

**Development of Protection Scheme for Non-
Conventional Instrument Transformer (NCITs) Based on
IEC 61850-9-2**

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Master of Engineering by Research Thesis**

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Abstract

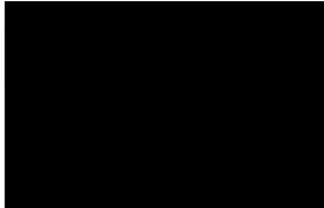
Substations are a fundamental part in electrical energy transmission and distribution. The role of a substation is to transfer and transform electrical energy by stepping up or down the voltage. To do this, high voltage switching equipment and power transformers are used, in addition to instrument transformers that supply the status of the primary system to the secondary equipment. Substation Automation Systems are then used to control, protect and monitor the substations [1]. The IEC 61850 standard developed digital substation with most advanced techniques. The IEC 61850 standard define in its sub-clauses IEC 600448 and IEC 61850-9-2 about digital interface, digital communication and Sampled Values transmission over an Ethernet link called Process Bus. This thesis is mainly based on the development of the non Conventional Instrument Transformers (NCIT), analogue to digital data converter and power system protection. The scope of this study includes the development of current and voltage transformer models in SIMULINK which gives the ideal behaviour of NCIT for protection and measurement. The research Methodology is modelling NCIT and a Merging Unit (MU) in MATLAB SIMULINK, and then the simulated results are verified according to the IEC 61850 standard. The 4 kHz output (Voltage/Current) signal is obtained in the digital form with 16-bit resolution. Final round of the research is to model the multi-bus electrical transmission power system in SIMULINK using SimPowerSystems Toolbox to run the verification tests on NCIT and Merging

Unit models. The Merging Unit functionality is validated by obtaining three phase analogue signals of both currents and voltages from NCIT. Signal processing is performed on these signals and then transmitted on the Ethernet port in the form of SV (Sampled Value) Stream according to the IEC 61850-9-2 standard. The developed Merging Unit is then connected to the different nodes of the power system to test the performance and reliability of the Merging Unit. The protection functions are not tested on Intelligent Electronic Devices (IEDs) as the available SEL, Areva and ABB IEDs were not compatible at this stage with the Process Bus of IEC 61850-9-2. The aim of this research is educational or is an IEC 61850-9-2 Process Bus concept demonstration tool, to test protection IEDs before they can operate in a real system. The field engineers need a calibrating relay setting tool to perform troubleshooting. Electrical engineering students, researchers and electric utility integration engineers will be able to use the developed NCIT Unit for basic testing and demonstrating the Process Bus technology concept -IEC 61850-9-2 based testing environment- and also interface the Process Bus with bay level, which is highly required tool by the industry. The model can easily run on any PC with average processing power which is ideal for electrical students and researchers. The required software packages are MATLAB, Simulink and SimPowerSystems, which are commonly used and accessible research tools.

Masters by Research Student Declaration

“I, Muhammad Salman Khan, declare that the Master by Research thesis entitled “Development of protection scheme for Non-Conventional Instrument Transformer (NCITs) based on IEC 61850-9-2” is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

Signature:



Date: 28/08/2015

List of Publications

Peer-Reviewed Journal Papers

- [1] Khan, M. S, Kalam, A. and Zayegh, A., 'Development of Matlab based Model for an IEC 61850-9-2 Non-Conventional Instrument Transformer (NCITs) ' International Journal of Science and Technology Management, IJSTM 2015. (*Pending Publication*)

Referred Conference Papers

- [1] Khan, M. S, Kalam, A. and Zayegh, A., 'Overview of Protection Scheme for Non-Conventional Instrument Transformer on Process Bus Based on IEC 61850-9-2 Standard in Smart Grid' International Conference on Renewable Energy Utilisation, ICREU 2014, Coimbatore - India

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List of Abbreviations

ABB	Asea Brown Boveri
ADC	Analogue to Digital Conversion
BI	Binary Input
BO	Binary Output
CB	Circuit Breaker
CIT	Conventional Instrument Transformer
CoS	Class of Service
CT	Current Transformer
DSP	Digital Signal Processing
ECT	Electronic Current Transformer
EVT	Electronic Voltage Transformer
FPGA	Field Programmable Gate Array
GE	General Electric
GSE	Generic Substation Events
GSSE	Generic Substation State Events
GOOSE	General Object Oriented Substation Event
GUI	Graphical User Interface
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers

LE	Light Edition
LED	Light Emitting Diode
LN	Logical Nodes
MMS	Manufacturing Message Specification
MU	Merging Unit
NCIT	Non-Conventional Instrument Transformer
OS	Operating System
PC	Personal Computer
PPS	Pulse per Second
QA	Quality Attributes
RJ	Registered Jack
RMS	Root Mean Square
SAS	Substation Automation Systems
SDO	Smart Digital Optics
SF₆	Sulfur Hexafluoride
SMV	Sample Measured Value
SV	Sampled Value
TC	Technical Committee
VT	Voltage Transformer

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Chapter 1: Introduction

1.1 Introduction

Power System consists of generation, transmission and distribution; safe power system operation is essential to ensure client satisfaction. Power System protection is an essential event for the safety and reliable operation of the power grid. Within substation automation, electromechanical relays were the first to start in the protection field. Solid-state relays replaced the first generation of electromechanical relays and were more efficient in the sense of their operation functionalities. Later on the electronics revolution brought microprocessor-based relays -as the state of the art- with many advanced operating principles, the use of which has achieved the highest level of substation automation for more reliable energy output to customers [1, 2].

In power transmission system, the power substation plays a significant role since one of its roles is to transfer the voltage from high to low or vice versa by utilising the power transformer. In the substation, the monitoring, control, protection and other automation functions are provided by the Substation Automation System (SAS). The communication network within the substation is divided into three levels: station level, bay level and process level [2]. NCIT and Merging Unit are located on the process level. The communication network

between primary equipment on process level and bay level is referred to as Process Bus. The communication aspect of Process Bus is known as Sampled Values service in the SAS, as per the recommendation of the International Electrotechnical Commission (IEC) standard 61850 for the use of Ethernet based communication in the substation automation field.

This thesis concentrated on the process level protection devices (NCITs and Merging Unit) and also its communication aspect, especially the Process Bus' Sampled Values service in the SAS. In order to make the readers familiar with these topics, the terms related to the topic and the scope of this research is introduced in this Chapter. As the IEC 61850 standard has been widely accepted and adopted in the substation automation, it is important that the testing tools keep up with this development [3].

1.2 Motivation

- NCIT logical model for measurement of current and voltage
- IEC 61850 9-2 based logical Merging Unit testing environment
- Quick Configuration
- Signal processing of all sensors - conventional or non-conventional
- Synchronization of all measurement with time stamped - 4 currents and 4 voltages
- Analogue interface - high and low level signals
- Digital interface - IEC 61850-9-2 or IEC 60044-8

Figure 1.1 illustrates substation automation with station and Process Bus. The red encircled portion of the Figure 1.1 is the main task of the research work where the Merging Unit is an interface between instrument transformers and the Process Bus. Subsequently, the Process Bus is the interface between the Merging Unit and IEDs.

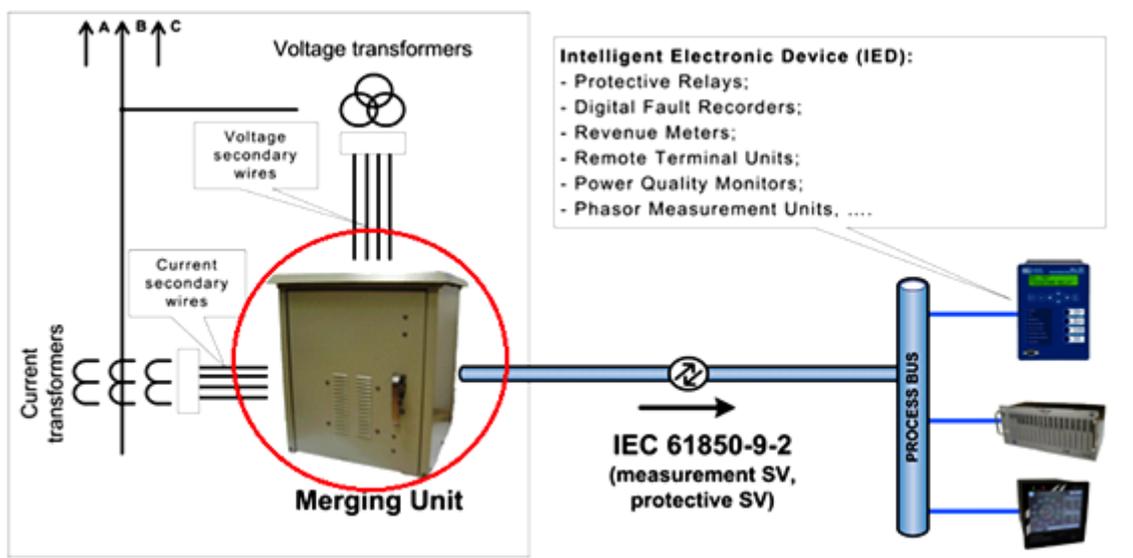


Figure 1.1 Substation Automation with Station and Process Bus [15]

1.3 Research Goals and Objectives

The objective of this research is to have a logical Merging Unit which allows running the simulations and testing on a PC which eliminates the need for any vendor specific products, which are available at a high cost. The final goal of this research is the development of a Merging Unit that complies with the IEC 61850 9-2LE standard, guidelines, understanding of its operation within NCIT

and the Process Bus. Figure 1.2 shows a complete Process Bus solution with logical Merging Unit.

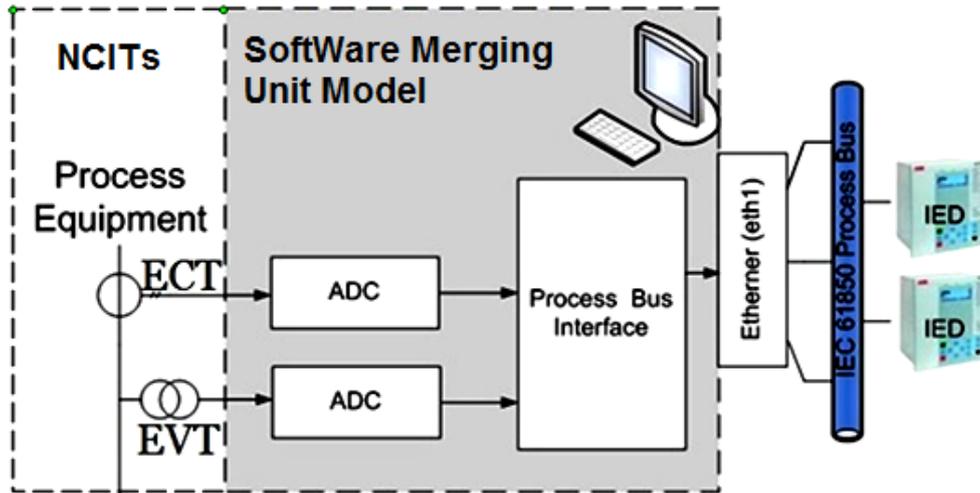


Figure 1.2 Complete Soft/Logical Merging Unit Model Project

1.4 Research Methodologies and Techniques

The research methodology and techniques for this thesis work are as follows:

1. Describe the IEC 61850 standard and its significance especially IEC 61850 sub-clauses IEC 60044-8 and IEC 61850-9-2 about digital communication and Sampled Values transmission over Ethernet link
2. Develop an understanding of IEC 61850 based SAS
3. Study the UCA Implementation Guideline for IEC 61850-9-2 (9-2 Light Edition or 9-2LE) which specifies Sampled Value data sets that are transmitted, sampling rates, time synchronisation requirements and physical interface

4. Research method for converting Analogue measurement signals from optical components to digital signals by the Merging Unit for digital interface between process level and bay level according to IEC 61850-9-2 LE guideline

These digital signals will have the information of primary currents and voltages. The available literature in this area of research is dynamic and highly informative.

1.4.1 Research Method

To achieve the requirements of this research, the following methodology and techniques are implemented:

Task 1: Literature review to get maximum exposure of research and related work

Task 2: Analysis of the currently available equipment (NCITs and Merging Unit) and its application

Task 3: Experimental setup

Task 4: Modulation techniques

Task 5: Performance analysis, testing and model validation

Task 6: Results

1.5 Original Contribution of the Thesis

High significance of NCITs relative to other technologies including, **Safety, Dynamic range, Bandwidth, Environmental, Size, Cost and Compatible**, NCITs can be implemented in existing substations or old substations and provide intelligent communication network to enable the real time monitoring which is the most important factor for any country's power sector. This research is significant as this will look into implementation of NCITs in the Smart Grid environment. The scope of this research is to parameterise the NCITs models developed in the Simulink and the model of Merging Unit to test and protect multi-bus electrical power system in Simulink.

1.6 General Limitations

As a general rule, cost, time factor and availability of technical apparatus bring constraint to each project which somehow affects the quality of the research work. Therefore, the constraint makes the expectation of the work more reasonable and close to final result and finding.

1.6.1 Technical Limitations

This constraint includes the unavailability of real time simulator which restricts this work to off-line simulations. The unavailability of IEC 61850-9-2 Process

Bus on the ABB, AREVA and SIEMENS IEDs provided in the electrical lab prohibited the use of interoperability tests.

1.6.2 Time Constraint

The time factor plays an important role in any project. Due to this constraint were not able to arrange Process Bus enabled-IED to perform test bed and perform interoperability tests. Even though it was not in the tasks to compete in priority list but it could be an interesting work to add up to the research work or future works.

1.7 Organisation of the Thesis

Chapter 1 Summarises the introduction, motivation behind this study work, the selected research methodology and purpose of research

Chapter 2 Summarizes literature review

Chapter 3 Covers the basic theory and modelling of the NCIT, the theoretical background of signal processing and explains the existing modelling of the Merging Unit

Chapter 4 Gives the experimental analysis and results

Chapter 5 Conclusion and future work

Chapter 2: Literature Review

2.1 Introduction

The demand of electricity generation is day by day rapidly increasing, on the other hand, the environmental and climate issues such as carbon dioxide emission and green house gases are more of a concern to governments, Local bodies and the common public as well. As a result, the clean energy and renewable are preferred and many new green energy power plants are under construction. Transforming the existing power plants as well as building new green energy power plants with intelligent power network to meet not only future demand of electricity, but also efficiently control and distribution of energy flow. The Smart Grid is the vision of future power grid [4].

2.2 Smart Grid

Recent trend in the power industry across the globe is to use advanced state-of-the-art communication techniques and information technologies in electric utility to realize the concept of Smart Grid; it integrates new innovative technologies and the action of all the participants throughout the power system for smart generation, transmission, distribution and utilization of electrical power as shown in Figure 2.1. Having said that, it is also must be mentioned that Smart Grid

implementation requires an intelligent communication network in order to enable real time monitoring of valuable grid assets, improving the automation functionalities and intelligence in the existing power network.

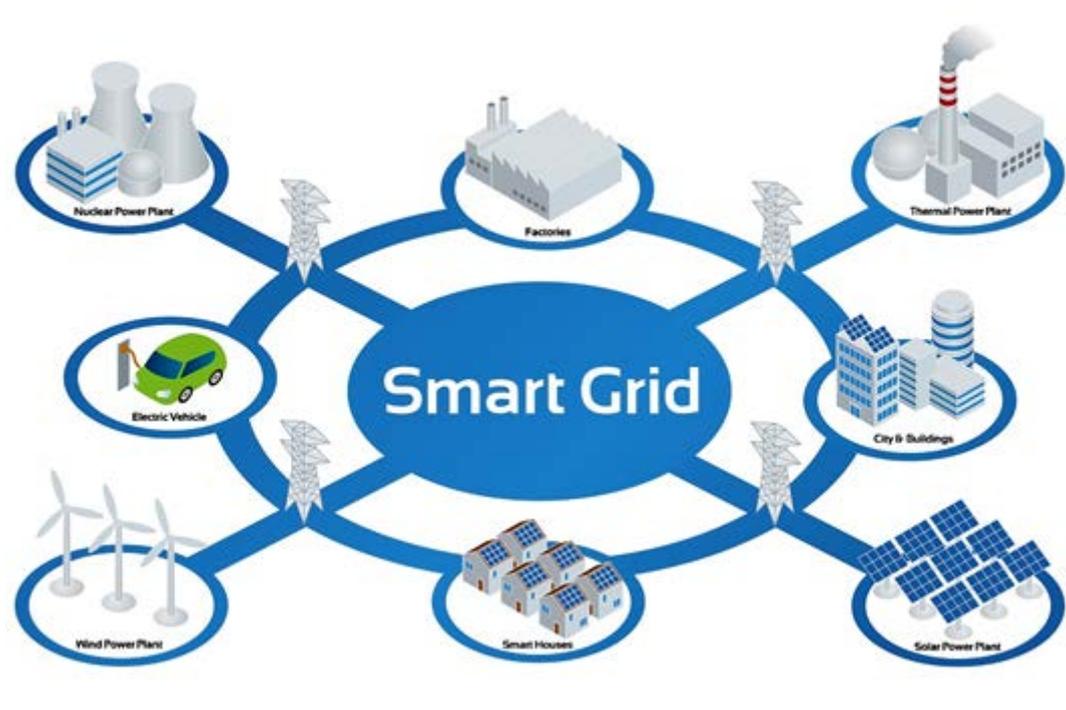


Figure 2.1 Smart Grid Concepts [4]

The Smart Grid also interface all the players in power grid which includes the end user customer, industrial user, industrial plants, building automation system, electric network and energy storage installation [5, 6]. Figure 2.2 explains roadmap to Smart Grid.

