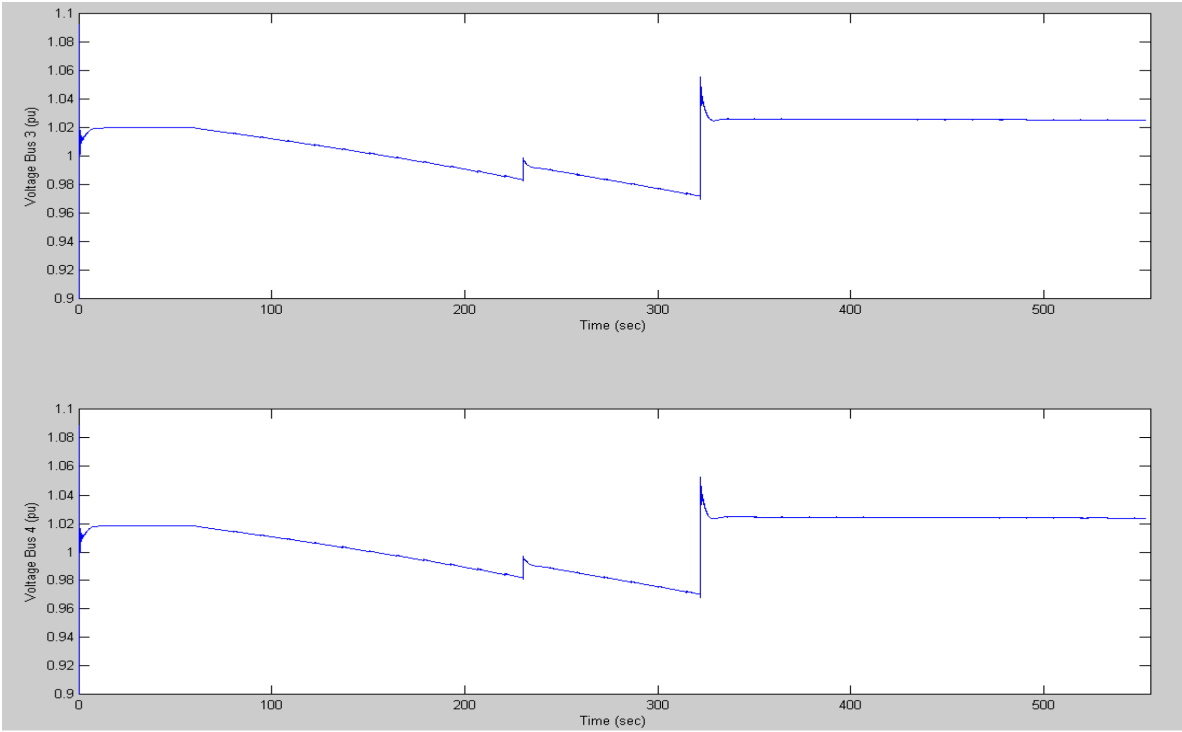


Fig. 6-35: Voltages at Bus 3 and Bus 4 (Capacitor Switching at t=230sec)

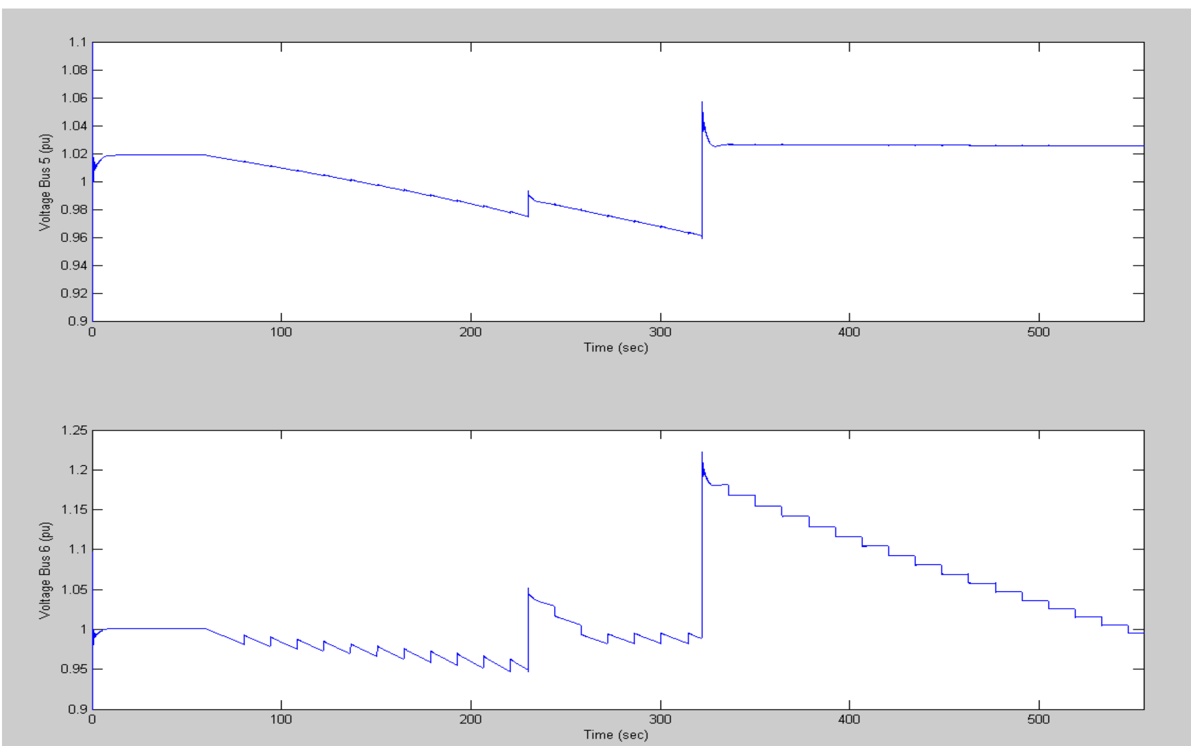


Fig. 6-36: Voltages at Bus 5 and Bus 6 (Capacitor Switching at t=230sec)

The voltage scenario is initiated at t= 60 sec. The voltage at Bus 6 starts to degrade and the OLTC changes its tap to keep the voltage to the reference (1 pu) as shown in Figure

6-36. At t= 230 sec, the voltage at Bus 6 drops to 0.95 pu as shown in Figure 6-37. The 2 MVar capacitor is switched on to provide reactive power compensation. As a result the voltage at the Bus increases to 1.03 pu. The OLTC now changes its tap in reverse direction to bring the voltage down to 1 pu meanwhile the load is constantly demanding more and more reactive power. However at t=315 sec, the overcurrent relay operates and disconnects the load. As a result the voltage at the bus increases to 1.16 pu. The OLTC operates and brings the voltage back to 1 pu.

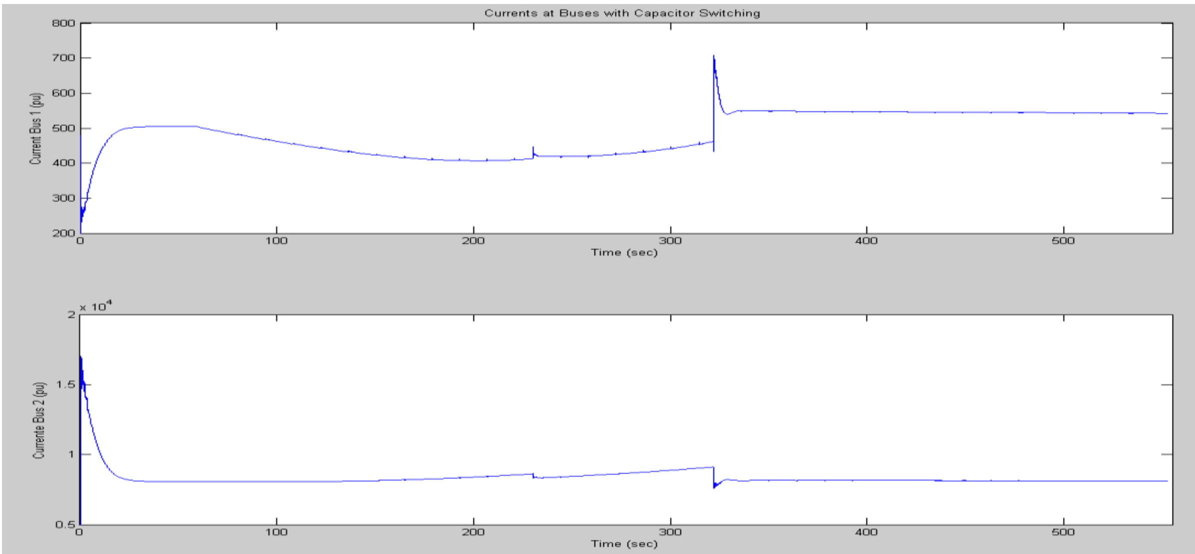


Fig. 6-37: Currents at Bus 1 and Bus 2 (Capacitor Switching at t=230sec)

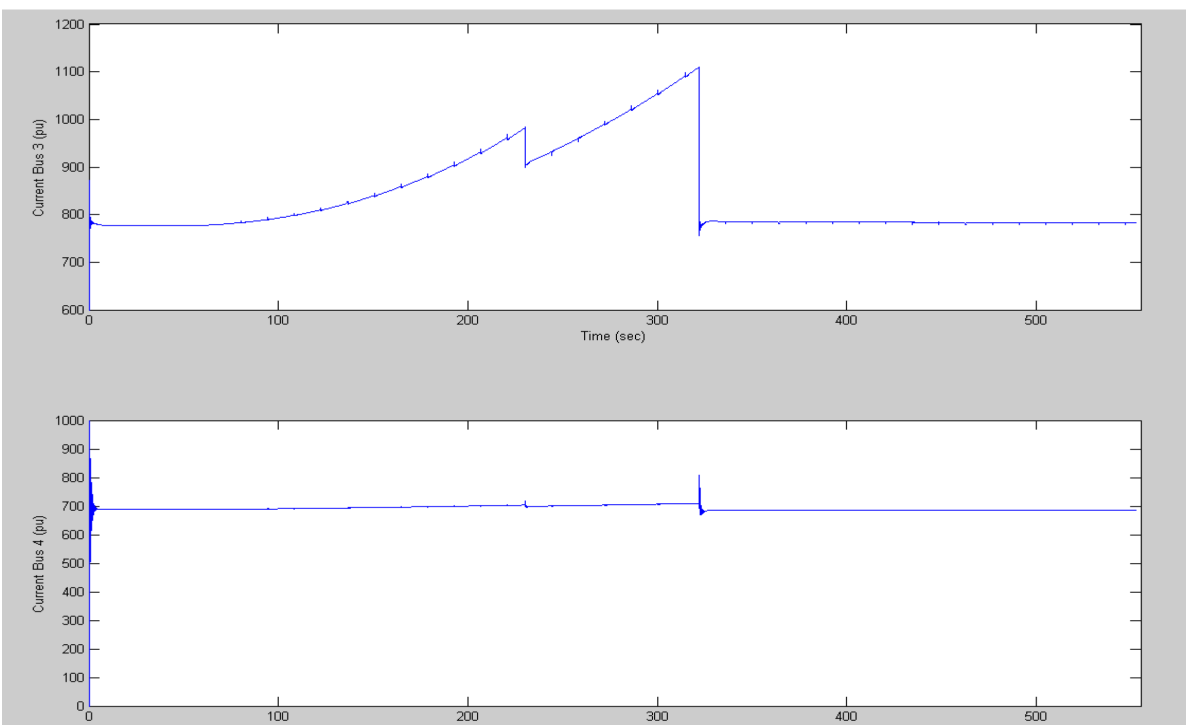


Fig. 6-38: Currents at Bus 3 and Bus 4 (Capacitor Switching at t=230sec)

