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Real Time Test Bed Development For Power System Operation, Control And Cybersecurity

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CONTROL AND CYBER SECURITY

By

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The operation and control of the power system in an efficient way is important in order to keep the system secure, reliable and economical. With advancements in smart grid, several new algorithms have been developed for improved operation and control. These algorithms need to be extensively tested and validated in real time before applying to the real electric power grid. This work focuses on the development of a real time test bed for testing and validating power system control algorithms, hardware devices and cyber security vulnerability. The test bed developed utilizes several hardware components including relays, phasor measurement units, phasor data concentrator, programmable logic controllers and several software tools. Current work also integrates historian for power system monitoring and data archiving. Finally, two different power system test cases are simulated to demonstrate the applications of developed test bed. The developed test bed can also be used for power system education.

DEDICATION

I would like to dedicate this thesis work to everybody who understood and stood behind me since my childhood for everything I did to be a part of this beautiful world, and to the special person whom I miss the most.

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LIST OF ABBREVIATIONS

PMU	Phasor Measurement Unit
PDC	Phasor Data Concentrator
SVP	Synchrophasor Vector Processor
PLC	Programmable Logic Controller
NI	National Instruments
OSI	Open System Interface
PI	Plant Information
MW	Mega Watt
SCADA	Supervisory Control and Data Acquisition
SPS	Special Protection Schemes
RAS	Remedial Action Schemes
EMS	Energy Management System
RTDS	Real Time Digital Simulator
LAN	Local Area Network
SG	Smart Grid
DDAC	Digital to Analog Converter card
PXI	PCI eXtensions for Instrumentation
PCI	Peripheral Component Interconnect
GPIB	General Purpose Interface Bus
DAQ	Data Acquisition

VI	Virtual Instrument
MAX	Measurement and Automation eXplorer
IP	Internet Protocol
PAC	Programmable Automation Controller
SEL	Schweitzer Engineering Laboratories
DNP	Distributed Network Protocol
IEC	International Electrotechnical Commission
GPS	Global Positioning System
DFR	Digital Fault Recorders
FTP	File Transfer Protocol
IRIG	Inter-Range Instrumentation Group
GE	General Electric
UDP	User Datagram Protocol
PERL	Power and Energy Research Lab
OPC	OLE for Process Control
OLE	Object Linked Embedding
PI ICU	PI Interface Configuration Utility
PI SMT	PI System Management Tool
TVA	Tennessee Valley Authority
BPA	Bonneville Power Administration
3PC	Triple Processor Card

CHAPTER I

INTRODUCTION

1.1 Introduction

The electric power system is a complex network consisting of generation, transmission, distribution, and electric power loads requiring real time balance. A power system networks need to be highly reliable, secure, and economical using automatic control and optimization techniques [1]. Power systems are highly dynamic and it is essential to adjust the system parameters and controls in real time to accommodate the change in energy load demand. Hence, power system monitoring, control and protection schemes play a very important role in power system operation.

The aging grid infrastructure, growth in energy demand, market based operation, integration of renewable generation and ongoing smart grid modernization initiative are leading to further complex behavior of the power grid [2]. These developments and complexities, demand for new technologies and solutions, will make the grid more reliable and secure in current contexts. This research work focuses on development of a real time power system test bed for testing new power grid operations and control algorithms at the laboratory level before they are applied to the actual power system. This work also addresses testing of algorithms related to wide area monitoring, real time control, phasor measurement units, power system data acquisition and archiving methods by using several hardware devices, software tools and power system simulations.

1.2 Overview of power systems

This section describes the general overview of the power system including the operation and control of the system and then focuses on the challenges faced by the current power system network operation.

1.2.1 Power system structure

Conventional power system structures are comprised of three different parts: generation, transmission and distribution. The generation units are generally located in remote places to accommodate the higher MW size generation and space requirements. Electric power is generated more commonly by using steam, gas or hydro turbines. Each generating station may contain more than one generator, and depending on the type of generation they are classified as hydro, thermal, nuclear etc.

The electric power generated at remote locations is transmitted to load centers through a transmission network that essentially consists of transmission lines and transformers. The transmission system may be further divided into sub-transmission lines supplying electric power to industrial and other heavy loads after stepping down the voltage level as needed. The distribution system is used to supply power to domestic customers for home use and supplying three phase power for small scale commercial use. The power generation stations generate electric power at generation voltages of 11kV to 35kV. These voltages are stepped up by the transformers to the typical transmission level voltages of 138kV or 230kV and above [3-4]. Transmission at higher voltage reduces the transmission losses by reducing the current and minimizing the power losses. These high level voltages are then stepped down to sub-transmission levels, typically 26kV and 69kV and, are used to supply power to large industrial consumers, these are further stepped down to distribution voltages of 13kV and 4kV for small or primary customers, and down to 120V and 240V for secondary customers [4]. The electric power system is equipped with several sensors, actuators and control devices to balance the generation with load demand in real time.

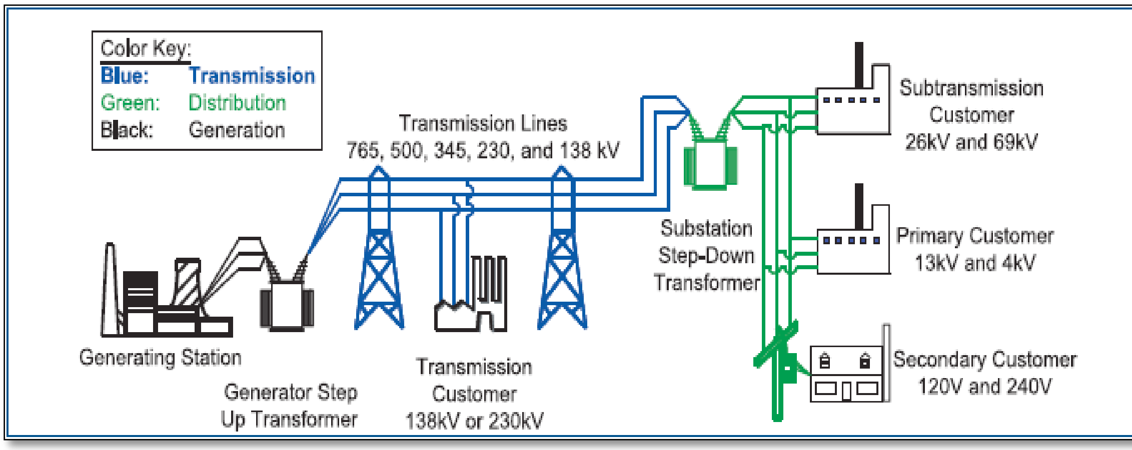

Figure 1.1 Basic Structure of the Electric System [4]

1.2.2 Power system operation and control

The continuous and reliable supply of electric power without any disturbances through power system control is of prime importance to electric utility. A number of power system devices are integrated to monitor continuous changes in the system and also concurrently making control decisions to keep the normal operation intact and avoid any unwanted impacts of disturbances.

Since the electric power is generated and consumed in real time, it is essential that the system meets the continuously changing load requirements for active and reactive power, maintaining near constant frequency and voltage [3]. Conventional power system control comprises of generation, transmission and distribution controls. Generation control includes control of frequency, voltage, speed and parameters for economic operation. Transmission control includes active and reactive power control with minimum losses. Distribution system control requires transformer and compensation control to keep the voltage at required level. Advancements in control, signal processing and processing power technologies now allow wide area control where system-wide disturbances are monitored and controlled at control center level in real time.

1.2.3 Challenges faced by the power system

The modern electric power system structure is evolved with significant improvements over several decades but there are several other challenges which need to be resolved. One important challenge for electric utilities is to operate the power system in a stable and reliable manner with real-time balance of generation and load demand. At the same time electricity markets would like to maximize the available transmission capacity and operating the grid closer to its "true" limit [2]. The aging grid infrastructure is a major challenge as it needs to incorporate a variety of changes due to the rapid technological enhancements towards smart grid. Distributed generation, increased interconnection of systems and also the concept of plug-in hybrid vehicles will alter the grid more dynamically and randomly and it should sustain these impacts with enhanced control for reliable and operational power grid. Challenges faced by the power system operators are increasing and some of them are, to operate the power system with minimum cost and at the same time to include growing demand, real-time demand response, electricity markets and new intermittent renewable generation technologies including plug-in-hybrid vehicle.

1.3 Real time control of power system

Historic studies of power system failures in various countries highlight the need for more sophisticated monitoring and control of the power system. In case of August

2003 blackout, the primary causes of the failure were poorly equipped monitoring systems for operators, the lack of real time control actions taken in order to prevent the cascading faults on the system, and the failure of the state estimator to quickly analyze the system state and propose necessary solutions [4]. The primary cause of the conventional state estimator failure is due to its dependency on non-synchronized SCADA data to compute the power system states. In the case of August 2003 blackout it was unable to solve the state estimation algorithm due to faulty data, more precisely due to unavailability of one of the system states and the estimator failed to produce any solution which further impaired the operator in handling the situation.

Time is of critical essence in the case of such failures. In case of 2003 blackout, the entire system lost power in matter of few minutes after the start of cascading events before any action was taken to control it [5]. This is mainly because the protection and control schemes employed are purely based on models which are generated offline based on previous system states but not on the actual current system conditions. These events show the importance of real time monitoring and control. Time synchronized data utilized by the state estimator to solve the system and present a real time system situational awareness at every interval will be very useful. Further, the control center and operators will be better equipped to handle the scenarios, if they identify the fault as soon as it occurred saving precious time in taking the appropriate control actions. Real time control is further strengthened in modern power system due to the introduction of synchrophasors. Synchrophasors are time synchronized system data accurate to about 1ms and are obtained rapidly [6].

1.4 Problem statement

The existing methods for power system protection and control include special protection schemes (SPS) and remedial action schemes (RAS) along with tools for energy management systems (EMS) to control a modern power system in case of failures. The main problems with the above implemented schemes are dependency on extensive offline studies using hypothetical scenarios and, equally importantly using models that possibly include errors [2]. As reported by U.S Department of Energy in [4, 6], more blackouts are occurring as a result of lack of automated analysis, slow response times of mechanical switches, and a lack of situational awareness among grid operators. The growing demand for electric power, increasing power system geographical area and integration of new generation and dynamic control to push the system towards its limits for economic operation are causing significant challenges in operation.

There is an immediate need to address the above issues by strengthening the gird infrastructure with more responsive devices and elements, such as finding alternatives for the existing protection schemes by a real-time adaptive control. These new developed algorithms need to be tested and validated using real time simulation of power system networks. Also, testing and validation is needed before implementation for all algorithms to improve the power system data monitoring and alarming capabilities to assist the operators, and to improve the grid visibility for better control.

1.5 Thesis Objective

The main objective of this thesis is to develop a platform to implement and demonstrate a fully integrated power system and control through real time simulations using Real Time Digital Simulator (RTDS) and other monitoring and control elements for testing and validation of new developed algorithms. First, a fully functional power system test case is studied and developed using RTDS. Second, different hardware and software components have been integrated with RTDS for implementation of a control schemes. Third, for real time monitoring of the system, phasor measurement units (PMU) are integrated into the test bed. Fourth, to build a fully functional test bed using Ethernet/IP as the main standard, the PI data historian and a phasor data concentrator (PDC) have been integrated for archiving and monitoring requirements. Finally the thesis seeks to create a scenario in order to facilitate the cyber security studies on the power system.

Objectives include, using the developed test bed to validate the operation of real time monitoring and control schemes by running different power system test cases on RTDS. Additional objectives also include cyber security analysis and testing of power system devices and components including the PI server, PMUs and PDCs.

1.6 Thesis outline

This thesis is organized into six chapters.

Chapter 2 briefly introduces the need for enhanced development and testing in the area of real time operation and control. This includes an introduction to wide area monitoring control along with cyber security aspects. It describes several hardware tools and software HMI's used in this work along with their application to this work.

Chapter 3 explains the development of real time test bed architecture along with different hardware interconnections and settings. This chapter provides a thorough explanation of the way the test bed is developed in an organized manner. This also describes the several challenges faced and solved in the development of this test bed.

Chapter 4 presents the operation of the developed real time test bed by introducing the developed power system test cases in RSCAD. Two test cases are explained along with corresponding modeling detailing the operation and data monitoring of the test cases.

Chapter 5 explains the results obtained using developed test cases on the system. It also proposes some of the applications using the test bed, including testing different power system elements.

Chapter 6 summarizes the results obtained and the main conclusion regarding benefits of having such a test bed at laboratory level for real time solutions. This chapter also includes the several contributions and future enhancements of the test bed for better operation and implementation of the system.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

There is an increasing need for real time power system modeling and simulation, which are critical in the development of new control and stability algorithms for emerging smart grid operation. This chapter introduces the need for real time simulation studies and the current related activities reported in literature. Next, it introduces the cyber security requirements for protecting the grid. Finally, a brief introduction of the test bed is followed by a description of the hardware and software tools used in the current work.

2.2 Wide area monitoring and control

One of the vital lessons learned from the recent power system blackouts is the importance of real time monitoring and control and also the need for wide area system visibility. These specific topics gained importance in the modern power systems and, most of the electric utilities are equipped or planning to be equipped with sophisticated infrastructure to provide real time view of the wide area power system network. The cascading failures in the previous blackouts are attributed to the lack of a system wide view of operating conditions and failure to take necessary action in real time [7].

Phasor measurement units (PMUs) offer the measurement of voltage and current phasors together with synchronized satellite triggered time intervals down to 20 ms [8]. The PMU devices are used in the current power system architecture for wide area monitoring and control applications. PMUs offer considerable advantage over the traditional SCADA based methods of data acquisition because they update the system state in real time, thus acting as powerful tools for power system visualization.

2.2.1 Phasors and synchrophasors

All voltages and currents in a power system can be represented in terms of phasors, which are essentially measurement quantities consisting of voltage magnitudes and corresponding phase angles. The phase angles are measured with respect to certain reference voltage bus. With the introduction of Global Positioning System clocks, a standard reference is created depending on the satellite clock and, the phase angles are measured corresponding to the reference. The satellite clock is the same anywhere in the world and, therefore the phasors generated across a power system network can be used for studying its operating state in real time. These time synchronized phasors are called synchrophasors and, each synchrophasor message provides a magnitude and phase angle for each quantity with a time stamp. The Figure 2.1 shown below provides an important comparison between traditional SCADA methods and the synchrophasors.

SCADA Data	Phasor Data
Refresh Rate 2–5 Seconds	Refresh Rate 30 Samples/s
Latency and Skew	Time Tagged Data, Minimal Latency
"Older" Legacy Communication	Compatible with Modem Communication Technology
Responds to Static Behavior	Responds to System Dynamic Behavior
Freq Change Means: Generation-Load Imbalance	Angle-Pair Change Means: MW Change or "Electrical Distance Change"
X Ray	MRI

Figure 2.1 SCADA versus PMU measurements [2]

2.3 Cyber security

The modern power system incorporates a high level automation which is further expanding to make the electric power grid more stable and reliable. The recent increases in technological changes are introducing a large number of computer software automated methods for data acquisition and control. Modern power system consists of improved communication infrastructure and also a huge amount of critical system information flowing through the network. The current electric systems employ a large number of communication protocols which includes high speed LAN, radio, microwave or fiber optic medium for data transfer and are susceptible to cyber threats.

As reported in [9] "The operation and control of the current power grid depends on a complex network of computers, software, and communication technologies that, if compromised by an intelligent adversary, could be used to cause great damage, including extended power outages and destruction of electrical equipment." Cyber security of the power grid is of paramount importance because of the huge economic losses the previous blackouts caused. An important factor to be considered is that a cyber attack can be launched from anywhere in the world and can be targeted remotely to cause enormous disturbance to power system network, leading to widespread interruption of energy supplies and operations [9-10].

Hence, there is a need to develop cyber security analysis methods to secure the grid. The first priority is the testing of the devices that are remotely controlled through computers for vulnerability to cyber attacks. A large number of devices employed in the current power system network are focused on their operational efficiency and advantages rather than considering their ability to shield themselves from cyber threats. The current study on developing a test bed provides an ideal setup for testing of several power system devices.

2.4 Real time power system test bed

As the electric power system is moving towards the smart grid (SG) development for improved reliable, secure and economic operation, implementation of such a system requires enhanced testing and validation [6, 11]. Most of the control action schemes mainly rely on extensive offline studies using hypothetical scenarios and models that possibly include errors [2]. Current developments in control schemes are also more often theoretical and non-real time based models which are rarely evaluated. There is a need for testing and validating these 'Real Time Monitoring and Control' techniques involving different hardware equipments to achieve flexibility, ease of operation, interoperability, control validation, and more importantly redundancy of the control schemes. Testing on a real time test bed helps considerably in studying the power system interactions, when new control or protection schemes are applied on prototypes rather than the actual system. This test bed also helps to perform a variety of simulations consisting of only software, hardware or combined simulations for predicting specific operational times. The test bed also provides a flexible window to alter the test cases and power system architectures to run multiple tests on a single platform.

2.4.1 Previous work

There are certain research efforts performed previously on real time test bed and wide area control and this section of the chapter will highlight a few important works in this area and their limitations.

Authors in [12] presented a working model for remote hardware loading studies over the World Wide Web. The developed model consists of two sections, power system infrastructure and modules for testing software and communications which are helpful in conducting the test from remote location. Authors in [13] also present a different approach to computerized data acquisition for power system automation by simulating a power system prototype for data acquisition from several devices involved in the system. The ultimate goal was to develop a better database for power system operation and control. There are other works like [14], but they either depend on software analysis or limited hardware tests. The limitations of such works are that the power system architectures cannot be drastically altered due to limitations of hardware; these works do not incorporate the synchrophasor devices for real-time operation. They also provide only a minor study on security protection with a password authorization which is vulnerable in this modern internet age.

Industrial practices of synchrophasor applications are rapidly making strides as compared to the previous years. The North American SynchroPhasor Initiative (NASPI) a combined effort of North American Reliability Council (NERC) and Department of Energy (DOE) along with other vendors and utilities are primarily responsible for this advancement. The main vision of this group is to improve power system reliability through wide-area measurement, monitoring and control [15]. The utilities for the most part in the past are equipped with only few PMU installations and are rarely used for their critical applications, but with recent Smart Grid initiative and the increasing awareness of PMU applications has led to a rapid development and deployment of PMUs in the power grid. The latter part of this research work demonstrates an application of synchrophasors for wide-area measurement and monitoring of power system network.

The current research work incorporates all the basics of the previous efforts to certain extent and enhances the test bed development by incorporating the following advantages:

1. The developed test bed possesses the flexibility to carry out multiple tests on different power system architectures.
2. It prototypes the actual power system very closely by including the remote control center and redundant control elements in case of failures.
3. It acts as single platform for testing different relays, PMUs and PDCs.
4. It includes a data historian for monitoring and archiving all the power system data, including the synchrophasor messages.

2.5 Hardware and software tools employed

This section of the chapter provides an overview of the hardware and software tools employed in the development of the test bed.

2.5.1 RTDS and RSCAD

The Real Time Digital Simulator (RTDS) is an electromagnetic transient based system power system simulator which simulates power system models in real time. This is unique in the sense that it utilizes parallel processing technique of digital signal processors and executes the program developed on its processors and produces output both graphically and through the output interface cards incorporated into the system. Power system programs are developed using RSCAD user interface which is specially designed for RTDS and is used for both development of the different power system scenarios and also for viewing and studying the results graphically [16].

RSCAD provides the main interface for RTDS and is a powerful tool. Users can build different power system test cases using RSCAD and then simulate them on RTDS. The software consists of many common power system components in its library along with different control components [17]. RSCAD has three main components:

1. The file manager window through which users can access previously developed programs and other files.
2. The draft window in which the power system model is built using the available components.
3. Finally the run time window which produces the real time output for the users through multiple plots and meters.

The RTDS present in the research lab at Mississippi State University consists of two racks with eight triple processor cards and two Giga processor cards, in addition it contains several input and output interface cards for sending and receiving analog and digital signals. One of the important interface cards used in this work is the Digital to Analog Converter Card (DDAC) from which 12 signals can be sent out of the RTDS;

front panel inputs can also be used to send the digital control signals into the RTDS to control the elements in the simulated power system. Figure 2.2 shows the Real Time Digital Simulator at MSU.

Figure 2.2 RTDS at MSU power and energy research lab

2.5.2 National Instruments hardware and software

National Instruments PCI eXtension Interface system (NI-PXI) is a real time embedded controller from National Instruments used for real time testing purposes. Built on the PXI architecture which is an open PC-based platform for test measurement and control [18], this system is a low cost high performance model used in various technologies. The system consists of three main components: chassis, system controller and peripheral modules. The chassis provides a rugged and modular packaging for the system, it also contains the high-performance PXI backplane, which includes the PCI bus, timing and triggering buses.

The NI-PXI system at the MSU research lab shown is in Figure 2.3. It is a standard 8 slot 1084Q chassis consisting of a NI-PXI 8196 Embedded Controller and two

I/O 6608 and 6251 cards responsible for sending and receiving analog and digital signals in and out of the controller. The controller is a stand-alone system running a program written in LabVIEW software.

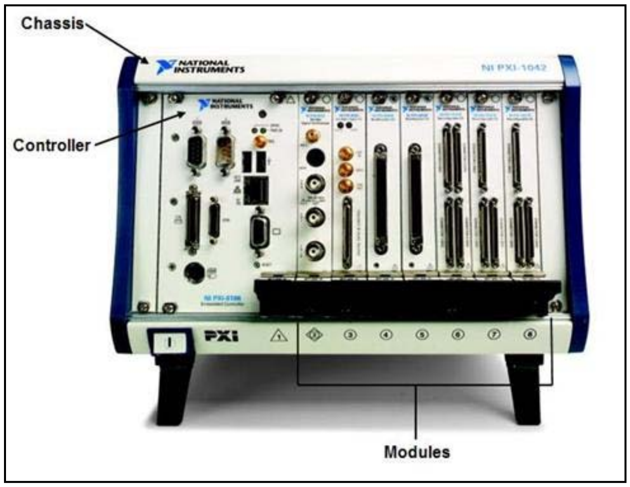

Figure 2.3 NI-PXI system with 8 slot chassis [19]

The NI-PXI 8196 real time controller is installed in slot 1 of the chassis. The 8196 controller is a high performance Pentium M processor and is equivalent to the 3.0 GHz Pentium 4 system [18]. The controller comes integrated with express card slot, GPIB interface, and four USB ports. The communication channels include serial, parallel and high Ethernet ports. The controller is the core of the NI-PXI system and runs on Windows or LabVIEW real time operating system. When the system boots up, the controller recognizes all the peripherals and initiates the start of the embedded program for real time simulation. Figure 2.4 shows a NI-PXI 8196 controller.

Figure 2.4 NI-PXI 8196 Real time controller [18-19]

The peripherals included in the system are the NI-PXI 6251 and 6608 data acquisition cards. These cards are used as main interfaces for sending analog power system data out of the RTDS and for sending digital control signals into the developed power system. The NI-PXI 6251 shown in Figure 2.5 is a National Instruments M series multifunctional DAQ card capable of operating at maximum data acquisition rate of 1.25 M samples/sec. It includes analog and digital triggering along with 16 analog input channels, two analog outputs and 24 digital I/0 channels.

Figure 2.5 NI-PXI 6251 Analog input DAQ card [18-19]

The National Instruments PXI-6608 is a high precision timing and digital I/O module with eight 32-bit counter/timers and 32 lines of digital I/O. The NI PXI-6608 features a 10 MHz oven-controlled crystal oscillator for high-precision applications. This interface card is particularly used in the current work for sending digital control signals from external devices to the power system simulation running on the RTDS for real time control. The NI-PXI 6608 is shown in Figure 2.6.

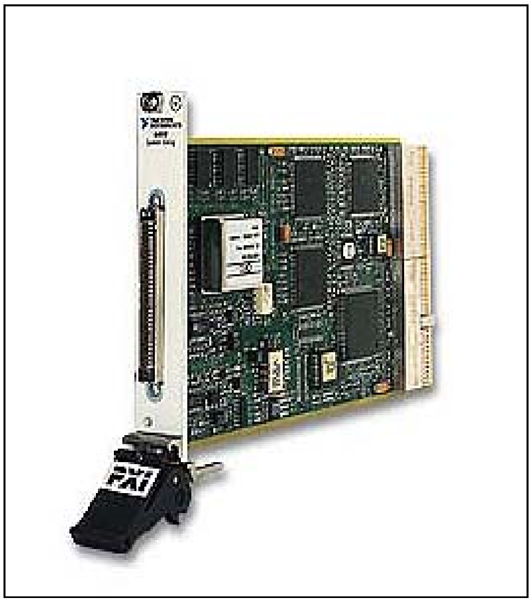

Figure 2.6 NI-PXI 6608 Digital I/O card [18-19]

National Instruments LabVIEW is used as the main software interface tool for establishing operational functionality between different devices. LabVIEW stands for Laboratory Virtual Instrument Engineering Workbench. It is a user-friendly graphical programming language used to develop applications for measurement and control. The applications developed in LabVIEW are called Virtual Instruments (VIs) due to their similar appearance and operation to the real world instruments.