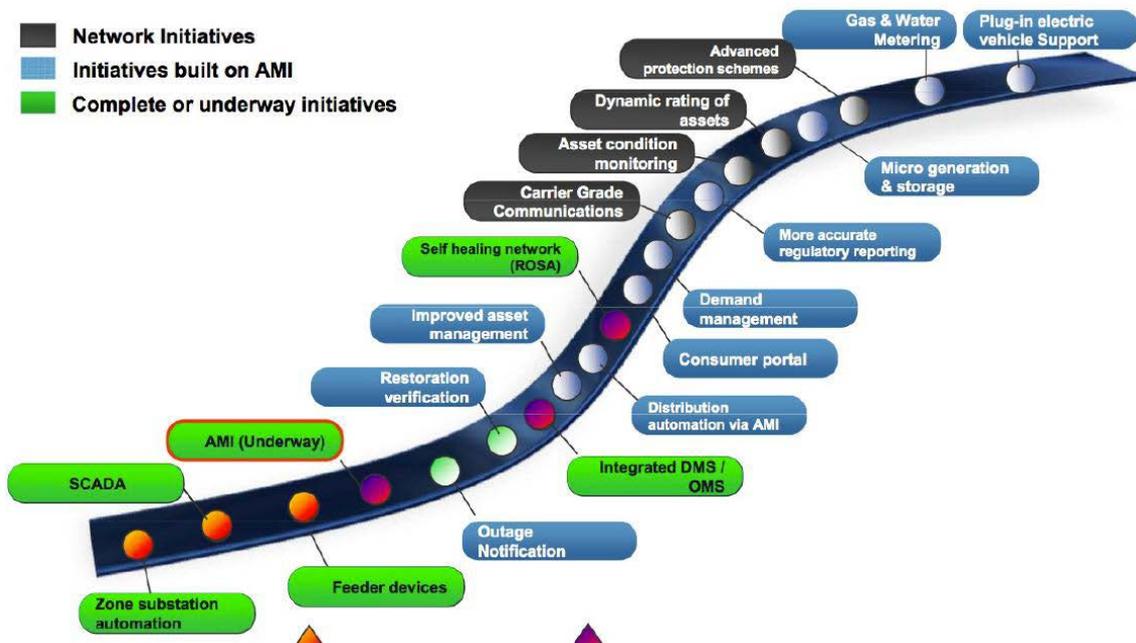


Figure 2.2 Roadmap to Smart Grid [36]

2.3 Substation Automation System

The electricity is generated by the power plant (e.g. Thermal plants in Australia). The power generated needs to be delivered to the consumers. Substations are a fundamental part in electrical energy transmission and distribution. The role of a substation is to transfer and transform electrical energy by stepping up or down the voltage/current. To do this, high voltage switching equipment and power transformers are used. In early technology fuses are used to protect the power transformers in the substation. As advancement in technology emerged, electromechanical relays replaced fuses. Similarly, microprocessor technology has seen the electromechanical relays replaced by IEDs. Furthermore, an instrument transformer on process level that supplies the status of the primary system to the secondary equipment has been added. In the substation, SAS

provides monitoring, control, protection, communication and other automation functions within the standard protocol IEC 61850 [7]. This integration not only affects substation design but almost every system or component in it such as: monitoring, protection and control by replacing hundreds of hardwired connections with communication links, which leads to a more cost effective copper-less substation [8].

2.4 IEC 61850

Early times multiple protocols exist for substation automation, which include many protocols with custom communication links. Different vendor's devices Interoperability would be an advantage to/for user of substation automation device. About 60 members of IEC project group from different countries worked in IEC three working groups from 1995. After working on all the concerns and objectives, they created IEC 61850 standard. With the goal set for substation automation were:

1. A single protocol for a complete substation allowing for the modelling of different data required for substation
2. Classification of basic services required transferring data so that the complete mapping to communication protocol can be made future proof
3. Support of high inter-operability between systems from different vendors
4. A common method/format for storing complete data
5. Define complete testing required for the equipment which conforms to the standard [9]

To achieve Smart Grid vision outlined in the road map, the IEC 61850 is listed as a relevant and recommended standard. IEC 61850 with the help of modern Information and Communication Technology (ICT) to facilitate communication solution, Fibre optic or Registered Jack (RJ) cables, network switches and routers are used to reduce the copper wire. Digital information is transferred in a substation with the help of a microprocessor based device and automation solution which was absent in the past, which was the main reason behind holding back the digitisation of substation automation. Figure 2.3 shows digital substation automation system.

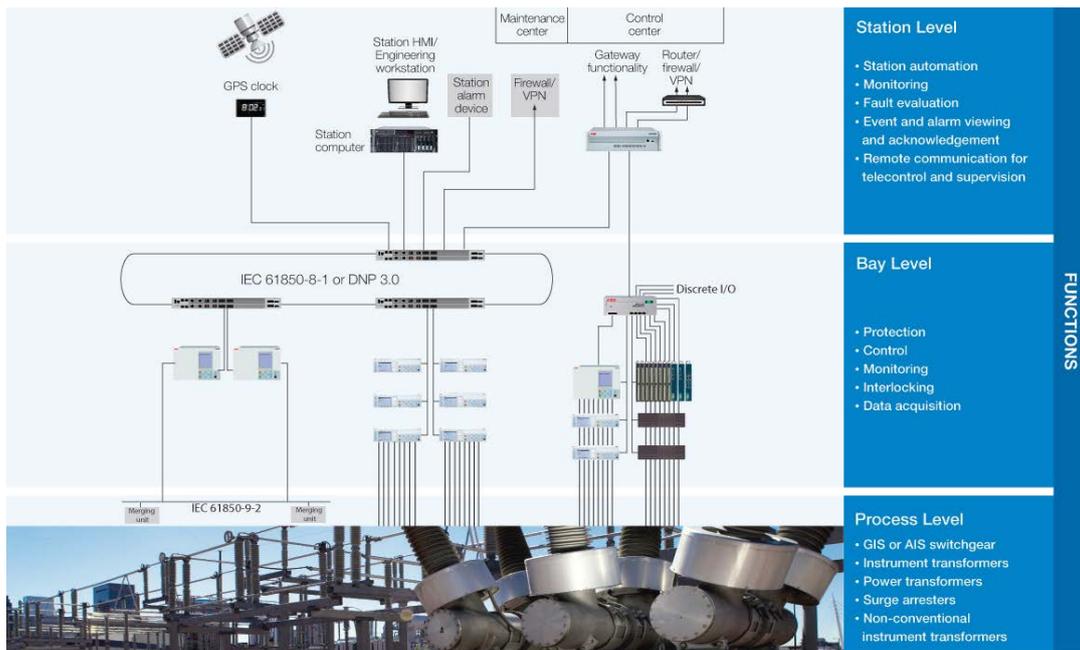


Figure 2.3 Digital Substation Automation System [10]

In order to address this matter IEC Technical Committee (TC-57) published the standard entitled “Communication Networks and Systems in Substation” in 2003 [11].

2.5 Conventional Substation Architecture

The conventional substation architecture as illustrated in Figure 2.4 utilises too much copper wire to connect conventional transformers with the protection system.

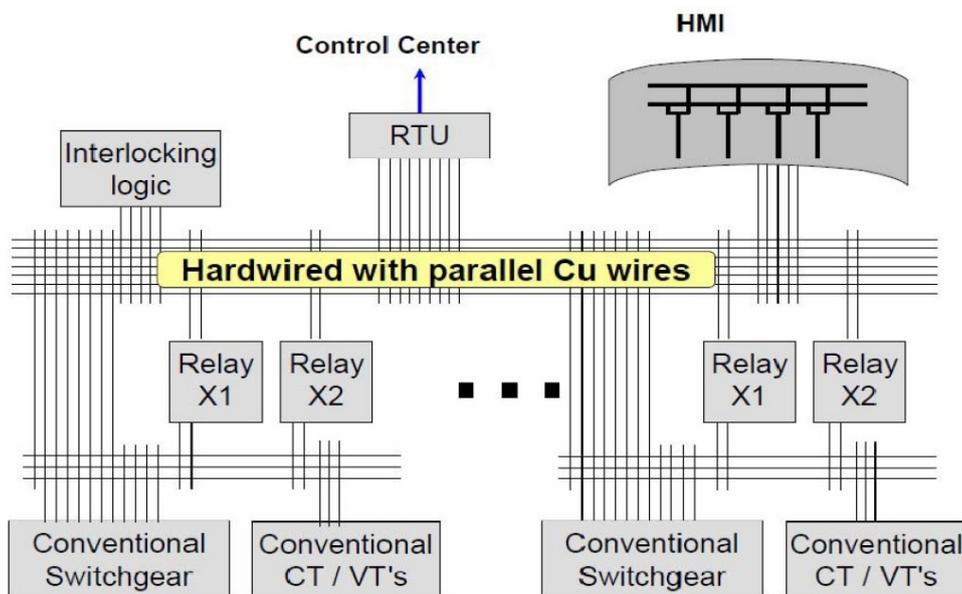


Figure 2.4 Station Bus and Conventional Wiring [12]

As can be clearly identified this Figure only illustrates one bay case. It is easy to picture and comprehend the complexity level of the connections with hundreds of bays to protect. Studying the same case with IEC 61850 standard implementation, it will be done by removing the conventional transformers and

using non-conventional transformers, serial point-to-point connections according to the standard for conventional switchgear. In this thesis the non-conventional transformers are modelled and then IEC 61850-9-2 interface is implemented. The architecture for IEC 61850 is also given in the Figure 2.5.

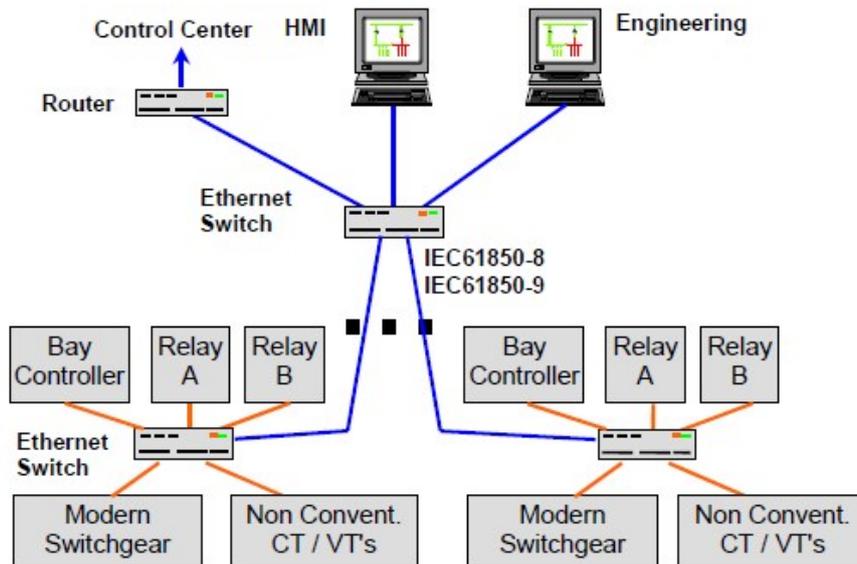


Figure 2.5 IEC 61850 Substation Architecture [12]

2.6 Digital Substation

The future of substations are complete digital substations according to IEC 61850 implementation. To achieve information sharing and interoperability between different vendor products based on IEC 61850 protocols e.g. Manufacturing Message Specification (MMS), Generic Substation Events (GSE) and Sampled Value. The GSE control model is further subdivided into GOOSE (Generic Object Oriented Substation Events) and GSSE (Generic Substation

State Events). Digital substations comprise of intelligent microprocessor based devices and networking IEDs. In comparison with the conventional substations, communication interfaces and protocols are different in bay level and the station level, but the major difference between the two is the Process Bus implemented in the digital substation. The digital substation includes Merging Units, intelligent primary devices and fibre optical connections. The fibre optical connections replaced conventional CT/VT and copper cable wiring. Digital substations with IEC 61850 standard, introduced GOOSE scheme which is the replacement of old traditional binary input (BI) and binary output (BO). The digital binary input and binary output are configurable and Ethernet switch is used to deliver GOOSE and reduce the wiring in the substation. IEC 61850 also introduced Sampled Value which makes the current/voltage sampling at primary side easier and more reliable. The voltage and current signals captured on primary side, converted to the digital signals and then delivered to the protection and control devices via optical fibre [13]. Sample Value source (Merging Unit) throughout a substation, time stamp each sample accurately that allow protection IEDs to use Sampled Value data from several sources. The clear comparison between conventional and digital substation is given in the Figures 2.4 and 2.5.

2.7 Non-Conventional Instrument Transformers (NCITs)

NCITs integrate new innovative technologies and the action of all the participants throughout the power system for the smart generation, transmission, distribution and utilisation of electrical power. Smart Grid needs an

intelligent communication network to enable the real time monitoring of valuable grid assets for improving the automation functionalities and intelligence in the existing power network. First Initiative of NCITs was taken by replacing CTs by Rogowski coil used as an AC current sensor. Rogowski coil is connected to an integrator circuit to obtain an output voltage proportional to the instantaneous value of the current. New development of Smart Digital Optics (SDO) in NCITs started a revolution in power protection. Optical current sensors are now introduced based on Faraday Effect which does not require any oil or Sulfur Hexafluoride (SF_6) gas insulation and now both CTs and VTs can be conveniently replaced by NCITs [1]. The Figure 2.6 shows the fundamental principle of optical current sensor based on Faraday's effect for measurement of current.

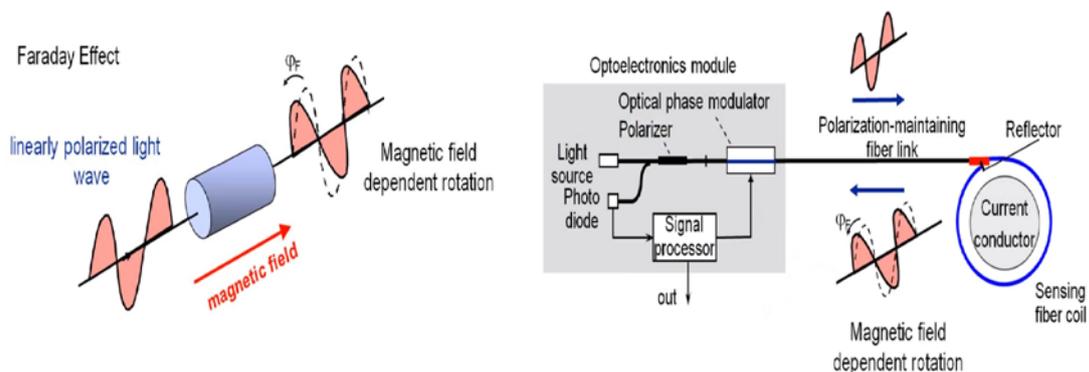


Figure 2.6 Fundamental of Optical and Fibre-optic Current Sensor [8]

It is an interaction between light and a magnetic field in a medium. The Faraday's effect causes a rotation of the plane of polarisation which is linearly proportional to the component of the magnetic field in the direction of

propagation [8]. Calculations of measurement of current are made with the help of phase shift angle. The Pockels effect is the linear electro-optic effect shown in Figure 2.7.