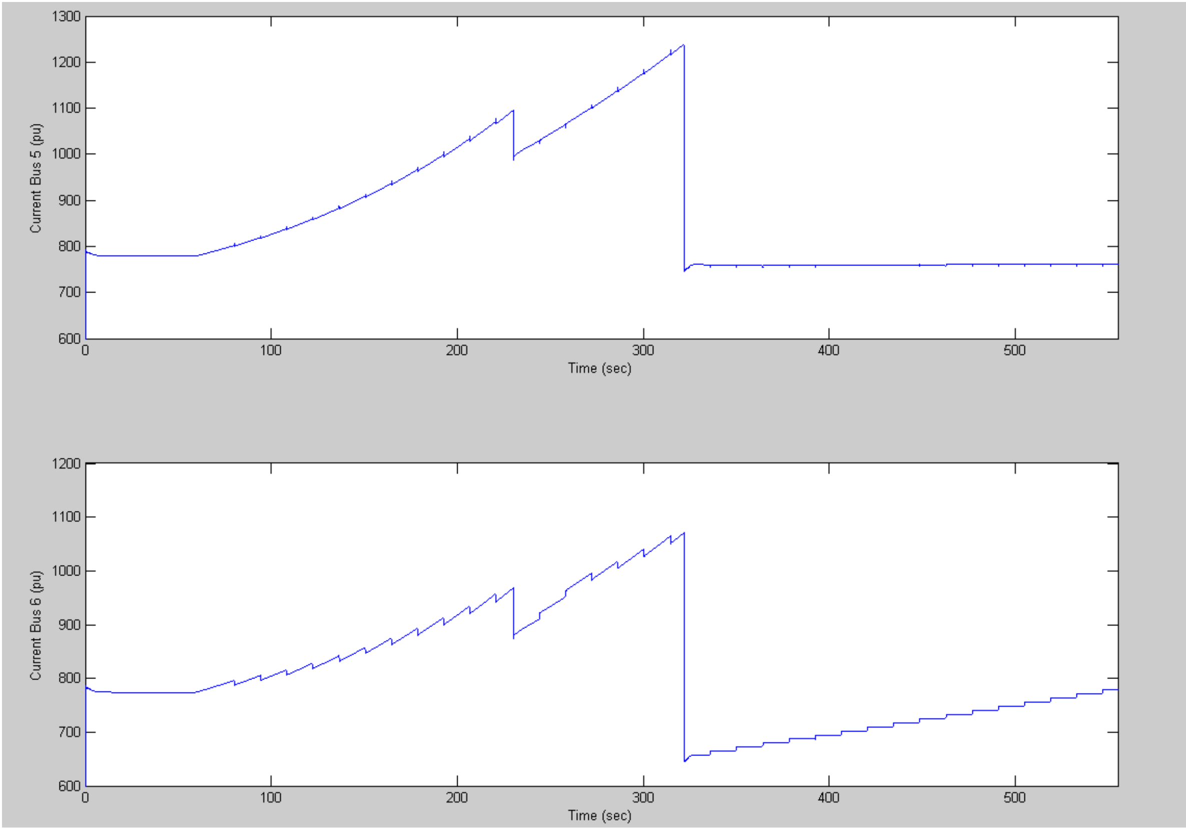


Fig. 6-39: Currents at Bus 5 and Bus 6 (Capacitor Switching at t=230sec)

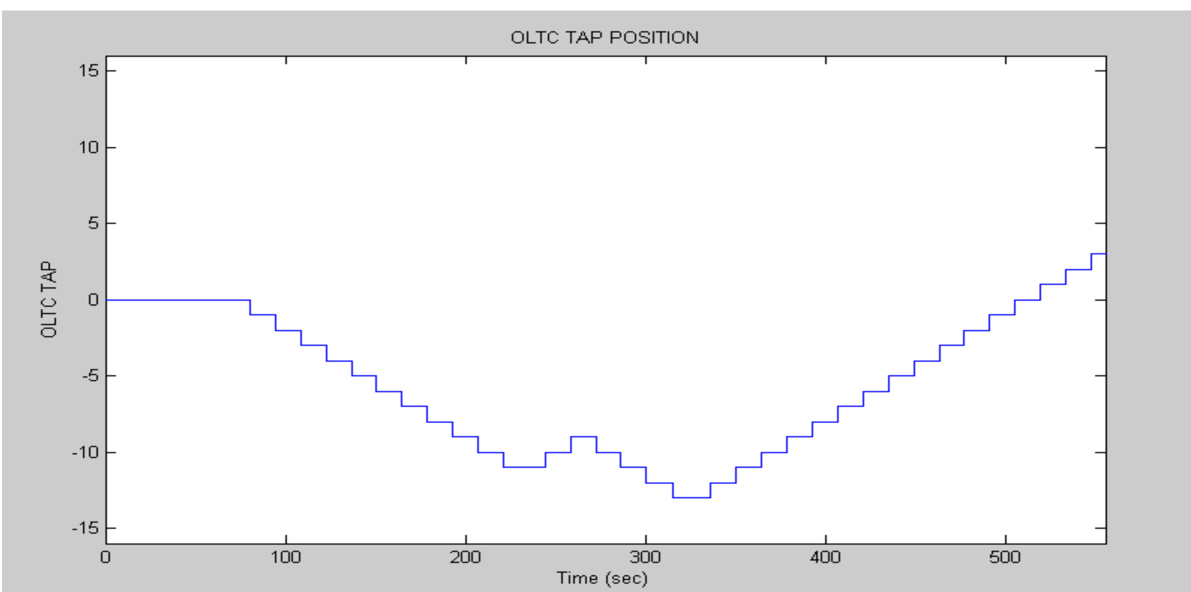


Fig. 6-40: Tap Position of OLTC

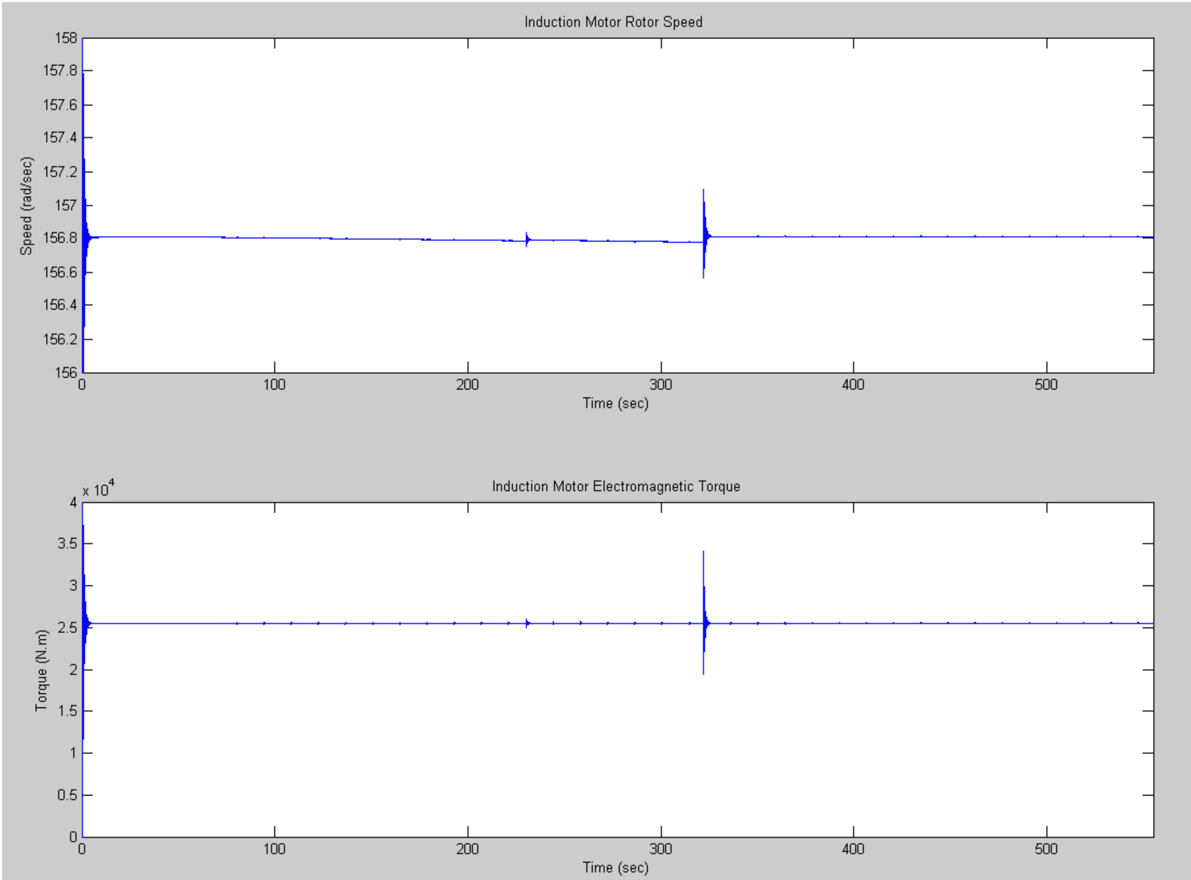


Fig. 6-41: Induction Motor

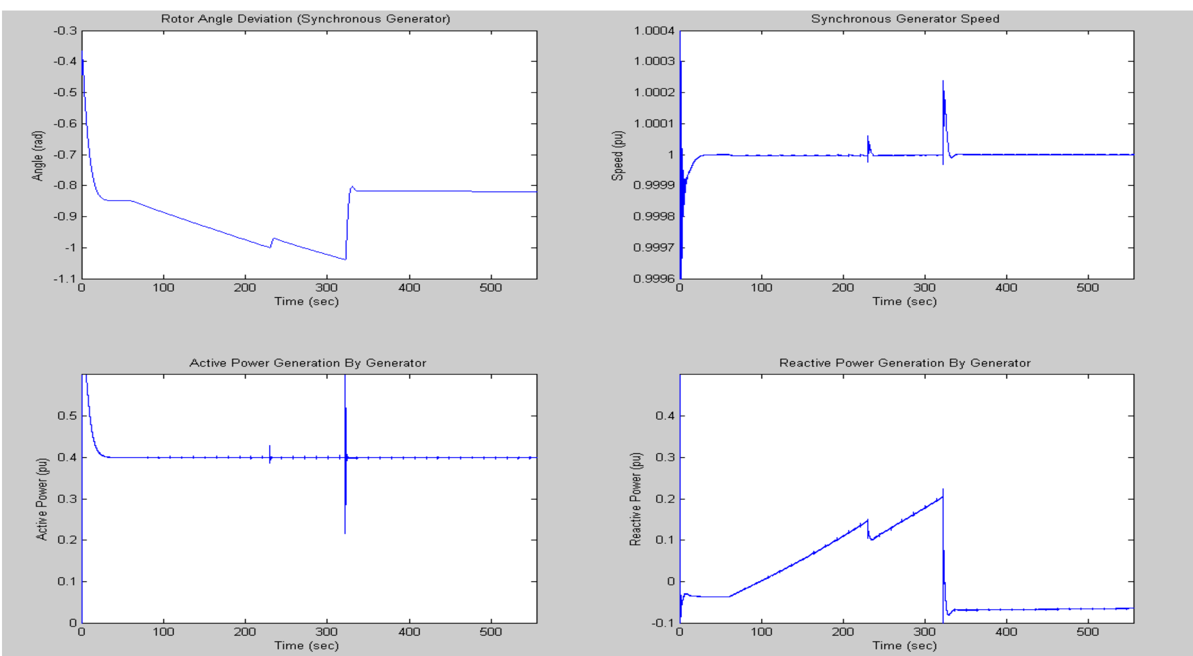


Fig. 6-42: Synchronous Generator

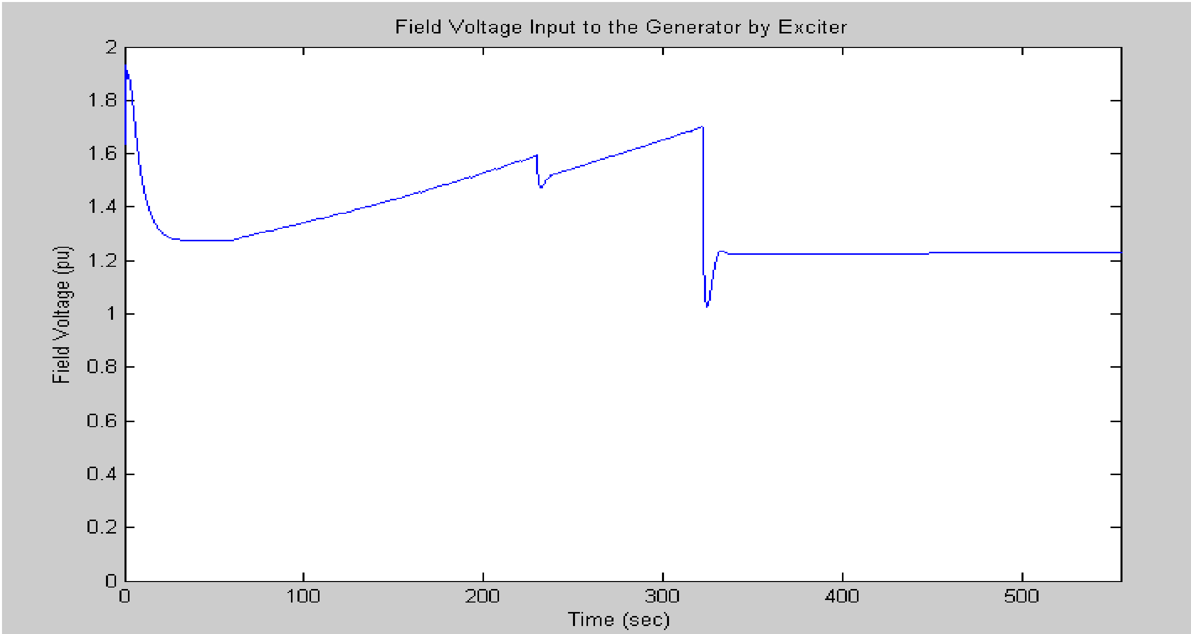


Fig. 6-43: Field Voltage Supplied by the Excitation System to the Synchronous Generator