A LabVIEW VI contains two main parts,

- Block Diagram
- Front Panel

The block diagram is the actual executable program written using different components which are connected using connectors. The front panel is essentially a user friendly interactive interface consisting of controls and indicators which display the output of the program after execution. The block diagram is written by using different blocks of code varying from simple addition block to complex signal processing blocks. The VI method of developing application is very powerful as it provides a visual execution of the written code and is easy to debug. The front panel can be user defined and is made as simple as possible with good visual constructs to analyze the output easily and efficiently. The following Figure shows the two main parts of LabVIEW,

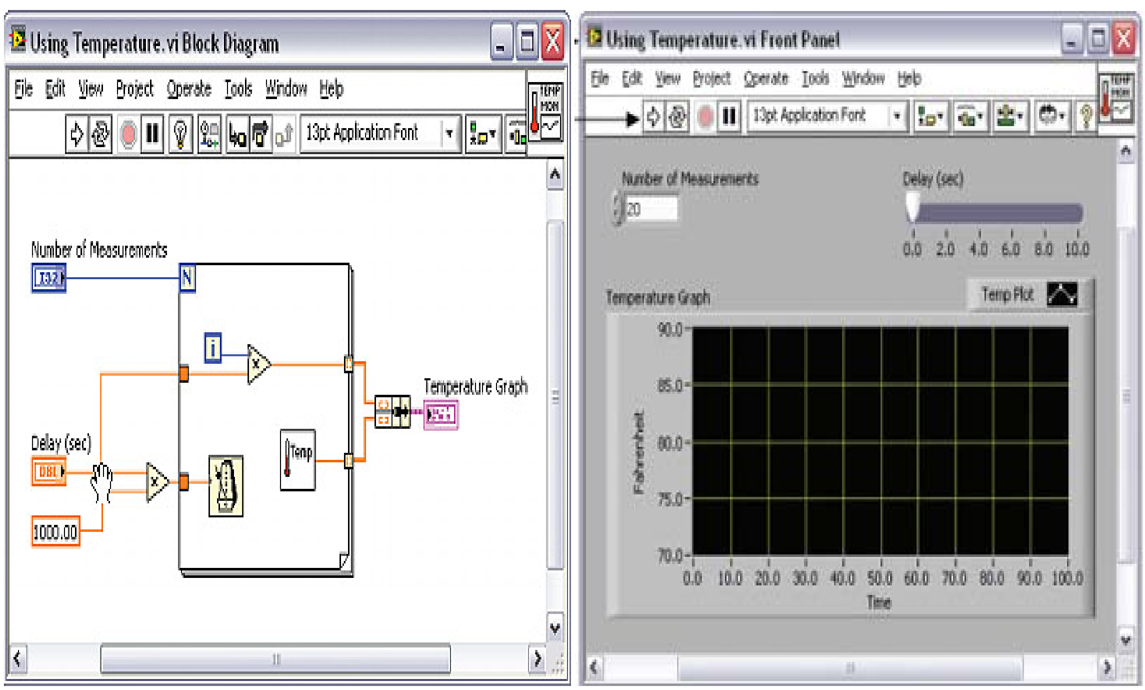

Figure 2.7 LabVIEW block diagram and front panel [18]

The Measurement and Automation Explorer (MAX) is the simplest and the best way to access and manage NI hardware. It manages all the hardware including any real time controllers and the software installed on the controllers. The I/O cards can be accessed and tested from the MAX interface. It acts as the main interface between the host and the remote targets. The MAX user window is shown in the following Figure 2.8.

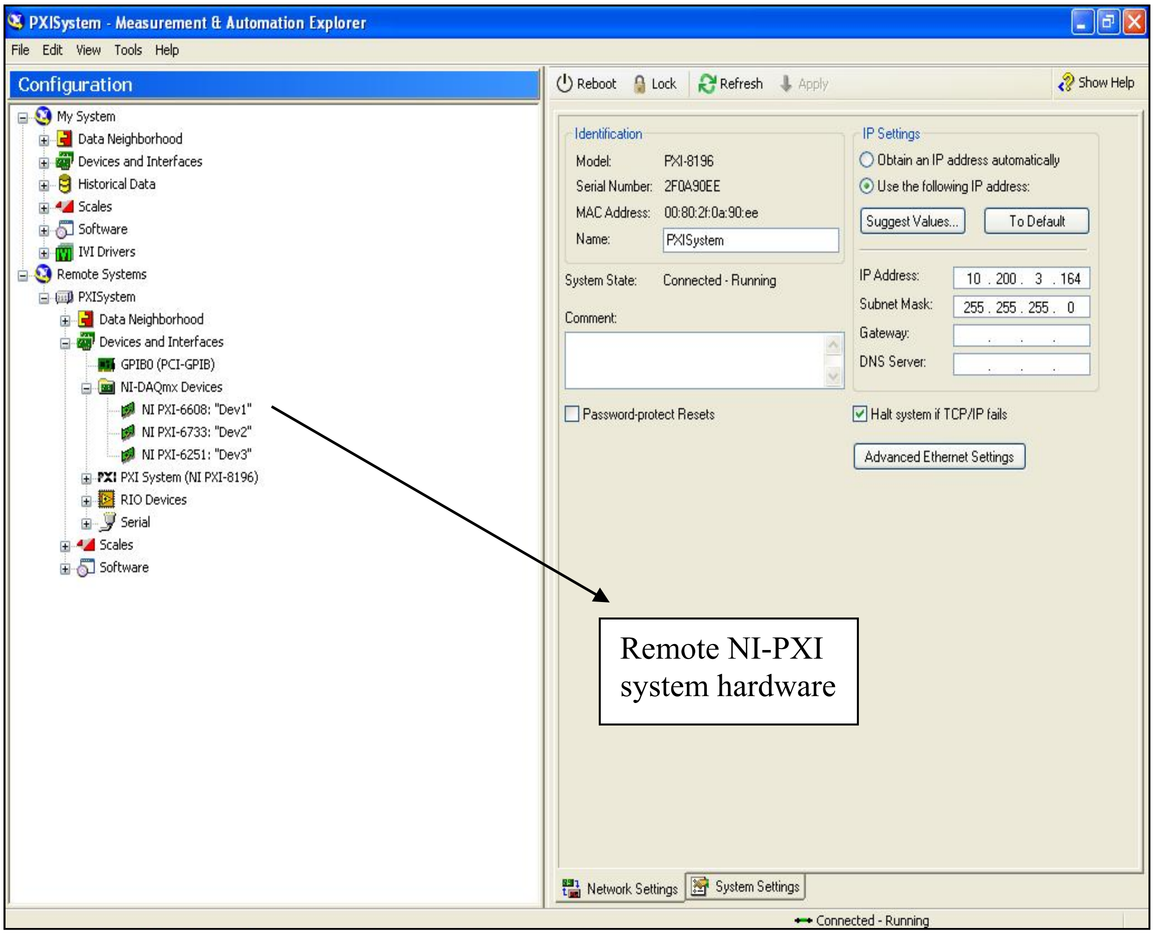

Figure 2.8 MAX software user window

The drop down menu on the left of the MAX user window provides a list of all the available hardware and software installed locally and remotely. The right side window panel is pointing to the remote PXI target IP settings for communication.

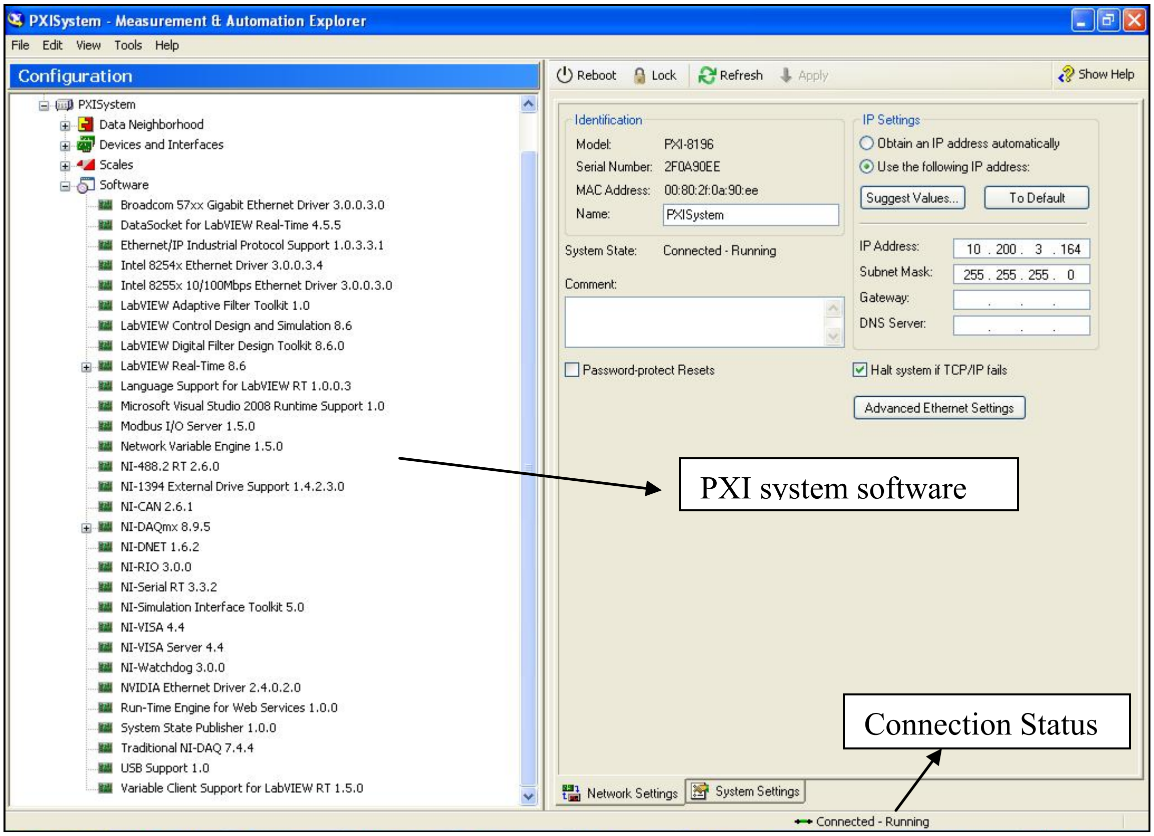

Figure 2.9 MAX window displaying remote system configuration

2.5.3 Allen Bradley Compact Logix and RSLogix 5000

Allen Bradley Programmable Automation Controllers (PACs) are highly integrated systems providing a single control architecture for discrete, drives, motion and process control systems. The PAC system used in the current work is THE Compact Logix L35E system. Compact Logix provides the benefits of a common programming environment, common networking protocols, and a common control engine in a small footprint with high performance [20]. The Compact Logix 1769-L35E system is connected to the Ethernet network through an integrated port for real time applications. This system includes a Programmable Logic Controller (PLC) and I/O modules for control applications and is programmed by using RSLogix 5000 software.

Figure 2.10 Allen Bradley Compact Logix system [20]

RSLogix 5000 is a simple easy to use integrated software suite for programming PLC applications. RSLogix 5000 software offers an easy-to-use, IEC61131-3 compliant interface, symbolic programming with structures and arrays and a comprehensive instruction set that serves many types of applications. It provides ladder logic, structured text, function block diagrams and sequential function chart editors for program development.

2.5.4 SEL hardware

This section of the chapter provides a background view of the Schweitzer Engineering Laboratories (SEL) hardware used. The devices integrated in the test bed are the SEL 421 Relay/PMU, the SEL-3306 PDC and the SEL-2407 GPS clock.

2.5.4.1 SEL 421 and AcSELerator

The SEL-421 is a Protection Automation and Control System consisting of relay based functionality along with synchrophasor measurements. The SEL-421 is a fully advanced automation system with integrated Ethernet, DNP3 and IEC 61850 protocols for communications [21]. It also has provision for GPS clock input for synchrophasor application and provides Digital Fault Recording (DFR) with COMTRADE output format. AcSELerator Quick Set software is used to communicate with the device to download event reports using FTP and Telnet and also to alter device settings. The SEL 421 system is implemented in the test bed as a Phasor Measurement Unit for providing synchrophasor messages in compliance with IEEE C37.118 standards.

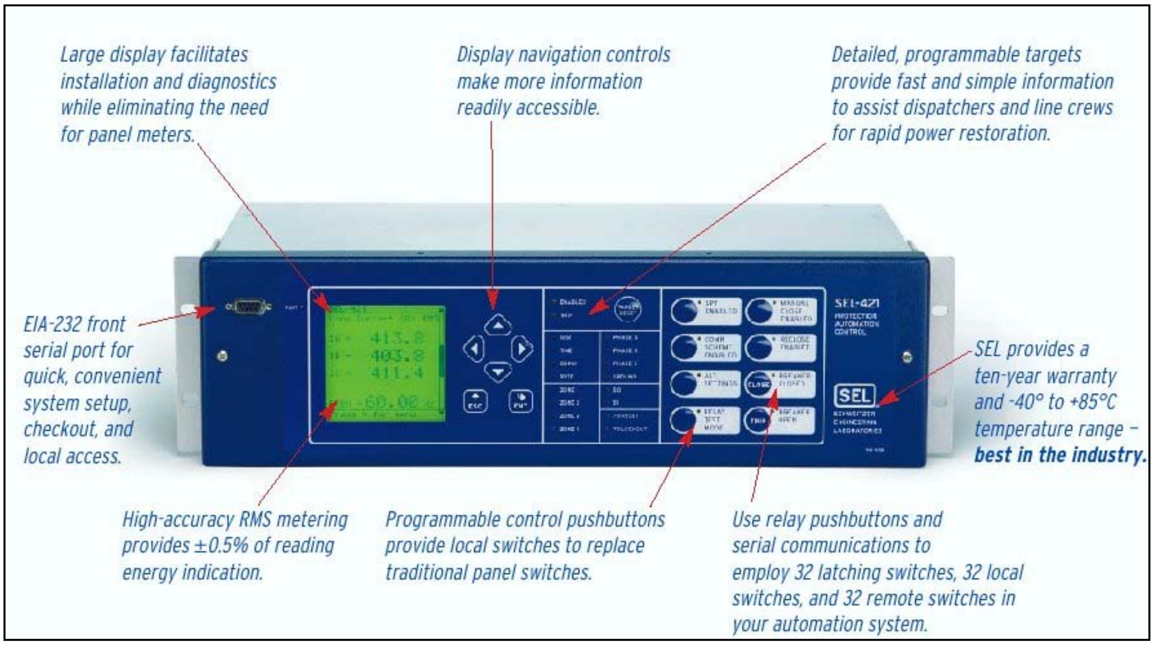

Figure 2.11 SEL-421 Protection, Automation and Control system [21]

2.5.4.2 SEL-3306 PDC

The SEL 3306 is known as the Phasor Data Concentrator because it collects synchrophasor measurements from a number of PMUs and sends them to external devices. This PDC simplifies the task of gathering data from different PMU stations by the central computer without actually connecting to each PMU. The key features of the SEL 3306 include synchrophasor data concentration, protocol conversion, and media conversion in a rugged, station-hardened device [21]. The PDC present in the MSU Power and Energy research lab is capable of connecting to 15 PMUs devices serially and 40 devices over Ethernet. It also transmits phasor data to six external devices simultaneously and has a provision for IRIG-B connection. The synchrophasor messages can be collected as IEEE 37.118, IEEE 1344, and SEL Fast Message protocols, and can be converted to other formats for transmission. The 3306 system has a simple browser interface for interacting with device settings and also for visual streaming of the synchrophasor data. The following figures show the front panel and the browser interface of the system.

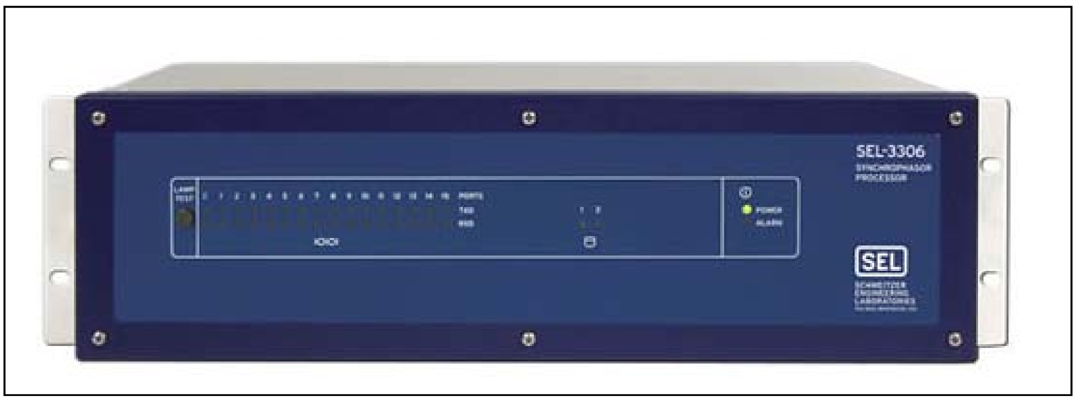

Figure 2.12   SEL 3306 Phasor Data Concentrator [21]

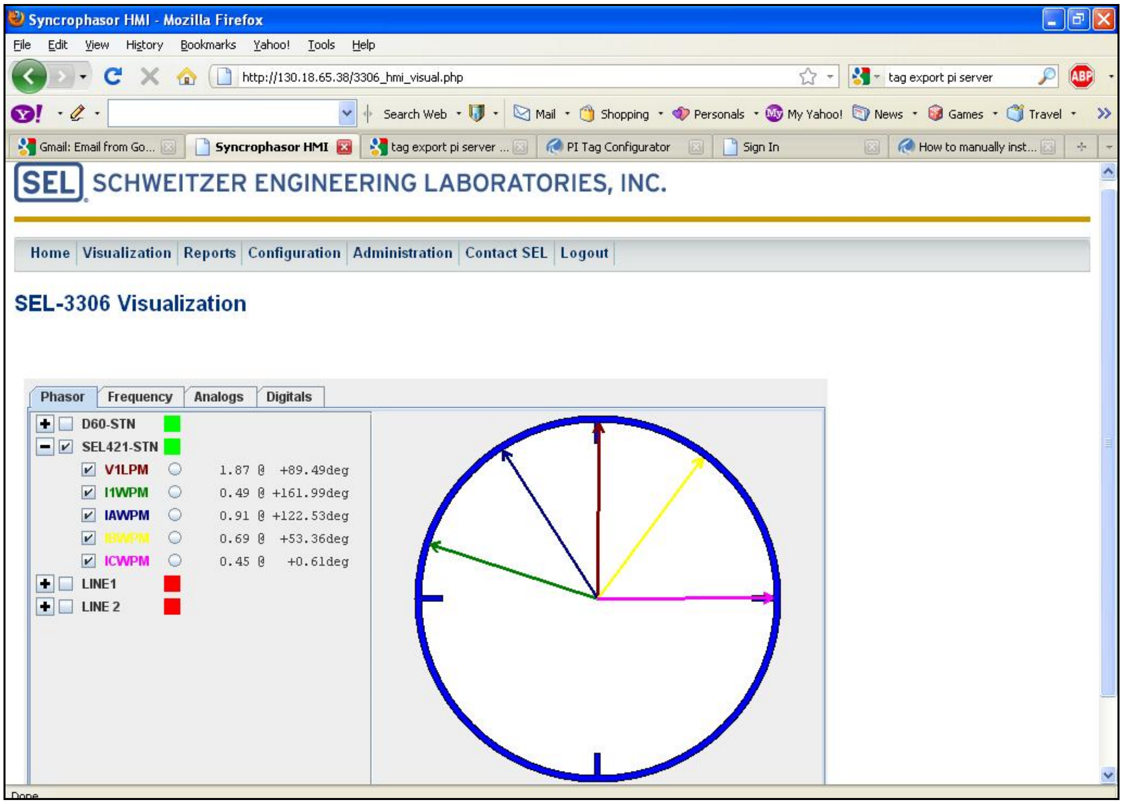

Figure 2.13 SEL 3306 Synchrophasor visualization window

2.5.4.3 SEL 2407 Satellite synchronized clock

The SEL 2407 is highly accurate, reliable and precise satellite synchronized clock. The clock is accurate to +/-100 nanoseconds. It provides six demodulated IRIG-B time code outputs for synchrophasor applications.

Figure 2.14 SEL 2407 Satellite synchronized clock [21]

2.5.5 GE PMU and Enervista

This section of the chapter provides background information on the GE hardware and software applied in the test bed development.

Enervista is a software suite for configuring and managing all devices in GE Multilin product line for power system applications. It provides an intuitive GUI interface where users can connect with any GE Multilin device and, can monitor and control the device applications. This suite is primarily used in the current study for configuring the GE hardware for monitoring and transmitting synchrophasor data. Figure 2.15 shows the user window of the Enervista software suite.

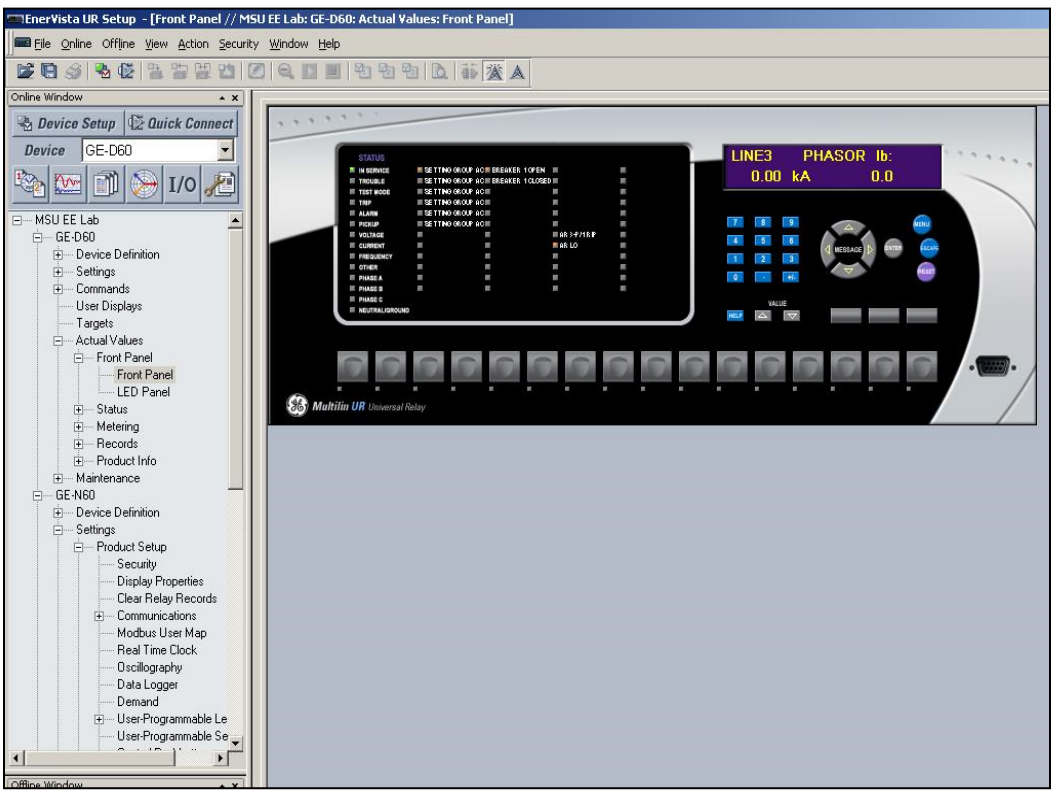

Figure 2.15 Enervista user interface

2.5.5.1 GE-D60 Line distance relay and PMU

The D60 is a high-end, cost-effective distance protection relay intended for protecting transmission lines and cables which provides reliable and secure operation [22]. The D 60 is used for different distance tele-protection schemes as it is primarily operated as a distance relay. It is implemented in the test bed as a synchrophasor measurement device, to provide data according to IEEE C37.118 protocol over Ethernet.

Figure 2.16 GE D60 Line distance relay and PMU [22]

2.5.5.2 GE-N60 PMU

The N60 Network Stability and Synchrophasor Measurement System is a flexible device intended for the development of load shedding, remedial action, special protection schemes, and wide area monitoring and control [22]. The N60 system is capable of performing communications over DNP3, MODBUS, IEC 61850 and Ethernet. This system provides additional functionality of event recording, synchrophasor data storage and advanced automation. The N60 system at MSU consists of two phasor measurement units capable of providing synchrophasor data in real time over Ethernet. The system sends synchrophasor data over Ethernet network either in UDP or TCP/IP communication protocol to external devices.

2.5.6 OSI PI Historian

Monitoring and archiving large quantities of power system data in real time using traditional database techniques is tedious and time consuming. The OSI Soft PI historian is a state-of-the-art data monitoring and archiving software for managing large amounts system data which has been successfully implemented in power system industry in recent times. The PI system acts as a highly reliable repository for monitoring and archiving synchrophasor data. For MSU PERL research, the PI system is used as the main tool for monitoring real-time power system data, archiving it for later investigative studies and for that reason it proves very beneficial. The following Figure 2.17 shows a general architecture of PI system in real world.