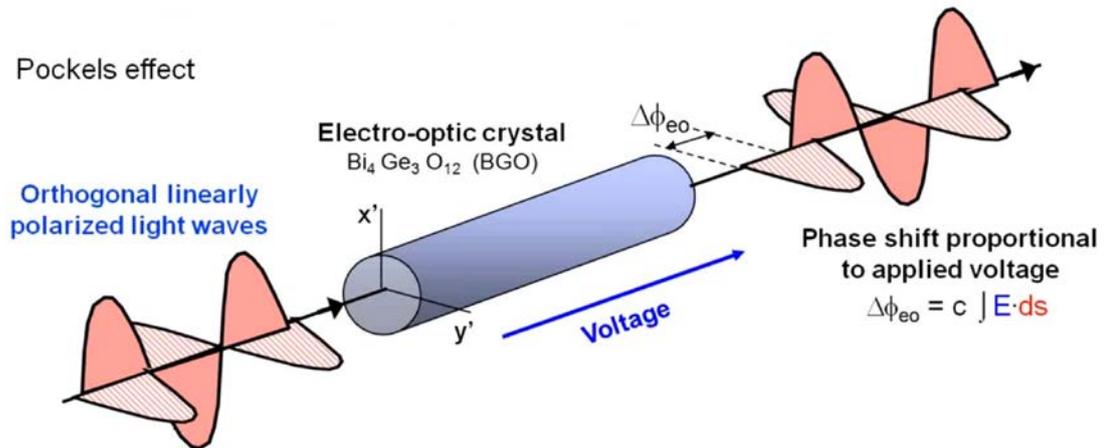


Figure 2.7 Fundamental of Electro-optic Voltage Transducer [8]

Electro-optic effect is the change in the refractive index resulting from the application of dc or low frequency, electric effect. Refractive index changes in proportional to the applied electric field (Pockels Effect). Where refractive index changes in proportion to the square of the applied electric field (Kerr Effect). This effect can occur only in non-Centro symmetric materials (crystal materials) [8]. Figures 2.8 and 2.9 shows the high significance of NCITs relative to other technologies including:

1. **Safety**, as optical output poses no safety risk as compared to CTs potential lethal voltage

2. **Dynamic range**, optical sensors do not have the limitation magnetising current and suffer saturation effects as in conventional CTs do and remain accurate down to zero current
3. **Bandwidth**, the actual limit is more likely to be anti-aliasing filters in the process of digitising the optical signals
4. **Environmental**, optical sensors do not require oil or SF₆ insulation and present very lower risk to environment
5. **Size**, small size and weight of the optical sensors reduce the requirement of mechanical support and have flexibility in mounting the device
6. **Cost**, relative to conventional CTs, optical sensors can provide significant cost reductions through reduced installation, maintenance and disposal cost, bulk copper, spares inventory and structure requirement
7. **Compatible**, NCITs can be implemented in existing substations or old substations and provide intelligent communication network to enable the real time monitoring which is the most important factor for any country power sector [1]

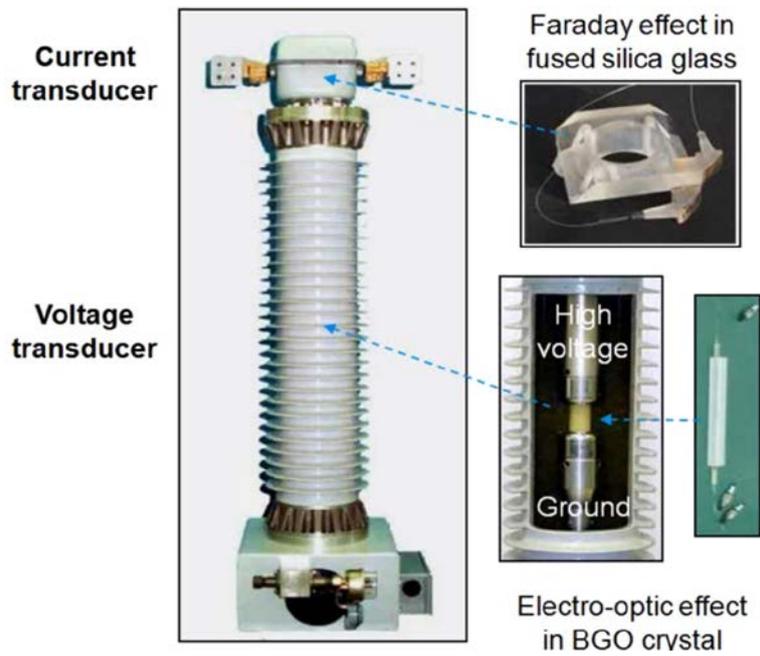


Figure 2.8 Placement of Optical Sensors in Electrical Substation [10]

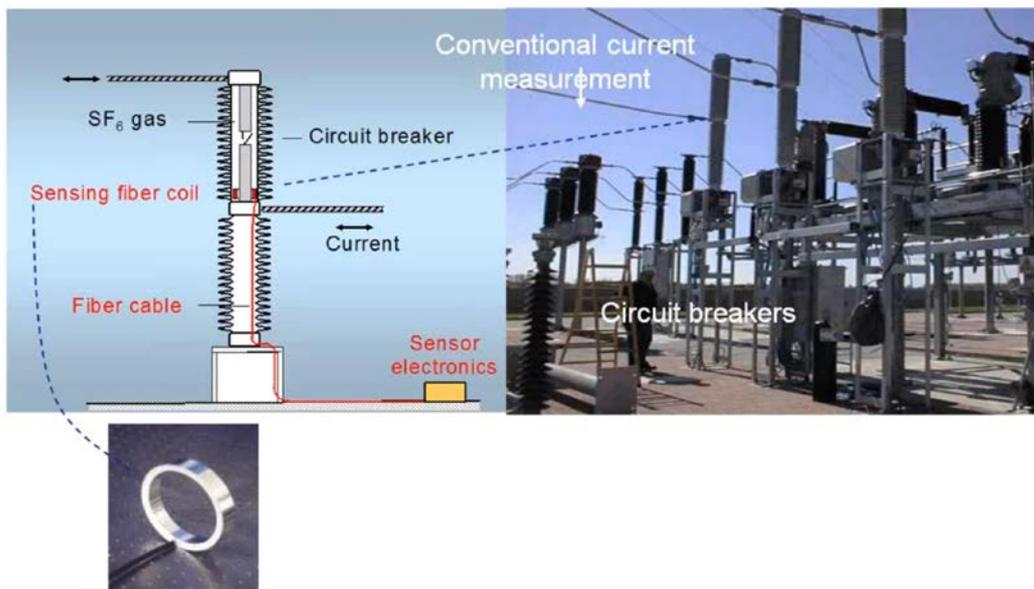


Figure 2.9 NCITs on Field Applied to 170kV live Tank Circuit Breaker [10]

2.8 Merging Unit

NCITs appear to be reliable and can measure current and voltage in order to simplify and compact the primary equipment, reduce environmental footprint and most importantly hazards associated with Conventional Instrument Transformers (CITs) [1]. Furthermore, NCITs are key components in the application of relays, meters and bay computers, all of which are used to measure, control and protect the operation of power networks. An accurate transformation of a secondary quantity is essential to feed substation IEDs and digital relays. To communicate with IEDs and digital relays digital interface is required and NCITs only measure the high transmission voltage and current in analogue signals [14].

The absence of a digital interface standard did not allow NCITs into IEC61850 high voltage transmission sector. New International Standard IEC 61850-9-2 first released in 2004 [1], which has given new exposure to digital interface standard for connection of NCITs to high voltage transmission domain in order to protect the equipment and revenue meters. Merging Unit is being introduced as shown earlier in Figure 1.1 which is best defined as; Interface Unit that accepts multiple analogue CTs/VTs (optical or conventional) in addition to binary input and produce multiple time-synchronised serial unidirectional multi-drop digital point-to-point output to provide data communication via logical interface 4 and 5 [16]. Interface 4 is defined for Current Transformer (CT) and Voltage Transformer (VT) instantaneous data exchange (especially samples)

between the process and bay levels, whereas Interface 5 is defined for control data exchange between the process and bay level. The “Process Bus” is defined in the IEC 9-2 LE (LE is the Light Edition) transmits not only position information but also Sample Values and trip commands [1, 17]. Existing Merging Units have the following functionalities [16]:

- Signal processing of all sensors - conventional or non-conventional
- Synchronisation of all measurement with time stamped - 4 currents and 4 voltages
- Analogue interface - high and low level signals
- Digital interface - IEC 61850-9-2 or IEC 60044-8

2.9 NCITs, Merging Unit and IEC 61850-9-2

The communication network in substation automation network is divided into three levels, station level, bay level and process level. Switchgears equipment, actuators and sensors are on process level. Communication network between process level and bay level is called Process Bus [18]. Figure 2.10 shows three level hierarchies of SAS in IEC 61850.

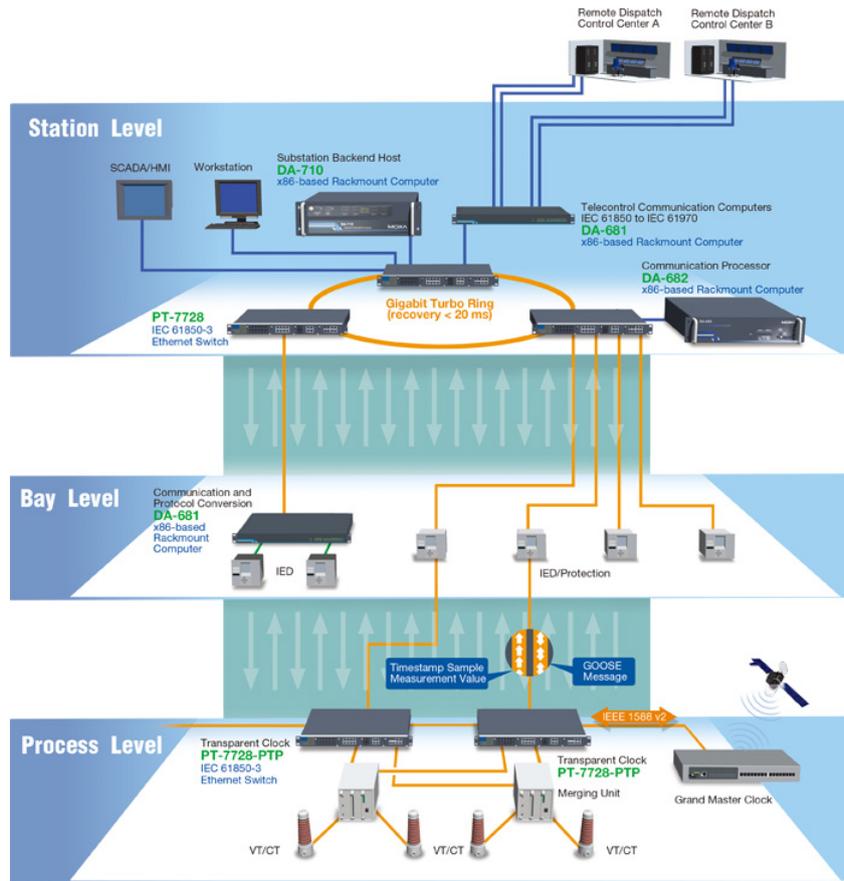


Figure 2.10 Three Level Hierarchies of SAS in IEC 61850 [19]

In general IEC 61850 the bay level specified in IEC 61850-8 is being widely used; IEC 61850 Process Bus part 9-2 standard has been implemented in some pilot installations. Introducing the Process Bus is obviously of great benefit, great reduction of copper wire, digitised information system, implementation procedure with automated testing makes it easier [20]. As aforementioned, Process level contain circuit breaker, current and voltage transformers and these devices exchange information with bay level equipment, then Merging Unit was eventually introduced [21]. Merging Unit was first defined in IEC 60044-8 and is shown in Figure 2.11.

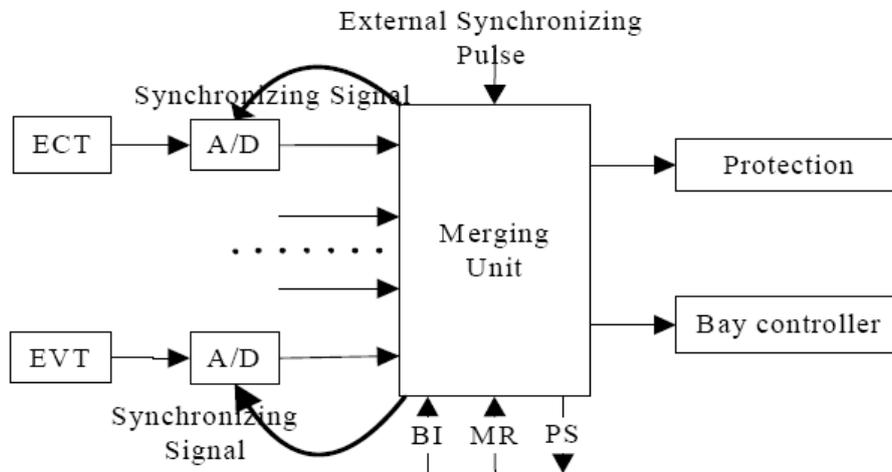


Figure 2.11 Merging Unit Definition in IEC 60044-8 [21]

The architecture of Merging Unit is shown in Figure 2.12, the first block contains analogue filtering which requires the NCITs signals to decide and cut off unnecessary frequency, and then the signals pass through the ADC (analogue to digital convertor) in order to convert signals to digital form. DSP (digital signal processing) block removes the noise from the signal and performs digital filtering of the signal.

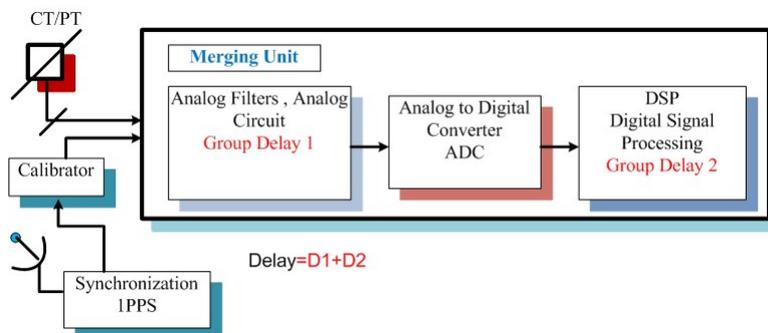


Figure 2.12 Architecture of Merging Unit [22]

This process causes the delay in the phase, which can be compensated by using synchronisation pulse from GPS clock or some cases internal clock. The delay in the phase can be realised in the Figure 2.13.

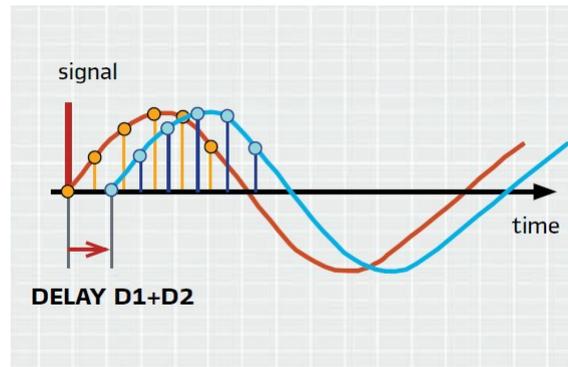


Figure 2.13 Phase Delay in the Signal [22]

The Merging Unit generates Sampled Value traffic that is fed into the Process Bus network so that bay level devices such as IEDs can collect the measurement. The Process Bus Sampled Value service is based on Data link layer [23]. Table 2.1 explains OSI Layer Communication Model.

Table 2.1 The Seven Layers of the OSI Model [24]

Layers	Function
1. Physical	Transmission of an unstructured bit stream over the physical medium
2. Data Link	Reliable transmission of frames over a single network connection
3. Network	End-to-end communication across one or more sub-networks
4. Transport	Reliable and transparent transfer of data between end points
5. Session	Control structure and management of sessions between applications
6. Presentation	Data representation (encoding) during transfer
7. Application	Information processing and provision of services to end users

The OSI layer model is divided into lower and higher layers, Physical, Data link and Network are lower layers and the rest of layers are the higher ones. It is lower layers responsibility to transfer the data between end systems while the higher layers are to provide services to user of the end system [24]. The information flow between OSI layers is presented in Figure 2.14.

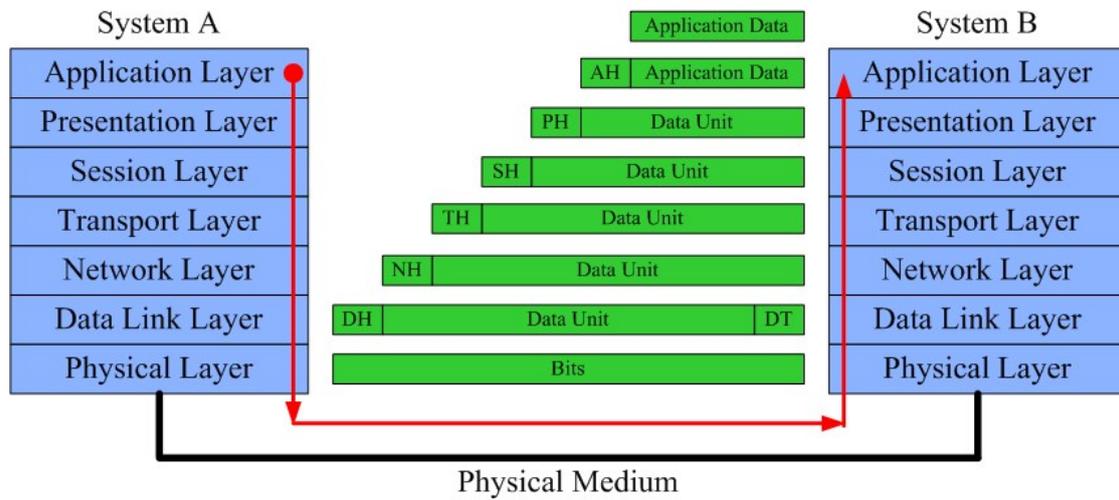


Figure 2.14 Information Flow and Encapsulation [24]

The encapsulation of data should be from top layer down to Data link layer, so all the headers are to be added in each layer [25]. The allowed time-critical packet communication delay such as Process Bus communication GOOSE and Sampled Value is 3 to 4ms. The studied results in reference [26] show that Sampled Value delay time with sample rate 1920-4800Hz are within the range by using 100 Mb/s optical fibre communication speed.