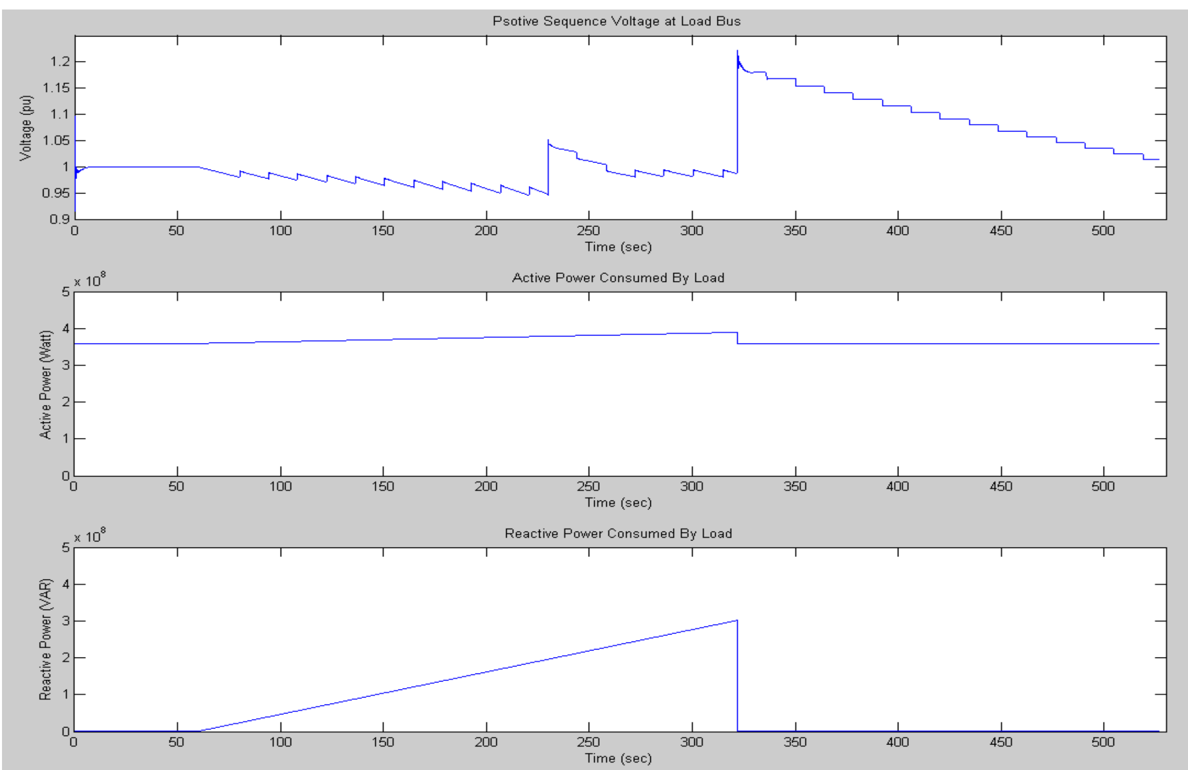


Fig. 6-44: Three phase dynamic equivalent load

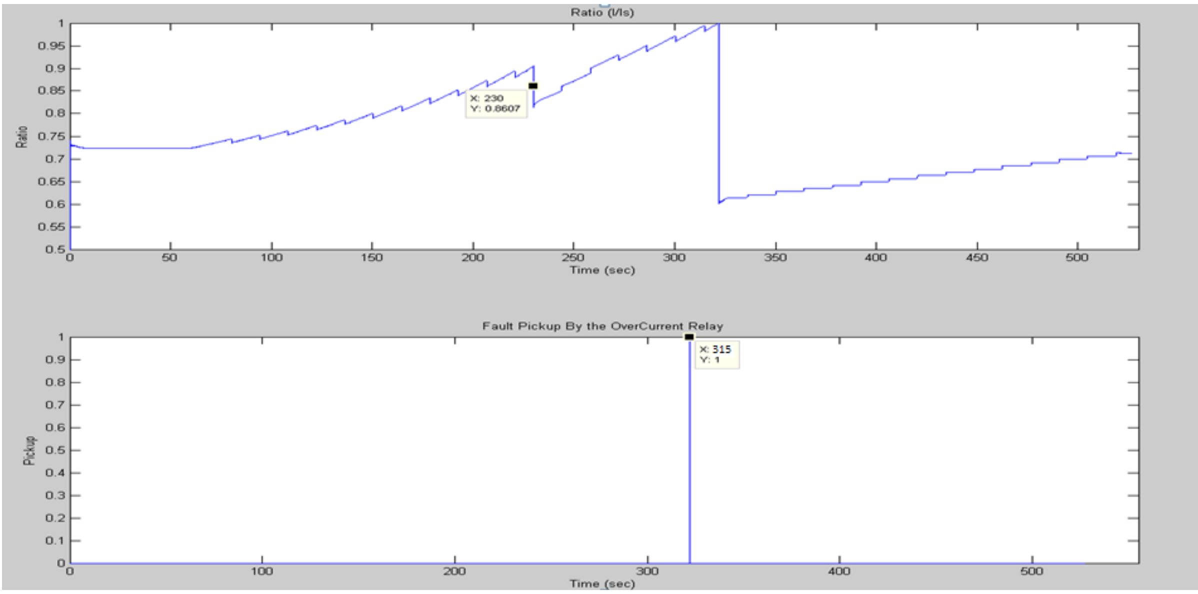


Fig. 6-45: Over Current Relay

The plot in Fig. 6-45 shows that the ratio (I/Is) drops at t=230, because the capacitor (2MVar) is switched in at this time. This increases the voltage at the bus and, as the load is constant power, so current reduces and so does the ratio (I/Is). Finally at t=315 sec, the relay operates and disconnects the load.

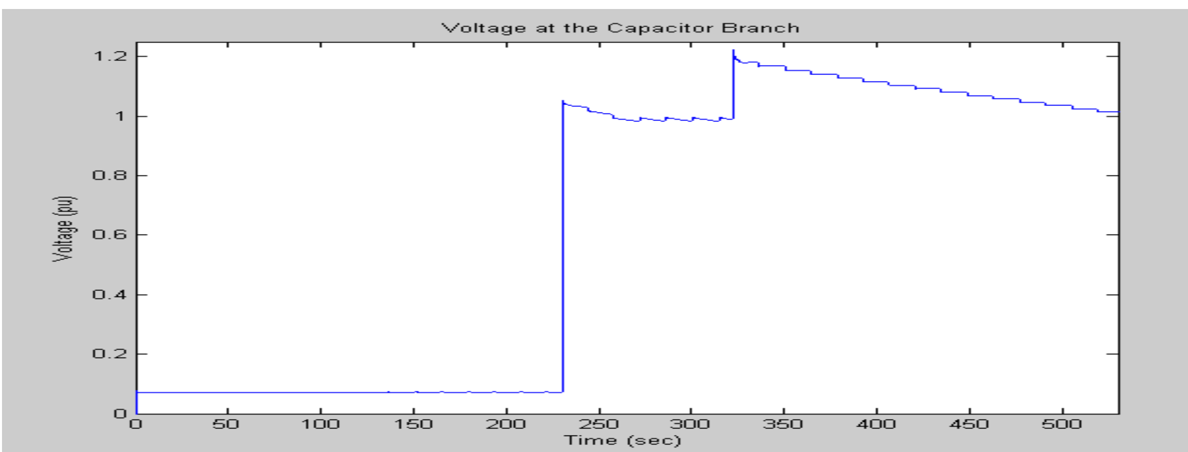


Fig. 6-46: Voltage at the Capacitor Branch

Figure 6-46 shows the voltage at the capacitor branch. Before t=230 sec, the capacitor was not connected so the voltage at his branch is close to 0. As soon as the capacitor is connected at t=230 sec, it increases the voltage at Bus 6 by injecting current which is shown in the plot below.

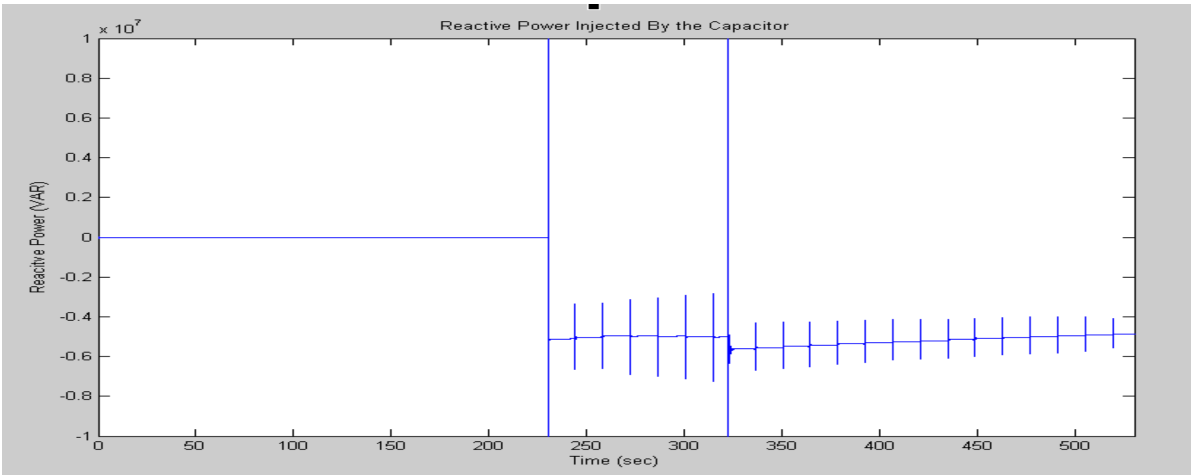


Fig. 6-47: Reactive Power Injection by the Capacitor

Figure 6-47 shows the reactive power injected by the Capacitor branch. Before t=230 sec, the capacitor was not connected so the reactive power injected is 0. As soon as the capacitor is connected at t=230 sec, the capacitor injects reactive power. The first spike is at t=230 sec due to the switching in of the capacitor. The second spike is at t=315 sec when the relay detects the fault and disconnects the load. The small notches are because of OLTC operation

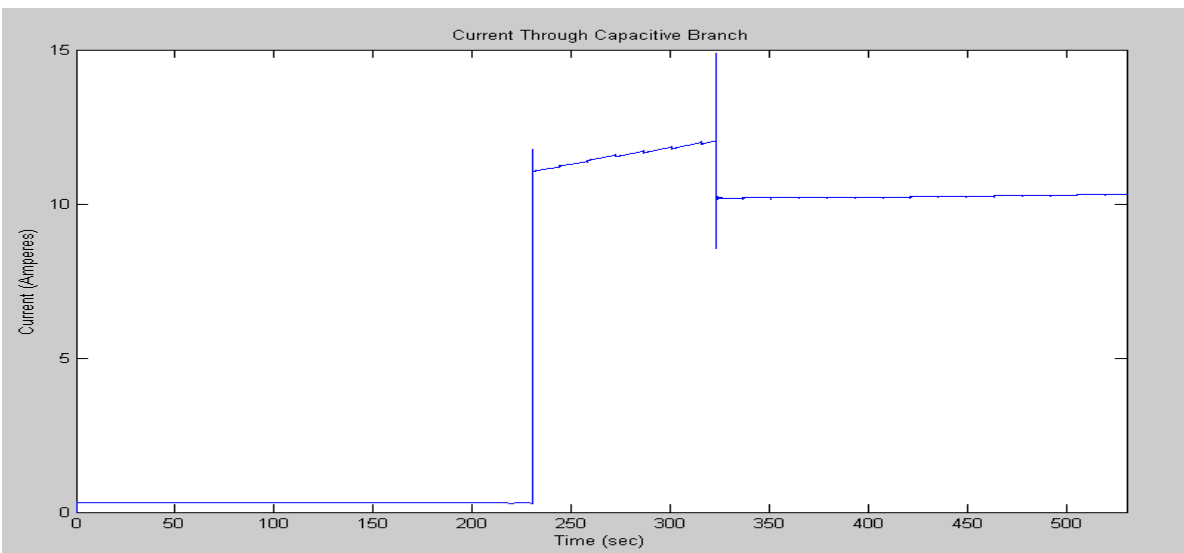


Fig. 6-48: Current through the Capacitive Branch

6.6. Comparison of Results of Active and Block Mode Operation of Reactive Power Compensation Device

Without the capacitor switching, the relay disconnected the load at t=284.2 sec. However with a 2MVar reactive power support with the aid of capacitor switching, the relay disconnects the load at t=315 sec. The load is fed and the limits of the system are stretched for another 30 sec before the loss of load or voltage collapse. In the next section the optimization of the model is carried out by using voltage indexes computed from PMU data. The aim is to develop an optimized model which can sustain voltage collapse or if it cannot avoid a collapse then at least give a certain time to the operators to activate the System Integrity Protection Schemes (SIPs) or Remedial Action Schemes (RASs).

6.7. Chapter Summary

The chapter involves modeling of VSC-HVDC and reactive power compensation devices in SimPowerSystems (MATLAB/Simulink) and their implementation in the All-in-One system. The system response is analyzed for voltage instability. The results are compared with the system without reactive power compensation devices. The detail of the coordination between reactive power compensation devices and protective relays is also discussed. The results prove that with reactive power compensation, the system can survivve a longer period in the case of voltage instability.

Chapter 7: PMU-Assisted Optimization of the Coordination between Protective Relays and Reactive Power Compensation Devices

7.1. Introduction

In the previous sections, it is shown how the all-in-one system was modeled, then incorporated with protection devices and finally implementation of reactive power compensation device in the system. The results were analyzed in the previous section.