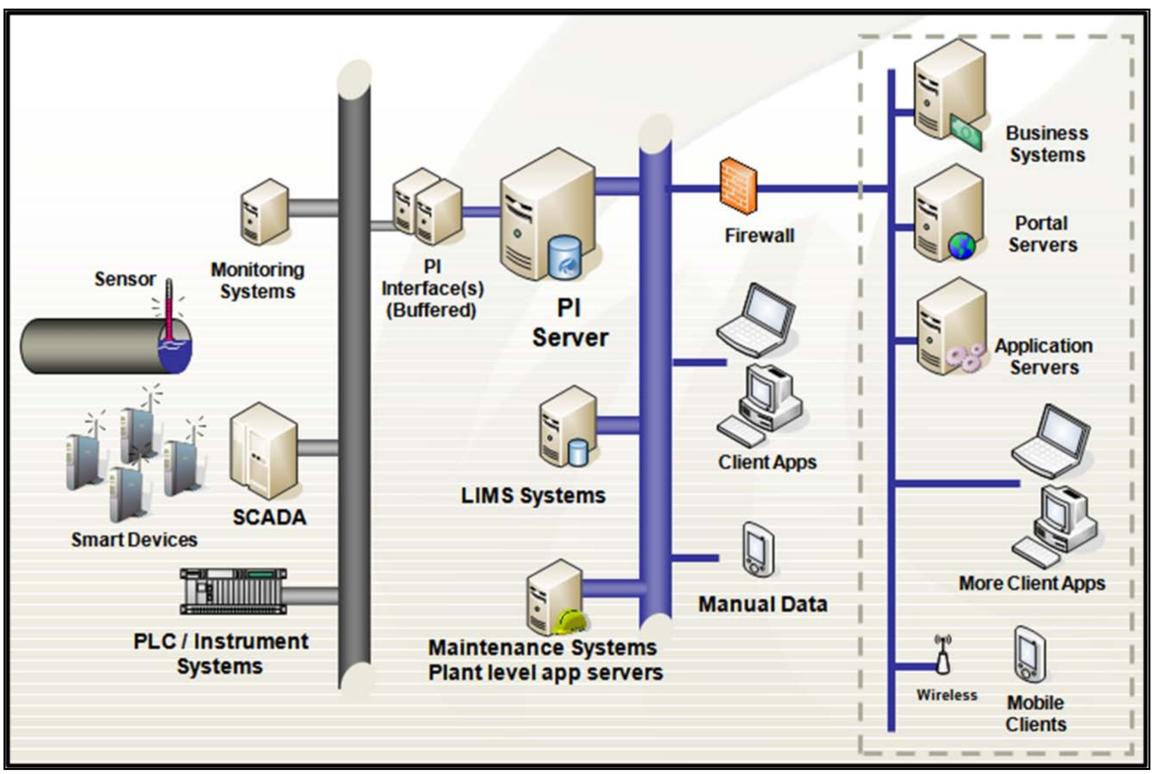

Figure 2.17 PI system architecture in an industrial setting [23]

2.5.6.1 PI OPC interface

OPC (OLE for Process Control or Open Connectivity) is a standard established by the OPC Foundation to allow applications to access plant floor process data in a consistent manner. The PI OPC interface is configured using the PI Interface Configuration Utility (PI ICU) to acquire data in the OPC standard industrial protocol. The PI OPC interface is used in this project for sending and accessing power system data from the Programmable Logic Controller for monitoring and archiving purposes.

2.5.6.2 PI C37118 interface

The PI C37.118 interface is developed by OSI Soft for handling the synchrophasor data from power system applications. The PI system collects the IEEE C37.118 standard synchrophasor data in real time at preconfigured message rate by running this interface. In the current work, this interfaced is configured to handle data coming from four phasor measurement units at a rate of 60 msg/sec. It currently handles 283 tags coming from different devices, and is capable of trending them in real time.

2.5.6.3 PI system management tools

The PI System Management Tool (PI SMT) suite is the core of the PI system. The PI SMT consists of different subcomponents for configuring the data and security features of the PI system. Key features include point builder for creating new data tags, current values, PI security keys, operations, and alarms. The PI SMT includes a connection manager for establishing a connection between the PI host server and the client server. Each connection is created in the host by providing trust authentication for the incoming connection, and is highly secure. The point builder is used to create new tags from scratch based on their data type and interface source type.

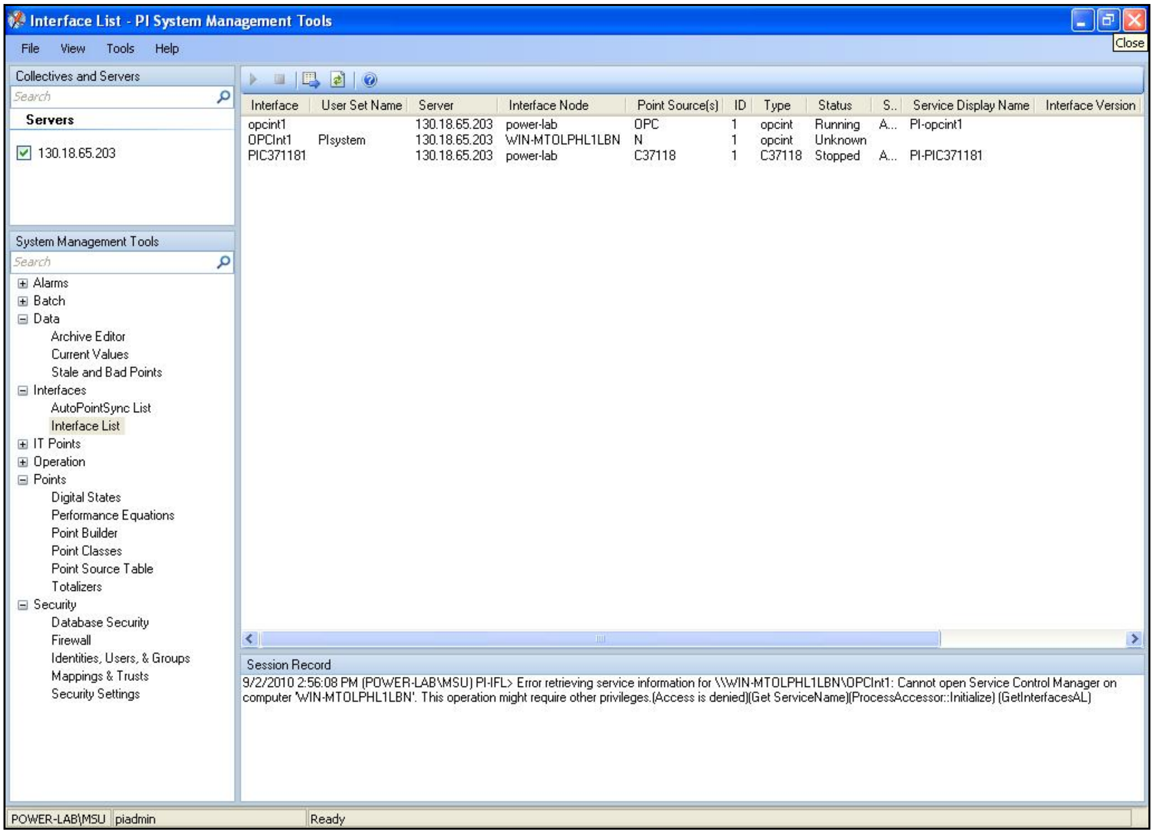

Figure 2.18 PI system management tools window

2.5.6.4 PI process book

The PI Process Book is a user friendly display interface tool for visualization of PI system data. It is used to create real time trends and other graphical displays which can be populated with live data for monitoring applications. It efficiently displays data residing in the PI system and other sources with ease and demonstrates wide functionality in exporting the data in different industry standard formats. The current work utilizes the Process Book to monitor and archive power system data along with synchrophasor messages. The Process Book provides a powerful interface to monitor and perform calculation on real time synchrophasor data.

2.5.7 PMU connection tester

The PMU connection tester is an open-source software tool developed by the Tennessee Valley Authority (TVA) for testing the data streaming from phasor measurement devices. It is a simple, yet powerful tool and is capable of handling IEEE C7.118, IEEE 1344, BPA PDC stream, SEL fast messages and Macrodyne protocols. This tool has the added functionality of capturing the synchrophasor data, configuration file, and also contains a playback option for viewing test data.

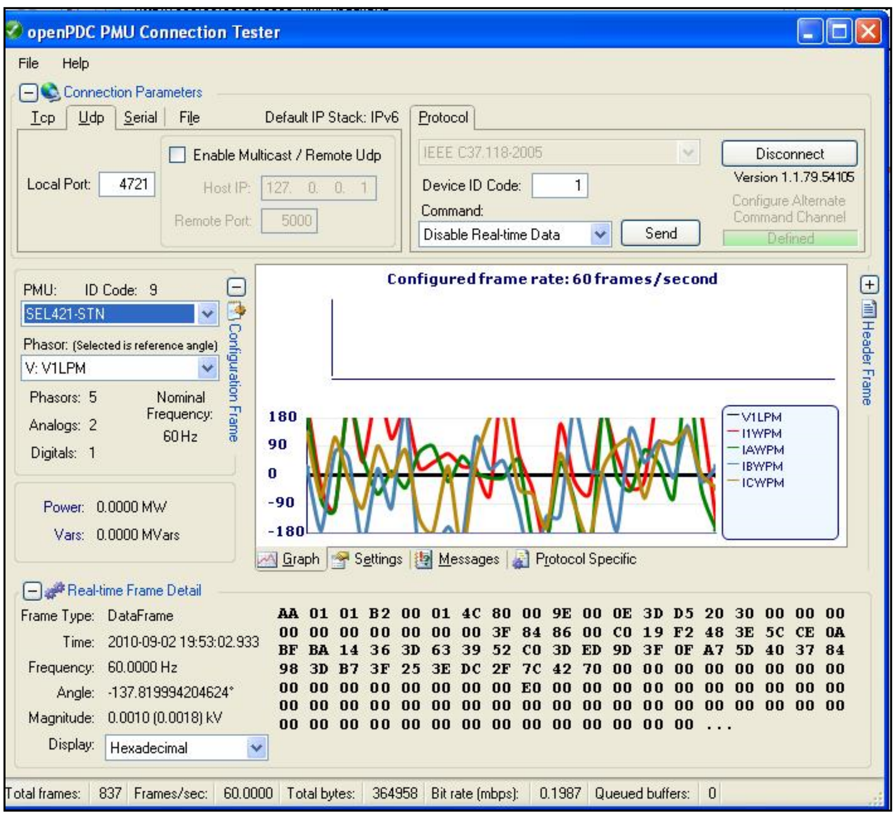

Figure 2.19 PMU Connection tester software tool

2.5.8 Wireshark

Wireshark is a network protocol sniffer used to analyze bidirectional Ethernet traffic through a PC. It is the most widely used application for performing laboratory testing and for analyzing common network protocols. The important features of the tool include high speed live data capturing, offline analysis, and filtering of different protocols while capturing. Wireshark is extensively used in the current work for studying synchrophasor messages, transmission and reception port addresses, and for analyzing network security issues.

Table 2.1 List of hardware used

	Name
1.	Real Time Digital Simulator (RTDS)
2.	NI PXI 8196 Controller
3.	NI DAQ Cards 6733, 6608
4.	SEL 421 Phasor Measurement Unit
5.	SEL 3306 Phasor Data Concentrator
6.	SEL 2407 Satellite Synchronized Clock
7.	GE D60 Line Distance Relay and PMU
8.	GE N60 Phasor Measurement Unit
9.	Allen Bradley Compact Logix L35E System

Table 2.2 List of software used

	Name
1.	RSCAD 2.010.3
2.	LabVIEW Real Time 8.5
3.	Measurement and Automation Explorer 4.7
4.	AcSELerator Quickset Software 4.9
5.	RSLogix 5000
6.	PI System
7.	PMU Connection Tester
8.	Wireshark
9.	Allen Bradley Compact Logix System

CHAPTER III

DEVELOPMENT OF TEST BED AND RESEARCH CHALLENGES

3.1 Overview of test bed architecture

The development of the power system test bed for executing real time simulation is the major task of the current work. There are several steps proposed for the test setup to provide real time simulation, wide area monitoring and control in real time. The test bed developed at MSU is designed to meet the following requirements:

1. A very close representation of the actual power system with real world power system and control components integrated into it.
2. Flexible enough to conduct different software and hardware in loop simulations in real time with interoperability.
3. Uses an easily adaptable Ethernet/IP and other communication system with possible studies of cyber security issues.
4. Provides a monitoring and control interface for remote operations.
5. Stores the power system data for monitoring and for subsequent investigative studies.

The integration of various hardware devices is done through Ethernet, serial port connection, radio signals or a hard wired connection. Power system test cases are developed in RSCAD and executed on the RTDS. Scaled signals from the simulated system are sent to the PLC which is integrated with RTDS using the NIPXI system. As there is no direct connection procedure devised to connect Allen Bradley Compact Logix

PLC with RTDS, the NI-PXI system is used for interconnection and monitoring power system data. The block diagram of the developed test bed architecture is shown in Figure 3.1.

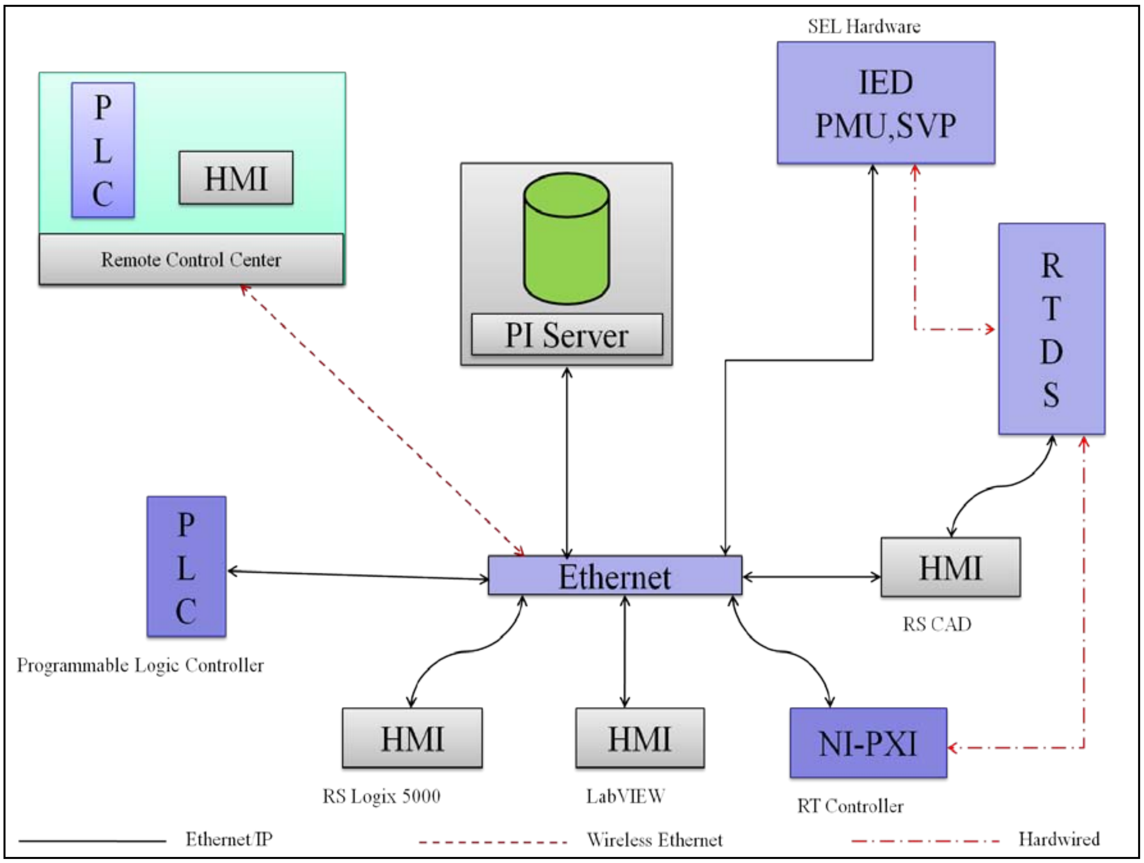

Figure 3.1 Developed test bed architecture

As Figure 3.1 illustrates, a remote control center is installed with Compact Logix PLC and HMI for remotely monitoring the data and sending the control commands over the wireless Ethernet. RTDS signals are hardwired to the SEL devices such as PMUs for monitoring the system and fault protection. In similar manner, the PLC is connected to the NI- PXI through the DDAC cards on the RTDS and the DAQ cards on the PXI system. The control logic is written using the RSLogix 5000 tool for both the local and remote PLC's. The NI-PXI uses Ethernet/IP suite available in LabVIEW to write and read data from the PLC data tags by directing the system to PLC IP address. The HMIs shown in Figure 3.1 are the corresponding software suites needed for the hardware operation. One important part of the test bed is the PI server system which is connected to the same Ethernet switch and acquires the system data in real time. The data acquisition is done by the PI server OPC interface. The RTDS data is accessed from the LabVIEW using OPC protocol, and the PMU (Figure. 3.1) data can be accessed by C37.118 interface installed on one of the systems. The detailed development and operation of the test bed is explained in the subsequent sections of this chapter.

3.2 Data transfer between RTDS and external devices

The RTDS presents different output options for sending data to external devices. The Triple Processor Card (3PC) and the back panel converter cards are used for analog data transfer from the RTDS. The interface panel inputs provided for the RTDS are used for sending digital control signals into power system simulation for breaker controls. The RTDS is interfaced with the PLC using National Instrument's NI-PXI system and DAQ hardware for mutual data transfer. The NI system is used to facilitate integration of RTDS with PLC and also for providing an intermediate level monitoring platform. The following section explains the several steps involved in this setup.

3.2.1 Connections to the NI-PXI system

A general hard wired connection is provided from the RTDS 3PC analog output ports to the SCB 68 I/O connector block, after enabling the ports in the RSCAD simulation. The connector block is further connected to the NI-PXI system using the proprietary National Instruments standard cables provided. The PXI system houses the

6251 and 6608 I/O which acquires analog data and sends digital control signals to the PXI system. The current setup consists of six outputs from the GPC expandable up to 48 connections and two incoming digital signals that are enabled in the interface panels.

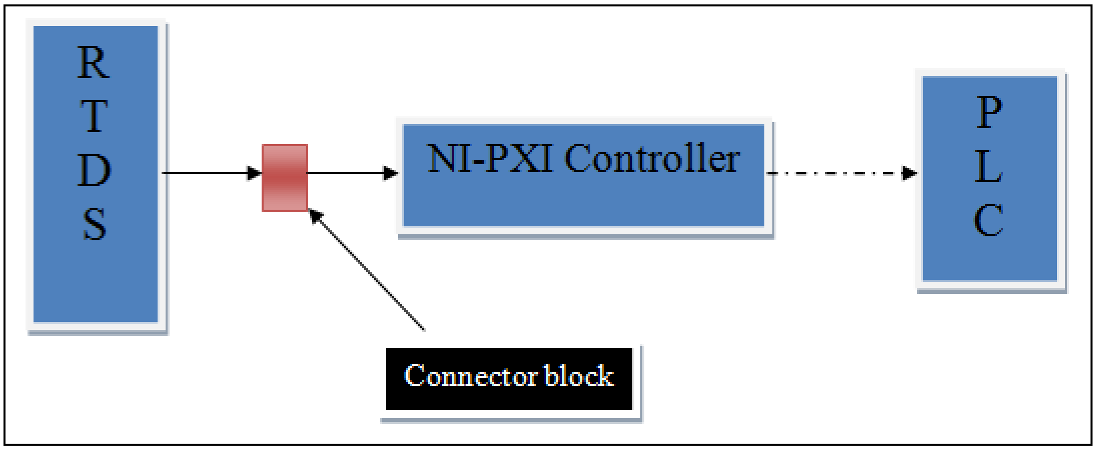

Figure 3.2 RTDS to PLC connection outline

The SCB 68 is the connector block used for connecting the PXI DAQ cards with the analog output wires from RTDS. Quick reference labels from NI are used to provide the necessary connections. The M series and 66XX label guides provide the required connection specifications. The SCB 68 uses Reference Single Ended (RSE) [24] configuration modes for providing the connections to GPC analog output ports and the differential mode for the digital inputs to the RTDS. The following Figures 3.3 and 3.4 illustrate the connection described:

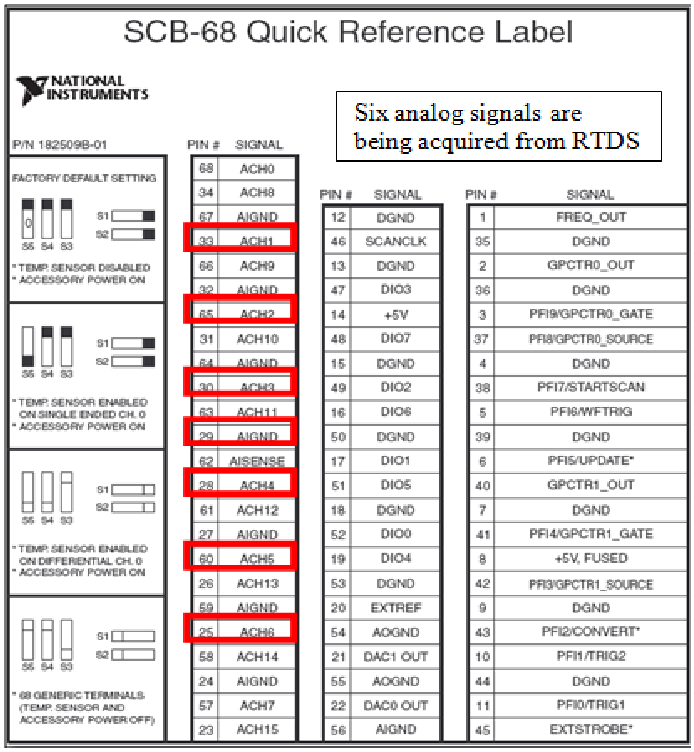

Figure 3.3 SCB 68 Channel connections for NI-PXI 6251 [24]

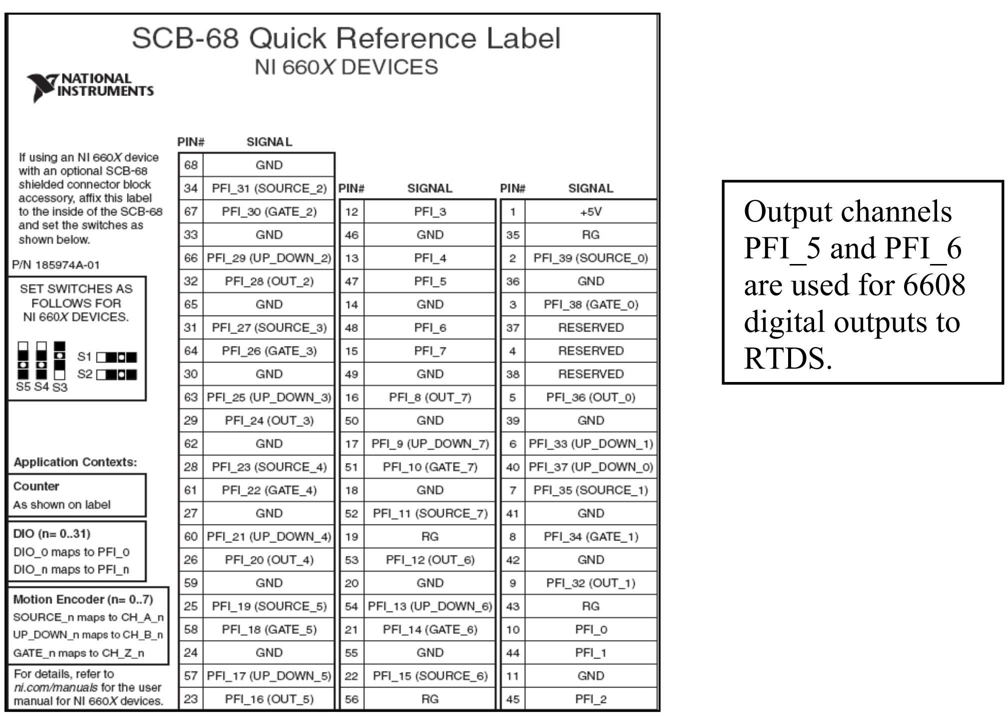

Figure 3.4 SCB 68 connections for NI 6608 [24]

3.2.2 National Instruments PXI system

The NI-PXI system is a real time controller with embedded developed VI's for several possible applications. The Ni-PXI system setup is configured using the NI Measurement and Automation Explorer (MAX) software. The system is connected to PC-running LabVIEW software through Ethernet/IP. The controller running on windows OS is configured an IP address for communication with LabVIEW from MAX window. The MAX interface is used to install the required software and for connection monitoring with the PXI controller. The following Figure 3.4 shows a visual image of the setup menu.

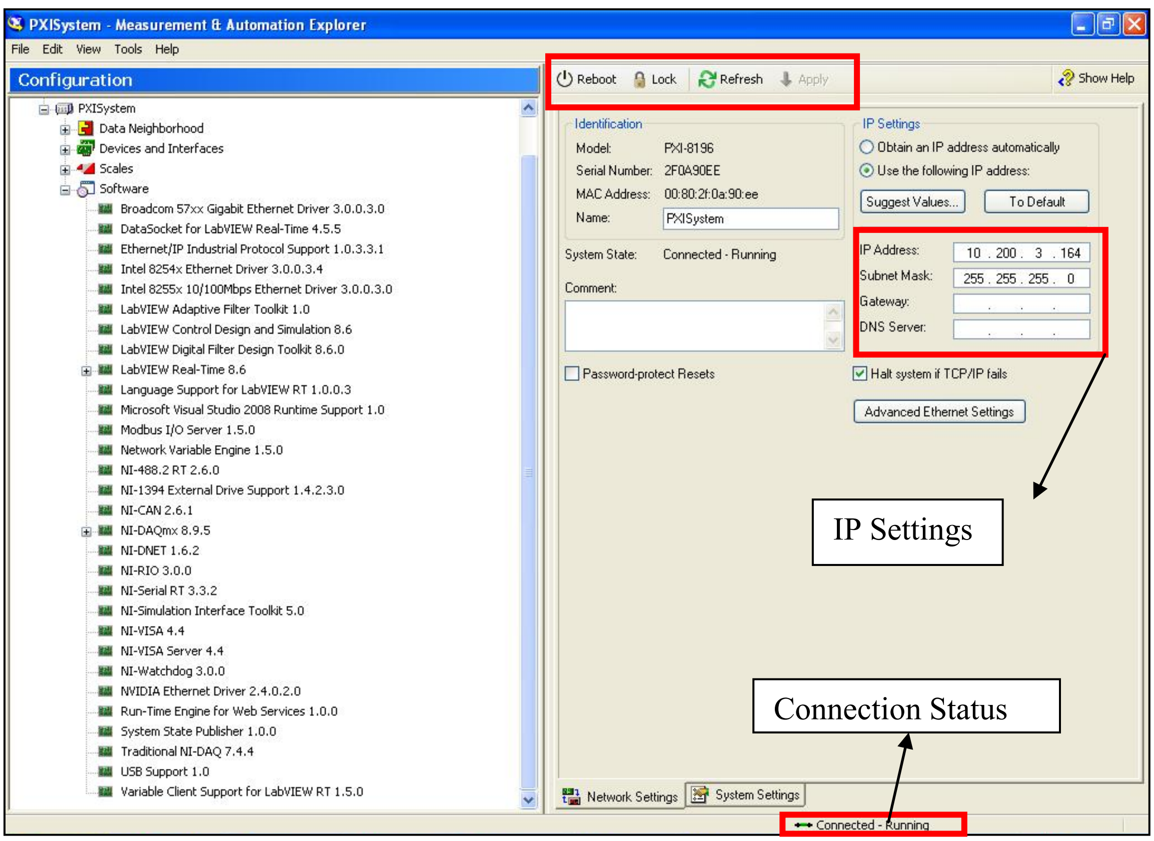

Figure 3.5 PXI setup window in MAX interface

The PXI system is first installed by adding a new remote device, and identifying the NI hardware devices. The IP settings are then entered in the MAX system setup window for PXI communication and the device is rebooted. The connection status is observed as shown in Figure 3.5, and the recommended software is installed after right clicking the device on the left pane in the MAX window. The devices and interfaces tree is also expanded to check for necessary hardware installed on the system.