2.10 Conclusion

The research is based on protection through Process Bus with NCITs and Merging Unit. The goal is to have educational purpose-built or used as a Process Bus concept demonstration tool, to test the protection IEDs before they can operate in a real system. The field engineers need a calibrating relay as a setting tool in order to perform troubleshooting. To evaluate the protection logic

through Process Bus, there are several options, such as Omicron and Doble test tools and also physical Merging Unit from any vendor but all of them are either expensive or inflexible for educational purposes. However, to develop an industrial level Merging Unit testing tool is too ambitious for the scope of this thesis. The proposal of real-time digital simulators together (opal RT) with MATLAB Simulink NCITs and Merging Unit modules are taken into account because of feasibility and manageability with respect to limited time.

Chapter 3: Models of NCITs, Merging Unit and Multi-Bus Power System

3.1 Introduction

This Chapter includes the modelling of NCITs in Simulink, use of Opel RT Simulink Merging Unit model and Multi-bus power system Simulink model through following steps:

1. Theoretical background about CITs and NCITs for the reader to understand the difference and functionality of both
2. Developed modules of NCITs are presented. These modules are not real models for CT/VTs but give the ideal realization of CT/VTs
3. Theoretical background of Merging Unit is presented for the reader to understand importance of Merging Unit and also the main functionality of Merging Unit
4. Opel RT Simulink Merging Unit model is presented
5. Introduction to the overall power system and its different components in addition to the modelling of a multi-bus power system in Simulink SimPowerSystems simulations
6. Developed power system modules in Simulink is presented

3.2 Conventional Instrument Transformers VS NCIT

Current transformers (CTs) play key roles as they produce the access to the high currents in a power system through replica on the secondary side with reduced level. IEDs detect the fault within time limits and isolate them; therefore these devices are totally dependent on instrument transformer measurement values. Problem with conventional current transformers is saturation in CT core because of non-linear excitation in high fault currents. This result in the measured value of current on the secondary side is no longer accurate according to the turn's ratio, which leads to triggering of wrong event [27]. The replacement for the CITs is NCITs, also known as Electronic Current transformer (ECT) and Electronic Voltage Transformers (EVT), which play an important part in Smart substation. Electronic transformers use the electronic technology to measure current and voltage of power system and deliver these measurements to protection relays and control system. Employing ECT has advantages of no saturation effect, no flammable materials such as oil, simple insulation structure and immunity to electromagnetic interference gives NCITs an edge on CITs [28].

3.3 Non-Conventional Instrument Transformers

NCITs nowadays, have achieved high performance in control and protection regarding substation automation. Rapid development and achievements in

electronics and information technology, has led to substations being more compact and digital data transmission is transported from process level. NCITs have proven its performance in worse condition of temperature, mechanical vibrations and electromagnetic compatibility [29]. The designs of NCITs are based on IEC 60044-8 and IEC 60044-7 respectively. The digital output interface of NCITs is based on IEC 61850-9-2. The detected current measurement is achieved by Faraday's effect while voltage measurements achieved by Pockels effect. Both measurements are transmitted to Merging Unit as optical digital signals. Therefore, the primary equipment and substation system wiring can be simplified by utilising optical fibre for communication of data and procedural commands [30].

3.4 Simulink Model of ECT/EVT

On the transmission level the values of current and voltage are very high. Instrument transformers step down the voltages/currents for monitoring and protection purposes. Instrument transformers usually transform the high-tension side to 110/220 V and 1/5 A depending on the measuring systems configuration. In this research, the voltage and current are stepped down to 110 V and 1 A. Once measurements are stepped down it further scales down with respect to ADCs requirements for Merging Unit to work properly on these measurements. Figure 3.1 shows the Simulink model used for both ECT/EVT.

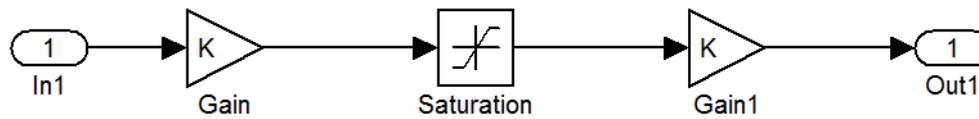


Figure 3.1 ECT/EVT Model

The given Simulink models have two gain blocks and one saturation block, the gain block on the In1 is used to step down ratio of the incoming currents and voltages from main transmission line. The next step is the saturation block which provides a lower and upper limit to the measured values. Reason for saturation limit is to block any extra high current and voltage at the time of abnormal or fault conditions. The last step is the second gain block which uses further scaling down, if required for Merging Unit to convert AC signal to digital signal. The second gain can be parameterised according to the given or required condition to make the model flexible for any input measurement values.

3.5 Merging Unit

Merging Unit plays an important role in digital substations. It exchanges the message between process level and the bay level (secondary equipment) of the substation automation. Merging Unit collects multi-channel analogue signals output from ECT and EVT, converts the analogue signal from ECT/EVT (NCITs) to digital signal and transmits these signal with the aide of IEC 61850 protocol to protection and control devices [21].

Much research has been already done and others are still ongoing by different researchers and vendors on Merging Unit. The cases studied in reference [32] (which is based on GE equipment) and reference [26], both project utilised physical Merging Unit in their experimental setup. Figure 3.2 shows a physical Merging Unit experimental setup.

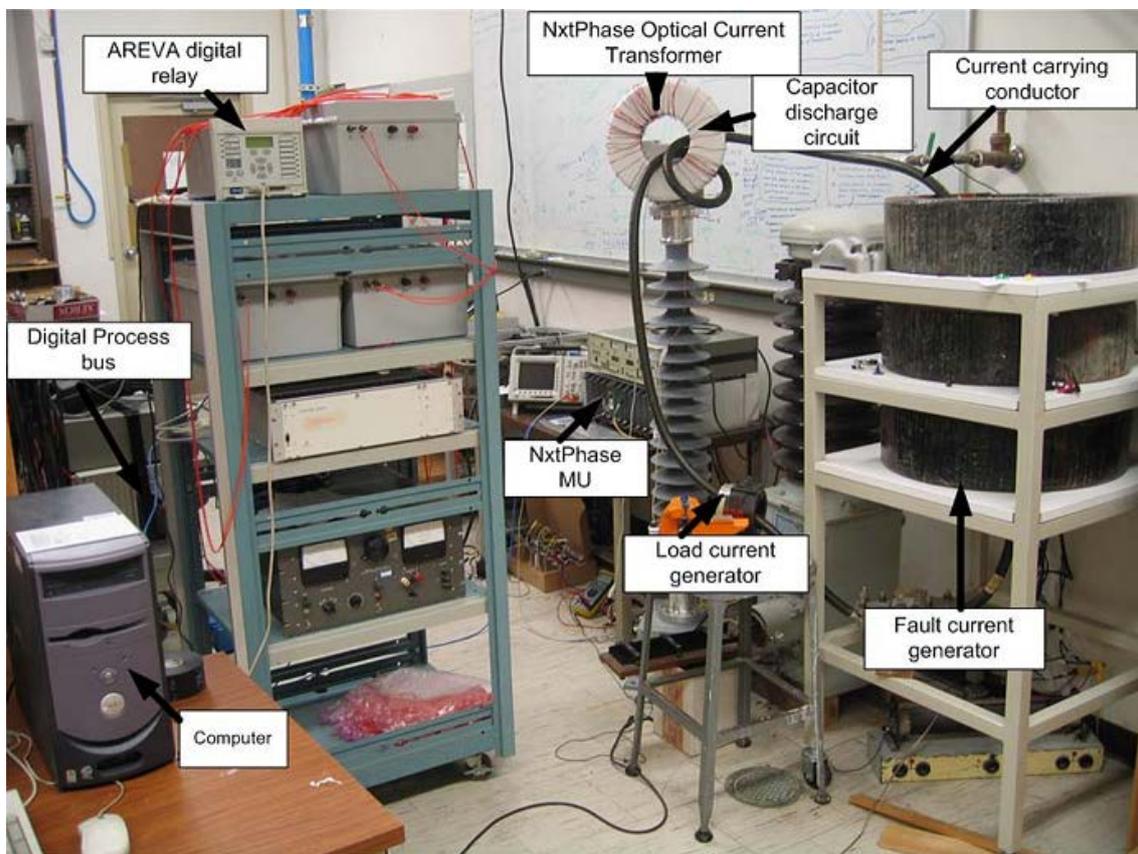


Figure 3.2 Physical Merging Unit Experimental Setup [26]

In presence of physical Merging Unit and professional tools shown in Figure 3.2, detailed IED protection function evaluation has been given in reference [26]. Physical Merging Unit is not feasible as in some cases large amount of Merging

Units are needed to test, which will be costly and inflexible for educational purposes. Software models and simulation of Merging Unit are preferred even in large scale test, when large amount of Merging Units are needed for testing purposes.

3.6 Design and Function of Merging Unit

Literature studies reveal, different researchers suggesting different designs for the Merging Unit with pretty much similar functionality. The work done in reference [21] is used as reference point for understanding the design and function of Merging Unit. The Merging Unit design comprises of three major parts Data Acquisition and Processing function, Synchronizing function and Packet transmission as shown in Figure 3.3.

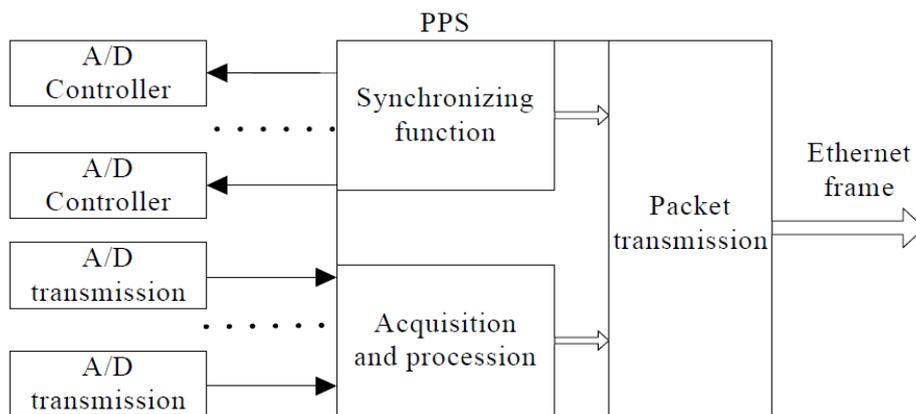


Figure 3.3 Function Model of Merging Unit [21]

Merging Unit after converting NCIT 4 current and 4 voltage analogue signals into digitized form with an output rate of 4 kHz according to IEC 61850 standard in Data Acquisition and Processing function. Merging Unit sends the information in form of Sampled Values or also known as Sample Measured Values (SMV). These Sampled Value service is based on Data link layer on Process Bus [23], where Data link is reliable for transmission of frames over a Single network connection [24] within OSI layer communication model. The Ethernet based in IEC 61850 is the same for conventional and commercial networking. Standard communications mapping for Sampled Values is specified in IEC 61850-9-2. Sampled Value requires VLAN frame tagging (VLAN ID, or VID) which is commonly referred to as '802.1Q tagging' according to IEEE 802.1Q-2005 standard. VLAN tags provide additional information to network switches about which virtual network a frame belongs and priority CoS (Class of Service) is assigned to the frame [33].

The Merging Unit, throughout a substation time stamps each Sampled Value accurately; in turn this allows protection IED to use Sampled Value data from several sources. IEC 61850-9-2 LE specifies an optical 1 pulse per second (1pps) timing signal with $\pm 1\mu\text{sec}$ accuracy for this purpose [34]. A standard 802.1Q tagged Ethernet frame is depicted in Figure 3.4.

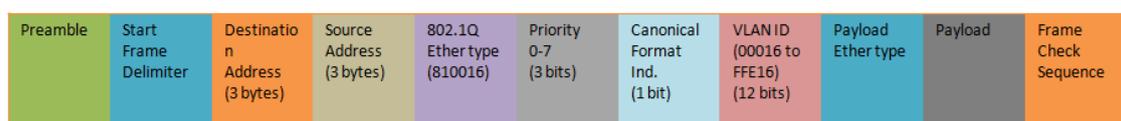


Figure 3.4 Generic 802.1Q Tagged Ethernet Frame [33]

IEC 61850-9-2 and 9-2LE has its own overhead which define Sampled Value payload with not only ASN.1 encoding but also other fields, identify the source of the sampled data and time stamp [33]. Figure 3.5 shows Sampled Value protocol overhead [33].

Ethertype 88BA ₁₆	Application ID (4000 ₁₆)	SV Data Length	Reserved	Protocol Overhead (APDU/ASDU)	svID Source Name	smpCnt Sample Counter	confRef Configuration Revision	smpSynch Synch. Sampling	Measurement Data
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Figure 3.5 Sampled Value Protocol Overhead [33]

IEC 61850-9-2 is a Multicast protocol; so specific destination addresses are used. IEC61850-9-2 recommend that destination MAC address in the range 01-0C-CD-04-00-00 to 01-0C-CD-04-1F-FF be used for Sampled Values [33]. The measurement data contains the measured values. Fixed scaling is used to convert primary quantities to integers like current $\times 1000$ and voltage $\times 100$. Sampled Value source for protection mode transmit waveform data 80 times per nominal cycle, which is 4000Hz for 50Hz power system and each frame of Sampled Value data contains one reading making 4000 frames per second transmitted for each three phase set [14, 15]. Figure 3.6 shows the Sampled Values measurement data.

$I_A \times 1000$ (32 bit int.)	I_A Quality (32 bits)	$I_B \times 1000$ (32 bit int.)	I_B Quality (32 bits)	$I_C \times 1000$ (32 bit int.)	I_C Quality (32 bits)	$I_N \times 1000$ (32 bit int.)	I_N Quality (32 bits)	...
...	$V_A \times 100$ (32 bit int.)	V_A Quality (32 bits)	$V_B \times 100$ (32 bit int.)	V_B Quality (32 bits)	$V_C \times 100$ (32 bit int.)	V_C Quality (32 bits)	$V_N \times 100$ (32 bit int.)	V_N Quality (32 bits)

Figure 3.6 Sampled Values Measurement Data [33]

3.7 Simulink module of Merging Unit

These above reference points Data Acquisition and Processing function, Synchronizing function and Packet transmission, which are explained methodically, explained the basic building blocks for the development of Merging Unit. The studied Merging Unit in the reference [21] used the FPGA (Field Programmable Gate Array) but the Merging Unit for this research was developed in Simulink. The ECT/EVT models are connected with Merging Unit and then Merging Unit will be connected through network switch with Process Bus and test like Merging Unit accuracy, correctness, speed and limitation will be done. Simulink module of Merging Unit model is shown in Figure 3.7.

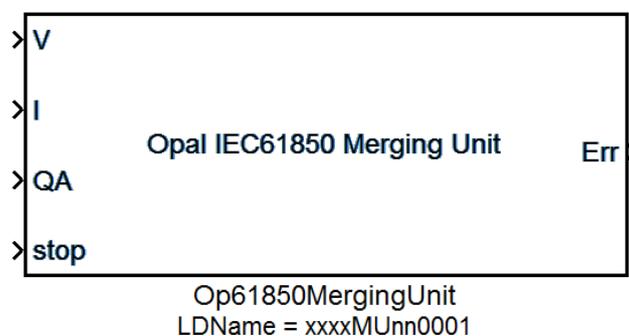


Figure 3.7 Simulink Based Merging Unit Model

Table 3.1 explains the significance of each bit.

Table 3.1 Quality Attributes of Dataset

Bit	Attribute Name	Attribute Value	Value	Default Value
0-1	Validity	Good	0 0	0 0
		Invalid	0 1	
		Reserved	1 0	
		Questionable	1 1	
2	Overflow		TRUE	FALSE
3	Out of range		TRUE	FALSE
4	Bad reference		TRUE	FALSE
5	Oscillatory		TRUE	FALSE
6	Failure		TRUE	FALSE
7	Old data		TRUE	FALSE
8	Inconsistent		TRUE	FALSE
9	Inaccurate		TRUE	FALSE
10	Source	Process	0	0
		Substituted	1	
11	Test		TRUE	FALSE
12	Operator blocked		TRUE	FALSE
13	Derived		TRUE	FALSE

V, **I**, **QA** and **Stop** are four input vectors used to specify the Sampled Value to be multicast during the RUN phase of the model. There is fifth input, which is **clock** but this only appears in the block if the External Clock is selected from the

parameters setting. The two vectors V (V_a, V_b, V_c, V_n) and I (I_a, I_b, I_c, I_n) are the three phase voltages and currents measurement.

The QA is an eight-element vector (each element represents a 16 bit value) which is used to input the quality attributes of the current/Voltage dataset ($QV_a, QV_b, QV_c, QV_n, QI_a, QI_b, QI_c, QI_n$).

The input “Stop” is a flag enabling which start the transmission of Sampled Values per nominal line cycle, Stop value “0” means enabled and Stop value “1” means disabled.

The only output is the error status “Err” which return the following values as shown in Table 3.2.