In this chapter, an optimized scheme for the all-in-on system is presented taking into account the minimum operation of OLTC, maximum power delivery to the load, maximizing the time to voltage collapse by coordinating the protective relays and reactive power compensation devices. This is achieved by using phasors from synchronized phasor measurement units to determine the most recent values of positive sequence voltages and currents in several critical devices. Using this knowledge in conjuction with information from protective relay settings allows for a local optimization of the system's response. The results are presented and discussed in detail.

Table of Figures

With an exponential increase in electric power demand, difficulties in obtaining permissions for the right of ways for building new overhead transmission lines, emphasizing more on the integration of renewable energy in the system, and the addition of power electronics equipment (FACTS and HVDC), the power system today has become a very complex network. As discussed earlier, a single fault, mal-operation of the devices or an operator's error can lead the power system towards a cascading failure. The overall responsibility of the power system operators is to maintain the reliable an efficient transmission of electric power from generation sites to the consumers at all time. The overall power system needs to be optimized, with respect to all the available resources, and then the power system should be operated at this optimum point. However, there can be large number of constraints in this problem, and defining an objective function which needs to be optimized.

7.2. Optimized Power System

An optimized power system is both reliable and economic. The system should be able to meet the load demands continuously and should keep the losses to their minimum [56]. In order to get an overall picture of the power system, the load flow studies, harmonic studies, short circuit studies, etc. are carried out with different power system configuration and then complex algorithm based on different techniques are used to find out the optimum operation point for the power system.

Power system operators try to reduce power losses and improve system security with minimum control actions [57], minimizing the load shedding in case of system collapse, optimal increase in reactive power support to compensate for the voltage instability etc. The power system planner on the other hand deal with optimization problems like minimizing cost expansion of the power system in which case not only the technical constraints come into play but also the social controversy [58].

7.2.1. Types of Optimization

In general, there are generally two types of optimization, as discussed below.

Local Optimization

When measurements are gathered from a single location to optimize operation, it is called local optimization. A power system consists of large number of devices but if a solution is to be provided for just taking into consideration the measurements and constraints from a single location, then only a local optimization of the devices near the measurements can be achieved.

Global Optimization

When measurements are gathered from several locations to optimize operation, it is called global optimization. A power system consists of large number of devices but if a solution is to be provided for taking into consideration measurements and constraints from a whole network then a global optimization may be achieved (in theory).

7.3. Voltage Stability Indices and their Application for Voltage Collapse Mitigation

As we have come up with a model of a power system which is subjected to a voltage collapse, one approach is to provide an optimum solution mitigating voltage collapse by exploring voltage indices. Voltage instability occurs due to inability of the combined generation and transmission systems to deliver the power demanded by loads [59]. This causes a decrease in the voltage at the buses. When this decrease is too much, the protection system (relays) operate and disconnects the faulty system from the healthy network. Sometimes protection system operation causes a cascaded failure which leads to blackout in the form of voltage collapse [60]. There are several voltage indices that use either the local measurements or the global measurements to serve as an indicator to voltage collapse proximity and which can be used to optimize the power system [61]. For the sake of example, two simple indices are discussed below.

7.3.1. Reactive Power Voltage Margin (QVM)

QVM is the minimum inductive load which is necessary to cause a voltage collapse under steady state power flow conditions. The mathematical computation of this index is made with the following equation;

$$QVM = Q_{Maximum} - Q_{Operating}$$

$Q_{Maximum}$= Maximum reactive power threshold at Bus j
$Q_{Operating}$= Measured reactive power at Bus j

Smaller the QVM, the more the system will be towards voltage collapse. At QVM = 0, the system is at the verge of collapse and even a smaller increase in reactive power demand will cause the system to collapse.

7.3.2. Incremental Reactive Power Cost (IRPC)

IRPC represents the reactive power which is needed by the reactive power sources to feed each additional MVAR at the Bus$_j$. It is given as:

$$IRPC_j = \sum_{k=1}^{n} \frac{\Delta Q_{genk}}{\Delta Q_{Busj}}$$

ΔQ_{genk}= Change in the kth generator reactive power output for a small change in reactive power load at bus j
ΔQ_{busj}= Reactive power load at Bus j
$n = \ number\ of\ reactive\ power\ sources$

The higher the IRPC, the more difficult it is to maintain the voltage at the bus when reactive load is increased. So larger the IRPC, the closer is the system towards collapse.

There are several other indicators which are used by the power system operators to predict the behavior of the power system. In theory, it could be possible to apply remedial strategies which can include adaptive protection i.e. changing the pickup values of the protection systems for some time so that they don’t trip the breaker even when the fault is detected. These schemes require very fast algorithm which can compute the status of the system accurately.

These indices can be used to block the OLTC operation to stop contributing to the voltage collapse. As OLTC is a mechanical device and the larger the Taps are operated, the lesser the expected life of the OLTC remains. One such scheme is discussed in the paper “Synchrophasor Based Power System Control and Protection Applications” [62].

7.4. PMU Assisted Coordination Approach

In this thesis, we are not computing any index for voltage instability detection. Instead, we propose using local measurements: voltages and currents from PMUs at different buses and the tap position information at the load bus to propose the optimum scheme. This scheme is able to consider load supply, protection relay operation and OLTC operation. The aim behind the scheme is that, it should support the maximum load, the OLTC operation should be minimum and the relay should have some adaptive setting to take into account the increased load demand.

The coordination of the reactive power compensation devices (switching capacitors) and protection relays is done in such a way that the relay uses locally computed phasor to perform a comparison and send a signal to the switching capacitor just before the current level becomes equal to the pickup value of the relay (overcurrent fault detection). As a result the capacitor provides reactive power support to safeguard the system from voltage collapse. The optimization is done by blocking the OLTC operation when noticing the trend of the voltage. If the capacitor are switched on and the voltage goes above 1.0 p.u., and the trend of voltage is still decreasing, then blocking the OLTC operation is carried out so that it should not operate in reverse order (i.e. moving tap to decrease voltage at bus to bring it down to 1.0 p.u.). This overall scheme is shown in Figure 7.1.

Finally the results are presented in the tabular form to analyze the optimum scheme and the additional time which this scheme can provide in order to do intelligent load shedding, remedial action scheme, reactive power support coordination, System Integrity Protection Scheme, etc.

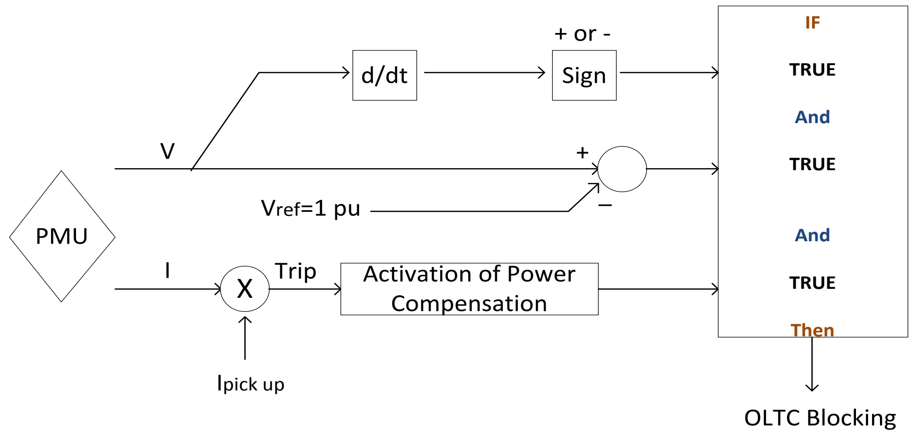


Fig. 7-1: PMU Assisted Coordination Approach

7.5. Optimized All-in-One System Model

In the previous section, the behavior of the “All-in-One model” in presence of protection relays and reactive power compensation devices was analyzed. In this part the optimization of the system is done just to show that with the same components and same rating of the equipment, the time to voltage collapse can be increased. This is just an example of how by using PMU measurements, it is possible to coordinate the OLTC, and protective relays with the reactive power compensation devices. It could be done more efficiently and effectively by using voltage indices (mentioned in previous sections) and coming up with an algorithm for either global or local optimization.

The results of the optimized scheme for all-in-one system are shown below. The voltage collapse scenario is initiated at t=60 sec, as a result the voltage starts degrading at the load bus. The OLTC operates to bring the voltage back to nominal. When the voltage at load bus decreases down to 0.95 pu, the reactive power compensation device with 2MVar capacity is switched in. The voltage at load bus jumps up to 1.05 pu. At this stage the OLTC operation is blocked so that it should not operate in reverse order to bring down the voltage to 1.0 pu. As the load is continuously increasing reactive power demand, the relay picks up the fault at t=322 sec and disconnects the load. The figures are shown below in Figure 7-2 to Figure 7-13.

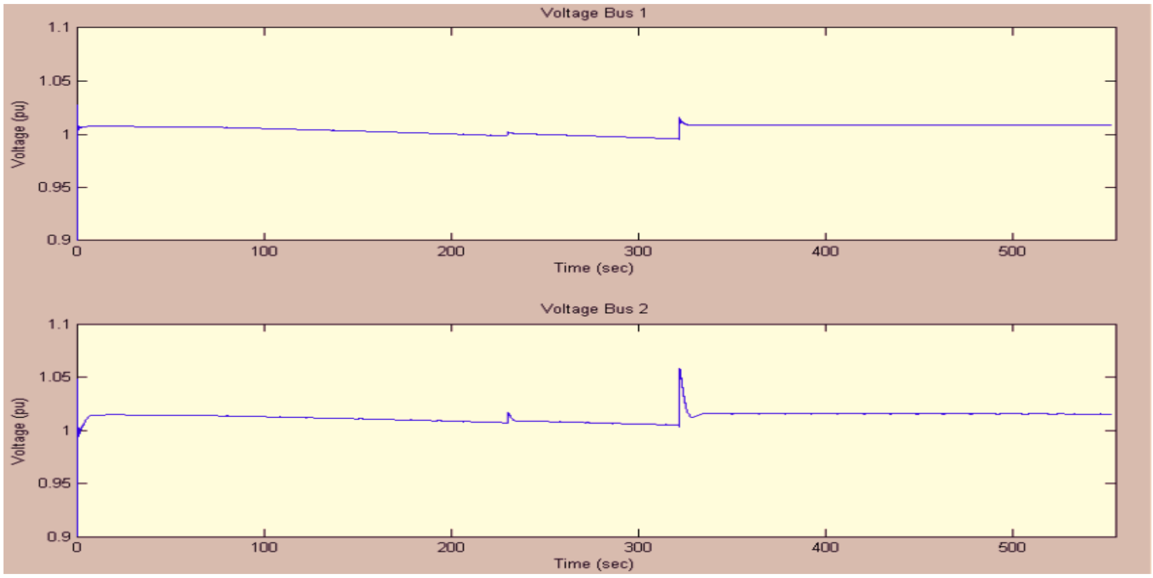


Fig. 7-2: Voltage at Bus 1 and Bus 2 (Optimized)

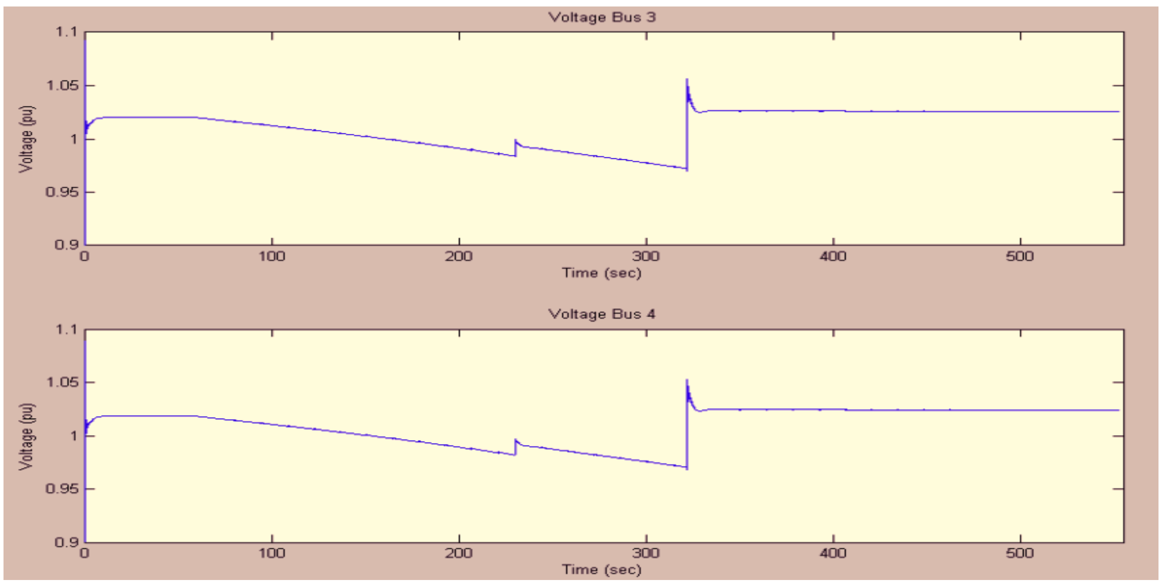


Fig. 7-3: Voltage at Bus 3 and Bus 4 (Optimized)