3.2.3 LabVIEW modeling

LabVIEW is the software HMI implemented for developing a VI for data transfer between RTDS and the PLC system. The developed LabVIEW model acquires the analog data from RTDS using an in built DAQ assistant component. The analog data is displayed continuously and also written to the PLC. The analog data from RTDS is converted to OPC data and written to the PLC using the Ethernet/IP industrial communication driver provided by National Instruments. The driver provides a simple VI component to which data is written in LabVIEW by pointing to the device IP addressing. The data from PLC is also read into the LabVIEW VI in a similar manner. The following Figure 3.6 shows the overview of developed LabVIEW model.

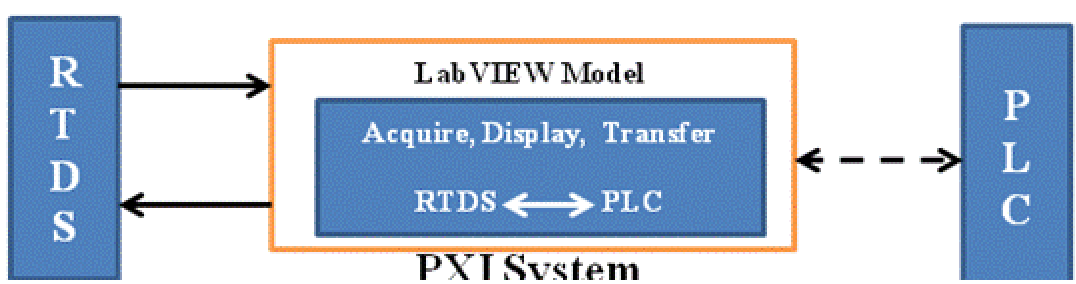

Figure 3.6 Implemented LabVIEW model

3.3 Integration of PLC and remote control center

The PLC system present in the MSU PERL is commissioned as local control station for the test bed, and a remote control center is established in another different physically located MSU Department of Computer Science and Engineering building. The remote control is essentially a SCADA lab used for cyber security research studies. The local PLC connects to the remote control center using a wireless Ethernet through the radio network. An antenna system installed on the Simrall ECE building roof top is used for communicating with remote center. The local PLC is connected to an identical PLC in the SCADA lab and exchanges periodic signals in between them. The remote PLC actually acts as a backup to the local PLC and provides all data from the local PLC for monitoring in the remote control center.

3.4 Phasor measurement units integration

The PMU devices are hardwired into the RTDS system to facilitate HIL simulations and for real time monitoring of the simulated power system. The Power and Energy Research Lab (PERL) is equipped with one SEL 421 PMU and three GE PMUs. The SEL 421 is a dual purpose PMU used for both industrial and laboratory applications and is hardwired to the six channels of the RTDS DDAC card. Omicron CMS 156 amplifier is used to amplify the currents and voltages for feeding into the GE PMU devices. The GE PMUs are connected to the RTDS through the amplifier to the RTDS backplane through the remaining six channels. The data is duplicated into the three GE PMUs for testing purposes and the limited availability of the amplifier channels. The PMUs monitor the simulated power system data and transfer the data to the PDC, and display the synchrophasors in their corresponding user interfaces. The following sections explain the PMU connections and settings applied in their implementation.

3.4.1 Connecting cables

Since the development of the test bed involved integrating numerous hardware devices together, it is important to list the details of the connection cables used for the test bed implementation. This section provides essentially a list of connection cables used for synchrophasor measurements with PMUs and PDC.

Table 3.1 Connecting cables

To	From	Cable
SEL 2407 (Clock)	SEL 421	C953
SEL 2407 (Clock)	GE relays	C953 (T Joint)
SEL 421 (PMCU)	Computer (commands)	C234A
SEL 421 (PMCU)	PDC	C276
GE D60 (PMCU)	PDC (data)	Ethernet
GE N60 (PMCU)	PDC (data)	Ethernet
SEL-3306 (PDC)	Computer (commands)	C235
SEL-3306 (PDC)	Computer (data)	Ethernet
PI Interface Client	PDC	Ethernet
PI Server Host	PI Client	Ethernet

The GE PMU and the Omicron amplifier are connected with hard wires labeled sequentially to identify currents and voltages. All the Ethernet connections are provided through a dedicated 100 Mbps Multilin ML2400 managed switch. The OSI PI server host and client are connected to the switch to capture the data for archiving and monitoring.

3.4.2 SEL and GE PMU settings

The SEL 421 is a line distance protection relay with added functionality to provide synchrophasor measurements. First, a serial connection is established to the device and a second level access is achieved to change any setting on the device. The SEL 421 synchrophasor measurements are enabled by setting the ‘EPMU’ to ‘Y’ in the device global settings and the IRIG clock source is checked. The SEL 421 working mode of PMU operation is checked in the terminal window by sending the ‘met pm’ command to the device. The following Figure 3.7 shows the synchrophasor operation in SEL 421.

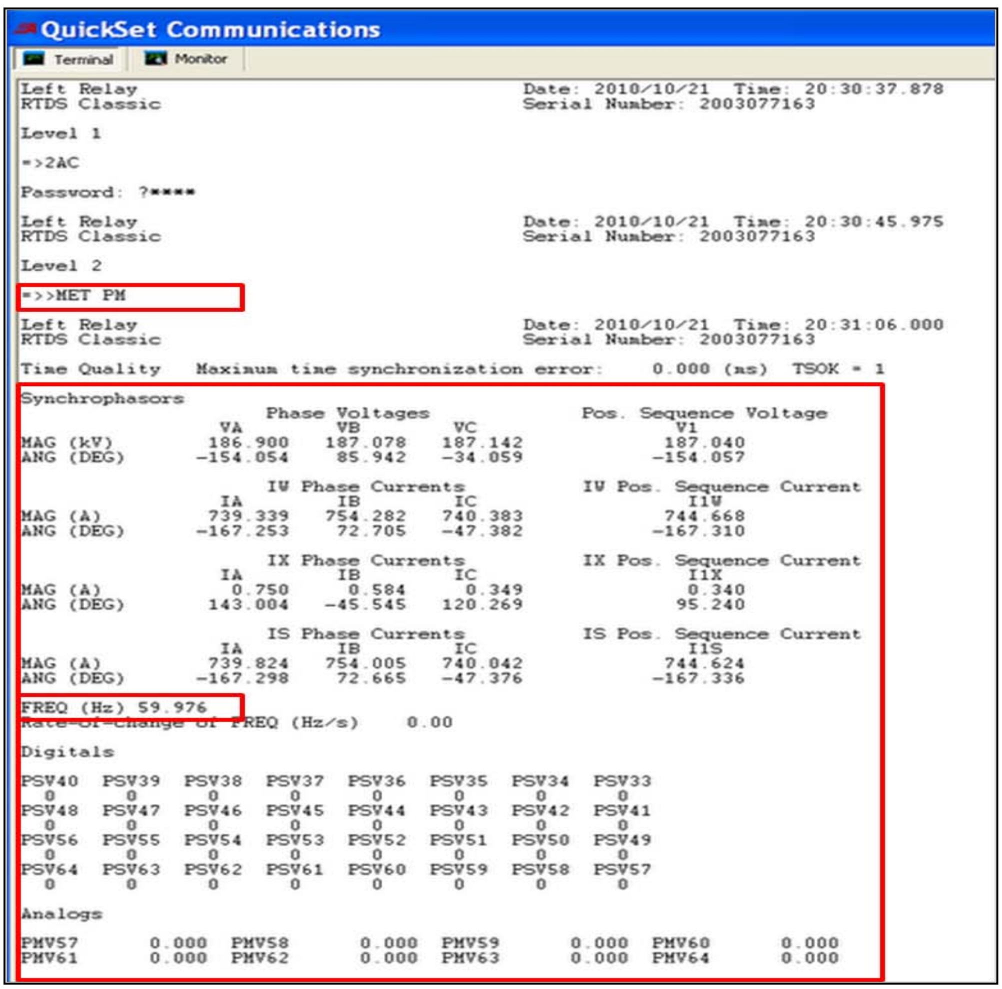

Figure 3.7 SEL 421 PMU status through MET PM command execution

The GE N60 is a network protection system and GE D60 is a line distance protection system. The devices are capable of providing synchrophasor measurements and sending the data to external devices. The software interface to enable synchrophasor measurement settings is basically the same for both the devices, EnerVISTA software is used for this purpose. The settings include enabling the scaling factors for the CT and PT measurements, and also for transmitting data externally to the Phasor Data Concentrator. The following Figures 3.8 and 3.9 show the GE PMU settings.

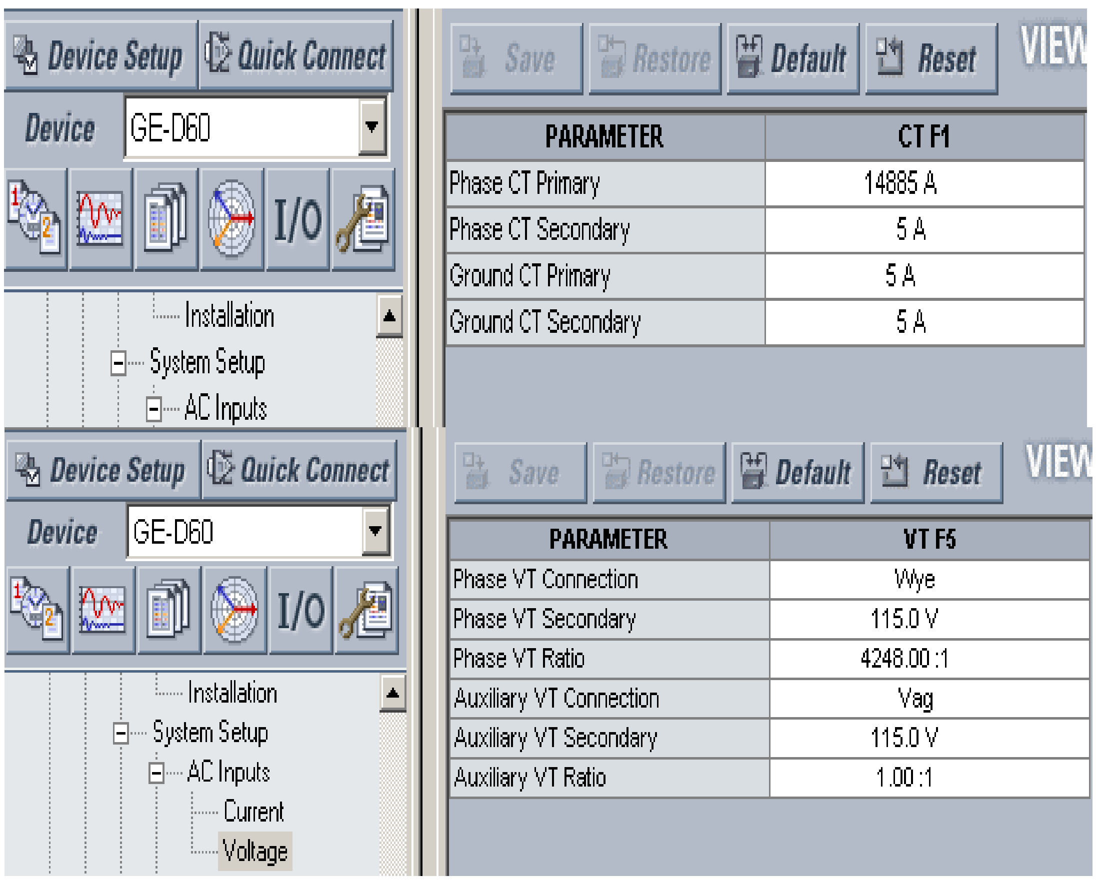

Figure 3.8 Scaling factors setting in the GE PMUs

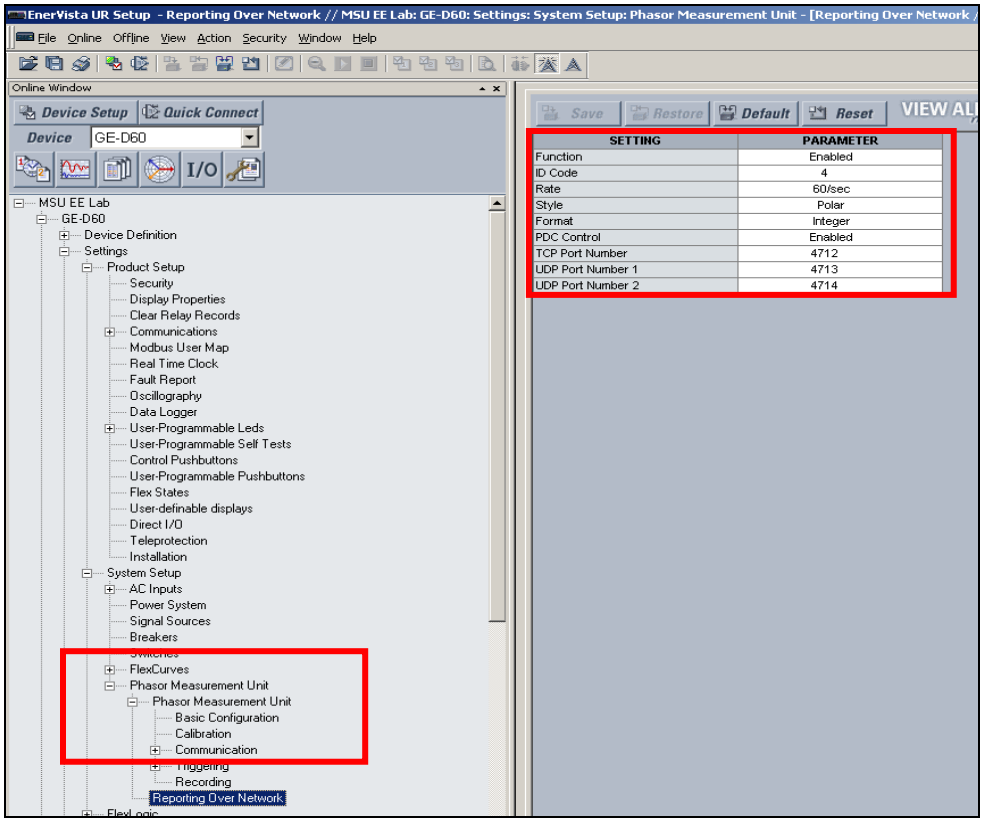

Figure 3.9 Synchrophasors enabled GE PMU

3.4.3 Phasor data concentrator settings

The SEL 3306 is the core of the synchrophasor network in the developed test bed. The PDC acquires the synchrophasor messages at 60 msgs/sec and transmits the whole data externally to the PI server system. The SEL 421 PMU is connected serially to the PDC, and the GE PMUs and the PI system are connected over the Ethernet network. The PDC Ethernet and serial port are need to be configured to enable the data communication, and is achieved by using the PDC browser interface.

The SEL 421 is connected to the PDC serial port 2 with C276 cable, and the GE PMUs are connected over Ethernet to the PDC. The corresponding port settings are enabled in the PDC as shown in Figure 3.9

Serial02	
SPEN	Y
SMFMT	C37.118
SNAME	02SP
SPMUID	0x0009
SPHFMT	P
SVCOMP	0.00
SICOMP	0.00
SSPEED	57600

PMU-Ethernet-Configuration

Ethernet01	
EPEN	Y
EMFMT	C37.118
ENAME	GE-D60 PMU
EPMUID	0x0004
EPHFMT	P
EVCOMP	0.00
EICOMP	0.00
EAD_IP	130.18.65.97
ETXDP	UDP
ETEL	N
ENDP	4713
ENCP	4712

Ethernet02	
EPEN	Y
EMFMT	C37.118
ENAME	GE-N60
EPMUID	0x0005
EPHFMT	P
EVCOMP	0.00
EICOMP	0.00
EAD_IP	130.18.65.87
ETXDP	UDP
ETEL	N
ENDP	4714
ENCP	4712

Figure 3.10 PDC settings for the PMU data

The data from the PDC is sent to the PI client in IEEE C37.118 message format by enabling the output ports, and finally all settings are saved by loading the configuration to the PDC (Figure 3.10).

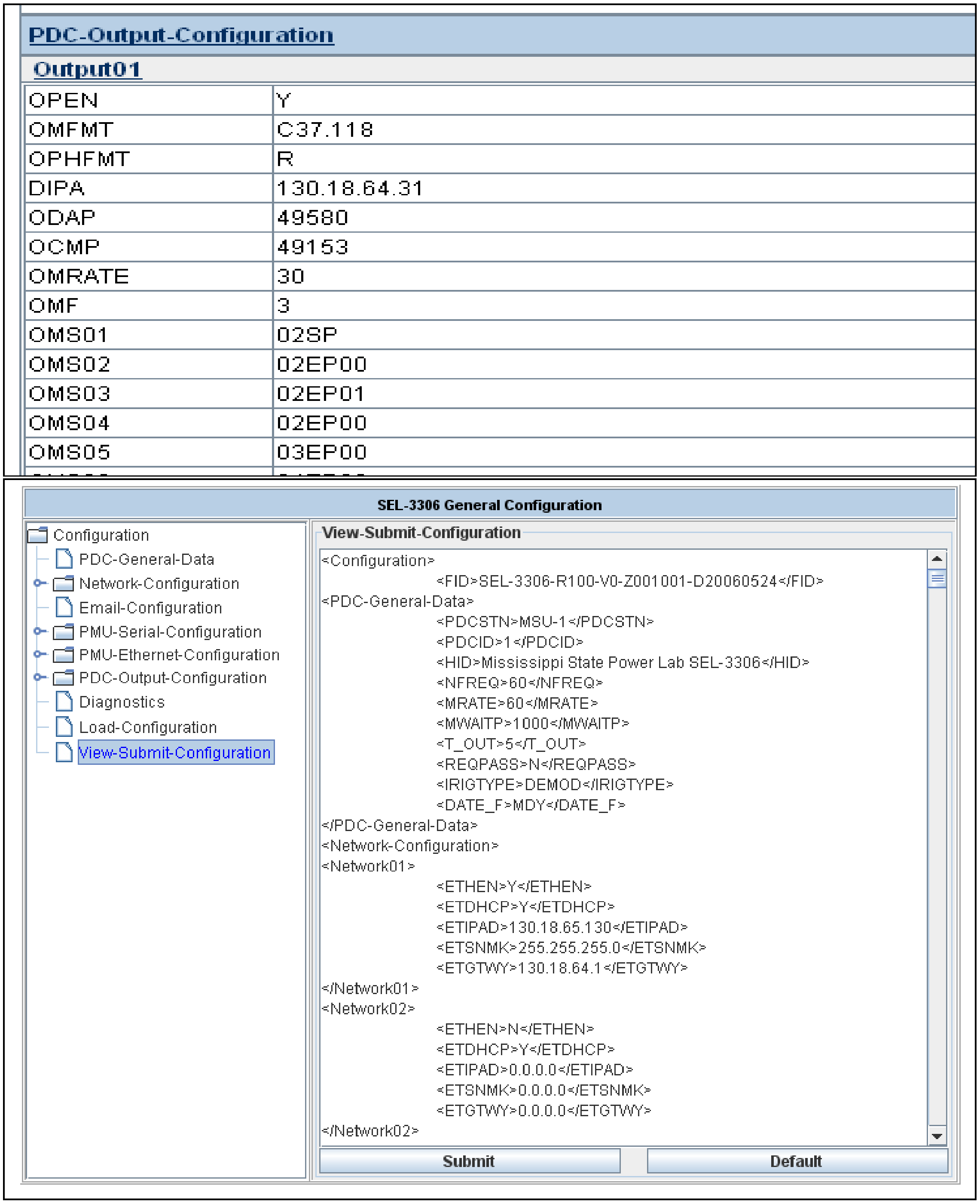

Figure 3.11 PDC output and submit configuration windows

3.5 Deployment of OSI PI historian

The OSI PI system is deployed as the main database historian for monitoring and archiving power system data. The PI historian is chosen for its advanced functionality in the industrial data management, and with release of C37.118 interface, this software became one of the most successful implementations in the synchrophasor industry. This section of the chapter explains the PI system architecture in the current test bed.

3.5.1 PI system architecture

The PI system installed in a dedicated server computer is used as the host system. The PI client is the system that interacts with real world devices and acquires data using different interfaces. The PI host and client system are connected to each other through the Ethernet network. The interfaces are installed on the client computer which is connected to the PDC and PLC and acquires the normal OPC SCADA data and the time synchronized phasors from the PDC. The host acquires the data through the client, and the client also acts as a buffer system in case of connection failure to the host server. The Figure 3.11 shown below gives a visual description of the PI system.

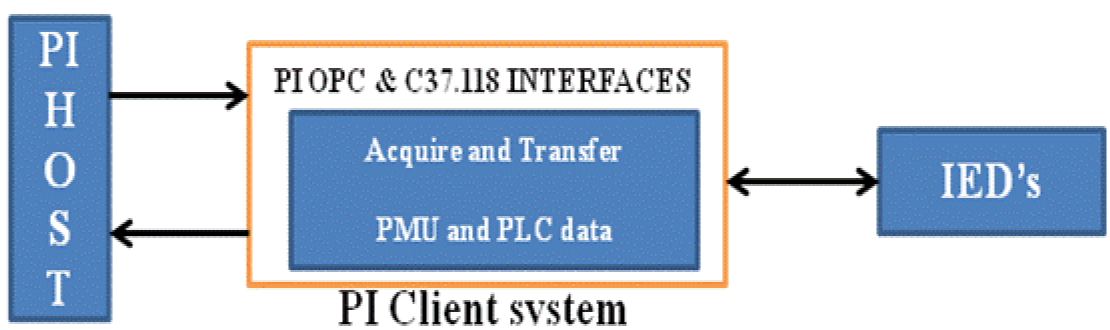

Figure 3.12 PI System implementation in the test bed

3.5.2 PI system settings and data acquisition

After completing the software installation and establishing a successful connection through Ethernet to the PI server. The PI OPC and C37.118 interfaces are installed in the client using the PI Interface Configuration Utility tool (PI ICU) and are setup to connect with the external data sources. Every connection from the client to the host should be registered in the host system by creating security trusts. Trusts are created on the host computer using PI System Management Tool (PI SMT), and each interface is registered.

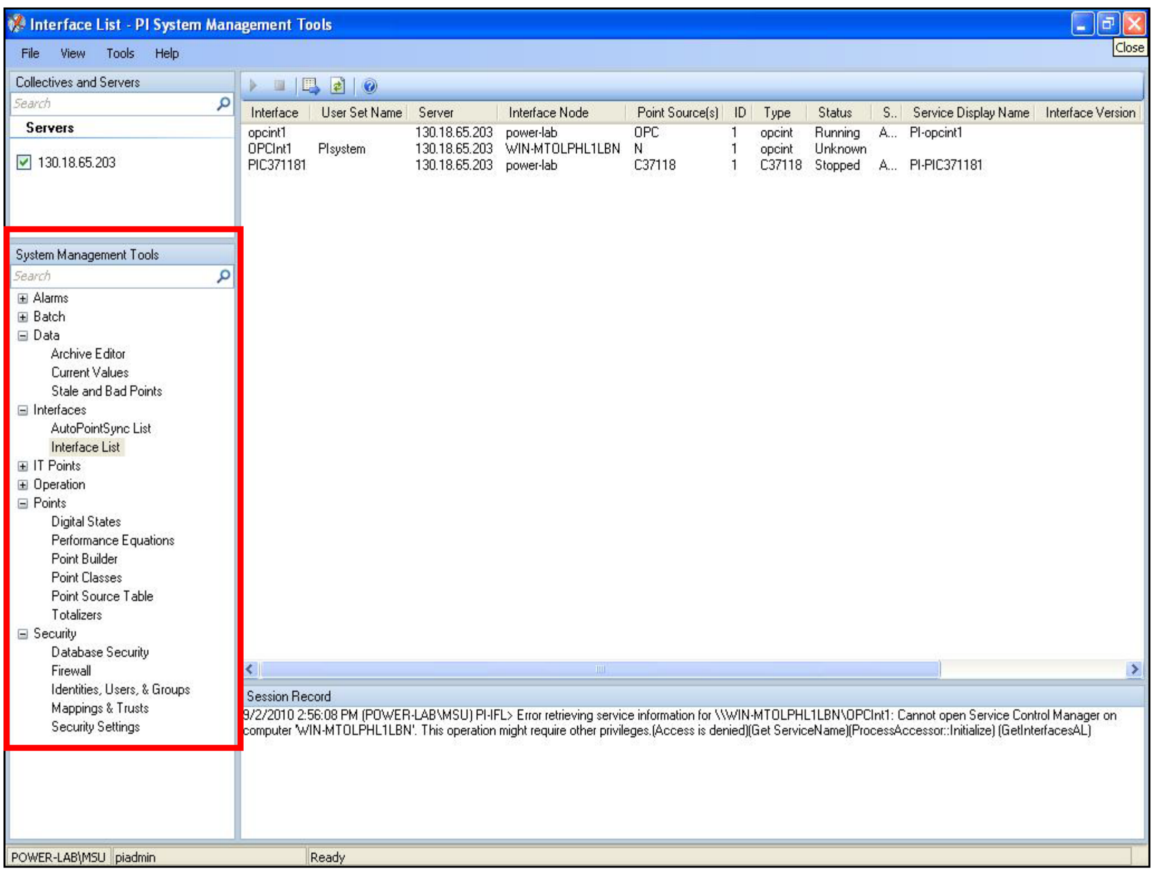

Figure 3.13 PI SMT user window displaying interface list

Data is acquired from external devices by running the installed interface in the PI ICU, and by creating data tags. Each data variable is called ‘tag or point’ in the PI system and is created using PI point builder present in the PI system management tools. The data validity is checked by opening the current values section of the SMT tool and checking for continuous stream update.