Table 3.2 Merging Unit Error Status

0	The block completed the send operation successfully.
-1	The driver didn't initialize properly.
-2	The block <i>stop</i> input flag is enabled.
-3	The send operation could not be completed (error returned by the Ethernet driver).
-14	Could not communicate with the interface specified by the <i>Ethernet adapter</i> parameter.

Parameters detail of Merging Unit model is explained in Figure 3.7a.

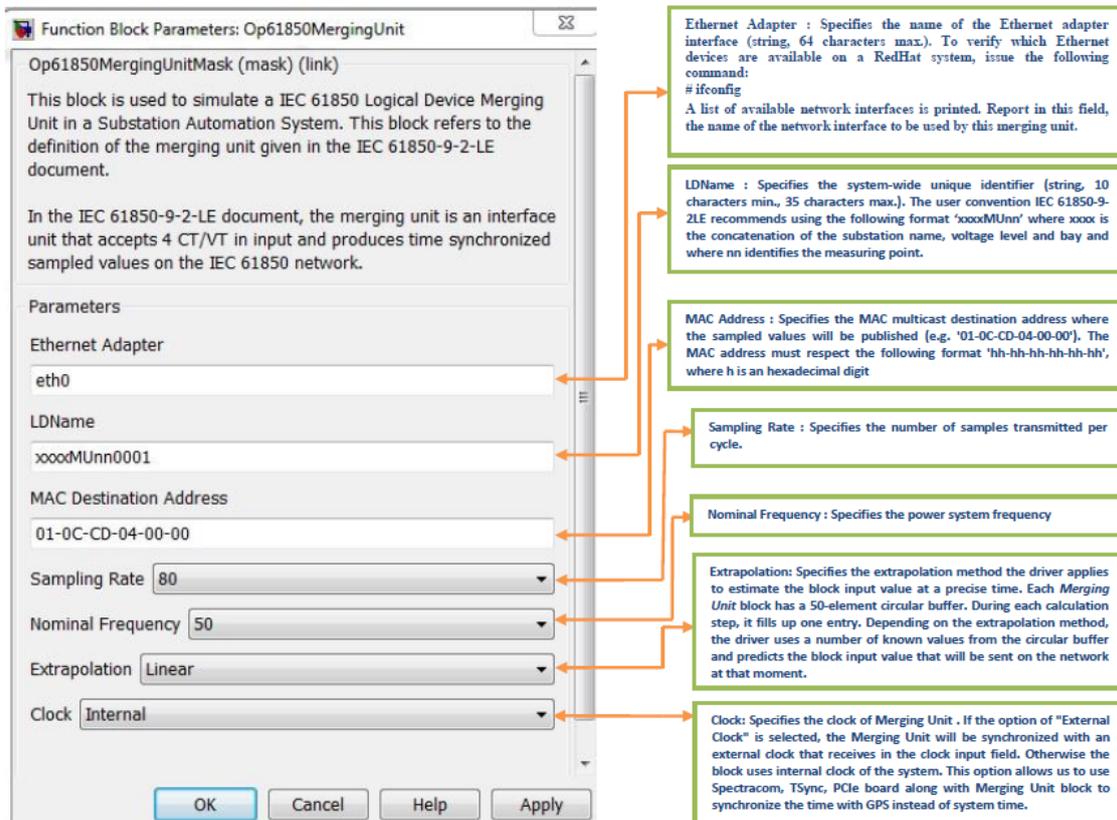


Figure 3.7a Parameters Detail of Merging Unit Model

3.8 Simulink modelling of Power system

In order to test the developed product of Merging Unit and ECT/EVT the next task was to model a power system, which can give the simulated values to check the flexibility and dynamics of the Merging Unit. The next task is to model a power system in Matlab/Simulink SimPowerSystems toolbox. SimPowerSystems toolbox is a dedicated tool for modelling and simulating the

generation, transmission, distribution and utilization of electrical power. It contains built-in models of three phase electric voltage source, transmission line, load and transformers. The Merging Unit block represents a sample Merging Unit model in IEC 61850 architecture. It performs a time coherent combination of the current and voltage data. Merging Unit combines the currents and voltages from three phases and additionally also the currents and voltages neutral in one dataset that include the Logical Nodes (LN) TVTR (voltage transformer) and TCTR (current transformer) for transmission with the Sampled Value service to all subscribing IEDs. The Merging Unit version follows the recommendations of the UCA International Users Group and it is published in the user convention IEC 61850-9-2LE (Implementation Guideline for Digital Interface IEC 61850). Especially, Sampled Value dataset is composed of four ECTs/EVTs transmitted using 80 or 256 sample per cycle. The Merging Unit block input data is computed by the sample rate and also nominal frequency of the block [35]. The reason of using Simulink SimPowerSystems is because it is compatible with the OPAL-RT Real Time Simulator and can be used to further test the overall system in the real time environment.

3.9 Power System Modelling In SimPowerSystems

The single line diagram of the power system, which was modelled in the SimPowerSystems, is shown in the Figure 3.8.

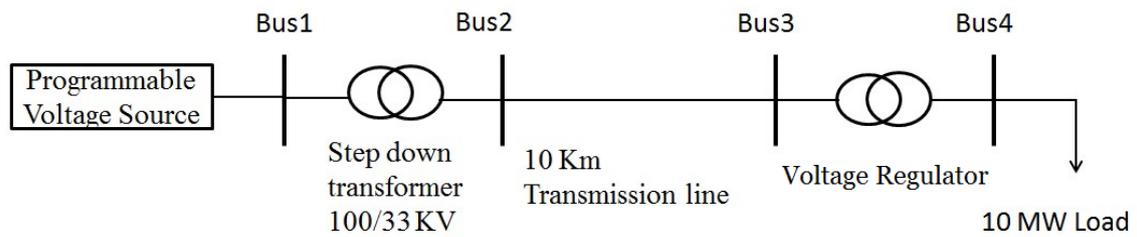


Figure 3.8 Single Line Diagram of Test System

Figure 3.8 illustrates how various power system components are connected together to form a power system model. These components and their respective parameter setting details are discussed in subsequent sections.

3.10 List of SimPowerSystems Blocks Used

The used components are presented in the following list and are explained subsequently.

1. Three phase Programmable Voltage Source
2. Three phase Pi Model For Transmission Line
3. Three phase Series RLC Load
4. Three phase two winding transformer
5. Voltage Regulator
6. Three phase Discrete Sequence Analyser
7. Power GUI (Graphical user interface) Block

3.11 Three phase Programmable Voltage Source

In Simulink SimPowerSystems library, it contains various electrical sources which are based on modelling a certain power systems requirement. The three phase programmable voltage source is used in this thesis. Figure 3.9 shows the block used in the model.

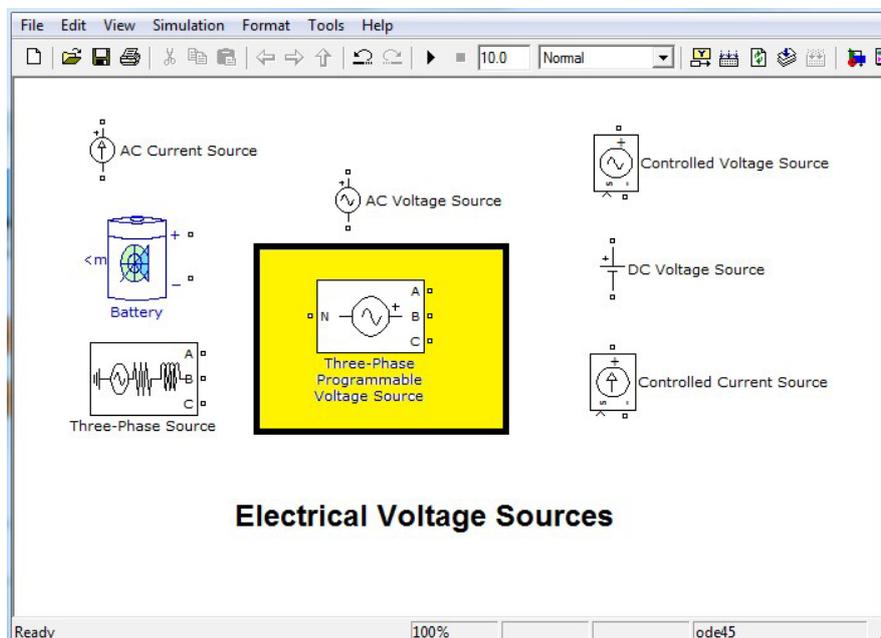


Figure 3.9 Three Phase Programmable Voltage Source Block

The output of three phase programmable voltage source is as follows:

1. “N” in electrical term represents Neutral. It connects either neutral or ground. In this case it connects to external ground
2. “A B C” represents three voltage phases with programmable frequency, phase, amplitude and harmonics

The Figure 3.10 shows the block parameters detail of three phase programmable voltage source.

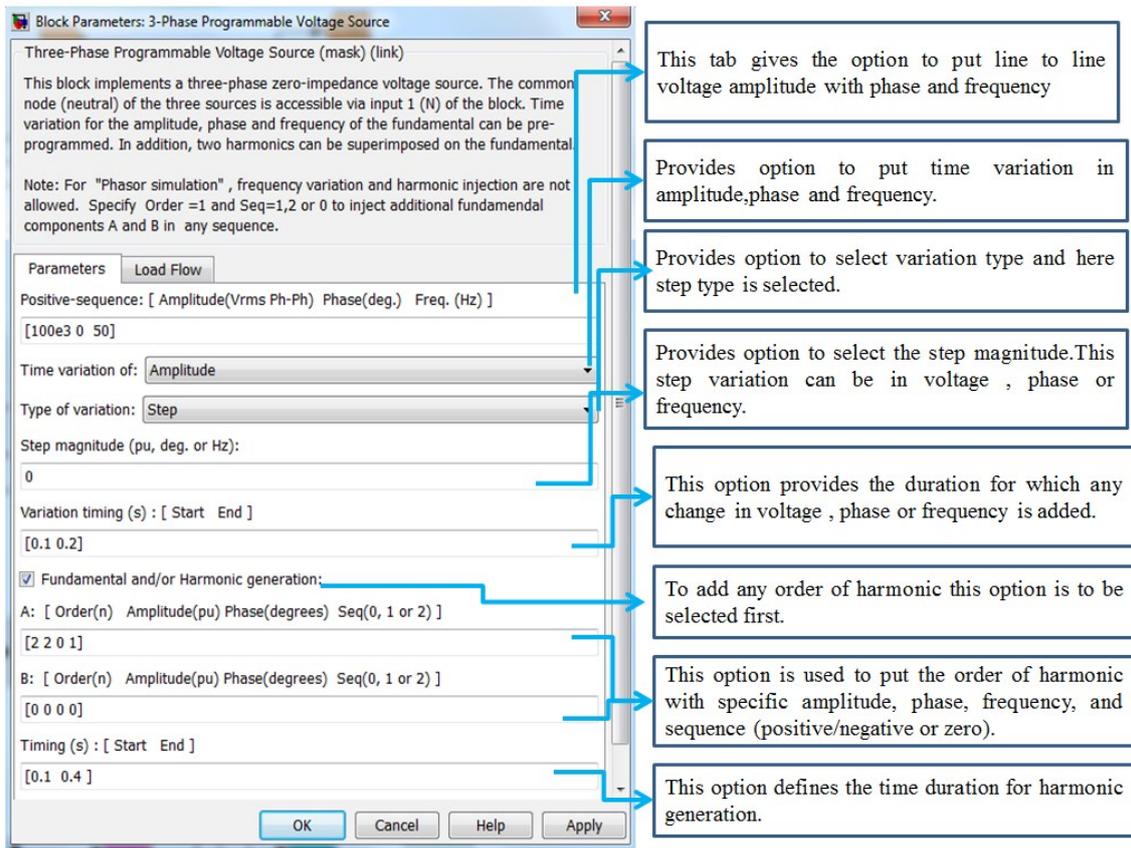


Figure 3.10 Block Parameters Detail of Three Phase Programmable Voltage Source

3.12 Three Phase PI (π) Section Line

Three phase PI (π) section line block implements a balanced transmission line with parameters lumped in a PI (π) section line. Three phase PI (π) section line

block from SimPowerSystems library is used to connect bus 2 to bus 3. Three phase PI (π) section line block Figure 3.11 is shown.

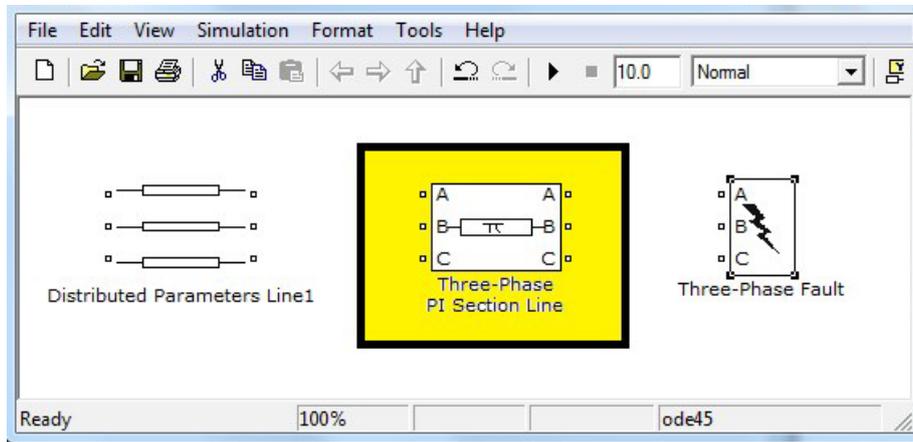


Figure 3.11 Three Phase PI (π) Section Line Block

The parameters of terminals of both end of the transmission line will implement a PI (π) section. Details are shown in Figure 3.12.

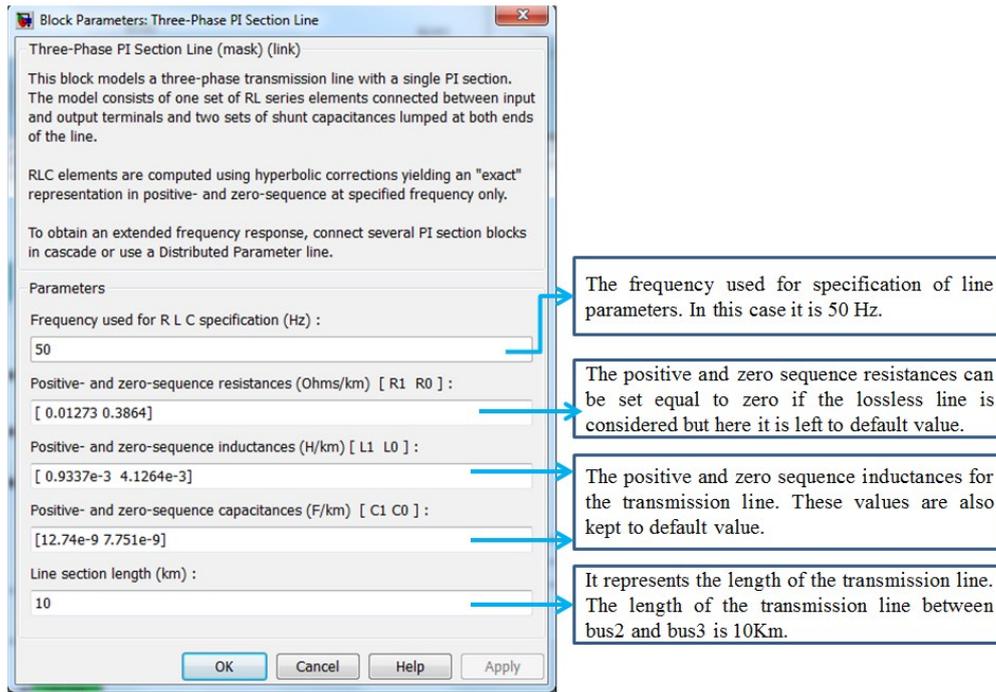


Figure 3.12 Parameters Detail of Three Phase PI (π) Section Line

3.13 Three Phase Series RLC Load

Three phase RLC load is also selected from SimPowerSystems library, which provide constant impedance through series combination of resistance, inductance and capacitance. The block diagram is shown in the Figure 3.13.

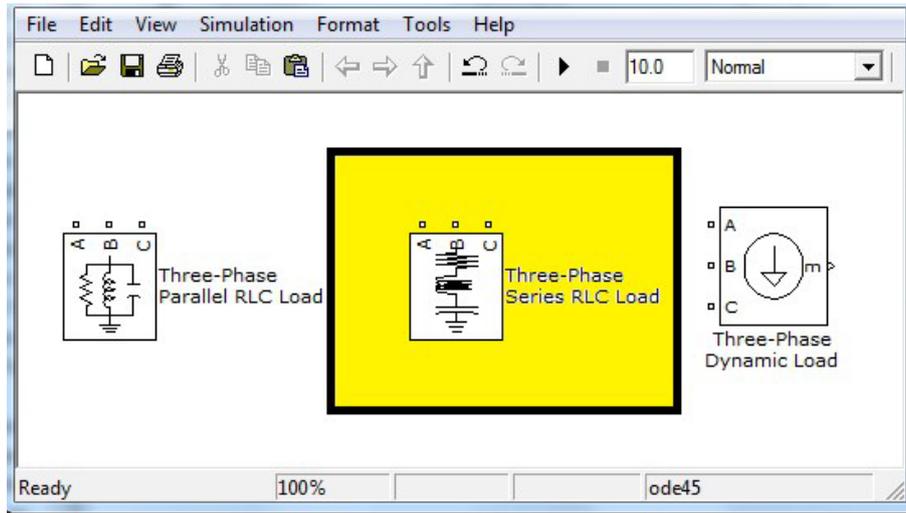


Figure 3.13 Three Phase Series RLC Load Block

Parameters detail can be seen in Figure 3.14.