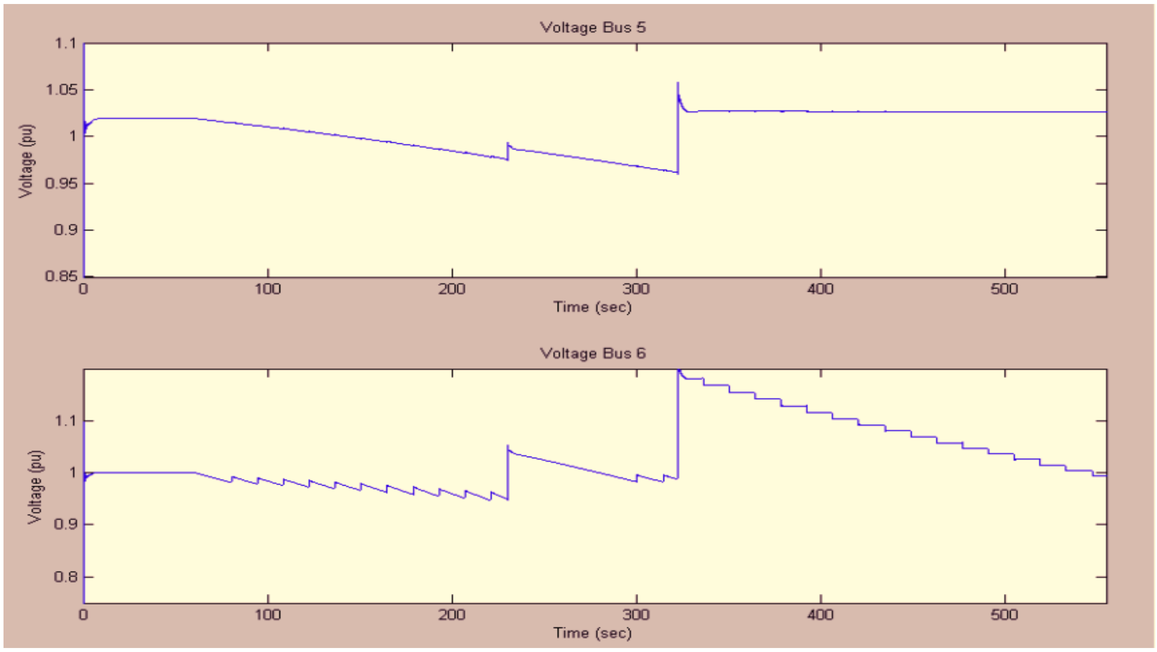


Fig. 7-4: Voltage at Bus 5 and Bus 6 (Optimized)

As shown in Fig. 7-4, the reactive power compensation device is connected at t=230 sec. The voltage at Bus 6 jumps up to 1.05 pu, and at this point OLTC operation is blocked till the voltage itself degrades below 1.0 pu. At t= 295 sec, the voltage goes below 1.0 pu and OLTC is again unblocked. Finally at t=322 sec, the relay disconnects the increasing load.

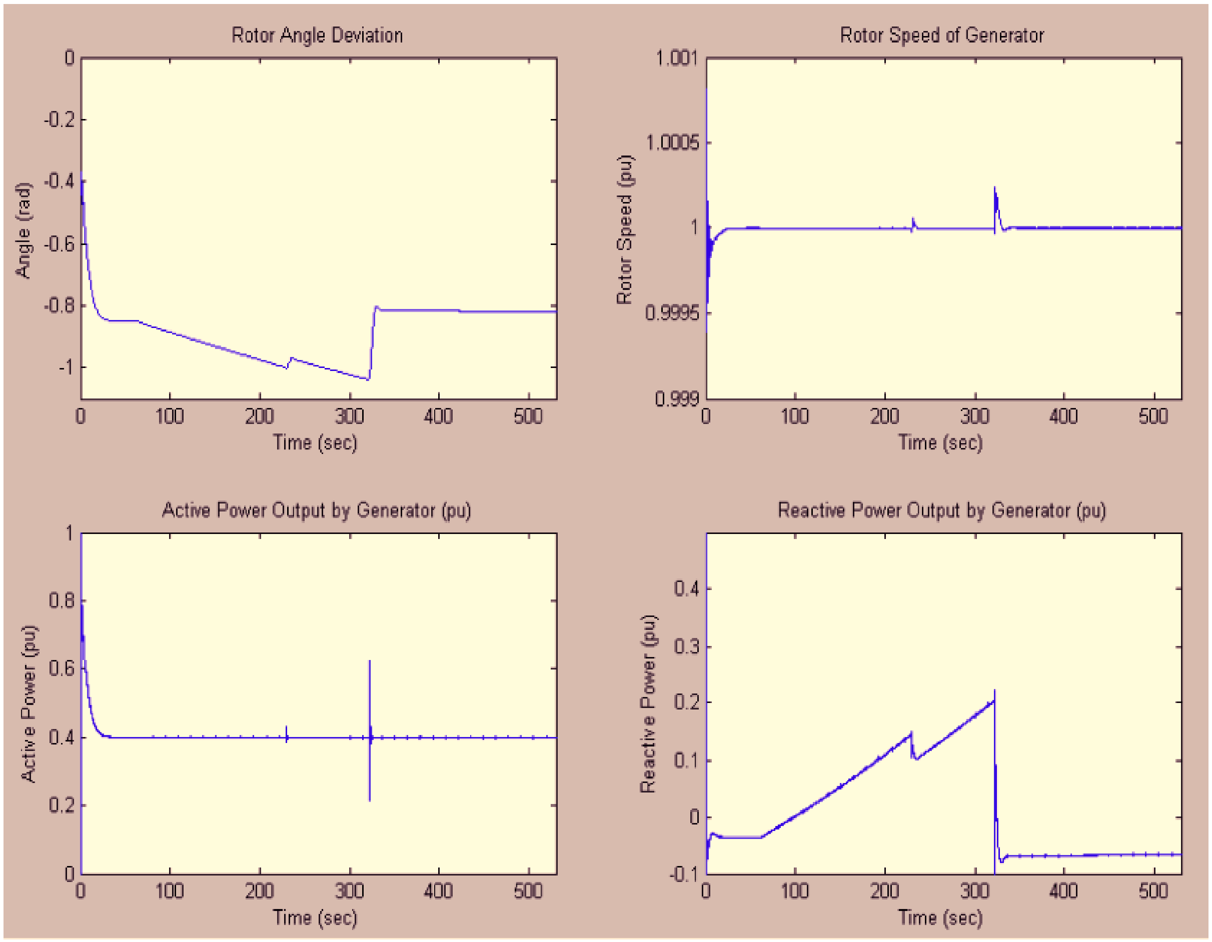


Fig. 7-5: Synchronous Generator Characteristics

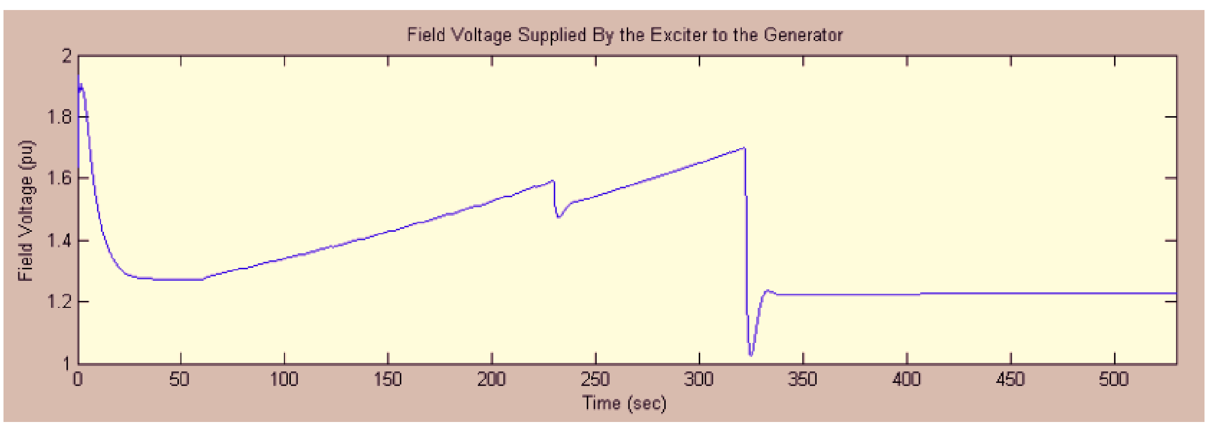


Fig. 7-6: Field Voltage Supplied By Exciter

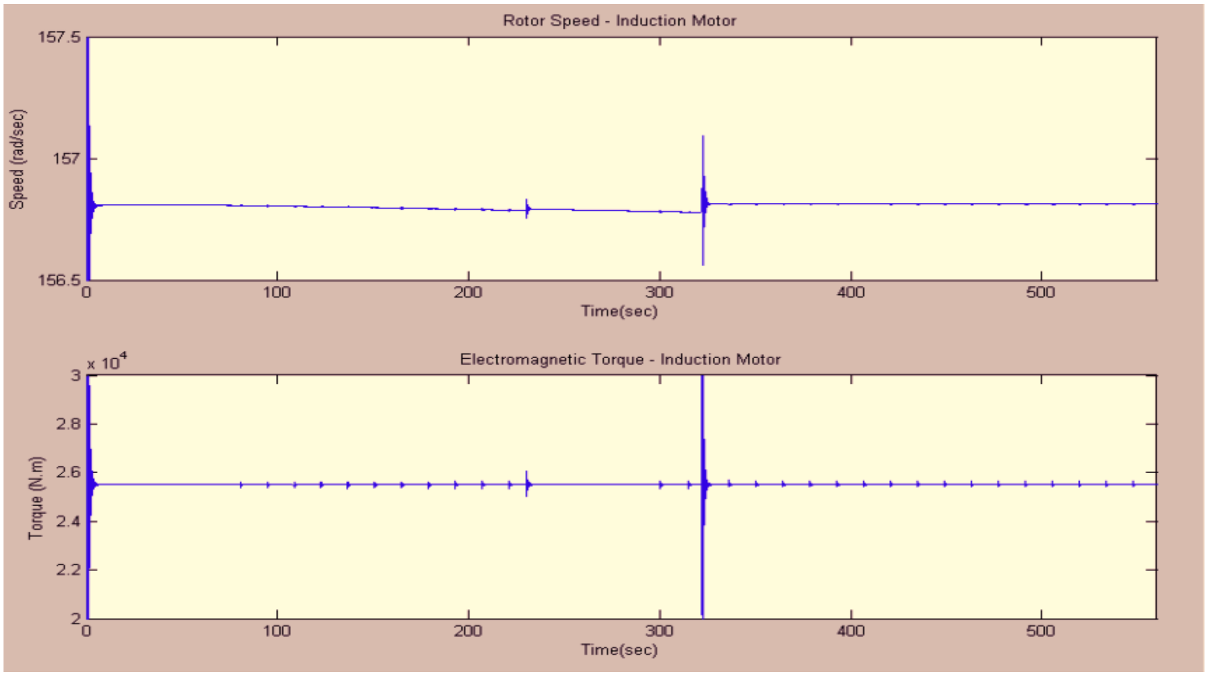


Fig. 7-7: Induction Motor Characteristics

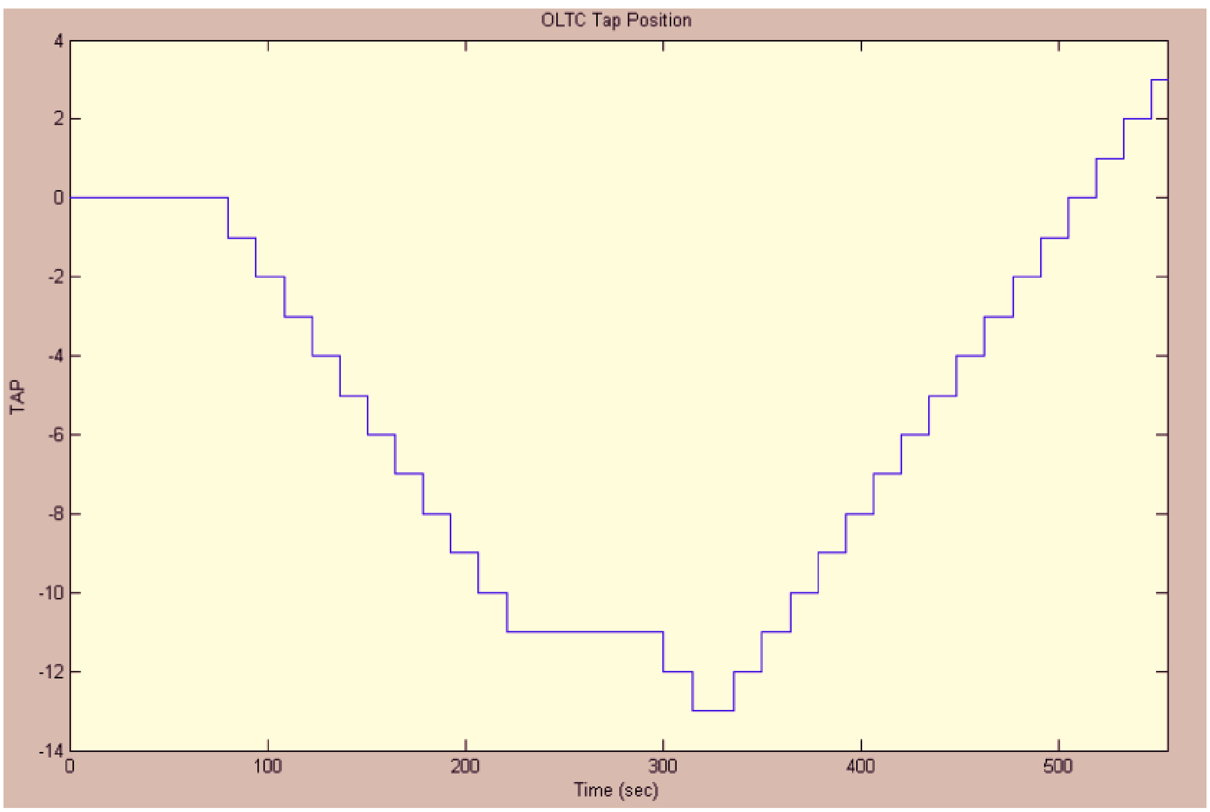


Fig. 7-8: OLTC Tap Position

Notice from Fig. 7-8, the blocking of the OLTC between 230 sec and 295 sec. Between this time the voltage at Bus 6 is greater than 1.0 pu but the OLTC is blocked to operate in reverse mode otherwise it will bring the voltage down to 1.0 pu and further contribute to voltage collapse.