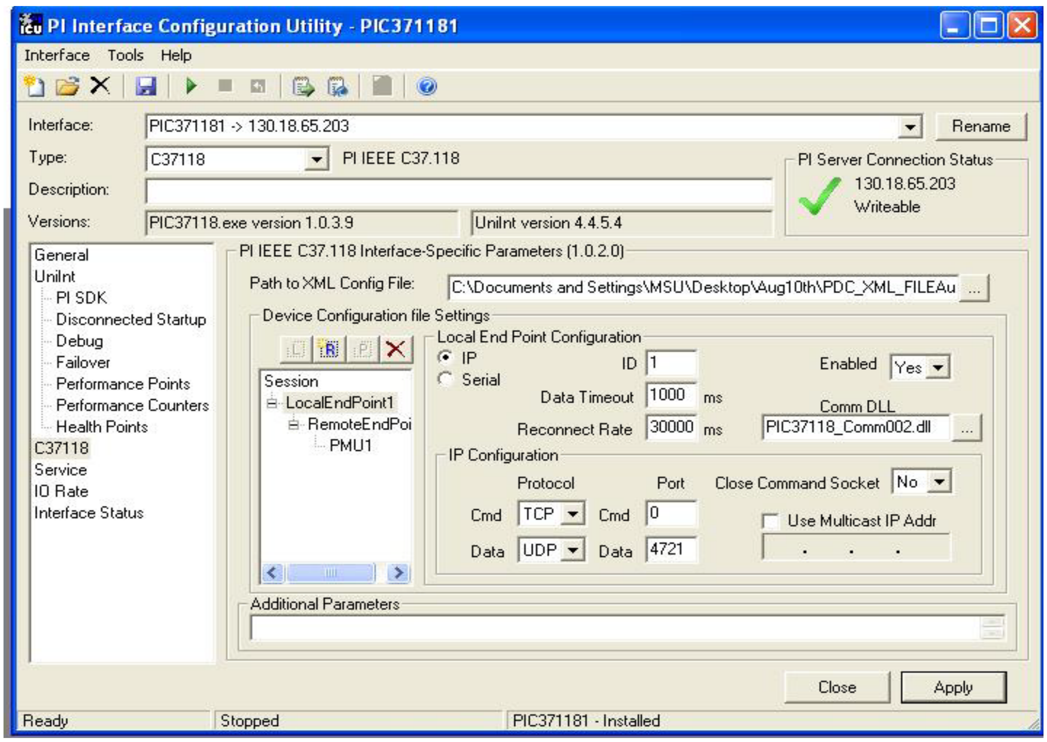

Figure 3.14 PI ICU interface running C37.118

The PI Process Book is used to build operator interface for monitoring power system data. The Process Book application consists of trends which are selected to plot one PI point or multiple points over certain period of time. The developed trends plot the data against time stamp updating at user configured intervals or in real time. The data from the process book is also available for exporting to other systems in standard industrial protocols.

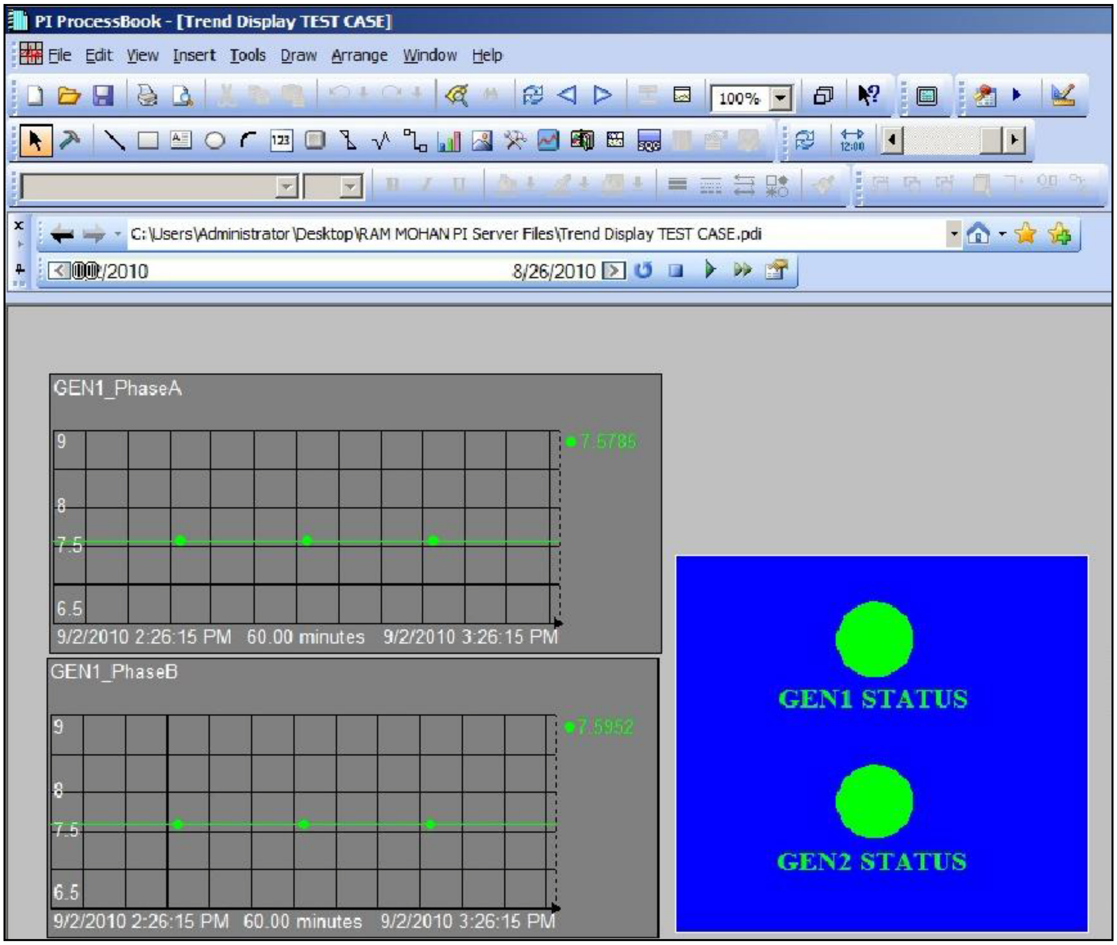

Figure 3.15 PI Process Book user interface

3.6 Challenges involved in the development

The test bed developed at MSU PERL lab integrates several hardware and software devices to mimic an actual power system. Due to the different products installed, and the varied functionality and complexity of the devices, the test bed encountered several challenges in its development. This section of the chapter briefly explains the different factors that posed a problem for the test bed development.

3.6.1 Deployment of monitoring and control components

The deployment of monitoring and controlling devices into the test bed to integrate with the RTDS hardware was one of the critical phases of the project. The devices are chosen carefully to monitor and control the power system simulated in RTDS with a high level of versatility. Multiple vendor devices are integrated to showcase the real-world power system automation. Several software interfaces are used to achieve interoperability between the hardware. The OSI PI Historian is being used at a university research level, and is implemented to acquire, monitor and archive power system data. The following section provides a detailed insight into the interoperability and communication schemes implemented in the success of this test bed.

3.6.2 Interoperability and communication between different hardware

Due to versatile hardware implementation, communication between the devices for operation of the test bed is a major challenge. The PLC and RTDS present in the test bed had no direct vendor specified standards for interfacing each other. The interoperability between these devices was of prime importance for the whole test bed operation.

The RTDS and PLC system are integrated together by using a third party device, the NI-PXI real time controller system. There have been some major problems encountered while acquiring data from the RTDS through the NI DAQ cards, due to several levels of signal scaling involved. The analog data is first read by the NI PXI system after scaling and is written to the Allen Bradley PLC by Ethernet/IP industrial suite present in the LabVIEW system. The analog data is converted to OPC standard data through NI shared variable engine, and is written to the PLC data tags by pointing to the device IP address.

Deployment of PMU units is achieved with considerable difficulty, with the major problems being the power system data transfer from the RTDS to the PMUs. The GE PMUs are real industrial devices, and therefore the scaled signals from the RTDS back panel are again amplified by the Omicron amplifier and fed to the GE PMUs. The SEL-421 is wired directly to the back panel.

The PDC is connected to the SEL 421 PMU serially and data capabilities are limited due to serial connectivity, and the GE PMUs are connected through Ethernet network. The synchrophasor data acquisition by the PI historian from the PDC is also hampered by the mismatch of device ID codes and PI interface problems, which took considerable time for solving.

3.6.3 Real time execution of the test bed

The real time execution is one of the most important factors in the current project. Real time operation of simulation implies that the specified calculations and processing operation are completed within a given window of time. The numerous hardware devices involved created significant problems for real time execution of the complete test case. The remote control center is one area where the wireless Ethernet network was partially successful in providing real time data, and is identified in the first phase. The internal network communications between the devices is boosted from 10 Mbps LAN to 100 Mbps network to account for the large amount synchrophasor data at high speed data rates. The RTDS is capable of performing simulations with a time step of 2µs, and the PMUs are able to monitor and transfer synchrophasor messages at 60 msgs/sec. The PI Historian data acquisition is altered to reflect laboratory limitations of limited data storage and processing speeds, but not before testing and achieving near real time monitoring and control operations.

CHAPTER IV

DEVELOPMENT OF POWER SYSTEM TEST CASES

4.1 Introduction

This chapter explains the development of power system models developed in RSCAD for simulation on RTDS. A Simple two bus system (test case I) is developed initially to model a power system with local substation control. The second test case presented in this chapter includes a five bus power system (test case II) developed as a wide area operational system. The latter test case is particularly used to demonstrate a wide area monitoring and control application using synchrophasors. This chapter also explains the various intermediate schemes developed using the LabVIEW and PLC systems for the above stated power system simulations.

4.2 Test case I

This section of the chapter explains the modeling and control schemes developed to demonstrate a local control action using test case I.

4.2.1 Two bus power system model

A simple two bus power system consisting of two A.C sources acting as generators is chosen as test case I for demonstration of the automatic local control action. The power system model consists of two generators operating at nominal frequency of 60Hz at bus 1 supporting two dynamic RL loads connected to bus 2 of the system over a Bergeron type transmission line model. The generators are connected to bus 1 through circuit breakers for each of the generators and the current is monitored for fault conditions. These breakers are operated manually to simulate a power system contingency in case of a generator failure. Figure 4.1 below shows the power system test case model.

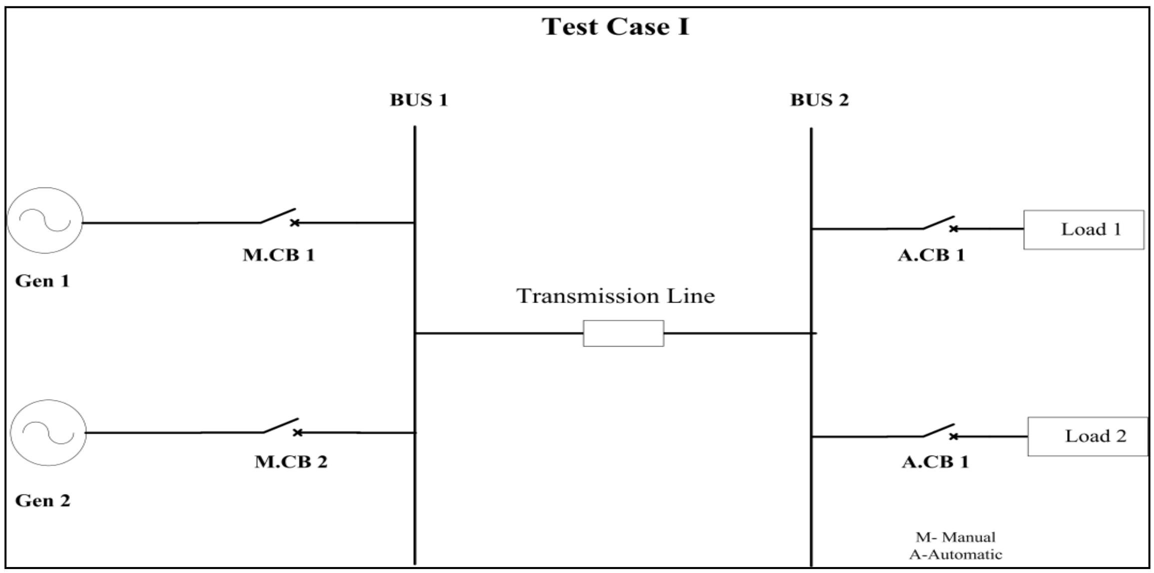

Figure 4.1 Two bus power system model

4.2.2 Control scheme

The main aim of this test case is to demonstrate real time local control in case of unforeseen failure of the power system components. The control scheme is designed such that circuit breakers placed in each of the generator's lines can be operated manually to simulate a fault on any of the phases and when this occurs the system may becomes unstable or stressed. Next to bring back the system to normal operation, one of the corresponding loads on bus 2 is shed. This is achieved by monitoring the breaker currents on the generator side. This scheme is a closed loop control, and the control actions are sent back in to simulated power system. A Control mechanism also monitors the system constantly and brings back the load into the system once the fault is cleared and the generator becomes operational. This control logic runs continuously and monitors the system for faults and implements the corresponding corrective actions necessary. Though the load shedding scheme is not the optimum remedial actions for these types of faults, here it is only employed to show the operation of the developed test bed.

4.2.3 RSCAD model

The RSCAD model shown in Figure 4.2 is the actual power system test case simulated in using the RSCAD software. This model is divided into three parts, actual power system, analog output block and digital input block.

The actual power system model consists of the two generators rated for 200MW and 300 MW respectively and two dynamic RL loads rated at 230 MW each. A Bergeron type transmission models is used and there are circuit breakers provided at the generator and load buses for monitoring and control action. The analog output block actually consists of DDAC RTDS component for routing the monitoring phase currents from each of the generator circuit breakers. The currents are first converted into rms signals through inbuilt components and are transferred into the DDAC block through output nodes. The DDAC component makes these signals available through the back panel of the RTDS for further connection to the DAQ cards of the NI-PXI system. Scaling of the analog signals from this block is very important and the scaling factors are chosen carefully to prevent attenuation of the original signal value.

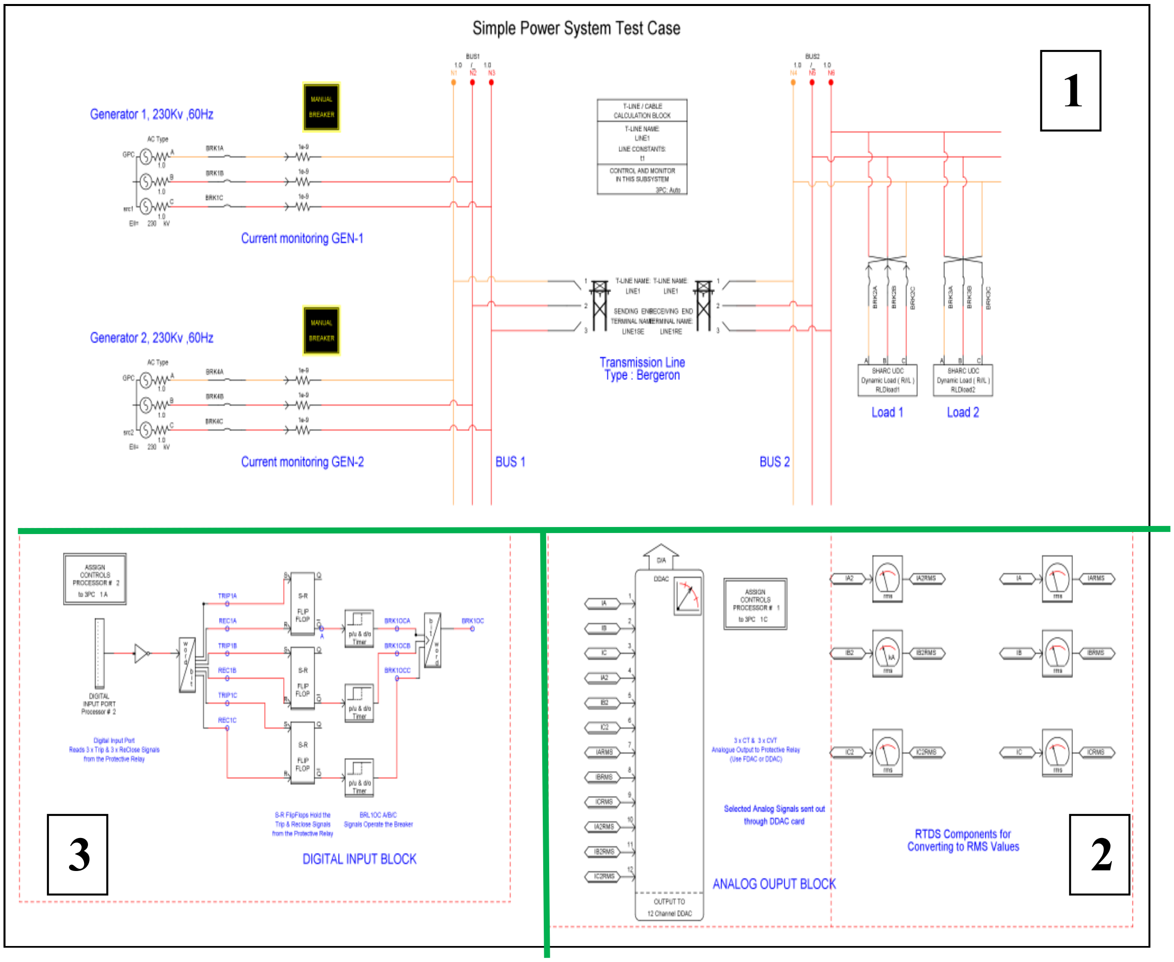

Figure 4.2 Two bus system: RSCAD model

The digital input block modeled in RSCAD actually consists of flexible control logic to operate the breakers on the load side i.e. on bus 2 for load shedding operation. The front panel ports on RTDS will take digital control coming from the PLC through the NI-PXI system for timely operation of the breakers on bus 2. This signal is used as the breaker control signal assigned in the circuit breaker modeling menu. These signal status values are also monitored on the RSCAD interface.

4.2.4 LabVIEW code

The LabVIEW and the NI-PXI module act as the intermediate interface for data communication and visualization of the operation between PLC and the RTDS. LabVIEW system works here as a two way interface translator commonly used in real system. After the physical connections are made between the PXI system and the RTDS and also the PLC and the PXI system, the LabVIEW code deployed plays very important role essentially acting as a data driver. The LabVIEW code can be divided into two sections for explanatory purposes, the input section and the output section.

The input section of the developed code mainly serves two purposes, data acquisition from RTDS and transfer to PLC module. Figure 4.3 shown below provides the input section of the code.

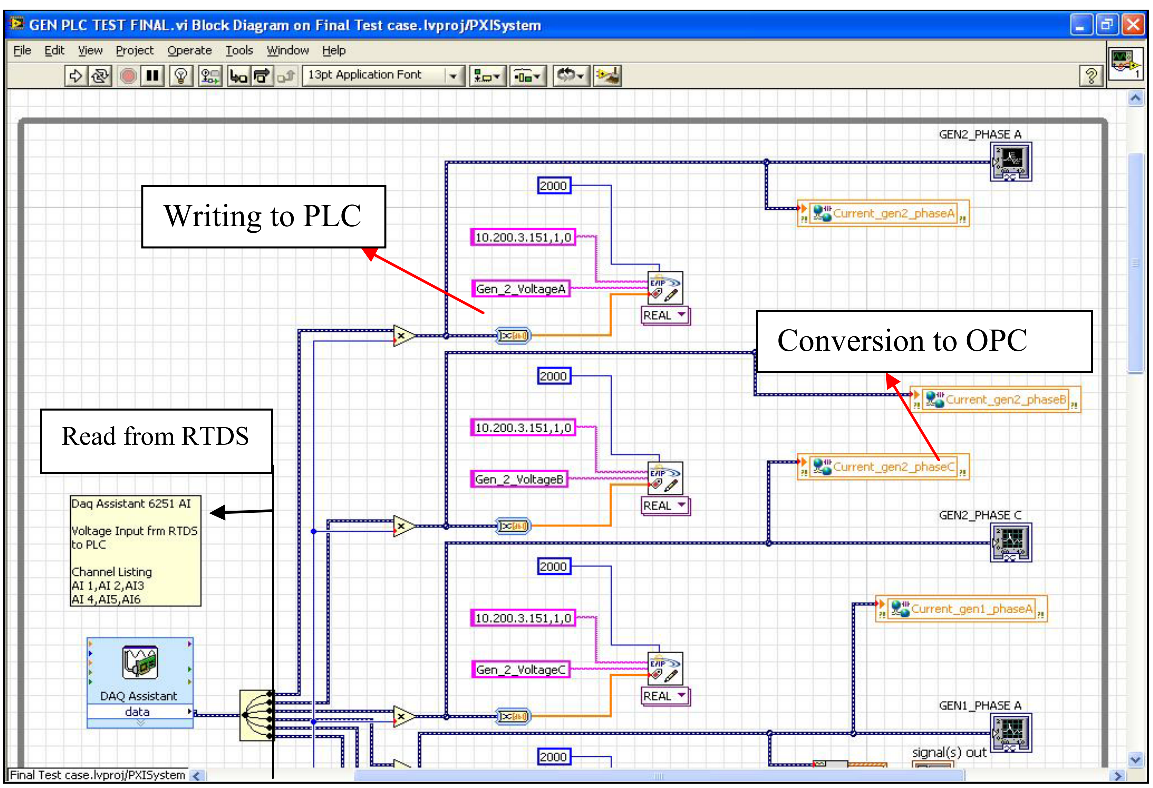

Figure 4.3 Input section of the LabVIEW code

This section performs the essential function of acquiring the analog power system data from RTDS through the DAQ assistant from six analog channels and then writes this data into the PLC tags through the use of Ethernet/IP industrial communication suite. The other important operation performed by this section is, the conversion of analog data into OPC data for monitoring and archiving by the PI system and also graphical interface for the LabVIEW front panel.

The output section of the developed code performs similar functions as the input section but the difference being the data being handled is the control signals read from PLC and sent to RTDS. This also executes a small logic to generate a digital signal after receiving the control command from the PLC for any operation on the system running on the RTDS. The Figure 4.4 shows the output section of the code.