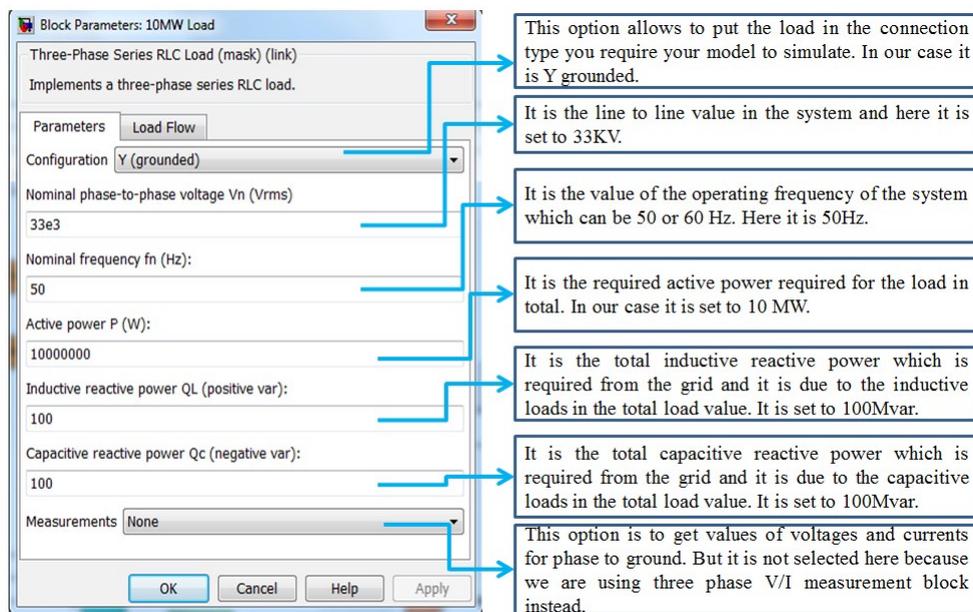


Figure 3.14 Parameters Detail of Three Phase Series RLC Load

3.14 Three Phase Transformer Two Winding

The SimPowerSystems library shown in Figure 3.15, demonstrates different kind of transformers. The model required for this project is a three phase transformer with two winding. The purpose of simple three phase two winding transformer is to step down the voltage from 100 kV to 33 kV.

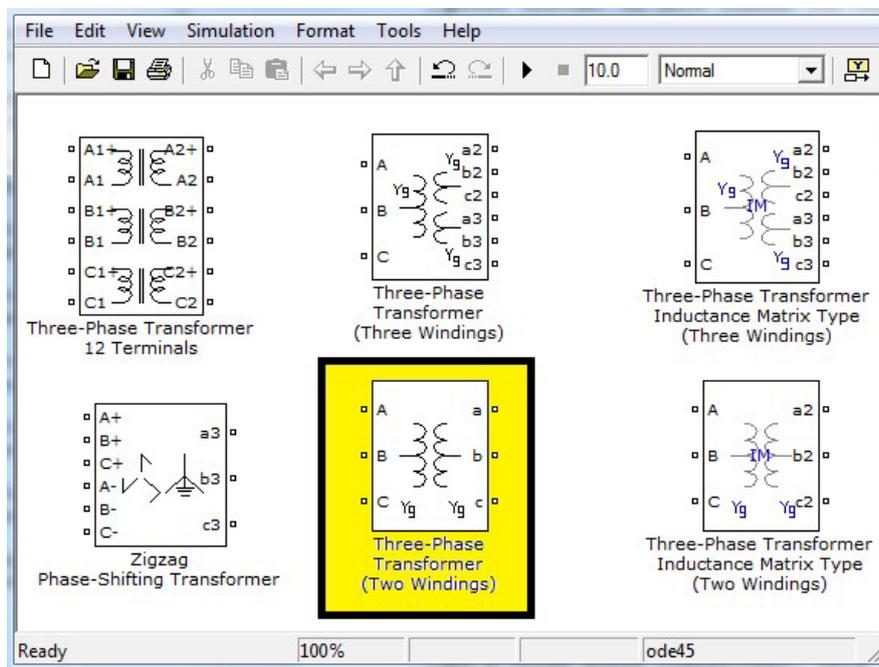


Figure 3.15 Three Phase Transformer Two Winding Block

Terminals “A B C” which are three phase input represents primary side of the transformer and terminals “a b c” which are three phase output represents the secondary side of transformer. Parameters setting especially step down configuration can be seen in Figures 3.16 - 3.18.

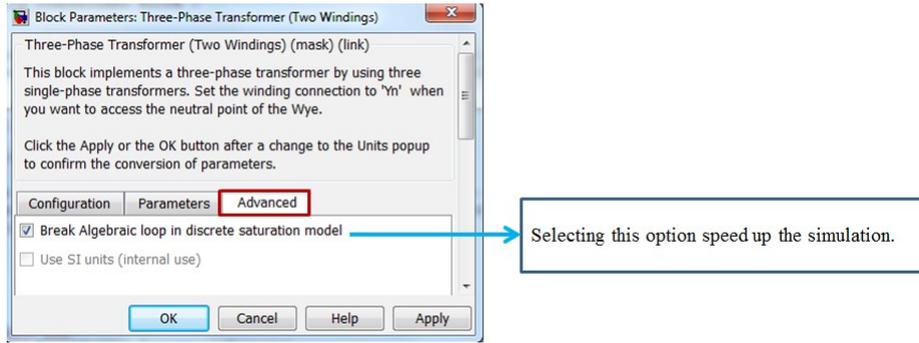


Figure 3.16 Three Phase Transformer Two Winding Advance Parameters Detail

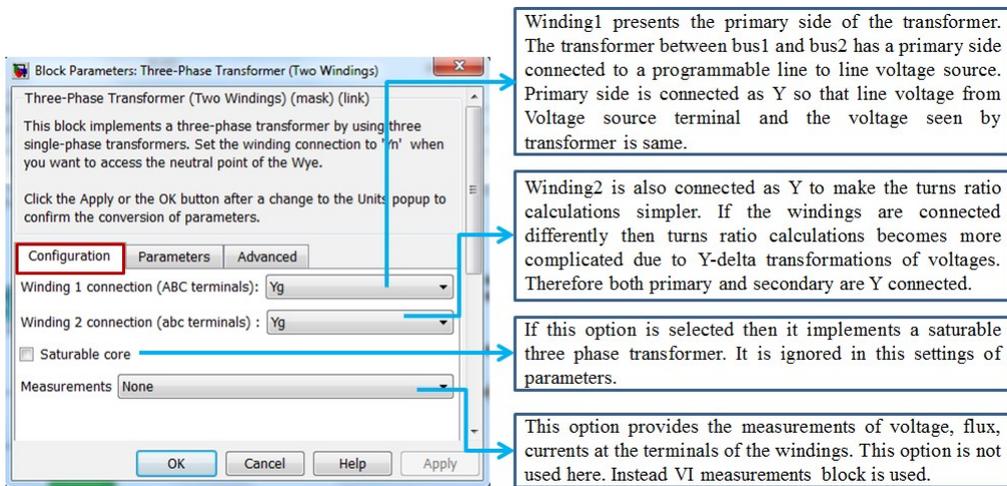


Figure 3.17 Three Phase Two Winding Transformer Parameters Detail 1

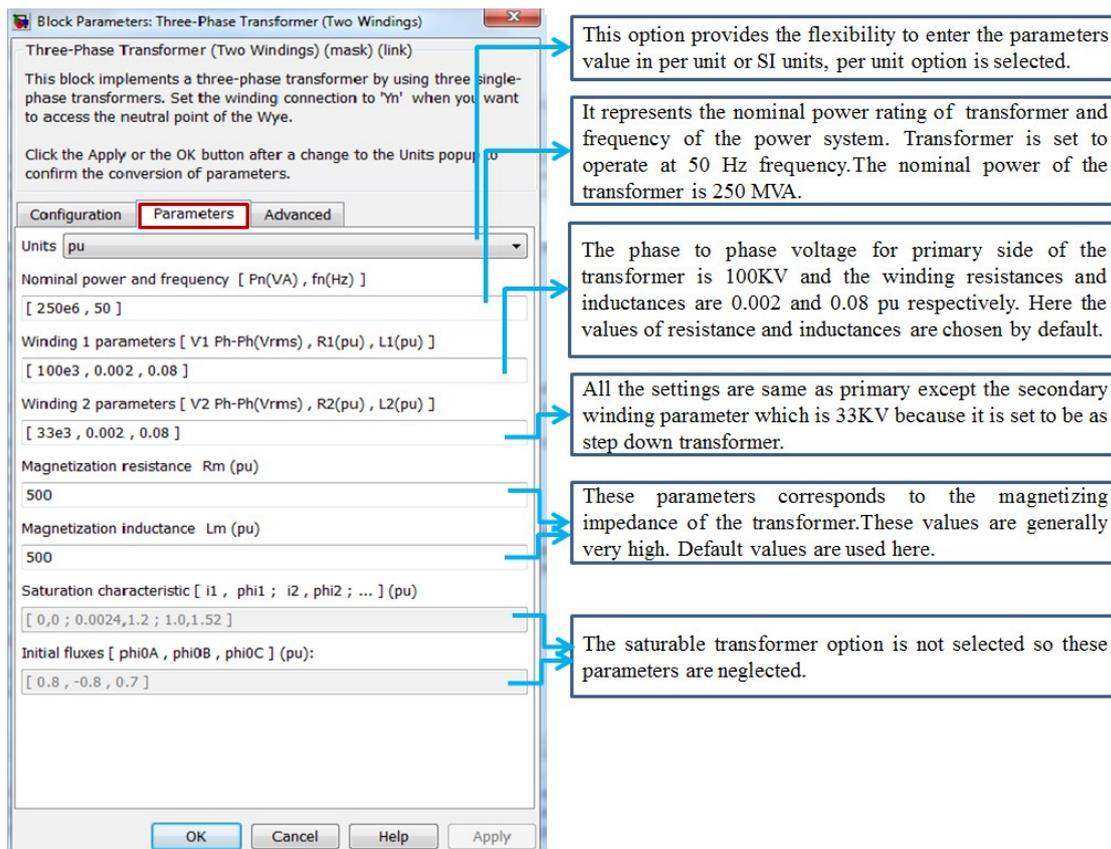


Figure 3.18 Three Phase Two Winding Transformer Parameters Detail 2

3.15 Three Phase Fault

To design a system to study the transient stability, voltage stability and Merging Unit performance during different system condition, the electric fault helps to understand system behaviour and also the behaviour of peripheral devices attached to the system. Three phase fault block is placed between buses 2 and 3 to mimic transmission line fault in the system in order to test the functionality of the newly developed Merging Unit. Figure 3.19 shows the three phase fault block provided in the elements category of SimPowerSystems library.

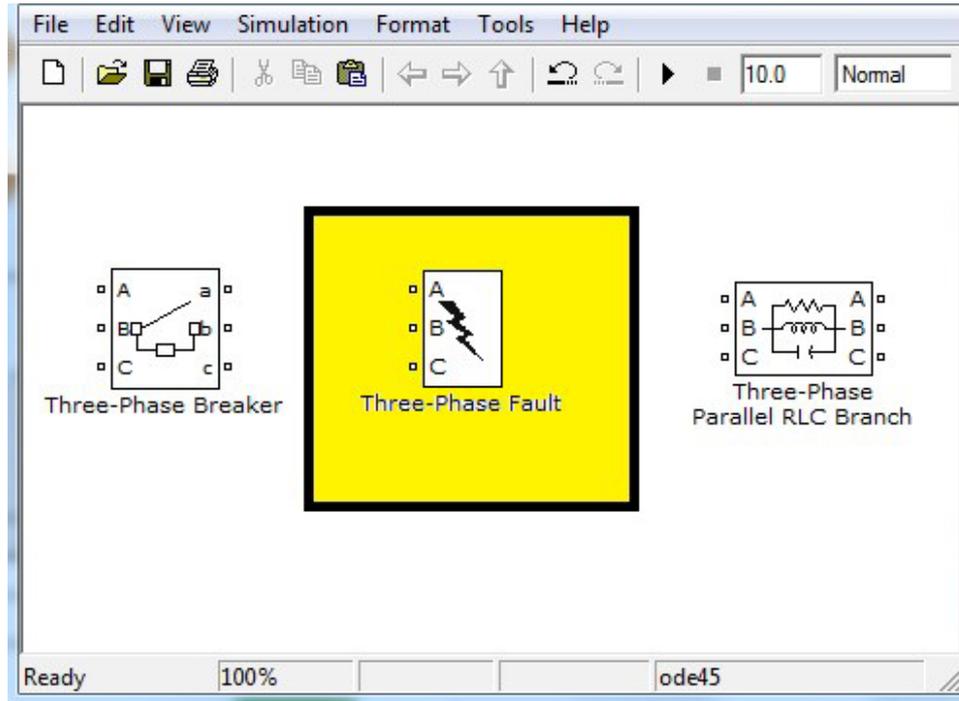


Figure 3.19 Three Phase Fault Block

“A B C” terminals represents the three breakers inside the block, A B C are connected to the ground. Figure 3.20 shows the parameter detail of three phase fault block.

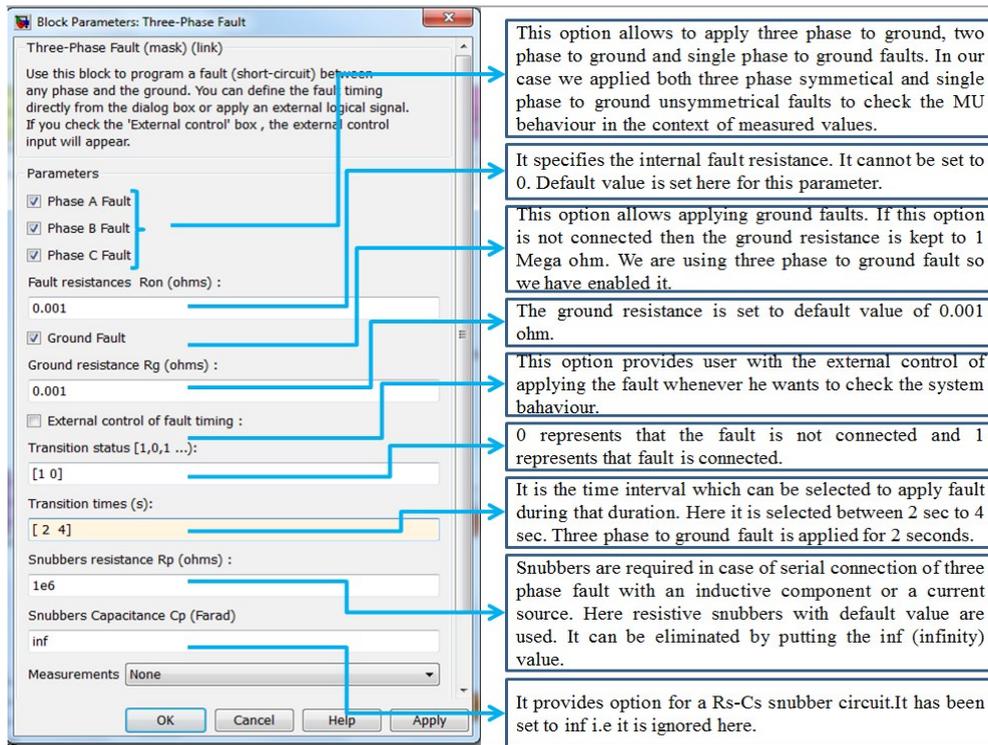


Figure 3.20 Parameters Detail of Three Phase Fault block

3.16 Three phase VI Measurement Blocks

Three phase VI measurement block is used to monitor and measure voltage and current in the system. Three phase VI measurement block often used as bus in the system and gives same output as the input to bus; it is available in the measurement category of SimPowerSystems library. Figure 3.21 show three phase VI measurement block.