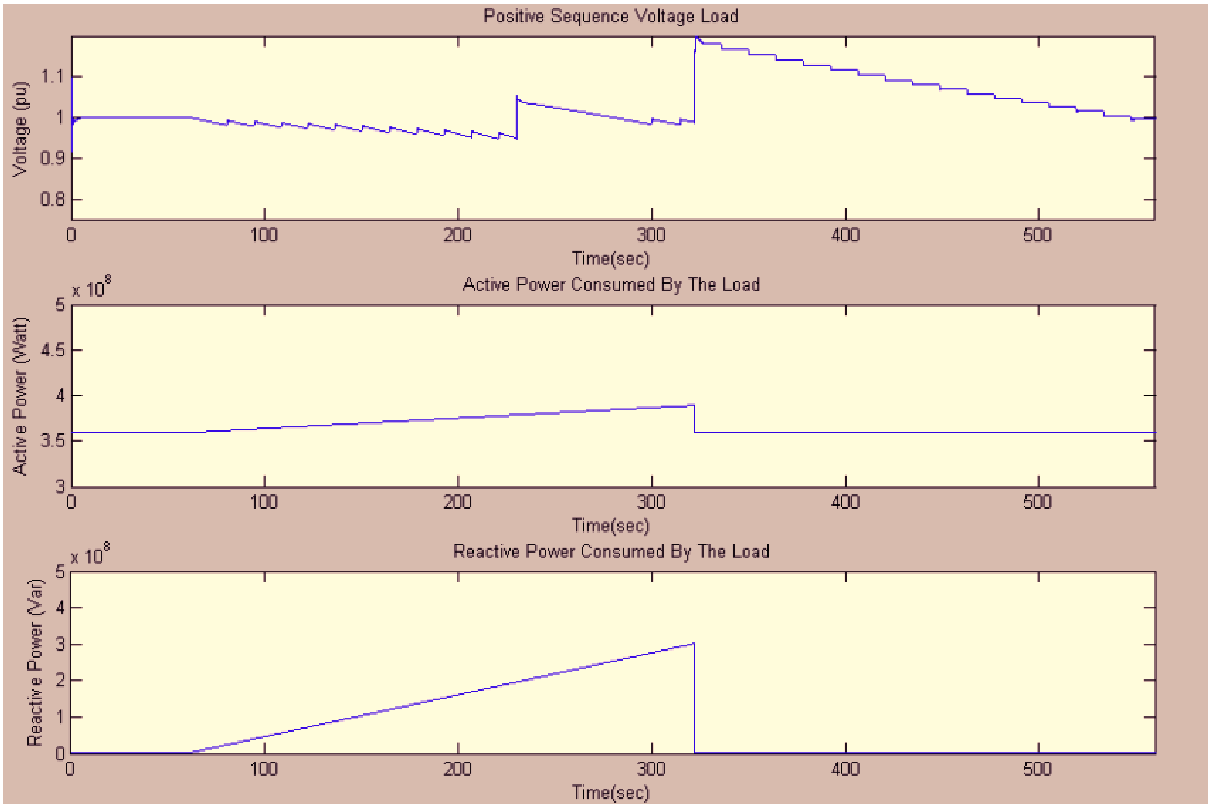


Fig. 7-9: Dynamic Load Characteristics

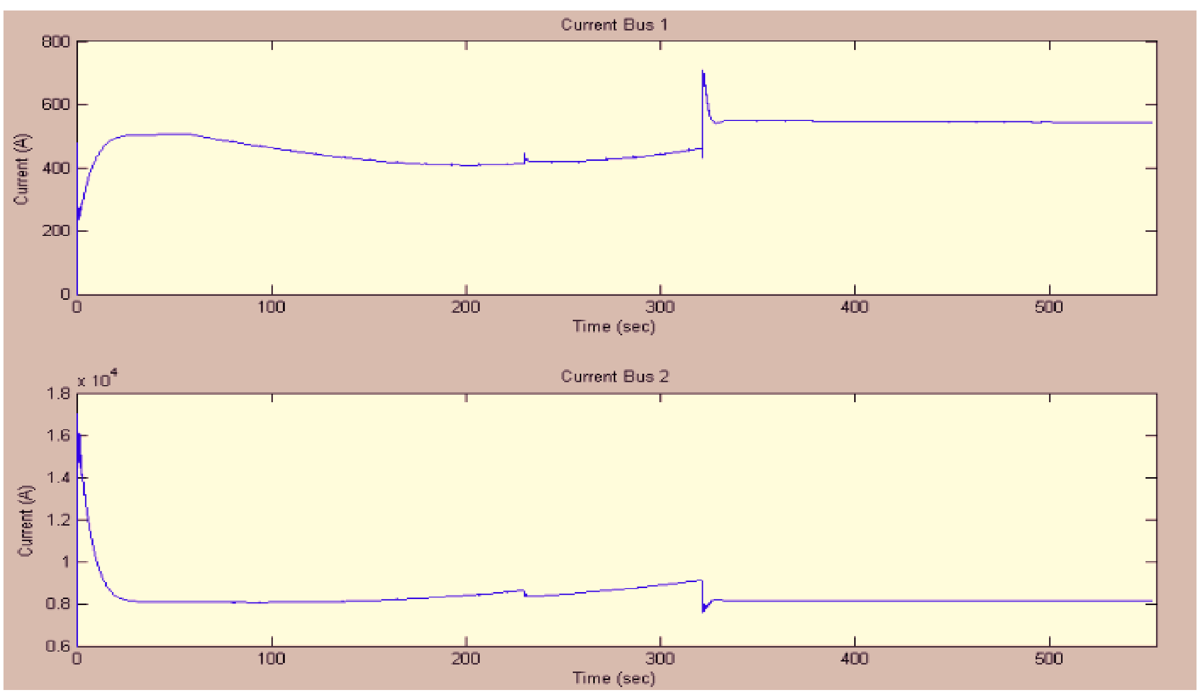


Fig. 7-10: Current Bus 1 and Bus 2

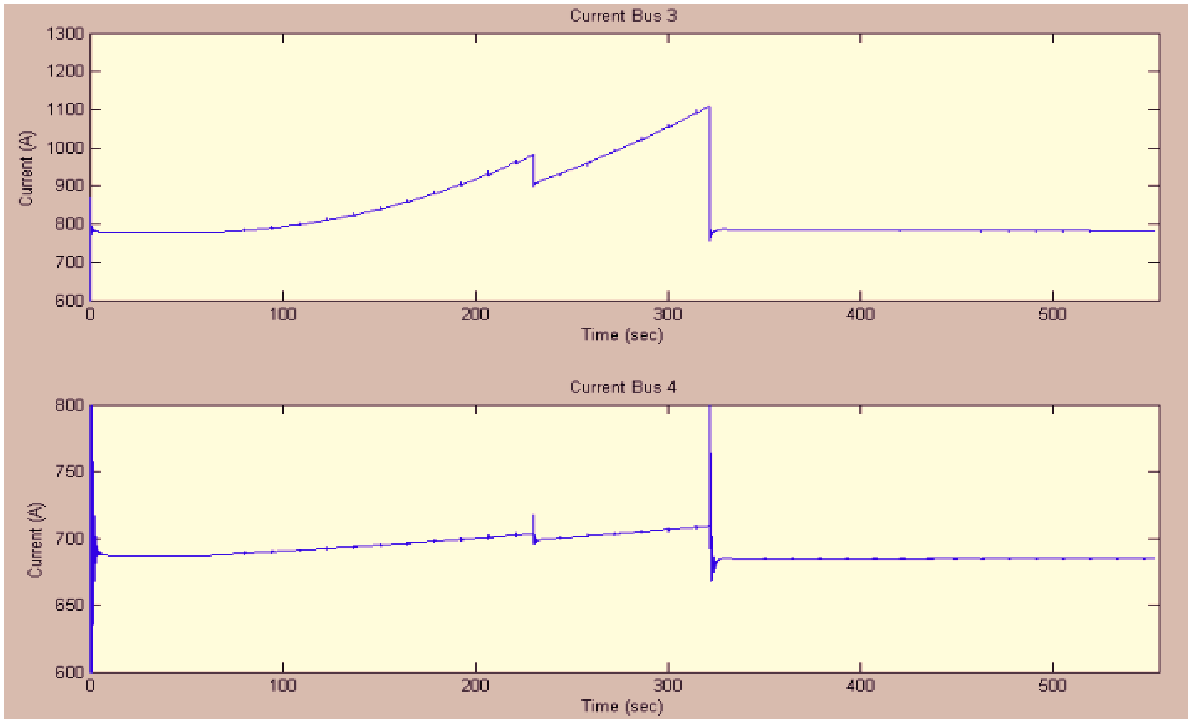


Fig. 7-11: Current Bus 3 and Bus 4

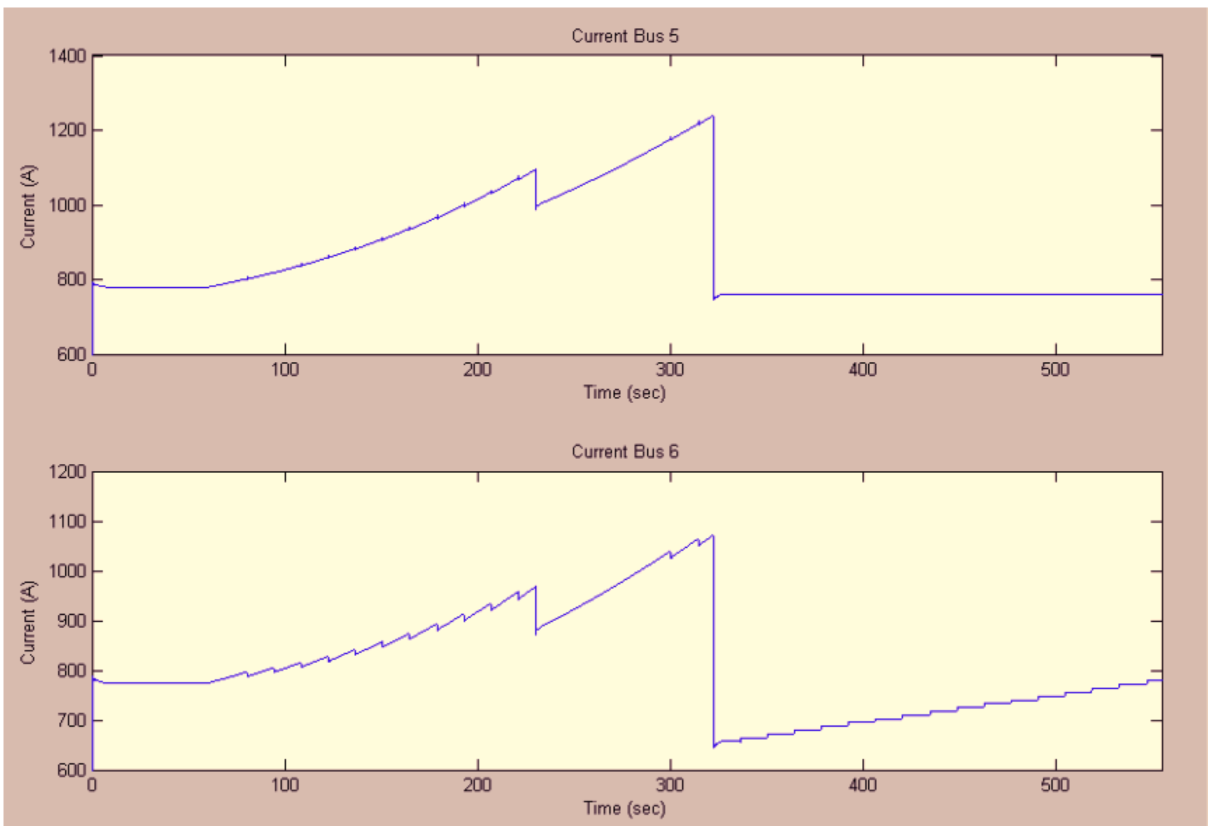


Fig. 7-12: Current Bus 5 and Bus 6

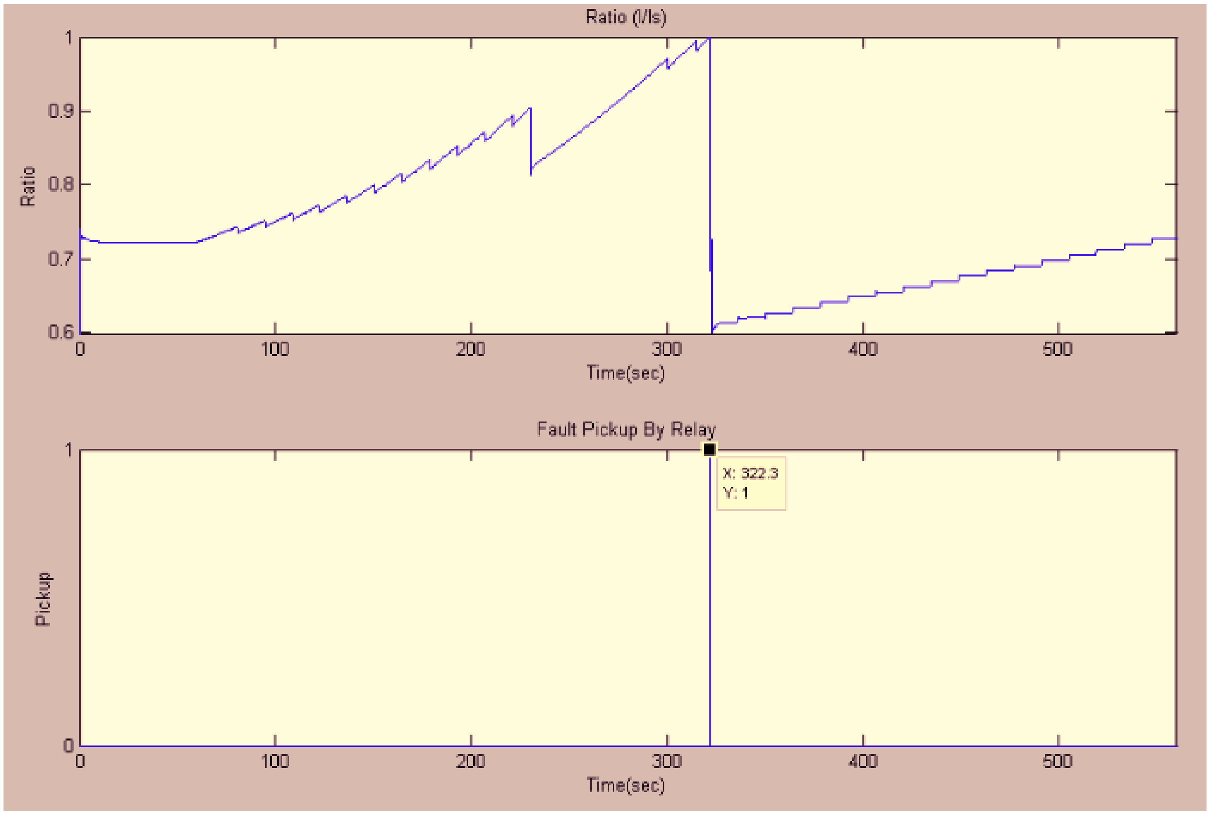


Fig. 7-13: Over-Current Relay Characteristics

7.6. Discussion

The simulations above show the switching of the reactive power compensation device when the voltage falls below 0.95 pu and the blocking the OLTC operation as soon as the voltage goes above 1.0 pu. With this simple optimization, the trip time has increased to 322 sec. previously without optimization it was 315 sec. This shows that by exploiting simple optimization techniques, coordinating the equipment present in the power system, a system can be designed not only to sustain an instability but also as an early warning system for the operator's to take remedial actions before reaching voltage collapse. With the optimized scheme the operator will be having an extra 7 sec to initiate a remedial action scheme, a system integrity protection scheme or intelligent load shedding to safeguard the overall system.

7.7. Chapter Summary

The chapter gives a description about the types of optimization and the different indices used for voltage instability detection. The overall process of optimizing the power system by ecploiting synchronized phasor measurement data for coordinating the OLTC operation, Reactive Power Compensation Devices and Protection Relays, has been discussed in detail. Finally the optimized power system is simulated in the real time and the results are discussed and compared with the un-optimized case.

Chapter 8: Conclusions and Future Work

8.1. Conclusions

The electric power system is becoming more complex with the integration of renewable energies, power electronic devices, and more and more emphasis on automating the whole process from generation of electric power to its consumption. In addition the exponential rise in the demand of electric power coupled with issues for getting rights-of-way for building new towers and the need to maximize the rate or return on the investment of the power network infrastructure, the power system is operated to its limit. This makes the power system more vulnerable and even a single equipment mal-operation can lead it to a cascaded failure or even system collapse.

It is indeed a necessity to verify the operation of the power system under all possible operating conditions and confirming the coordination of various power system equipment with each other before they are commissioned in the real world. It is perhaps not possible to design a real power system just for experimental purposes so that one can apply different faults in the network and can analyze the behavior of the system and propose a new refined and effective solution for the system. The most efficient way of carrying out such analysis is with the help of Real-Time Simulators.

Real time simulators help to model the actual power network and then simulate it in real time. The behavior of the power system i.e. dynamics, states are just the replica as it would be in the real world. This helps to analyze the system thoroughly and to compute the optimum operating conditions for the power network.

In this thesis, voltage instability is the main focus, and the real-time simulator OPAL-RT is used to analyze the voltage instability in a power system. The modeling platform for OPAL-RT is SimPowerSystems (MATLAB/Simulink). An All-in-One system was modeled to analyze its response for various instabilities. A voltage instability scenario was analyzed and the behavior of the power system was observed to determine how long the system can sustain such instability before it collapses. A detailed model of overcurrent relay with different characteristic curves was implemented in this system to protect the system from collapse. The purpose of the overcurrent relay was to detect the voltage instability i.e. decrease in voltage or in other terms increase in current at load bus (constant power load) and consider it as an overcurrent situation and send a trip signal to the load breaker to disconnect the load and avoid system collapse. The system was analyzed in real-time and the results were discussed in detail. The all-in-one system was then equipped with reactive power compensation devices (HVDC, switching capacitors) to analyze their impact on the system. The same voltage instability was introduced in the system and the system response was studied in presence of these reactive power compensation devices. It was noticed that in presence of reactive power compensation devices, the system can survive for a longer period when voltage instability is introduced and the overcurrent situation appears at a much later stage. The relay trips the load at a later time which means more load can be fed in presence of reactive power compensation devices. In the last section, the overall power system was optimized using the current and voltage phasors from PMUs. The PMU data was used in conjunction with the states of the OLTC and protective relays to develop coordination between these equipment so that the system can sustain a voltage instability for a much longer time. The main findings from the voltage instability scenario are listed in a tabular form.

Voltage Instability Scenario (Scenario Initiated at t=60sec)	
System Configuration (Topology)	**Voltage Collapse / Tripping of Load (Time)**
All in one System	Voltage collapse at t = 300 sec
All-in-one System equipped with overcurrent relays with pickup value of 120 %	Relay picks up fault at t= 284.5 sec and trips the load
All-in-one System equipped with overcurrent relay and reactive power compensation device (un-optimized)	The reactive power compensation device switched in at t=230 sec (load bus voltage 0.95 pu), the relay trips load at t = 315 sec
All-in-one System equipped with overcurrent relay and reactive power compensation device (optimized)	The reactive power compensation device switched in at t=230 sec (load bus voltage 0.95 pu), the OLTC operation is blocked in reverse order, the relay trips load at t = 322 sec

The table shows that by using the most recent values of voltage and current phasors provided by PMUs to coordinate the operation of reactive power compensation devices with protective relays, and then optimizing the system by blocking the OLTC operation in reverse order will optimize the system and with same configuration and relay settings, the system can sustain the voltage instability for a longer time i.e. 322 sec in this case. This extra time (322-284.5 = 37.5sec) can be utilized to initiate intelligent load shedding schemes, remedial action schemes, system integrity protection schemes, etc. to maintain the supply of electrical power to the load without the operation of relays to trip the breaker. Emphasis is made on phasor measurements from the relays in C37.118 format which can give data rate up to 50 samples per second. Such fast data rate reporting is used to develop and optimize scheme which tracks the trend of the voltage at the buses and initiates the remedial actions to mitigate the effect of instability in the power system.

8.2. Future Work