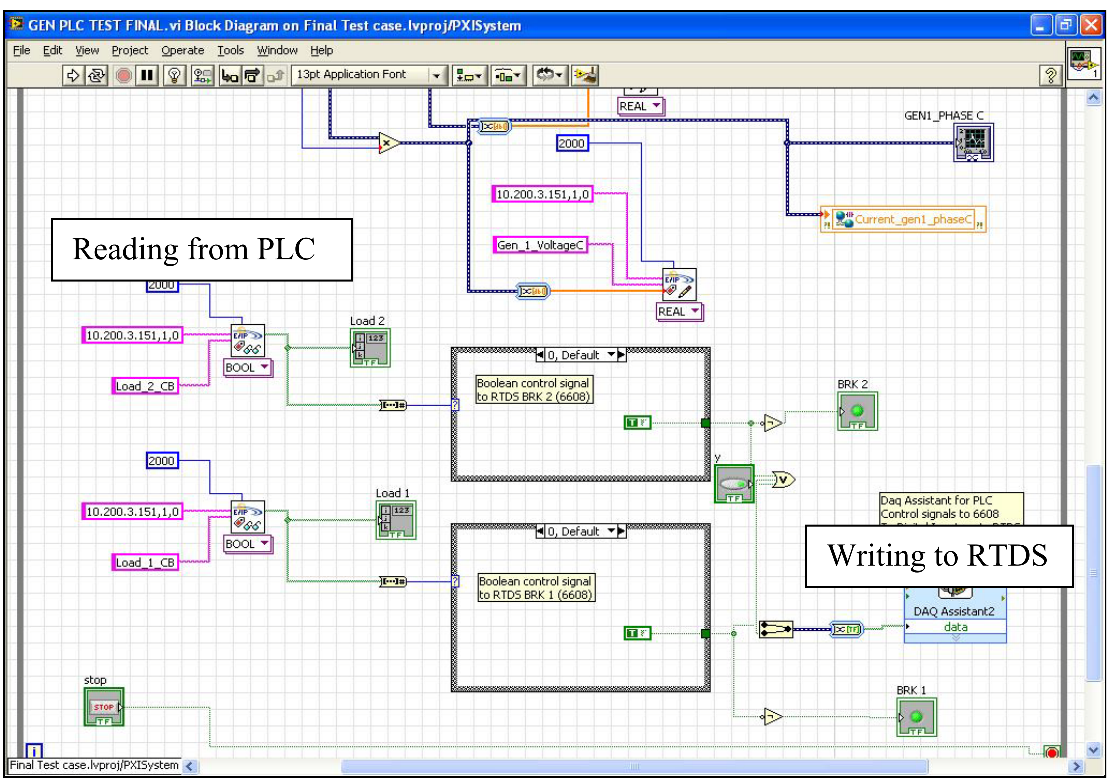

Figure 4.4 Output Section of the LabVIEW code

4.2.5 PLC control logic

The programmable logic controller is the hardware system, which monitors and controls the actions to be taken on the developed simulated power system in case of any failures. A Ladder Logic (LL) program is written and deployed in the PLC for the continuous operation. The LL program is partially shown in Figure 4.5

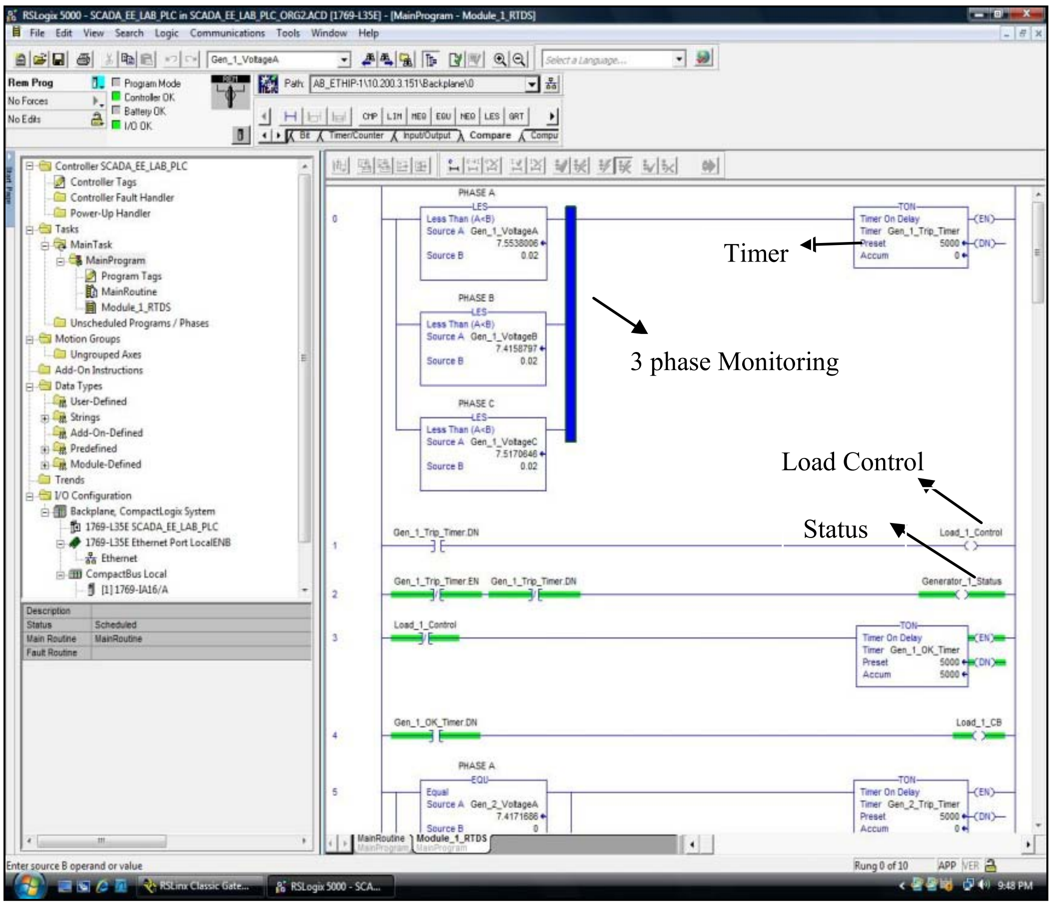

Figure 4.5 PLC Ladder Logic program

The LabVIEW program writes the data into the PLC system tags which are the analog voltages of the generator phases. The first part monitors the three phases in parallel for any possible failures and activates a timer in case of fault or fault clearance of the system to eliminate any actions due to transient disturbances. Once the timer times out, a control signal is activated and sent to the RTDS for corresponding action on the load side breaker and also the load status is updated in the system. This program runs continuously irrespective of the number of failures of the generator or cleared faults. The NI-PXI system is primarily used as the intermediate interface for the PLC to reduce the cost associated with PLC I/0 modules as the connection over Ethernet provides for unlimited number of tags to be used, and to act as source for OPC data for monitoring and archiving by the PI server.

4.2.6 Data monitoring and archiving

The PI server system performs the data monitoring and archiving for this test case using the PI OPC interface. The shared variable engine in LabVIEW converts the analog RMS current signals into OPC data. The OPC data is then read by the PI interface client and is transferred to the server where it is monitored and stored. The process book accesses this data and displays it with live trending, the interface also provides the status variables to be recorded and displayed by the process book interface. The stored system data can be later accessed in required formats like the ASCII, Comtrade and CSV formats.

4.3 Test Case II

This section of the chapter introduces the concept of voltage stability and presents the five bus power system test case developed to validate stability problem using phasor measurement units and synchrophasors.

4.3.1 Voltage stability

As the modern power system are pushed to their operating limits by the utilities due to increasing demand for power, it is essential to maintain stable operation of the power system. One of the main factors is the voltage stability concept. Voltage stability is defined as the power system capability to maintain steady state voltages at all buses under normal operating conditions and after being subjected to a disturbance [3]. Voltage collapse is a more critical failure of the system voltages due to cascaded failure of transmission lines due to initial voltage instability. Voltage instability can be due to three major factors,

1. Loss of generator due to which the reactive power demand of the system is not met causing voltage instability.
2. Loss of a transmission line which may lead to an additional stress on the adjacent transmission lines and may develop into cascade failures.
3. Unforeseen increase in load demand especially reactive power demand which is not being met by the existing power generation and control devices.

The above factors are taken into account while modeling the 5 bus system which demonstrates the application of the developed test bed in detecting voltage instabilities using synchrophasors.

4.3.2 Five bus power system model

The five bus power system model developed for voltage stability testing is inspired by [25]. It consists of three generators supporting two loads through a transmission network. Two phasor measurement units are placed on buses 1 and 2 to monitor the bus voltage phasors which provide the system state in real time. A line to ground fault is added into the transmission network to simulate transmission line failure, similarly other cases like the generator three is controlled though a circuit breaker to simulate loss of generation fault case. Finally, an extra load is introduced into system to simulate an increase in reactive power demand on the load side of the system. The one line diagram of the developed system is shown in Figure 4.6

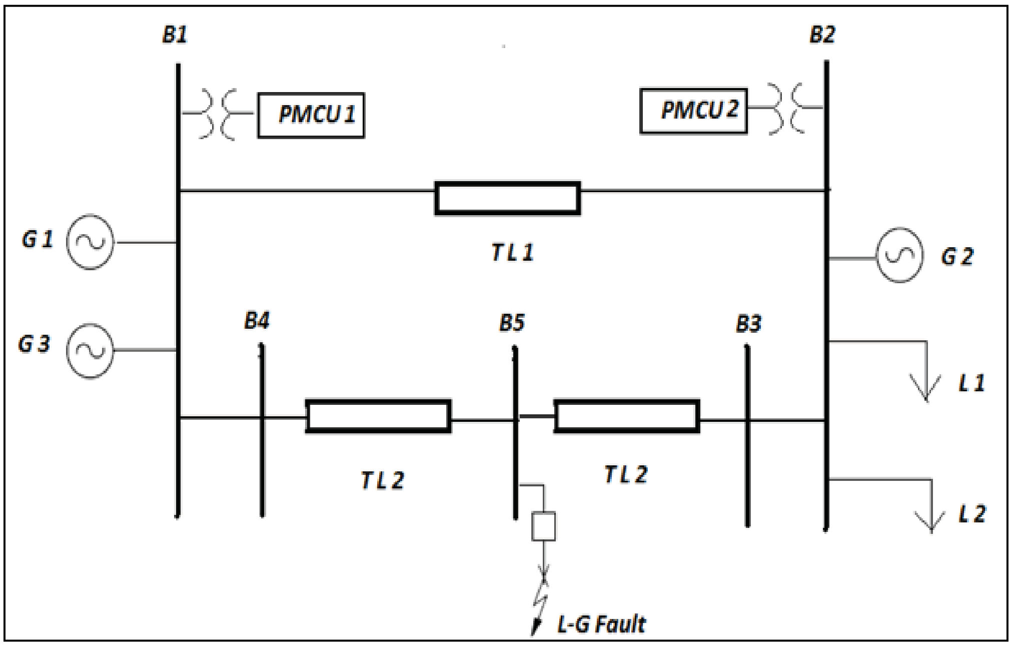

Figure 4.6 Five bus power system model

4.3.3 RSCAD model

The five bus system is modeled in RSCAD for simulating on RTDS. The RSCAD model is shown in Figure 4.7. The developed model is divided into four parts the actual power system, fault logic, analog output block and digital input block. The actual power system consists of three generators rated at 500 MW, 700 MW and 600 MW correspondingly. It also consist of two dynamic R-L loads with adjustable P and Q values, the third load is used to simulate the increase in reactive power demand by adding it into the system abruptly, causing voltage instability. The generator three is controlled manually by a circuit breaker to initiate a loss of generation test case.

The fault logic circuit simulates a line to ground fault scenario to trip a transmission line in case of a failure. The phasor measurement units are placed on buses 1 and 2 which are actually analog voltage signals by the DDAC analog output block transferring the system voltages and currents from RTDS. The digital output block brings the control signals into the simulation from relay. An angle difference component is also place to calculate the system voltage angle in real time for observing the system status.

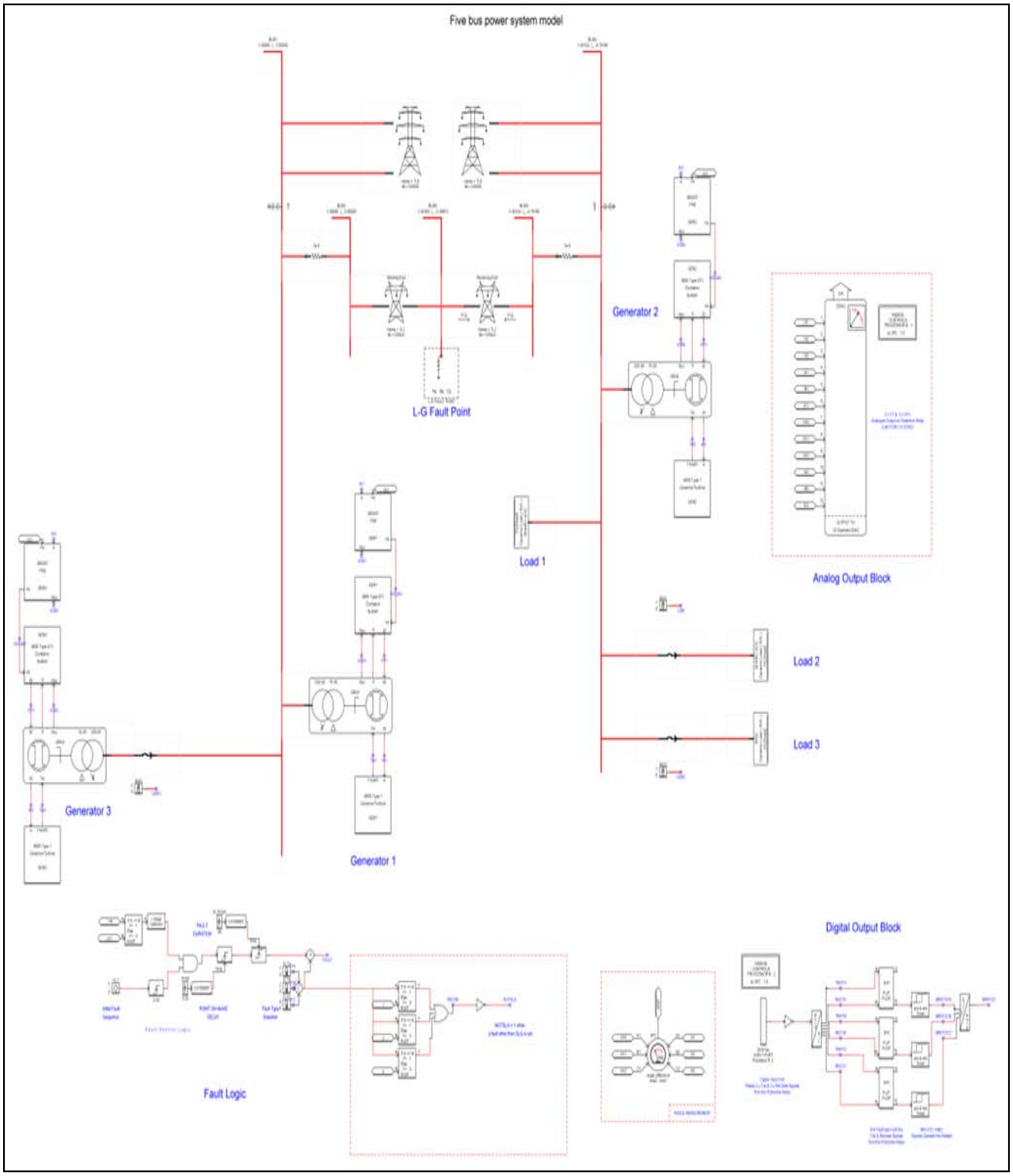

Figure 4.7 Five bus RSCAD model

4.3.4 PMU Settings and operation

Two phasor measurement units, an SEL 421 and a GE D60 are used to provide synchrophasor measurements for monitoring and operation of this test case. These units are placed on bus 1 and bus 2 of the developed system show in Figure 4.6 calculate and provide phasor voltage magnitudes and angles in IEEE C37.118 format along with digital and analog tags. These synchrophasor messages are collected by the phasor data concentrator to alter it into a single stream of synchrophasor data. The PDC output can then be used by the PI server for monitoring and archiving the PMU data.

The setting of each PMU is very important for proper function of the device. The SEL-421 is configured to send synchrophasor messages at a rate of 60 msgs/sec by enabling the global setting in the SEL-421 device. It is connected to SEL-3306 PDC serially and is configured to send all the voltages and an equivalent current component phasor to the PDC at baud rate of 38500. The GE D60 is connected to the SEL-3306 PDC through Ethernet and the settings are enabled through the Enervista setup software and the synchrophasor report setting is activated. This device is configured to send all the voltage and current components over the Ethernet network. The GE D60 provides synchrophasors in C7.118 standard at a rate of 60 msgs/sec over Ethernet using UDP_T protocol. Each of the PMU's must be provided with High priority IRIG-B signal which is demodulated DC level shift signal.

The SEL-3306 settings are carefully done by using the browser interface provided for the device. First, the input serial port is enabled for incoming synchrophasors from SEL-421 PMU and similarly corresponding Ethernet port is enabled for GE D60 messages. All the setting including the message format, frame rate and data standards are provided in chapter 3.

4.3.5 Data monitoring and archiving

The data monitoring and archiving of the five bus system is performed by the PI server system using the C37.118 interface. The interface is installed in the client system through the PI ICU and the phasor data concentrator is set to provide data to this system. The PI C37.118 acquires the synchrophasor data and transfers it to the server for archiving and monitoring. The PDC provides a number of tags in addition to voltage phasors which provide important information regarding the state of the system. The installed system currently is acquiring 283 pmu data tags from three PMU's and is readily capable of displaying them in the PI process book interface. The PI process book display is designed to provide voltage magnitudes and angles acquired from the synchrophasor messages for real time trending. This application is also capable of calculating angle difference in real time and a trend is created to display the same in real time and provides valuable information regarding stability issues with power system.

CHAPTER V

RESULT ANALYSIS AND APPLICATIONS OF DEVELOPED TEST BED

5.1 Introduction

This chapter provides details for the operation of the test bed with the developed test cases mentioned earlier in chapter IV. The operation and control of both the test cases with hardware devices-in-the-loop are explained and presented with supporting results. The PI system data archiving and retrieving of the stored data is also presented in detail. This chapter includes the applications of test bed and also the scope of utilizing the developed test bed.

5.2 Power system test case operation

This section of the chapter explains the operation of the developed test cases. The operation of the test cases is designed to cover different critical areas in power system operation and control. The first case simulates the local control action in case of any failure in the system. The second is designed to incorporate synchrophasor application for monitoring the power system state in real time and for post event analysis.

5.2.1 Test case I operation

The test case I modeled in RSCAD (refer to Figure 4.2) is designed to prototype a local control action in a laboratory environment using a programmable logic controller. The generators in the system are connected to BUS1 through the circuit breakers which are manually operated to simulate a fault scenario for generator failure.

The operation of this test case is as follows,

1. The normal operation of the system has two generators supporting two loads. The three phase RMS currents at the generator are monitored continuously for fault by the PLC and also monitored and archived by the PI system.
2. The breaker at the generator side is manually operated to simulate a fault in any one of the phases, and in this case the fault is simulated on phase B
3. The control program running in the PLC detects this fault as a loss of generation due to protective relay operation and initiates a command to shed one of the loads to make the system stable and balanced. This fault and control is also monitored by the PI operator interface which has alarm capability to alert the operator of the system status.
4. The control command from the PLC automatically operates the breaker on the load side detaching one of the loads, and the system status is updated.
5. The continuous monitoring of the RMS currents allows the system to detect the change if the generator comes back to its normal operation and immediately the load is bought back into the system to retain its normal operation.
6. The LabVIEW VI front panel developed also allows to monitor the system state and actions being performed acting as an intermediate operator interface. The NI-PXI system responsible for analog and digital signal transfer between the RTDS and the PLC system.
7. All the data is available through the PI system for post event analysis and is a very valuable tool for study of the power system operation.

5.2.2 Test case I results

The three phase rms current signals and status of the loads is monitored from the RSCAD system interface as shown in Figure 5.1

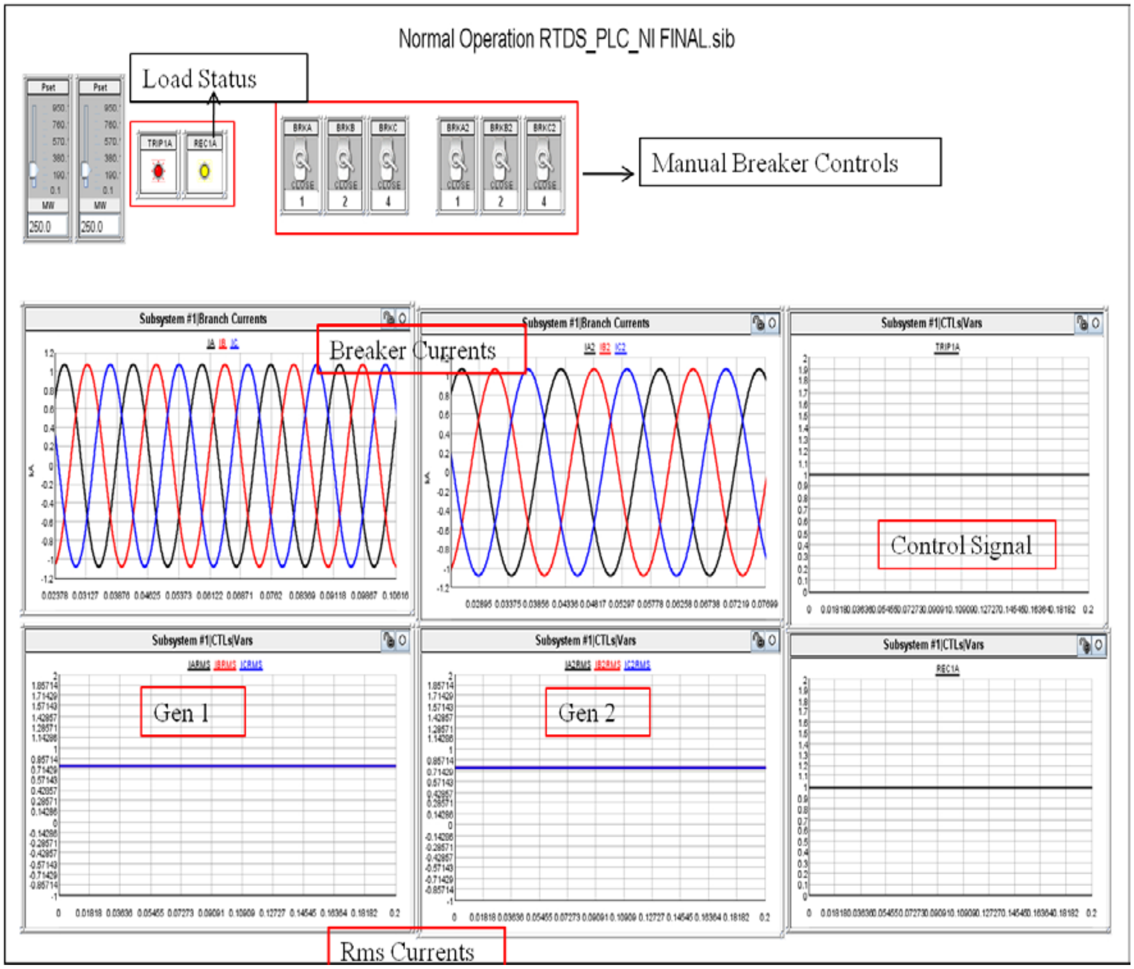

Figure 5.1 Normal Operation of system-Test case 1

The system operating normally all the currents are in phase and are at standard values of 0.7 kA. The control signal statuses are at 1 indicating that generators and loads are intact.

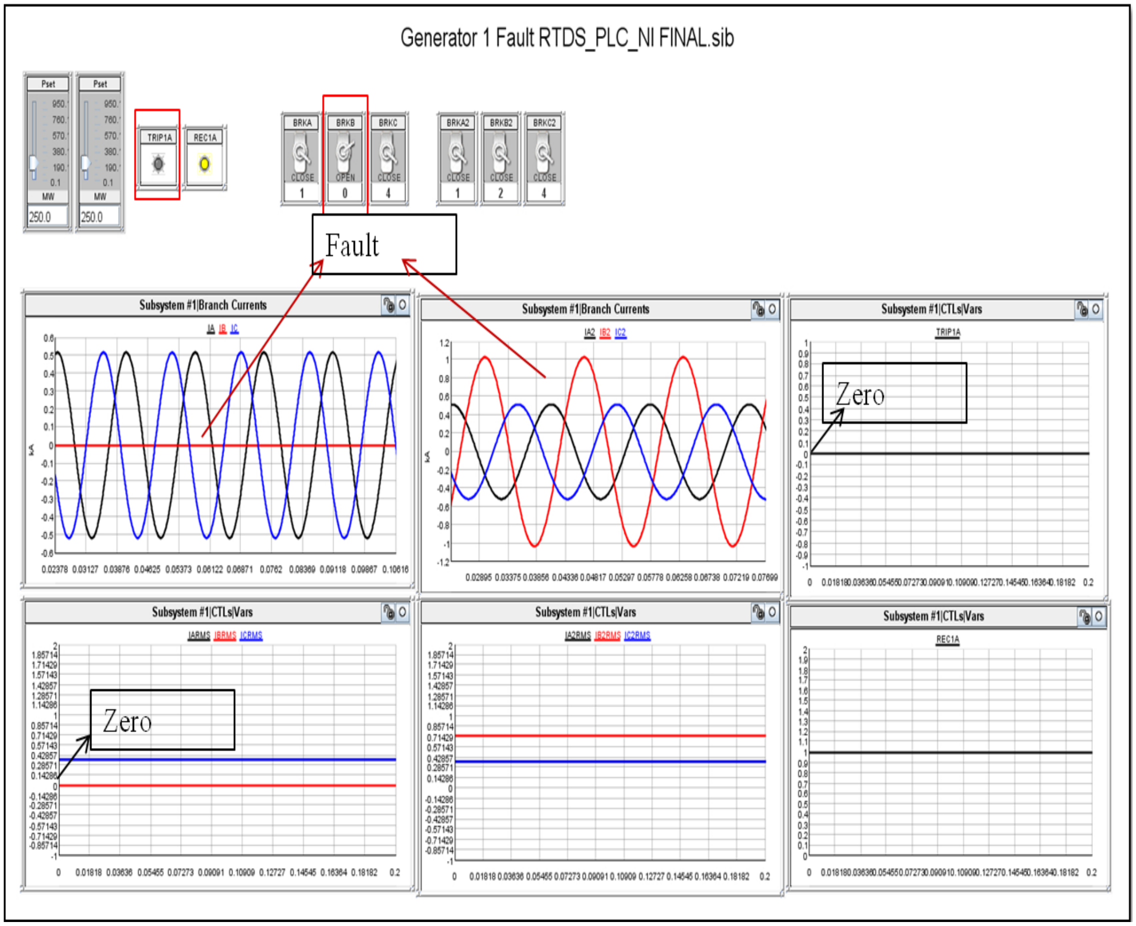

Figure 5.2 Test case I- Phase B fault

Figure 5.2 shows the fault scenario, where the fault was simulated by manual opening the phase B of the generator 1 breaker, which can happen by protective relay operation after the fault. Due to breaker operation, the current drops to zero and the other currents from generator B increase resulting in imbalance of the system. At the same time, in designed interface, load status LED's and control signals change their states indicating the action has been taken immediately and the load has been shed out of the system to retain normal operation of the system. The control signals are issued by the PLC. There is also a provision to limit the control action in case of transient conditions by means of a timer provided and also the monitoring threshold limits can be changed to achieve this flexibility.