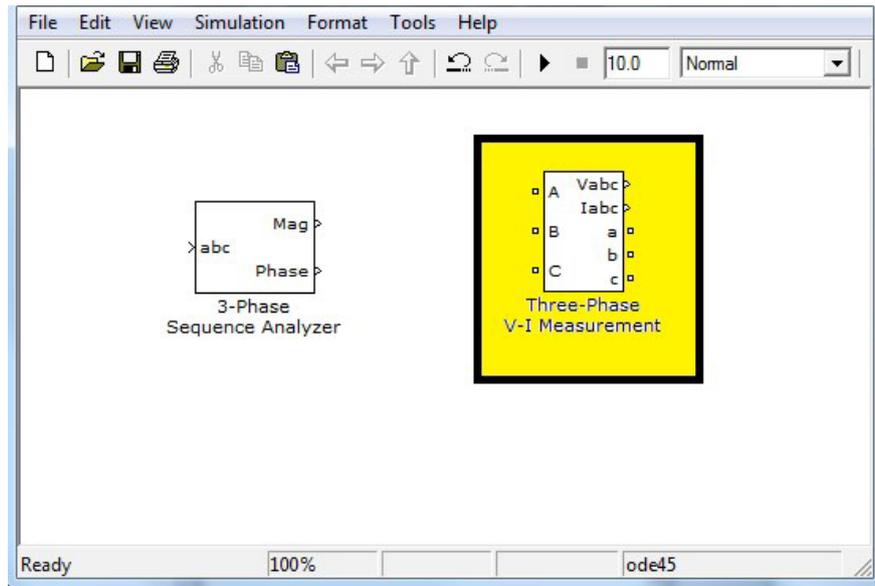


Figure 3.21 Three Phase VI Measurement Block

Three phase VI measurement block measures the three phase instantaneous voltage and current in system. Measurement can be either phase to phase or phase to ground.

1. Terminals “A B C” are the input terminals of three phase
2. Terminals “a b c” are the output terminals of three phase
3. V_{abc} and I_{abc} output contain three phase voltage and current measurements in a single vector form

Both V_{abc} and I_{abc} will be fed into the NCITs model to get the measurements values. Figure 3.22 gives the parameter detail for three phase VI measurement.

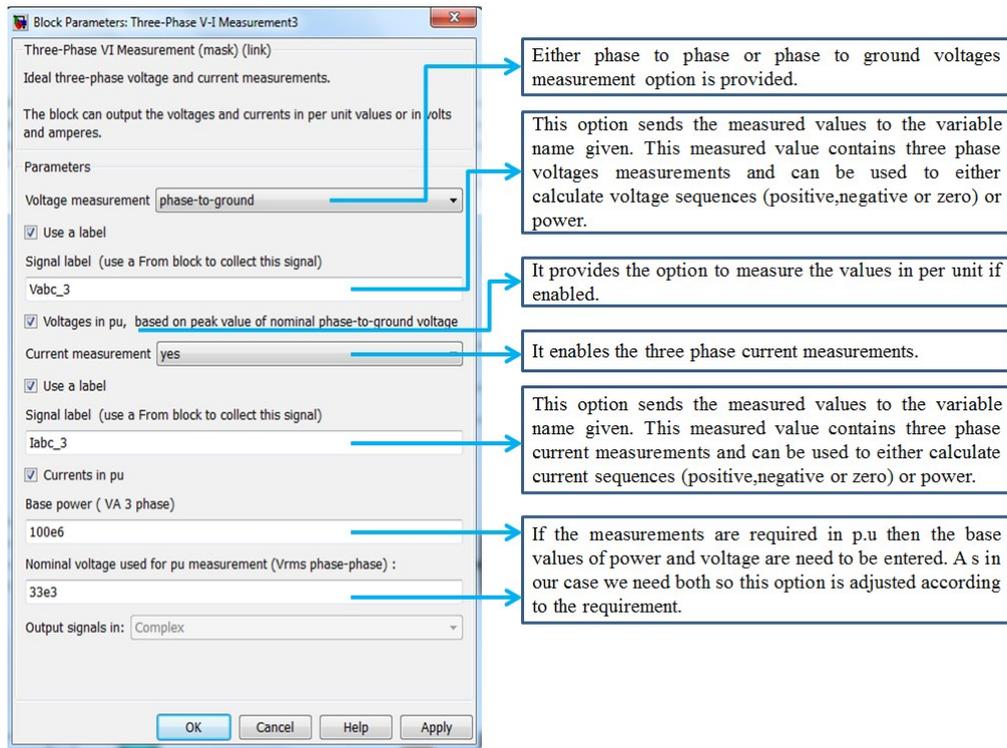


Figure 3.22 Parameters Detail of Three Phase VI Measurement

3.17 Power GUI Block

The most important environmental block is the Power GUI block for the Simulink models. Power GUI block provides multiple functions and is almost required in each and every model for starting the system. Details of power GUI block are explained in Figure 3.23.

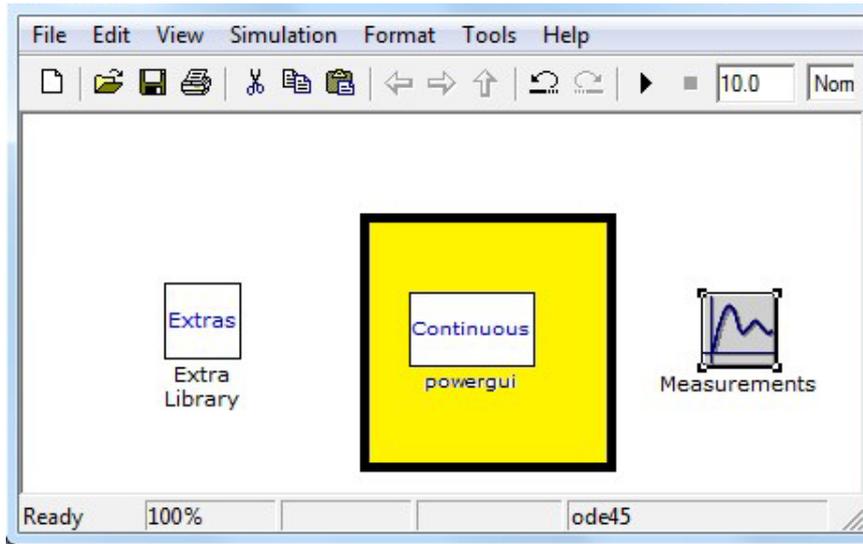


Figure 3.23 Power GUI Block

Parameters Detail of Power GUI Block is shown in Figures 3.24 – 3.26.

It allows us to use either continuous, discrete or phasor mode for solving the model. As in our case the model is to be simulated in the discrete mode. So discrete mode is selected with a sample time of 50 Micro seconds.

1. Specify the frequency at which load flow analysis will be performed.
2. The value of base power for load flow analysis.
3. It defines the tolerance between P and Q before the iterations stops.
4. It defines the maximum number iterations the Load flow tool will perform until the P and Q powers mismatch at each bus is lower than the **PQ tolerance** parameter value (in pu/Pbase).
- 5-6. The voltage and power units are defined in these two options to display output.

Figure 3.24 Power GUI Configuration Settings 1

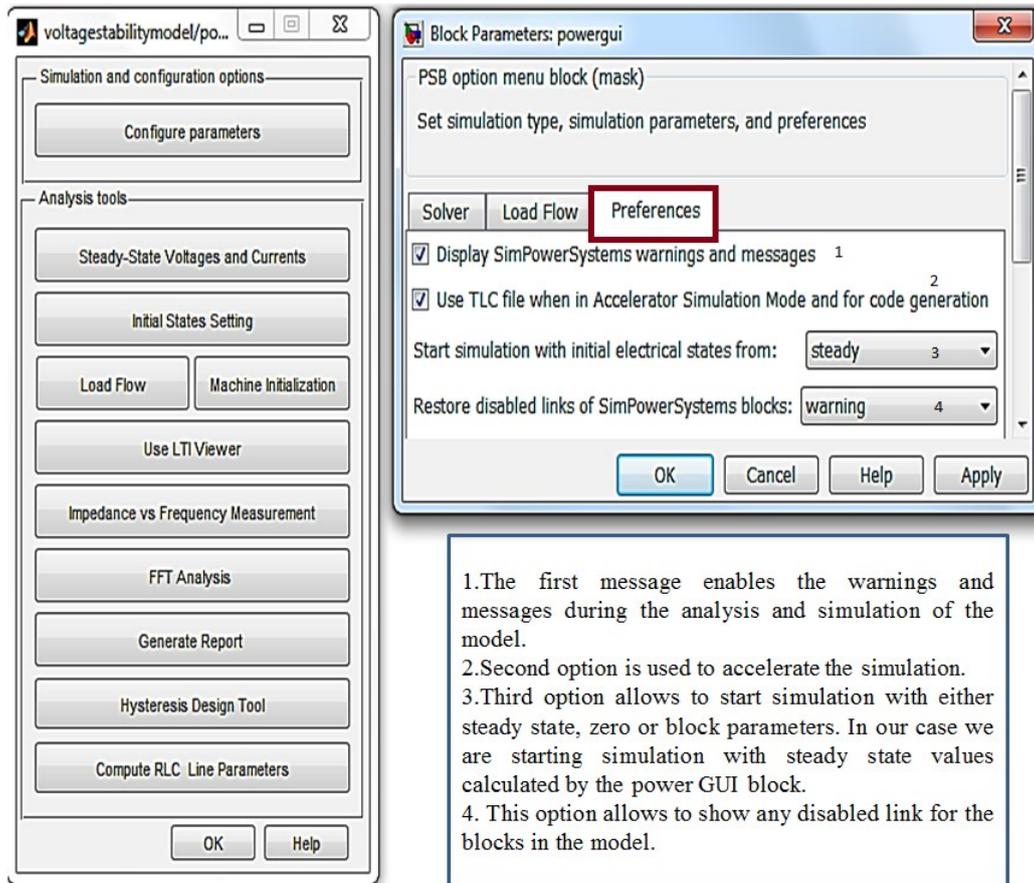


Figure 3.25 Power GUI Configuration Settings 2

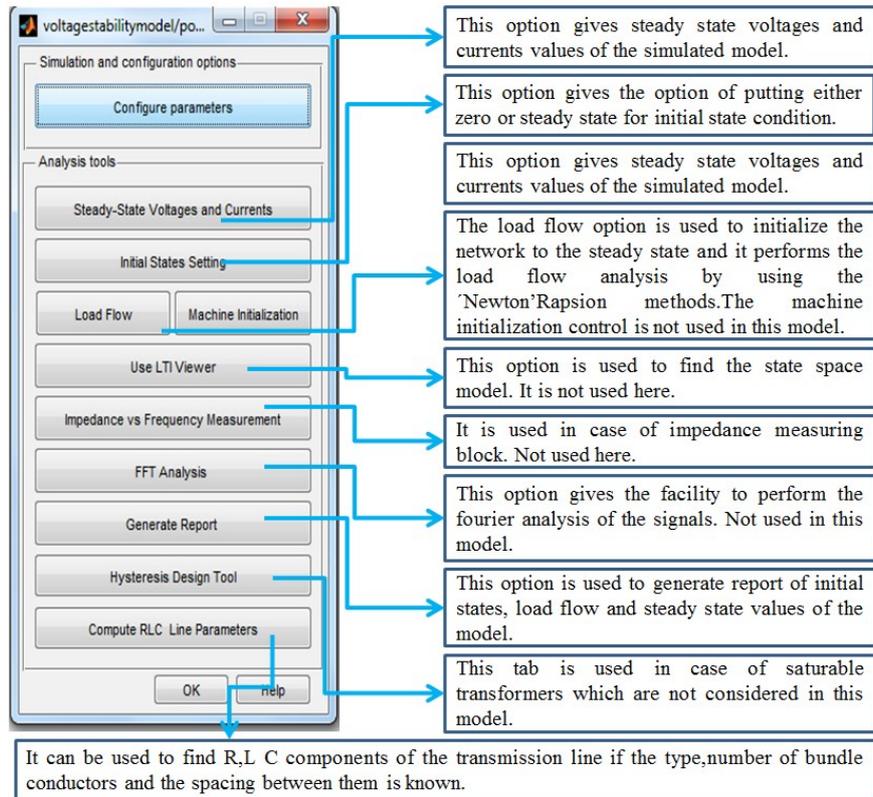


Figure 3.26 Power GUI Analysis Tools

3.18 Fully Modelled Power System

Power system model comprises of 100 kV programmable voltage source, 4-buses, 1-100/33 kV step down transformer, 10 km transmission line, three phase fault is applied between buses 2 and 3 and at bus 4 load is 10MW. Figure 3.27 shows the complete power system model.

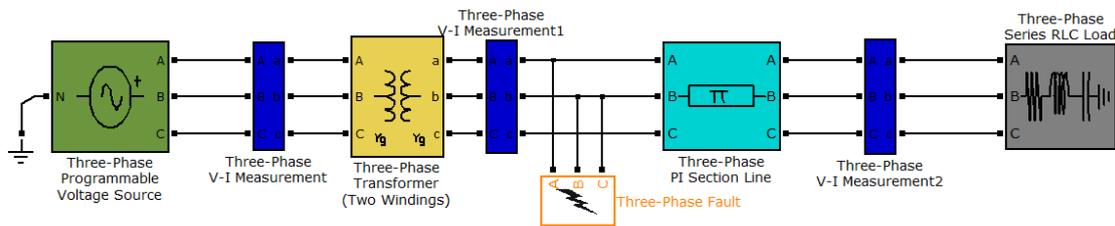


Figure 3.27 Three Phase Power System Model in Simulink

The reasons of modelling power system in this research are to test the NCITs and Merging Unit for different scenarios by simulating the power system described in Figure 3.27 under different parameter settings. The NCITs can be connected to any bus or at all buses to obtain the appropriate measurements, also it must be connected to the Merging Unit by optical fibres, transporting proprietary protocol signals. However the power system will be simulated under different parameter conditions to test the actual NCITs and Merging Unit performance.

Chapter 4: Experimental Analysis, Results and Discussion

4.1 Introduction

The experimental analysis and results are presented in this Chapter. The purpose of the experimental work is to prove the IEC 61850-9-2 Process Bus interface developed in Chapter 3 and the goal of the project defined in Section 1.3 (Figure 1.2) can be achieved. In this Chapter, NCITs and Merging Units are placed in developed power system at the different nodes to get the three phase voltage and current measurements. After the measurements have been collected then these measurements are sent on to the Ethernet port in the form of Sampled Value stream. Sampled Value stream from Merging Unit will be captured through Wireshark software as it demonstrates the evaluation procedure and results. Wireshark is an open source network packet analyser, which tries to capture network packets and display that packet data. This is a measuring and capturing tool used to examine what is going on inside the network traffic.

4.2 Experimental analysis

The aim of the experimental analysis work is to prove that the Process Bus interface behaves like real Process Bus and the Merging Unit also behaves like

Chapter 4: Experimental Analysis, Results and Discussion

the real Process Bus communication equipment so it can be used to test or illustrate the Process Bus concept with the help of NCITs. IED should operate normally with the measurement from the Process Bus interface. The criteria of normal operation is the measurement of NCITs will be sent from the Merging Unit in the form of Sample Measured Values and it will be received by the protection equipment on the Bay level normally according to the configuration. Wireshark software has been used in this research to capture the Sampled Value from Merging Unit to confirm and validate that the Process Bus interface works. If the test is successful then it can be concluded that, on simulating the Process Bus Sampled Value service through Process Bus Interface (Merging Unit) as the real Process Bus communication device.

The purpose of experimental work is to prove the protection function can behave normally with the real time Process Bus testing environment and the performance of the protection function with Process Bus testing environment. However the performance of the protection function with Process Bus network is out of scope in this research since the lab equipment is limited. In this research, unavailability of Process Bus IEDs, mapping of Sampled Value signal to IED and also further test for GOOSE are not accomplish, stop bit for both the Merging Units will not be obtained and also Circuit Breaker (CB) trip signals will not be studied, since the lab has no professional tool for measuring response time of all devices. Therefore, calculation and result of the response time is not recorded in this research. Rather, the focus of this research was to pass the

Merging Unit information into Sampled Value stream on Process Bus network under both normal and abnormal condition.

4.3 Experimental Setup

The first step is to setup the simulation model so that the measurement can feed into NCITs also check the scope result of NCITs measurements with normal and in fault conditions. While the second step, is to arrange four current and four voltage signals from NCITs and feed them into the Merging Unit. Finally, the last step is capturing Sampled Value message from the Merging Unit through Wireshark software under both normal and abnormal conditions to confirm the operation of real Process Bus interface.

4.3.1 Managing Signals to NCITs

As described in Section 3.18, and where the full Simulink model of power system is given in Figure 3.27, depicting the model simulation of a four-bus three phase power system. The three phase power with phase to ground fault is applied at bus 2. The measurements of buses 2 and 3 are coming from three phase VI measurement blocks 2 and 3 respectively. The measurements from both blocks contain vectors of three current and voltage values in I_{abc_1} , I_{abc_2} , V_{abc_1} and V_{abc_2} . To place the NCIT in the system, three NCIT models are required for single measurement or in general six NCIT models for one bus. Figure 4.1 shows the arrangement for single signal transformation for NCIT.