The thesis shows that real-time simulation is beneficial for detailed analysis of power system instabilities. There can be variety of work which can be done by utilizing the models and work developed for this thesis. Some of the recommended future works are listed below:

- ✓ Developing applications based on PMU data to detect transient instabilities, island detection, state estimation and other applications.
- ✓ Applying different faults on the power system and archiving the data in real time to use for data mining.
- ✓ Incorporating different protection relays (differential, distance, over/under voltage, frequency) and validating the test models in hardware-in the-loop (HIL)
- ✓ Integrating wind farm models in the All-in-One system and analyzing the impact of renewable energies on system dynamics.
- ✓ Validating the performance of different voltage stability indexes by using the synchrophasor measurements from the model and real-PMUs.
- ✓ Taking into account power system communication and substation automation by sending trip signals to real-hardware through GOOSE messages using IEC 61850-8-1 (Station Bus).
- ✓ The platform can be used to test complex protection schemes like breaker failure, bus bar and autoreclosure schemes.
- ✓ Testing of complex HVDC networks, SVCs, STATCOMs and FACTS devices control systems, under steady state and transient operating conditions.

With the help of the modeling platform and the real-time simulator, a complete hardware in the loop testing of protection relays, power system communication, and power electronic devices can be done. Modern power systems will keep evolving and that will require constant evaluation of new challenges and constraints. Real-time simulations are the most effective, efficient and professional way of carrying out major studies with the maximum level of confidence.

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Appendix

A.1.

This appendix includes the important protections which are generally applied for the units (generator, transformer, transmission line and motor). The chart exhibits the causes and effects of various faults which occur frequently in the power system and the necessary protection schemes which are applied to provide protection against such faults.

A.2.

This appendix includes the comparison of the features of microprocessor based relays. The features are compared for five different microprocessor based relays (Generator Protection, Transformer Protection, Line Protection, Over-current Protection and Under/Over Voltage Protection) manufactured by four different vendors (General Electric (GE), Schweitzer Engineering Laboratories (SEL), Areva-Alstom and ABB).

Important Protections for the Individual Units

Units	Type of Protection	ANSI Codes	Causes	Effect	Protection Scheme
GENERATOR	Protection against Overload	49	Increased power on load side of generator	Overheating of stator winding	Thermal image relay (keeping track of temperature) / over current relay
	Protection against unbalanced loads	46	Sudden loss or connection of heavy loads or poor distribution of consumers	Full capacity of generator cannot be utilized, gives rise to negative sequence components (tries to rotate rotor in reverse direction) that causes heavy currents in rotor and can damage it	Negative sequence over current relay (unsymmetrical loads would give rise to negative sequence components)
	Protection against reverse power condition	32	Parallel operation of generator with other sources may cause a generator to behave as motor (due to load unbalance or poor sharing of load between the generators)	Generator behaves as motor and draws power from network, turbine connected to generator will be damaged due to overheating	Directional power relay with reverse power setting option
	Out of Step Protection	78	Loss of synchronism because of line switching, connection/disconnection of heavy load, electrical faults	Winding stress, high rotor iron currents, pulsating torques, mechanical resonances	Out of step protection relay which tracks the impedance. In case of fault; there is nearly a step change in voltage/current
	Protection against frequency variation	81	Improper speed control, grid disturbance or sudden load cut off	Severe changes in speed and will cause over fluxing , serious damage to turbine generator set	Frequency protection relay which tracks frequency and trips the breaker in case of abnormal frequencies
	Protection against under/over voltages	27/59	System disturbance or malfunctioning of AVR	Over fluxing and winding insulation failure	Over/Under voltage relay with pre-set voltage limits defined in the settings
	Protection against internal faults (differential protection)	87	Internal faults (phase to phase and 3 phase to ground faults)	Gives Rise to Large amount of currents that can damage the winding	Differential protection with CTs on each side of generator (Unit Protection)
	Stator Earth Fault protection	64	Insulation failure of winding, inter turn fault	Thermal and magnetic imbalance and damage to rotor metallic parts	For isolated neutral network,
	Loss of Field protection	40	Loss of source to exciter, open or short circuit of field winding,	Loss of synchronism between rotor and stator flux, draws reactive power from grid and sever torque oscillations	Impedance relay is used to implement this technique. Most of the microprocessor based generator protection relays have this function incorporated in them
	Rotor Earth Fault protection	61F	Insulation failure of winding, inter turn fault	Thermal and magnetic imbalance and damage to rotor metallic parts	Voltage relay energized by neutral VT (depends on type of neutral connection)
	Synchro Check	25	Application that requires verification whether synchronism exists or not e.g. paralleling of generator etc.	Checks that the electrically interconnected parts are synchronized or not	Synchrocheck relay that measures magnitude, phase angle and frequency difference of voltages on both sides of the breaker
TRANSFORMER	Protection against Overload	49	Increased power on secondary side of transformer	Overheating of transformer	Thermal image relay (keeping track of temperature) / over current relay
	Over-current Protection	50/51	Phase and ground faults	Over current can cause damage to windings	Over-current relays
	Earth Fault Protection (Stator & Rotor)	50N/51N	Poor insulation, direct connection to earth	Causes current imbalance in system	Over-current relays with neutral module
	Differential Protection	87	Internal faults within the zone (virtually protects all the windings)	Internal faults can be short circuits or earth faults or overloading which can cause damage to transformer windings	Differential protection with CTs on each side of transformer (Unit Protection)
	Directional Protection (Phase and Neutral)	67/67N	Fault in nearby (parallel) feeder/bay causing tripping in the healthier feeder/bay due to poor selectivity of the relay	Tripping of healthier feeder and thus pushing system towards outages	Directional Over-current Protection Relay (Detecting the direction of fault current and if it is against the direction of detection of relay then it would not send trip signal
	Breaker Failure Protection	50 BF	Malfunctioning of the breaker	Unable to isolate the faulty equipment due to tripping failure (longer existence of fault current thus more damage to equipment)	Breaker Failure Relay which operates on its algorithm to try to open the breaker otherwise sends trip command to the nearby breakers to isolate the faulty equipment and stop feeding the fault current