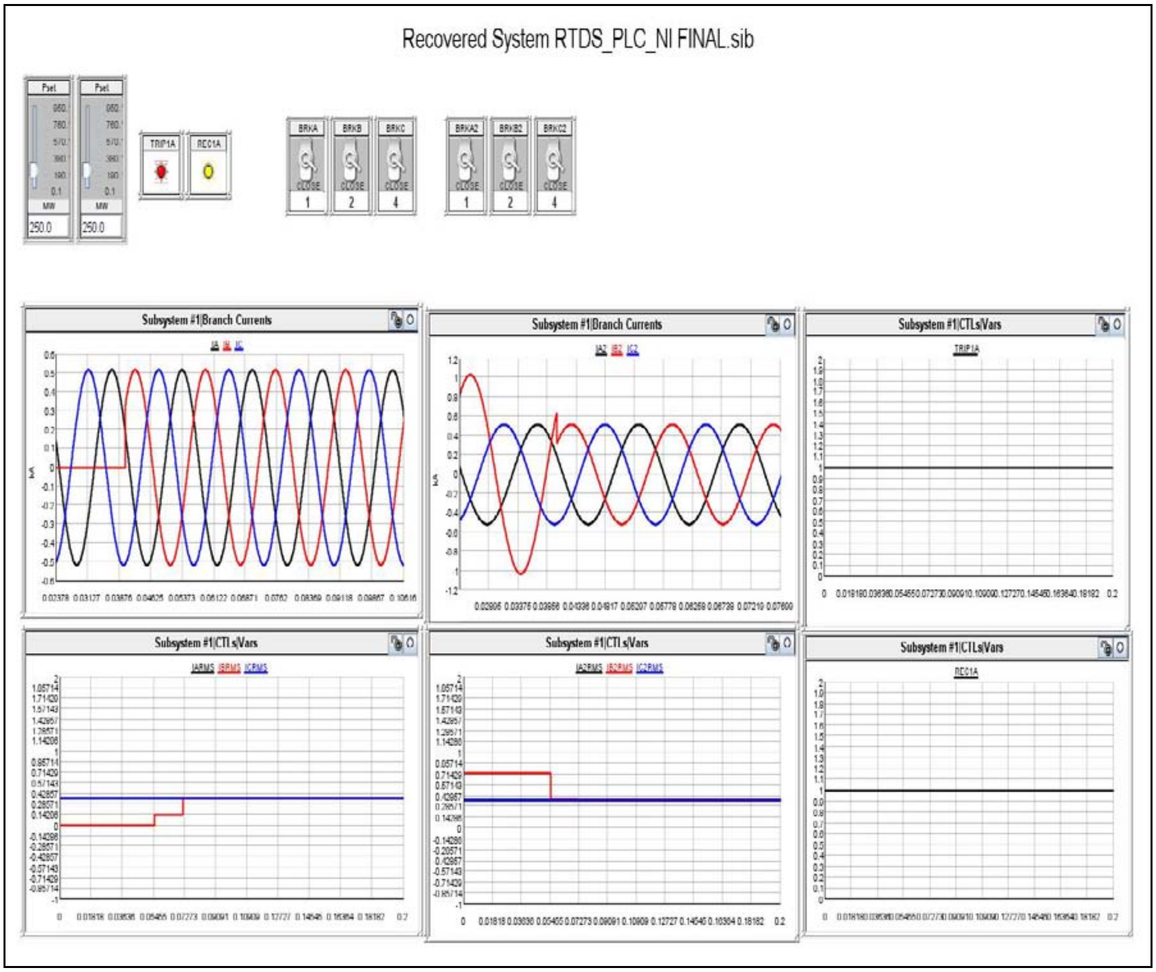

Figure 5.3 Test Case I - System recovery from fault

Figure 5.3 provides the system details during the recovery. The phase B breaker is closed manually to eliminate the simulated fault and the PLC logic immediately detects this change and issues another control to close the load side breaker and bring the load back into the system for normal operation. The load status indicators change indicating that the load is back into operation.

The LabVIEW program developed for the PXI system operation also acts as an intermediate monitoring and alarm interface. The front panel of the VI has plots which update in real time with RMS current data from the generators and any status change of generators or loads is detected by the LEDs status. Figure 5.4 provides a sample view of the system in case of generator one, phase A failure.

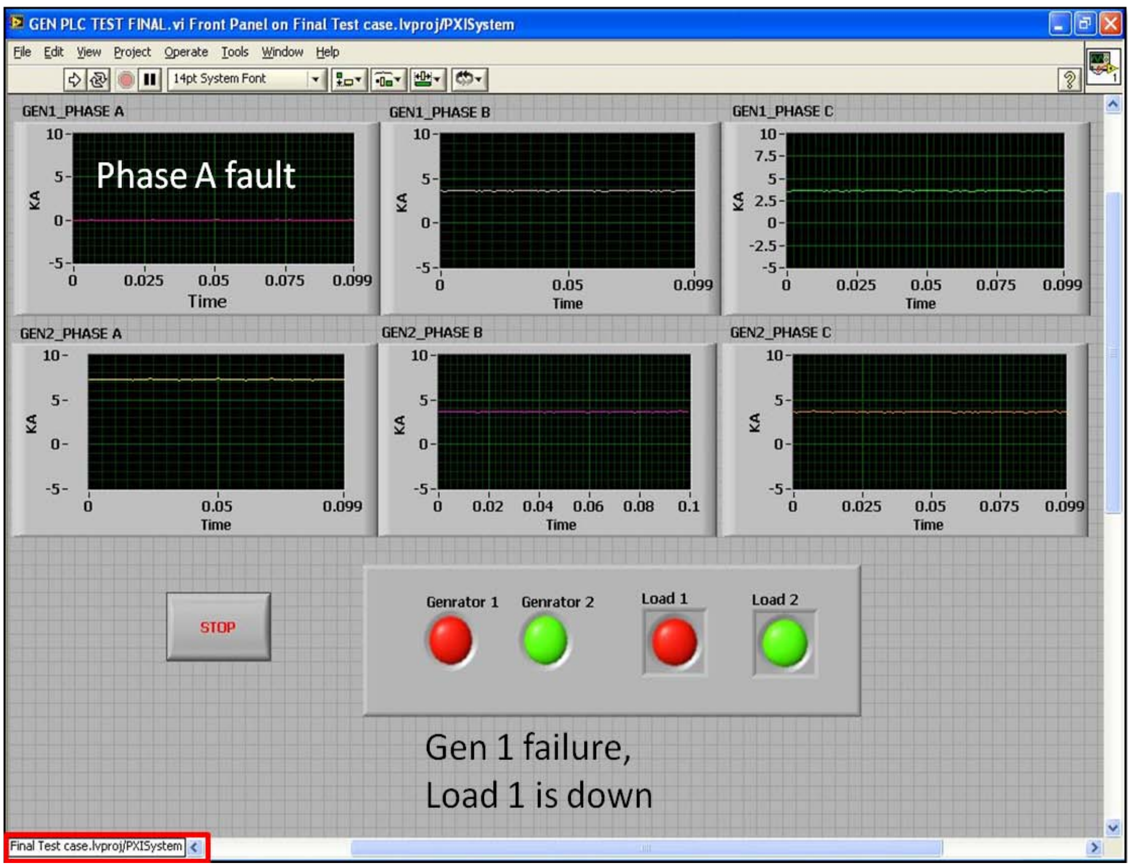

Figure 5.4 Intermediate LabVIEW interface.

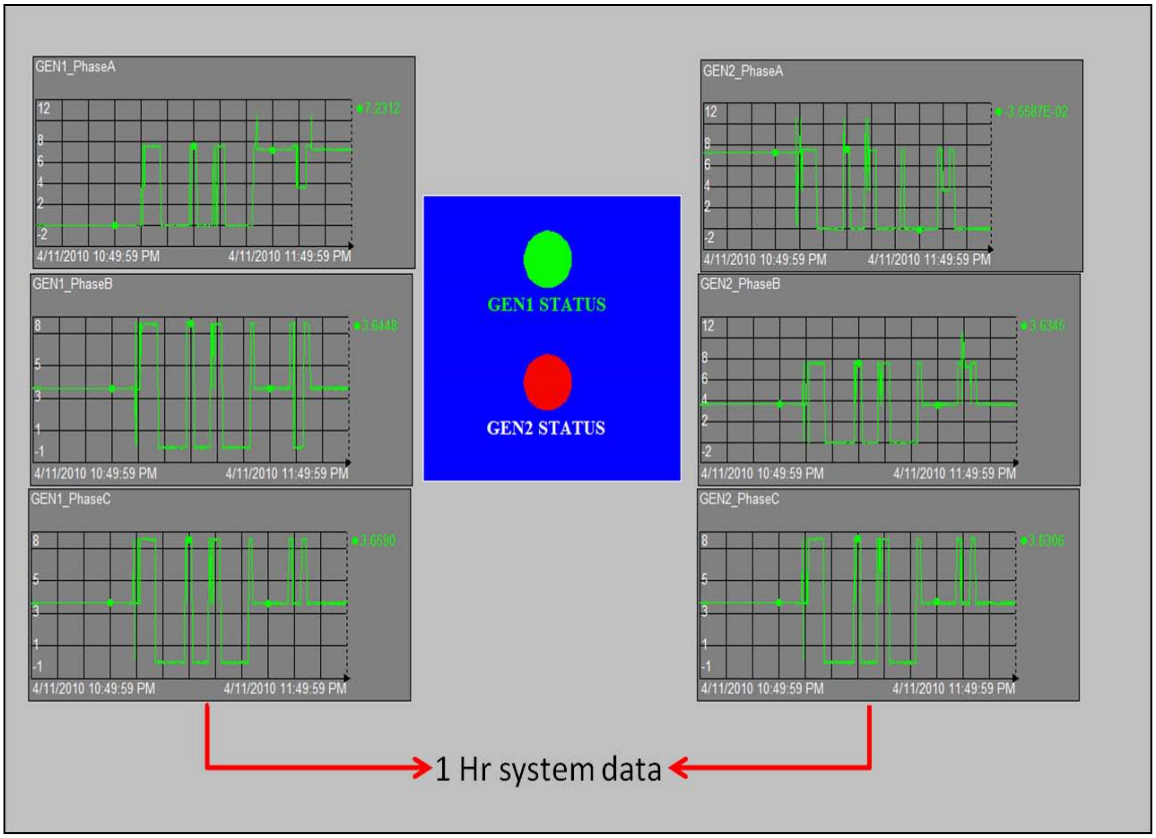

Figure 5.5 Test case I- PI Process book interface

The PI system acts as the main tool to acquire and archive the power system data during the operation of this test case. All the system branch currents are monitored and stored by the PI server through PI OPC server interface on the client computer. The LabVIEW converts the analog data into OPC data for the PI interface. The PI system also monitors and acts as a real time operator interface by providing real time trending of the data plots and also updating the system states through blinking LED indicators. PI Process Book provides the functionality of monitoring the PI data in real time. The Figure 5.5 shows the interface with data trending from past 1 Hr and the current status of generators with failure generator 2, phase A.

5.2.3 Test case II operation

The five bus power system (shown in Figure 4.7) is modeled in RSCAD for simulating the voltage stability problems and to demonstrate the use of synchrophasors for monitoring and archiving of the power system data using PI server system. The test bed for this operation includes two PMU’s for generating synchrophasors to monitor the simulated power system and the PI C37.118 interface logs the data of normal operation and all the events occurring during the simulation.

The operation of the developed test case II is as follows,

1. The developed system consists of three generators supporting two loads and an additional load for increase in reactive power demand, a line to ground fault provision on transmission line and a circuit breaker to control operation of generator three.
2. During the normal operation of the test case the node bus voltages as measured by the PMU’s stand at 186.5 kV on each bus and there exists a constant phase angle difference of 28.76 degree with fairly small transient variations.
3. The first phase of the test case involved applying an L-G fault of 80 cycles on the transmission line to disturb the voltage stability of the system. This fault disturbance is immediately picked up by PMUs as they are continuously monitoring and sending the data at a rate of 60 msgs/sec. This transition is recorded by the PI system and can be observed on the PI process book interface provided in real time.
4. The second phase of the simulation involves disturbing the balance of the system by suddenly increasing the reactive power demand by adding an

additional load into the system. The system unable to meet the demand undergoes severe oscillations which can be observed by monitoring the angle difference parameter. This is also monitored and archived by the PI system.

5. Finally the system is subjected to sudden loss of generation by simulating the breaker opening connecting generator three with the remaining system and the fluctuation in voltages and phase angle difference is monitored and archived.

The importance of this test case is to demonstrate application of synchrophasors in detecting the transient system parameters with very minimal time constraint and also providing the voltage angle calculations in real time. The PI system setup acts as a very powerful tool in monitoring and archiving synchrophasor data.

5.2.4 Test case II results

This section of the chapter provides the detailed results obtained in execution of test case developed on RSCAD for voltage stability analysis through synchrophasor measurements.

As explained previously, the system normally operating supports to loads through a transmission network with a phase angle difference of 28.76 deg between two major buses. The Figures 5.6 and 5.7 provide the system normal operating conditions in RSCAD interface and also through PI process book which is operating with generated synchrophasor data.

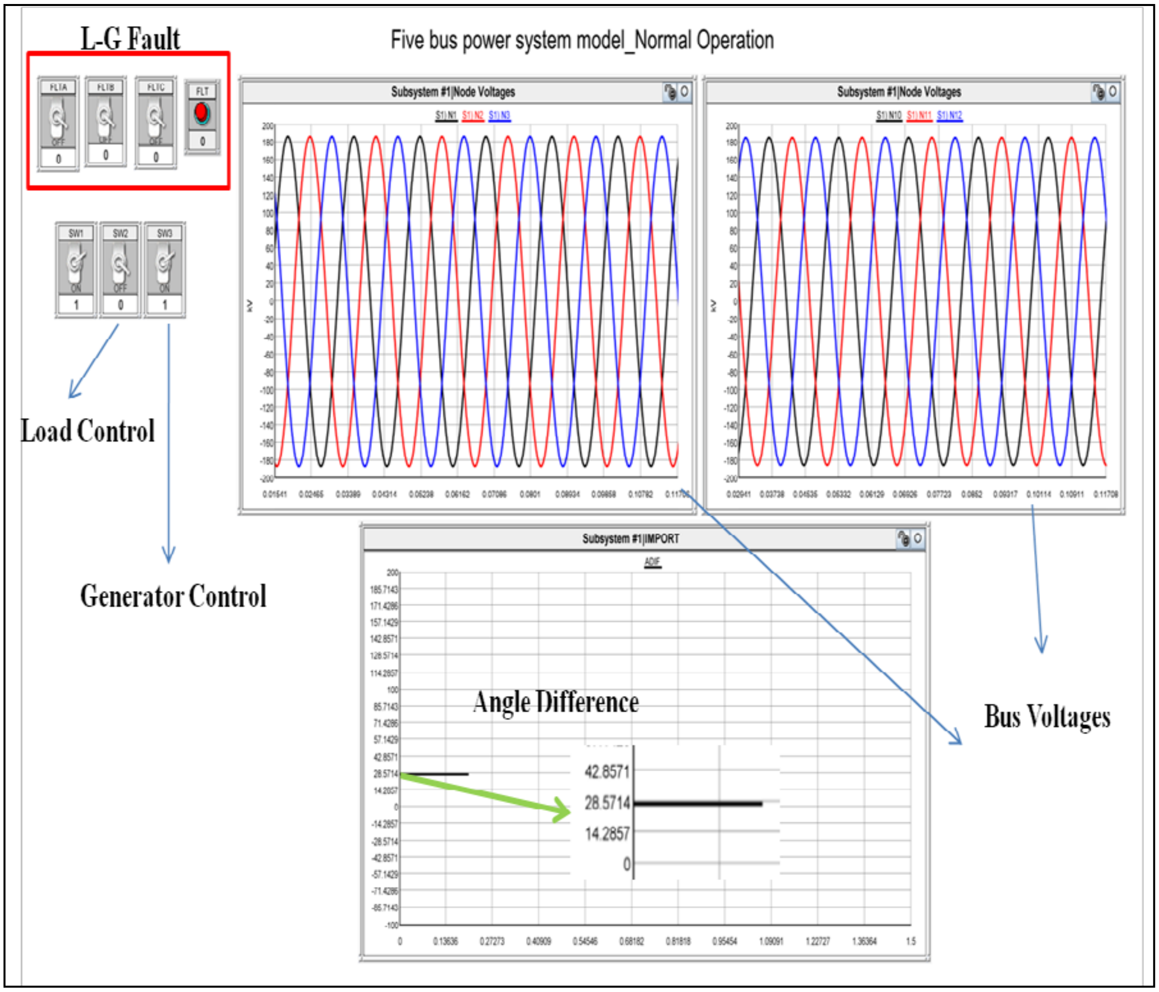

Figure 5.6 Test case II-RSCAD visualization during normal operation

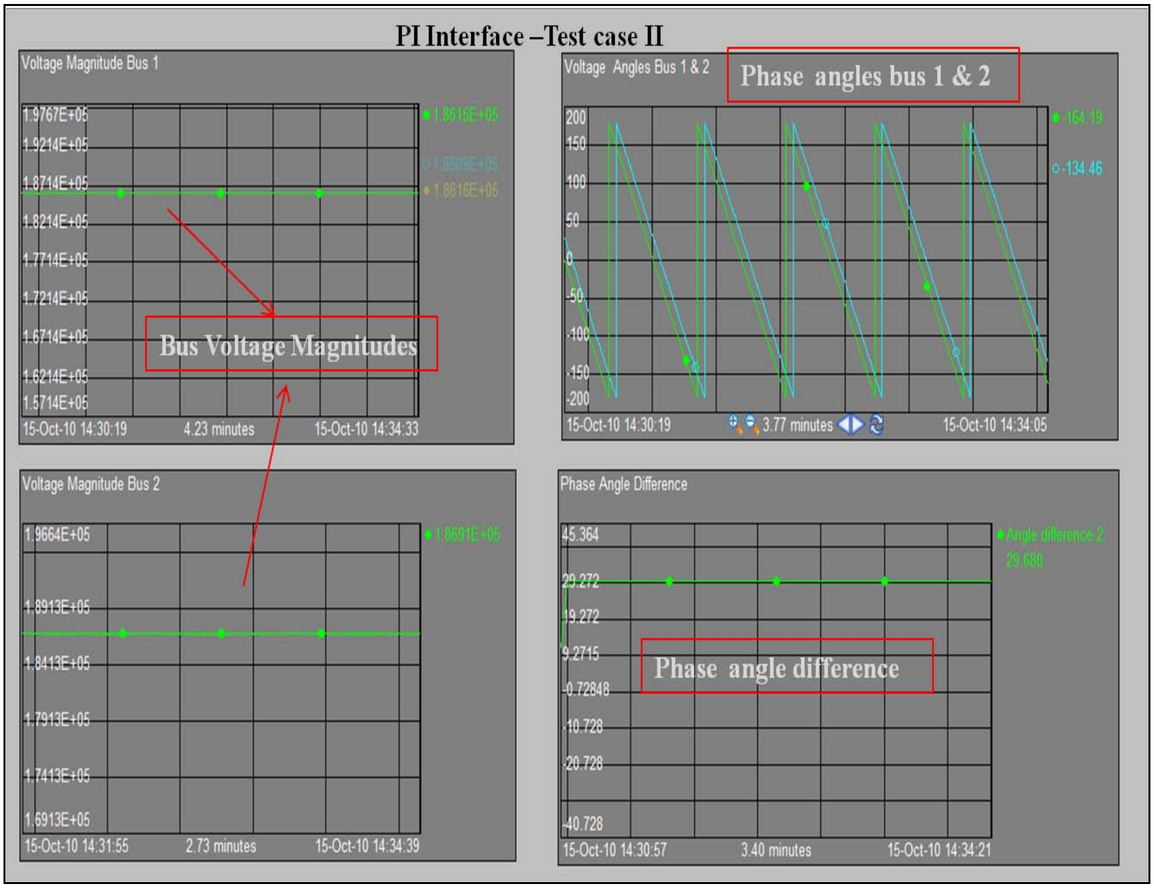

Figure 5.7 Test case II- PI process book monitoring interface

The first part of the simulation towards testing the voltage stability issues is done by applying a line to ground fault on the phase A of bus 5 for 80 cycles. The immediate result being a disturbance in major bus voltages i.e. bus 1 and 2. The instability can be seen by observing the phase angle difference which directly relates to the power flow through the system. In this case the phase angle difference is observed to be deviating from normal before settling down after the fault clearance. The PMU's placed on the buses 1 and 2 will provide the synchrophasors which are acquired by the PI system and the L-G fault is observed on the process book interface as well. Figures 5.8 and 5.9 provide the L-G fault visualization in RSCAD and PI system interfaces.

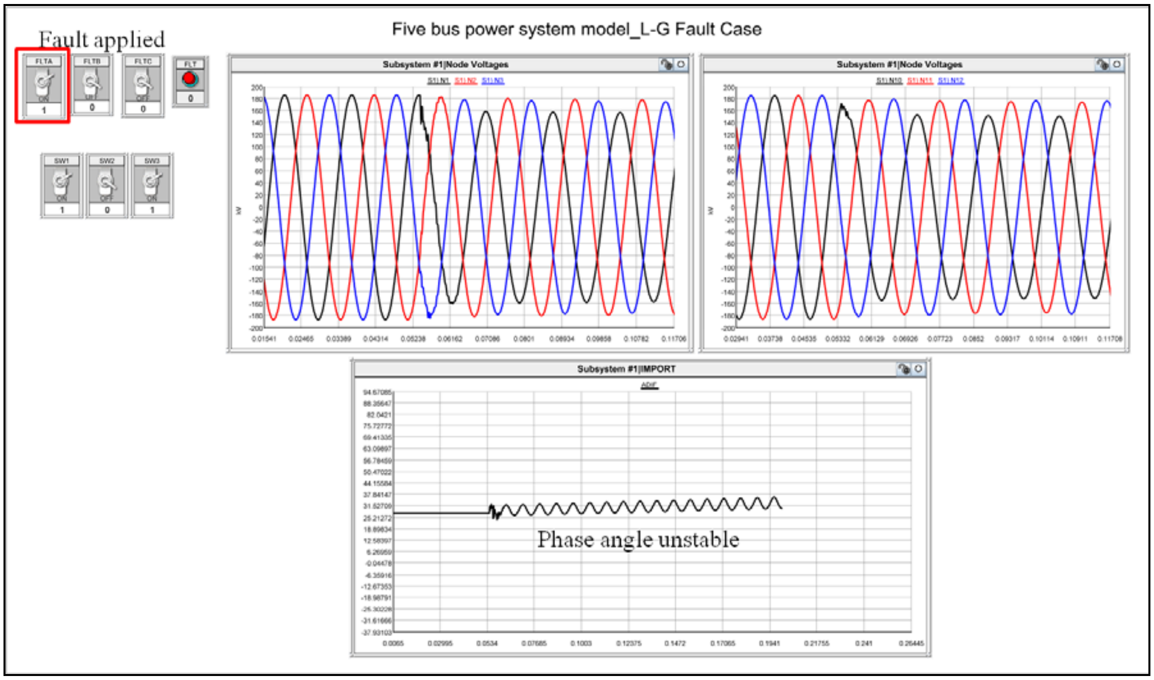

Figure 5.8 RSCAD L-G fault capture

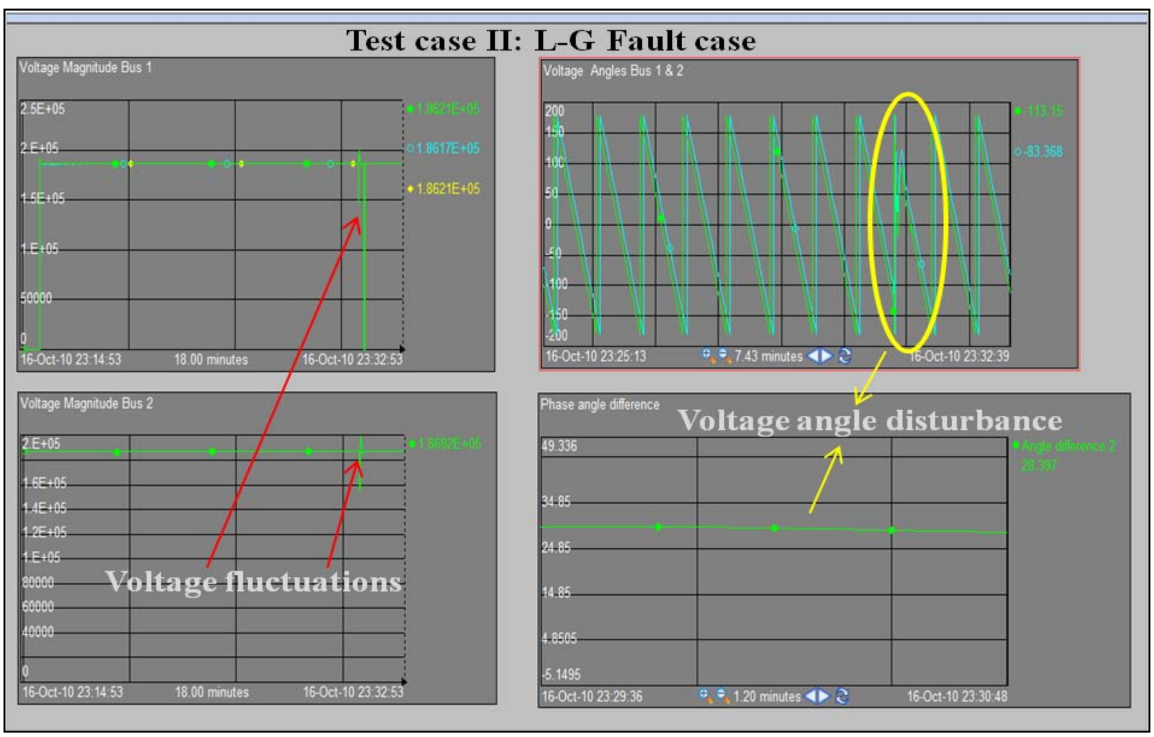

Figure 5.9 PI process book L-G fault capture

The second part of the test case simulation involved testing the voltage stability with a sudden increase in reactive power demand. This simulated by adding a extra load to the stable system and observing the fluctuations caused in the voltage levels and phase angles of the major buses 1 and 2. The captured results are shown in Figures 5.10 and 5.11 and it is observed that indeed the major bus voltages are subjected to large fluctuation resulting in the instability of the system. This is further strengthened by observing the phase angle difference between the two buses which is subjected to oscillations. The synchrophasors provided by the PMU's accurately report the data and is observed by the PI system with precision.