Important Protections for the Individual Units

Units	Type of Protection	ANSI Codes	Causes	Effect	Protection Scheme
TRANSMISSION LINE	Distance protection (Phase & Ground)	21	Reduction in overall line impedance (V/I) due to a faulty condition	Fault current can overheat the transmission line and can cause damage to the conductor	Distance protection relay serves as a primary protection for transmission lines. It keeps track of the impedance of line and sends trip signal to the breaker if the line impedance changes (due to fault)
	Over voltage Protection	59	Lightning, switching, temporary over voltage	Give rise to transient over-voltages which can damage the insulation	Surge Arrestors/ Over-voltage relay with preset voltage limits defined in settings
	Power Swing Blocking	68	Line switching, generator disconnection, addition/loss of load	Loss of synchronism between voltages, phase sequence, phase angles, frequencies resulting in swing in power flows	Blocking relay provides this protection and has the same type of characteristic as distance relay
	Over-current protection (Phase & Ground)	50/51	Due to short circuit, single phase to ground or phase to phase faults. Can occur due to tree limbs that can fall on the line etc	Gives rise to heavy current that flows through the conductor and causes overheating of conductor which will deteriorate it.	Over current protection relay which also serves as a back up for distance protection. In case the distance protection (primary protection) malfunctions, over-current protection will send trip command
	Earth Fault Protection	50N/51N	Direct connection to the ground of one or more phases	Gives rise to higher voltages on other lines and stresses the insulation of cables and other equipment connected to system	Over-current relay that continuously monitors the current through the neutral and sends trip signal to the breaker upon detection of fault
MOTOR (LOAD)	Protection against Overload	49	Increase of the load torque or decrease in the motor torque due to busbar voltage dipping or decrease in DC Field current (Synchronous motors)	High currents drawn by the motor badly affects the insulation and thus reduces the machine life expectancy	Thermal image relay (keeping track of temperature and has a thermal time constant) / over-current relay
	Short circuit	50/51	Phase to phase short circuit in the winding , at the motor terminals or between cables	Destroy the machine due to over-heating and electro-dynamic forces created by the high currents	Over-current relay with a preset value of current settings which sends a trip signal if the current exceeds its preset value
	Earth Fault Protection	50N/51N	Machine insulation damage	Results in a fault current that flows from windings to earth via stator laminations	Over-current relays with neutral module
	Number of starts supervision	66	If the operator or automatic function tries to switch on the motor more than specific number of times within a specific duration	The thermal state of the machine changes due to number of starts occurs. Adequate cooling of machine is required before the machine is given another start otherwise the life expectancy of machine will decrease due to deterioration of insulation	Notching or jogging relay that uses a counter to control the number of starts in a certain time. They take into account the machine thermal state and doesn't allow any further starts if the machine has already attained specific starts in a specific time
	Under voltage protection	27	System disturbance or increase in load	Under voltage results in over-currents which can damage the insulation,	Under voltage relay with pre-set voltage limits defined in the settings
	Loss of Synchronism (Synchronous Machines only)	55	Increase in load causes decrease in busbar voltage or due to decrease in the field current that causes the motor torque to decrease	Damage occurs to the dampers and rotor windings due to loss of synchronism	Power factor relay that responds to the change in power factor that occurs when there is pole slipping (weakening of synchronizing torque to maintain synchronism under same load)
	Protection against unbalanced loads	46	Sudden loss or connection of heavy loads or poor distribution of consumers	Gives rise to negative sequence components (tries to rotate rotor in reverse direction) that causes heavy currents in rotor and can damage it	Negative sequence over current relay (unsymmetrical loads would give rise to negative sequence components)

Characteristics Comparison of Protection Relays From Different Vendors

Characteristic	Protection Relay		Vendors: General Electric (GE)	Vendors: ABB	Vendors: SEL	Vendors: ALSTOM
Units from Manufacturer	Relay Type	Generator Protection	G60 (Generator Protection System)	REG 670 (Generator Protection)	SEL-700G (Generator Protection Relay)	Micom Alstom P-345 (Generator Protection)
		Transformer Differential Protection	T60(Transformer Protection System)	RET 545 (Transformer Protection)	SEL-487E (Transformer Differential Relay)	Micom Alstom P-645 (Transformer Protection)
		Over-current Protection	MIFII (Digital Feeder Protection)	REF 545 (Feeder Protection)	SEL-551C (Over-current Relay)	Micom Alstom P-145 (Feeder Protection)
		Distance Protection	D60(Line Distance Protection System)	REL 512(Line Protection and Breaker Control)	SEL-311A (Protection and Automation System)	Micom Alstom P-441 (Distance Relay)
		Over/Under Voltage Protection	MIV (Digital Voltage & Frequency Relay)	REM 545 (Over/Under Voltage Relay)	SEL-387E (Voltage Protection Relay)	Micom Alstom P-923 (Voltage Protection)
Function	Relay Type	Generator Protection	Current, voltage and frequency protection	Current, voltage and frequency protection	Current, voltage and frequency protection	Current, voltage and frequency protection
		Transformer Differential Protection				
		Over-current Protection	Over-current protection for feeders	Over-current protection for feeders	Over-current protection for feeders	Over-current protection for feeders
		Distance Protection	Phase and ground distance protection	Phase and ground distance protection	Phase and ground distance protection	Phase and ground distance protection
		Over/Under Voltage Protection	voltage protection for substation /motors	voltage protection for motors	Current differential and voltage protection	voltage and frequency protection relay
Available Measurements	Relay Type	Generator Protection	RMS and Phasors for current and voltage, current harmonics and THD,symmetrical components, frequency, power, power factor, energy	Voltage, Current, apparent power, reactive power, real power, frequency, power factor	positive, negative and zero sequence voltages and currents, system frequency, power, energy, power factor, V/Hz, Generator thermal capacity	Current, voltage, power, energy, frequency, phase, differential quantities, V/Hz, rate of change of frequency, CTs current magnitude and phase
		Transformer Differential Protection			Voltage, current, power, energy, differential harmonic quantities	Phase and neutral currents, frequency, power factor, maximum demand, power, differential currents
		Distance Protection	RMS and Phasors for current voltage and power metering	RMS and Phasors for current voltage and power metering	Current, voltage, power, energy, power factor, frequency, demand and peak current, demand and peak power, sequence components	RMS and Phasors for current voltage and power metering
		Over-current Protection	Phase and ground currents, thermal image	Phase currents, line and phase voltages, frequency, power factor, energy, power, THD	Currents, residual ground current, negative sequence current, demand metering values	Current, voltages, power, power factor, frequency, energy
		Over/Under Voltage Protection	Phase, ground and phase to phase voltages, frequency	Phase currents, line and phase voltages, frequency, power factor, energy, power	Voltage, current, power, frequency, V/Hz, harmonics, differential currents	Phase, ground and phase to phase voltages, frequency
Diagnostic Features	Relay Type	Generator Protection	Event Recorder (1024 time tagged events, Oscillography for up to 64 records	1000 events time tagged 100 disturbances	Event Recorder (1024 time tagged events,	512 events, 5 fault records, 10 maintenance records
		Transformer Differential Protection		100 events each time tagged	Event Recorder (1000 time tagged events,	
		Distance Protection		Fault Records 20 (each 16 cycle),	Event Recorder (512 time tagged events,	500 events , 28 disturbance records each time tagged
		Over-current Protection	Event Recorder (32 events each time tagged), one oscillography record	Disturbance record for 16 waveforms and 16 digital signals(total 32)	Event Recorder (20 time tagged events	512 events , 50 disturbance records each time tagged, 5 fault records
		Over/Under Voltage Protection	Event Recorder (24 events each time tagged), one oscillography record		Event Recorder (512 time tagged events,	Event records 75, fault records 5, disturbance records 5 of 2.5s each

Characteristics Comparison of Protection Relays From Different Vendors

Characteristic	Protection Relay		Vendors: General Electric (GE)	Vendors: ABB	Vendors: SEL	Vendors: ALSTOM
Operating Time	Relay Type	Generator Protection	5 to 20 ms	About 15 ms	< 20 ms	<30 ms
		Transformer Differential Protection		< 35 ms		< 33 ms
		Over-current Protection	20 to 30ms	< 30 ms	<25 ms	<30 ms
		Distance Protection	10 to 30 ms	< 30 ms	<30 ms	17 to 30 ms
		Over/Under Voltage Protection	< 30 ms	< 30 ms	<25 ms	< 30 ms
Additional Functions	Relay Type	Generator Protection	Loss of excitation, generator unbalance, accidental energization, power swing detection, rate of change of frequency	Loss of/ under excitation, restricted earth fault, over/under frequency, directional power, pole slip, thermal overload, breaker failure, rate of change of frequency	Over-current, restricted earth fault, over excitation, loss of field protection,over/under voltage, system backup, Rate of change of frequency, thermal overload	Over/under voltage, over/under frequency, rate of change of frequency, loss of field, over fluxing, thermal overload
		Transformer Differential Protection	Volts per hertz, over/under current, over voltage, over/under frequency, thermal overload, synchrocheck	Over-current, under impedance, earth fault, over load, over/under frequency, over/under voltage, over excitation	Over/under voltage, breaker failure, Restricted Earth Fault, Volts/Hz, Current imbalance	Restricted Earth Fault, Thermal Overload, V/Hz, over-fluxing, breaker failure, over/under frequency, CT/VT supervision
		Over-current Protection	Thermal Overload, Cold load pickup, Breaker Failure to open,	Earth fault, over/under voltage, Thermal overload, Breaker Failure, Auto reclosure, frequency	Auto-reclosure, Demand Current overload, CT saturation	Auto reclosure, CT/VT supervision, overload, frequency protection, over/ under voltage, cold load pick up
		Distance Protection	Automatic Reclosure Power Swing blocking, Breaker Failure, Current Disturbance, over current, under/over voltage, directional elements	Breaker failure, Auto reclosure, over/under voltage	Over-current, loss of potential, load encroachment	Over-current, power swing, thermal overload, auto reclosure, over/under frequency, breaker failure
		Over/Under Voltage Protection	Voltage unbalance, under/over frequency, ground over-voltage	Over-current, earth fault, differential, under excitation, thermal overload, frequency	Over-current, differential, Volts/Hz, over/under frequency	Under/over frequency, trip circuit supervision, rate of change of frequency
Programming Capability	Relay Type	Generator Protection	GE ENERVISTA UR (to create or edit setting files offline or real time)	Protection and control IED Manager PCM 600	ACSELERATOR QuickSet SEL-5030 Software	S1 Studio Software for editing and extracting setting files, extracting events and disturbance records
		Transformer Differential Protection		CAP 505 Relay Product Engineering Tools,		
		Distance Protection		RELTOOLs (edit and retrieve settings)		
		Over-current Protection	ENERVISTA MII (to create and edit setting files)	CAP 505 Relay Product Engineering Tools (edit and retrieve settings)		
		Over/Under Voltage Protection				
Communication Method	Relay Type	Generator Protection	RS232, RS485, IEC 61850, Modbus / TCP, DNP 3.0, IEC 60870-5-104	RS 232, RS485, IEC 61850-8-1 IEC 60870-5-103 LON, SPA, DNP 3.0, Modbus RTU/ASCII	SEL, Modbus, DNP, FTP, TCP/IP, Telnet, IEC 61850, MIRRORED BITS, EVMSG, C37.118 (synchrophasors), and DeviceNet	RS 232, RS 485, Courier/K bus Modbus, IEC 60870-5-103, DNP 3.0, IEC 61850
		Transformer Differential Protection				
		Distance Protection		RS 232, RS485, DNP 3.0, Modbus RTU/ASCII		
		Over/Under Voltage Protection	RS232, RS485, IEC 61850, Modbus / TCP, IEC 60870-5-103	RS 232, RS485, IEC 61850-8-1 IEC 60870-5-103 LON, SPA, DNP 3.0, Modbus RTU/ASCII		
		Over-current Protection			EIA 485, Modbus RTU, EIA 232	