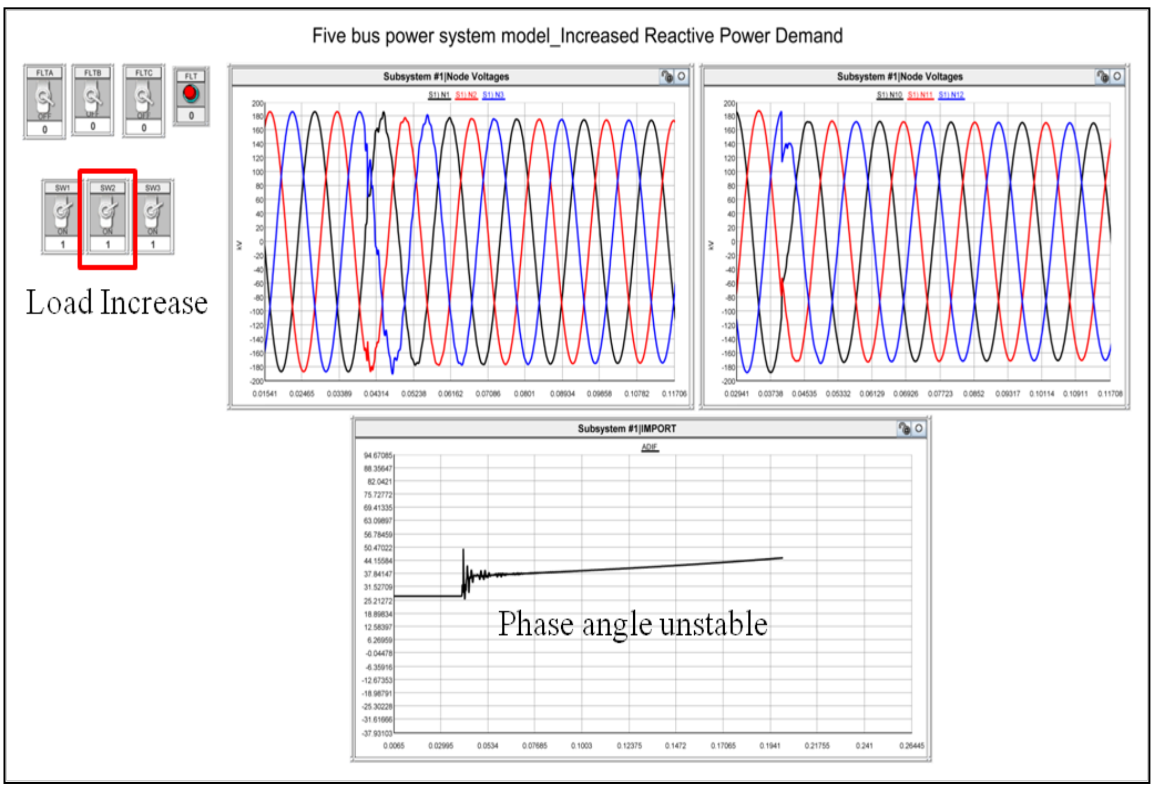

Figure 5.10 RSCAD Load increase fault capture

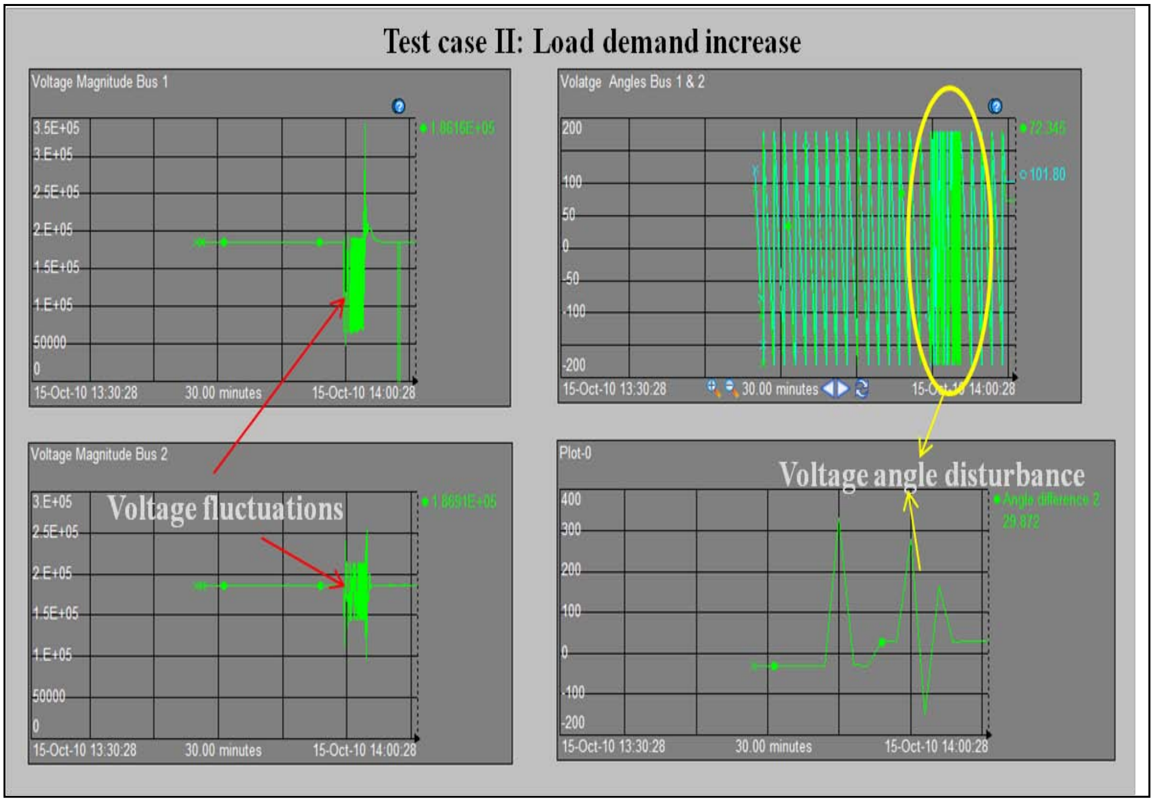

Figure 5.11 PI process book capture load demand increase

The final simulation run of the test case involves by inducing a fault due to loss of generation. This can be interpreted as, the system operating under normal circumstances as designed will meet all the active and reactive power demand needed by the loads. But if anyone of the generator fails the system becomes unstable due to its inability to meet the required demand by the loads. This condition in test case II is simulated by operating the breaker controlling the generator three. It is observed indeed there is a large amount of voltage fluctuations in the major bus voltages and the phase angle difference also oscillates considerably. These system oscillations can be visualized by referring to the RSCAD system state capture in Figure 5.12, and the phasor data provided by the installed PMU's through the PI system in Figure 5.13.

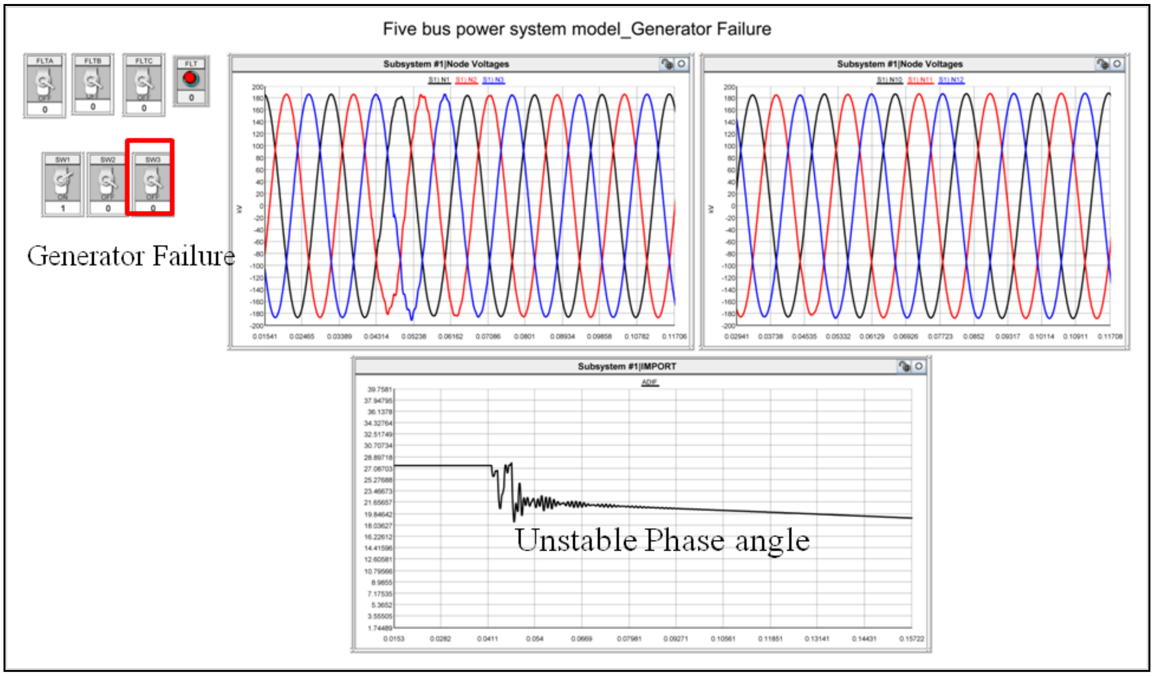

Figure 5.12 RSCAD system visualization test case II-Generation loss

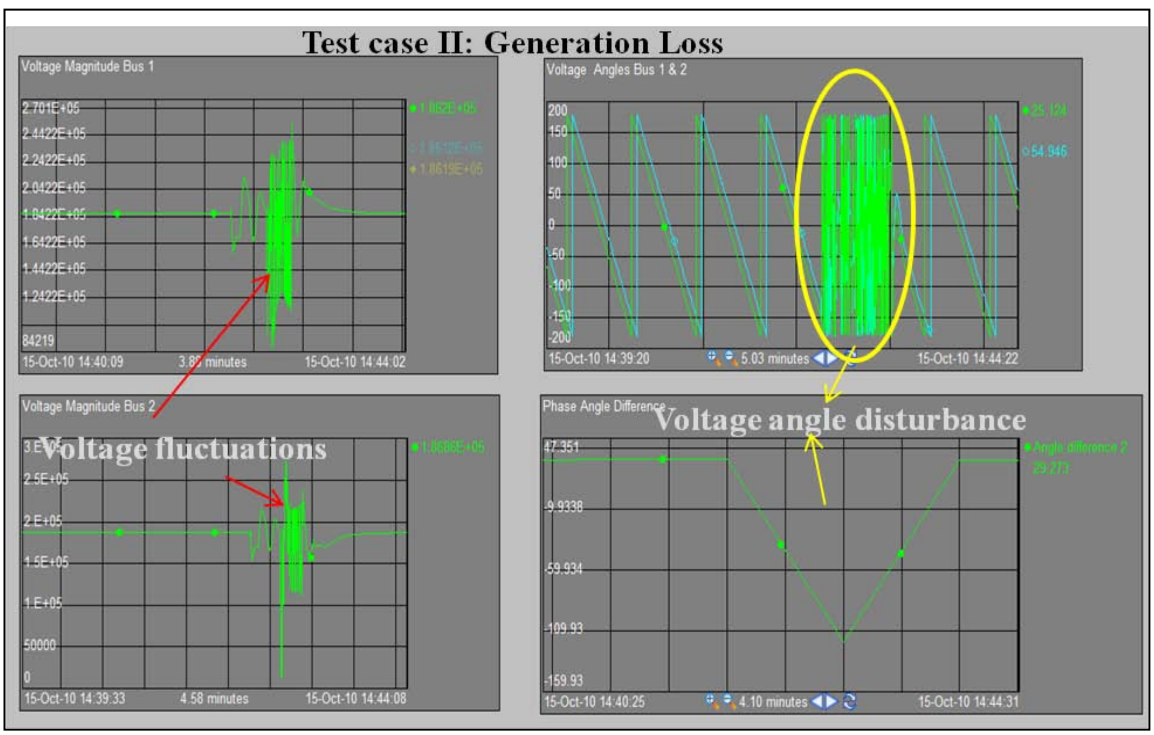

Figure 5.13 PI process book phasor data -Test case II generation loss

The PI system plays a very important role in acquiring and archiving the phasor data. The large amount of phasor data from the two PMU's installed in the system is first sent to the Phasor Data Concentrator and the PI C37118 interface acquires the data from the PDC. All the data is archived and updated at a specific update rate configured by the user depending on the amount of data storage capabilities. The illustration of this task can be observed by referring to Figure 5.14 in which all the three faults applied on test case II are recorded in a time span of 15 min.

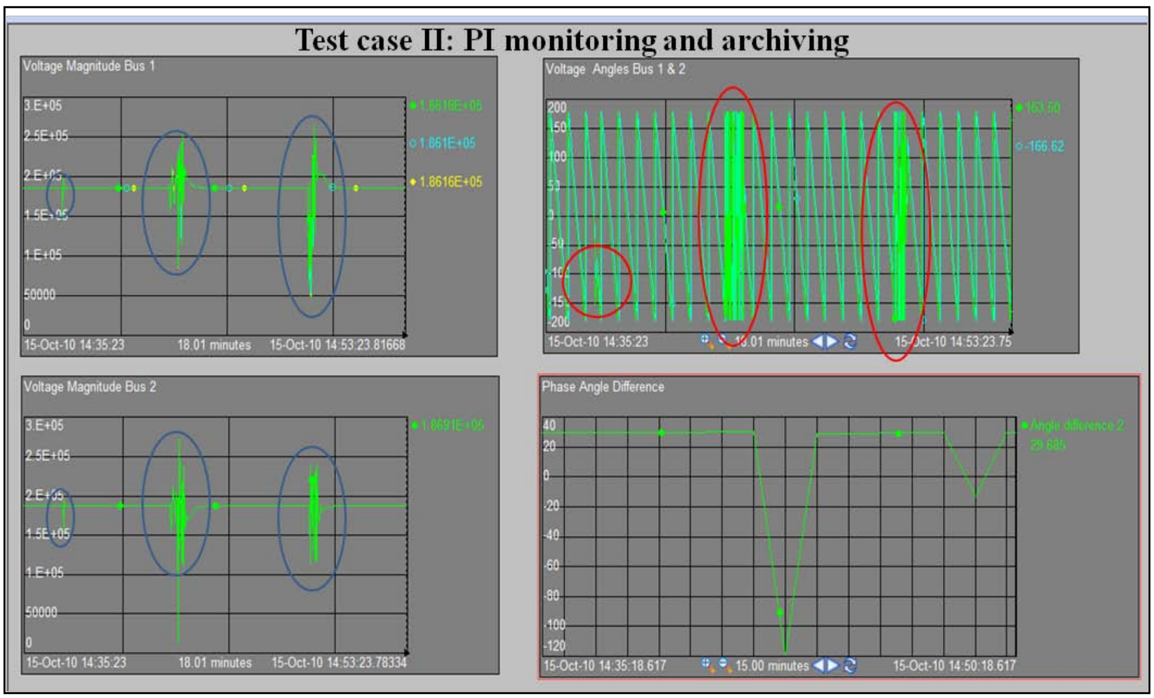

Figure 5.14 PI process book capturing all the system states

All the data obtained by the PI system is from PMU's and it can be seen that the data is archived and presented over a period of time in which all the faults are occurred. This is particularly useful for visualizing the system state over a period of time and is very helpful in post event analysis and is very accurate due to the synchrophasor data instead of SCADA data. The PI excel plug-in is another very useful tool which is used in this project to extract the archived synchrophasor data from the PI system and plotting it again. This plug-in provides numerous options to recall archived data by selecting data to be recalled on the basis of days, time interval, number of points and also data calculations. The data can be retrieved as an average or after performing inbuilt custom calculations, and is extensively used in this work to test the validity of the archived data. The following captured Figure 5.15 shows one instance of such use.

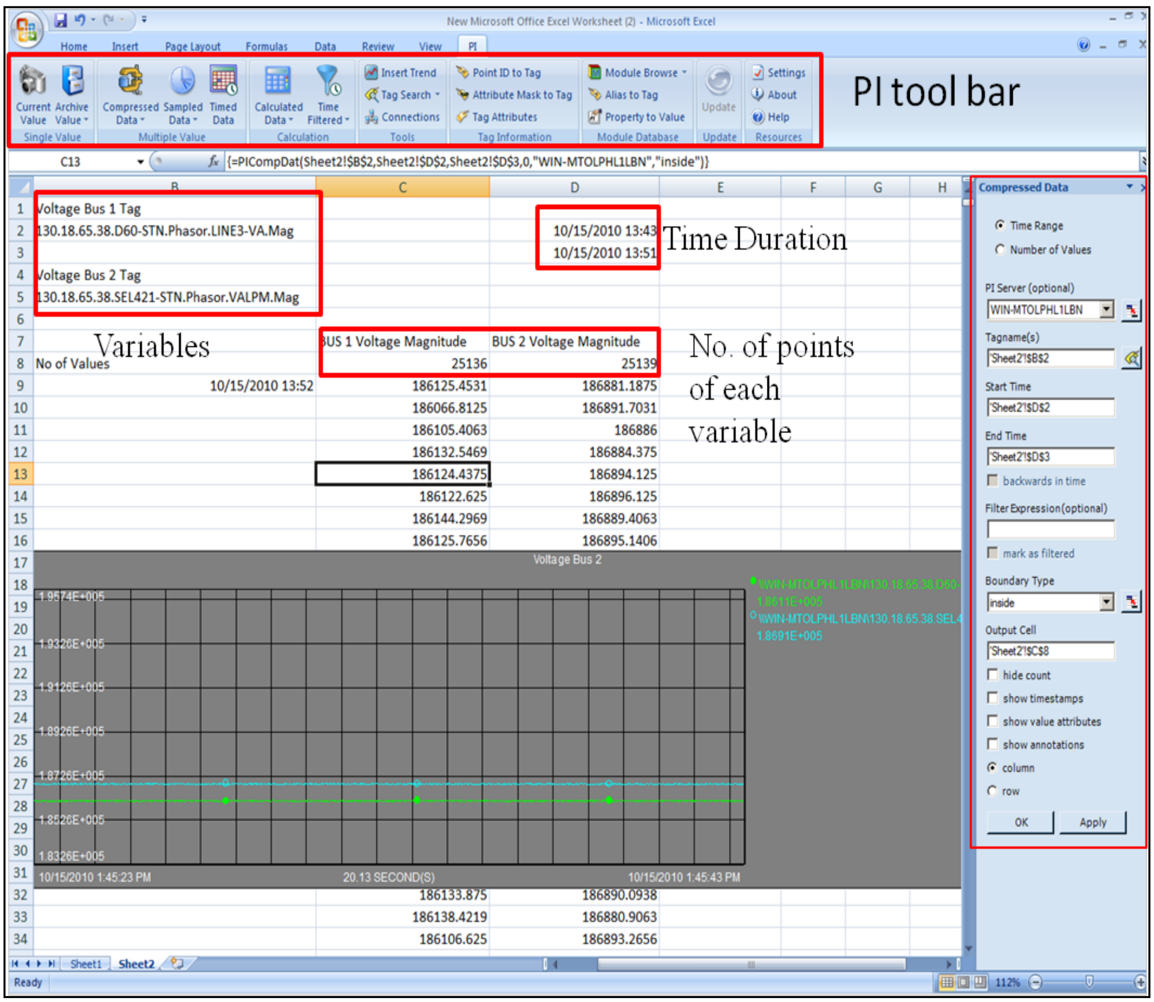

Figure 5.15 PI excel plug-in usage to retrieve archived data

5.3 Scope of utilizing the test bed

The developed real time test bed is flexible to carry multiple testing procedures. The test bed which includes Real Time Digital Simulator acts as a powerful platform and allows multiple power system tests to be performed. In the current work two different test cases are conducted, the first case implementing the automatic load shedding procedure using PLC and the second case demonstrating the voltage stability issues with enhanced measurement and archiving capabilities using PMU's and PI server system. These two test cases only demonstrate the few applications of this test bed and much larger systems can be simulated and tested with different algorithms and Hardware in Loop (HIL) simulations can be performed with ease. The test bed specifically aimed at providing varied tools including software and hardware for wide area applications combined with the synchrophasor technology. The other critical applications are outlined in the following sections.

5.3.1 PMU and PDC test facility

The current operations of smart grid activities are growing at a rapid pace. Recently, the U.S department of energy's proposed multiyear program plan for smart grid research & development plan [26] to increase the ongoing efforts towards smart grid. The first step towards the smart grid is the enhancement of measurement and control for automation of the existing power system in which synchrophasors play a major role. The current lab setup at Mississippi State Universities PERL lab is capable of testing different devices and can act as a small scale test facility. The developed test bed incorporated two GE PMU's and SEL-421 for testing the interoperability of the devices, this work also successfully implemented and tested phasor data concentrator to combine the PMU data.

5.3.2 Cyber security studies

As the power system network is rapidly undergoing transition [27] to smart grid with increased automation capabilities by incorporating large number of newly designed fully automated devices, the security of the devices is of utmost importance for the survival of the grid. Since the large amounts of critical data and automated control actions are being done through communication network it is highly important to secure them along with devices to eliminate cyber threat attacks. Efforts are underway at MSU PERL lab for testing the cyber security issues with PMU and PDC devices. The developed test bed is very useful in allowing the test to be performed as the entire network is built on Ethernet/IP as well as radio network. It allows for testing intrusions by third party and also hacking of system critical information. As the test bed employs IEEE C37.118 data standard for synchrophasor data it allows for the testing of the protocol strength against malicious cyber attacks.

5.3.3 Power Engineering Education and Device Operation Demonstration

The power systems area at present is rapidly making strides with new advancements in technologies for the efficient operation of the power grid. It is essential to develop interest and awareness among the power engineering students to be a part of the future power grid projects. In this regard there is a very limited availability of resources for the students to practically visualize and work with power systems. Though previous works like [28] exist for improvement in the curriculum structure, there very few facilities like Drexel university's IPSL laboratory [14], which actual provide good practical understanding of the power system.

The developed test bed in the present research work can be implemented to demonstrate the operation of a scaled down power grid operation and EMS applications to the students for enhancing their interest in this area. The developed test bed can simulate different power system simulation and can be very beneficial if it is used in the current curriculum for implementation of the theoretical concepts.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Power system monitoring and control is a large application area with continuous development in order to enhance the level of automation being applied to renovate the power grid. Especially, with the smart grid research initiative, the power system infrastructure is being strengthened at a rapid pace. In this thesis work, a real time automated power system network and control test bed is developed at the laboratory level to test and validate new algorithms and devices before implementation in a physical grid. The development of this test bed is achieved by integrating several hardware devices and software interfaces for enhanced automation and control. The integrated hardware devices are from different vendors and are particularly chosen to test and validate the interoperability standards between these devices. This work also contributed towards the study of different data transfers options from an RTDS system, and devised a new methodology to integrate PLC and RTDS using the National Instruments NI-PXI system for real time application. The first phase of the research work involved successfully modeling and simulating a simple power system test case to demonstrate real time control action through the developed test bed. This was successfully completed by automatic control action taken by the PLC during a faulty scenario simulated during the simulation run on RTDS.

The second phase of the research work involved more complex application of power system devices for monitoring and post event analysis functions using synchrophasors. For this purpose the entire test bed was built around Ethernet/IP to facilitate higher communication speeds and to achieve flexibility with devices that are connected to the network. The Ethernet/IP communication allows the test bed to have the capability of installing the new hardware as simple plug and play systems. The synchrophasor application is demonstrated by integrating a GE and an SEL PMU device into the power system simulator for hardware in loop simulation and is configured to send the synchrophasor measurement at a rate of 60 msgs/sec to the phasor data concentrator.

A five bus power system test case was developed to demonstrate the synchrophasor application. The power system simulated was subjected to different faults to study the voltage stability problem associated and the usefulness of the synchrophasor data stream. The other major achievement in this work is the inclusion of PI server system for monitoring and archiving of the entire power system critical data. The PI system inclusion played a major part in the application of synchrophasor data archiving and post event analysis of the power system simulations.

The highlights of this research are as follows:

- Developed a communication bridge between RTDS and PLC for simulating a local control action.
- Major part of the test bed is built on Ethernet/IP communication network to achieve flexibility with new devices and most importantly for testing the security issues with the new devices.

- Integrated phasor measurement units and data concentrators for successful implementation of synchrophasor application.
- Successfully installed and demonstrated the PI server system for monitoring and archiving the power system data including the synchrophasors in real time.
- Demonstrate the interoperability of different devices integrated in single testing platform
- Developed several test scenarios for two test cases to demonstrate few possible applications

6.2 Future Work

In this work, the development of a test bed is performed through integration of multiple devices for wide area monitoring applications. The synchrophasor data applications extend only to real time monitoring and post event analysis. There is considerable scope in developing and demonstrating real time control action for power system operation and control using synchrophasors. Efforts are already underway for real time control using SEL synchrophasor vector processor. This work integrates only a single hardware phasor data concentrator and an implementation of TVA's Open PDC can be included into the test bed. The other major future applications of this test bed are for testing and validating different power system protection and control devices as well as algorithms. Research efforts are in progress to test the security and strengthen the devices against malicious cyber attacks and this facility can be used to test different vendor hardware and software for synchrophasor applications before being actually substituting in the power grid. Developed test cases could be integrated in coursework to train students for industrial device operations and also can be utilized to expand knowledge of power systems in a broader perspective by demonstrating wide area operations on the test bed.

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