Chapter 4: Experimental Analysis, Results and Discussion

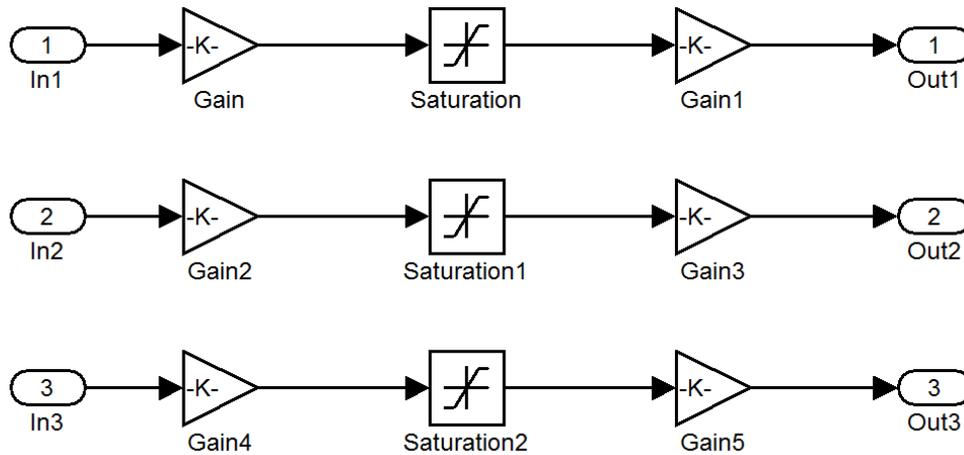


Figure 4.1 Arrangement of ECT/EVTs for NCITs

As shown in Figure 4.1, the arrangement is for a single signal either I_{abc} or V_{abc} . To simplify the circuit, convert the three NCIT model in subsystem model as shown in Figure 4.2.



Figure 4.2 Subsystem of ECT and EVT

Each signal of current and voltage is given in a vector form e.g. I_{abc} contains all three phase current information and V_{abc} contain all three phase voltage

Chapter 4: Experimental Analysis, Results and Discussion

information but into one vector signal. To separate each signal, DEMUX block is used to split vector signals into scalars or smaller vectors. DEMUX is included in the commonly used blocks section of the Simulink library. Figure 4.3 is the complete arrangement of Bus 2 measurement signals to NCITs.

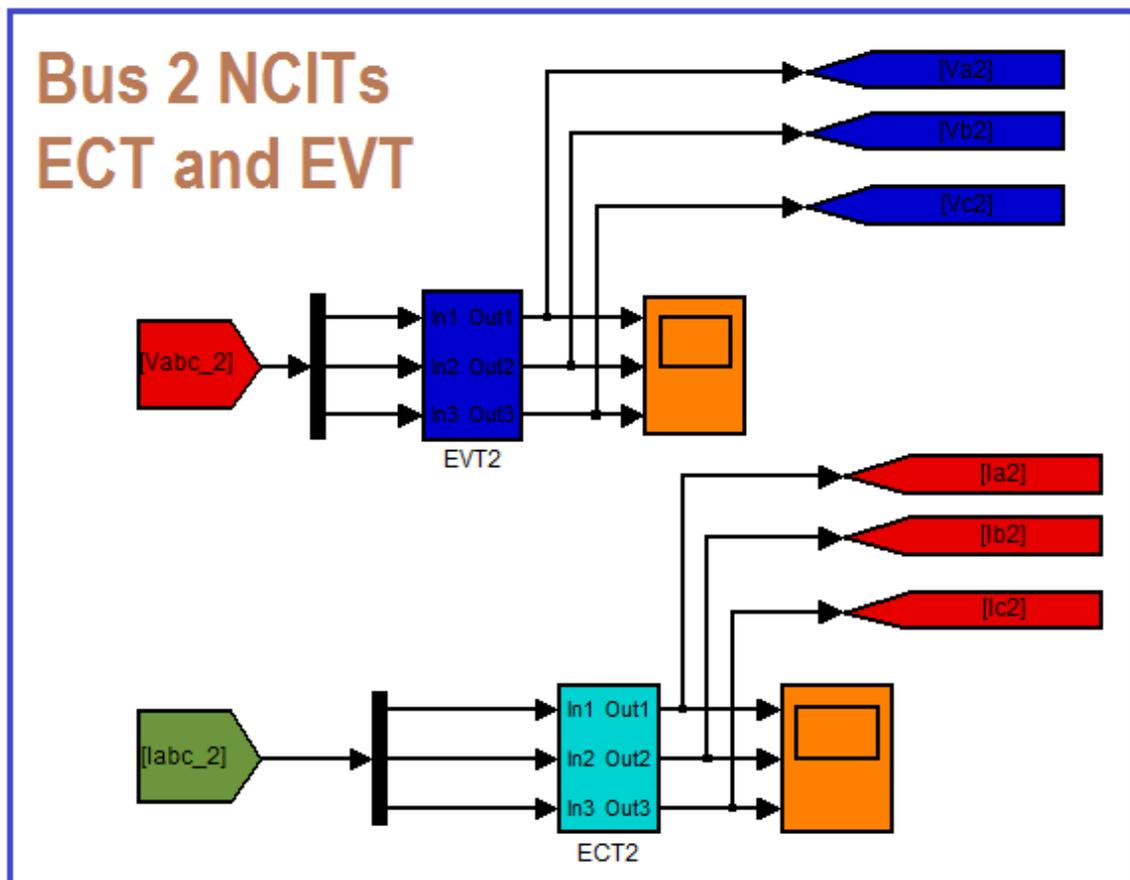


Figure 4.3 Bus 2 Signals Arrangement to NCIT

The same procedure (MUX and DEMUX) are repeated for Bus 3 signals arrangement, which is shown in Figure 4.4.

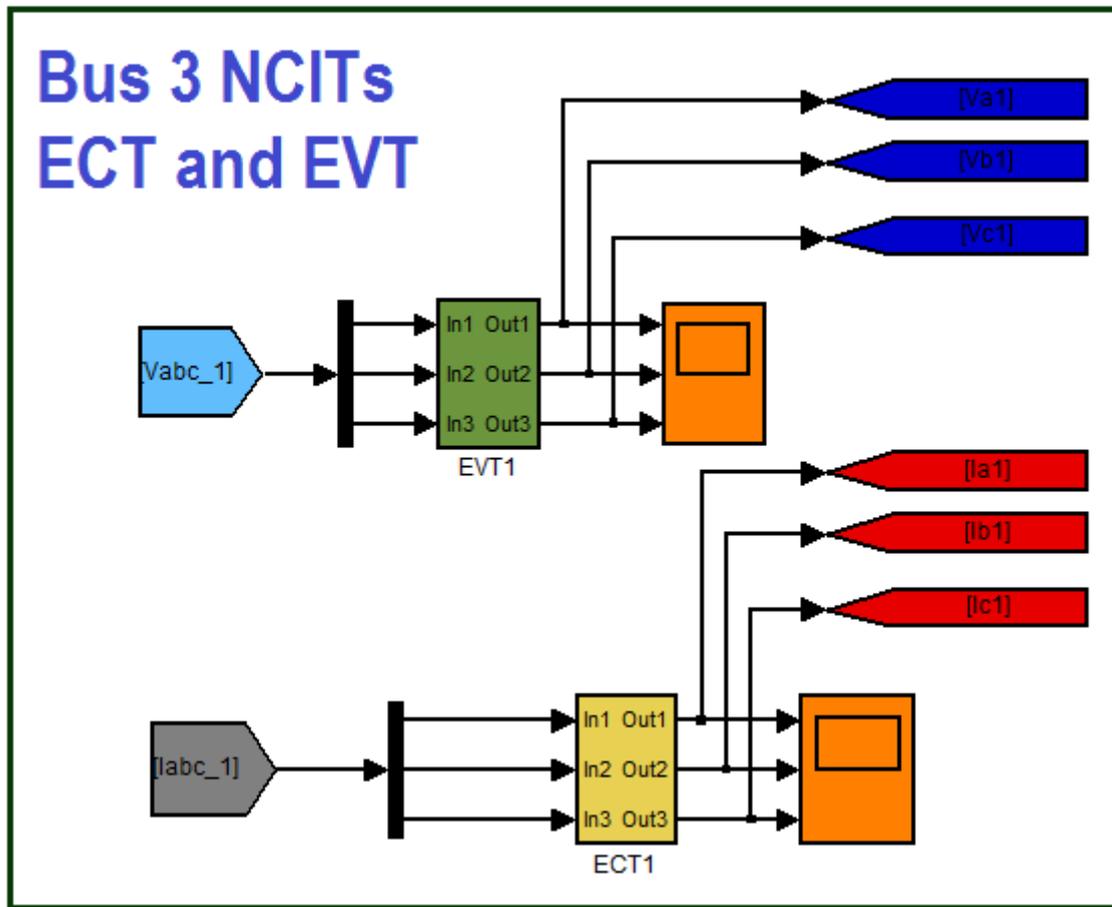


Figure 4.4 Bus 3 Signals Arrangement to NCIT

Figure 4.5 is the NCIT based power system model. Both buses are feeding signals into ECTs and EVT's.

Chapter 4: Experimental Analysis, Results and Discussion

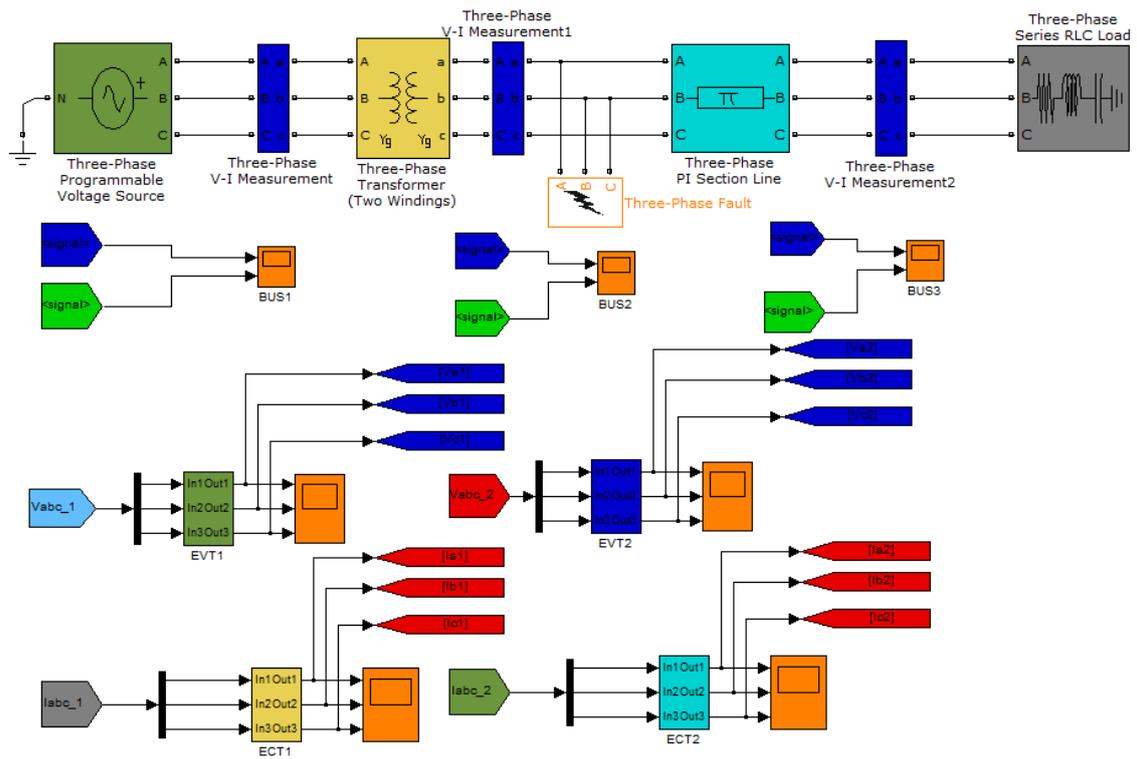


Figure 4.5 The NCIT Power System Simulink model

To check the power system and ECTs and EVT, the simulation is run for 30 seconds and the waveform of the current with fault is applied at Bus 2 is shown in Figure 4.6.

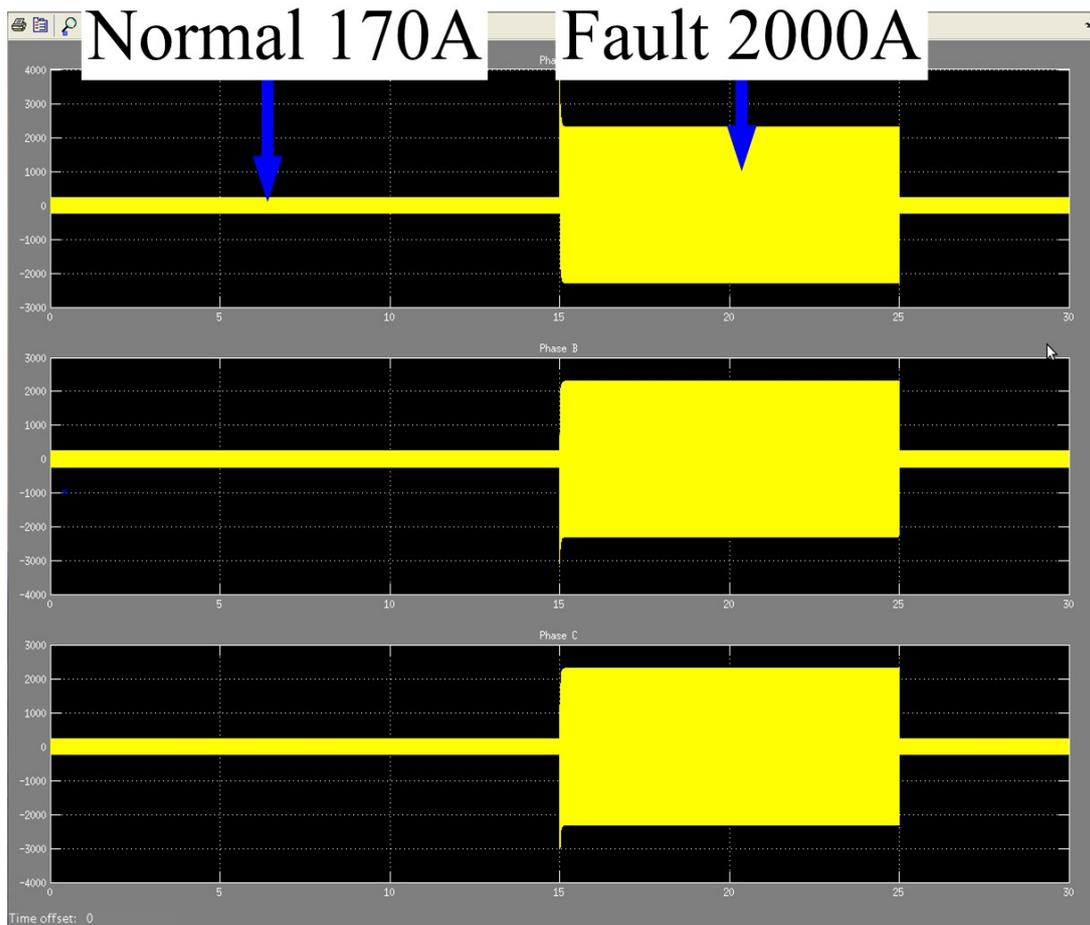


Figure 4.6 Bus 2 Three Phase Current Waveform

Simulation runs for 30 seconds with fault initiating at 15 seconds and finishing at 25 seconds. The fault is applied to the system for a total period of 10 seconds. From the waveform, it can be observed that the normal operating current is 170A (RMS) and during the fault, the current reaches up to 2000A (Peak value). The next step is to check if the Merging Unit sends the fault current information into Sampled Value Stream to Process Bus network.

4.3.2 Arrangement of Signals to Merging Unit

A detailed study is done in Section 2.8 and the Simulink model description is given in section 3.7. Merging Unit combines the currents and voltages from three phases and additionally also the currents and voltages neutral in one dataset that include the Logical Nodes (LN) TVTR (voltage transformer) and TCTR (current transformer) for transmission with the Sampled Value Service to all subscribing IEDs [35]. To configure the Merging Unit into the power system, following two steps are done, as shown in subsequent section.

4.3.3 Managing NCITs Signals According to Merging Unit

As explained earlier, Merging Unit combines the currents and voltages from three phases and additionally also the currents and voltages neutral in one dataset. The Simulink Merging Unit model described in earlier section requires single vector input for three phase current and voltage signals. NCITs signals are I_a , I_b , I_c and V_a , V_b , V_c . To combine three phase current or voltage signals into single vector form, the MUX block is used, which is readily available in Simulink library. In Figure 4.7, three voltage signals V_{a1} , V_{b1} and V_{c1} and three current signals I_{a1} , I_{b1} and I_{c1} are coming from NCITs from Bus 2, but the fourth input of both the MUX are constant which are labelled as V_{n1} and I_{n1} . V_{n1} and I_{n1} represent neutral CT/ VT signal. This arrangement is the recommendations of the IEC International Users Group and is published in the

Chapter 4: Experimental Analysis, Results and Discussion

user convention (Implementation_Guideline_for_Digital_Interface_IEC_61850) IEC 61850-9-2LE. Sampled Value dataset is composed of four ECTs/EVTs transmitted using 80 or 256 sample per cycle. Value of neutral is placed zero to get ideal condition of power system. Figure 4.7 explains the steps needed before feeding the measurements into the Merging Unit 1.

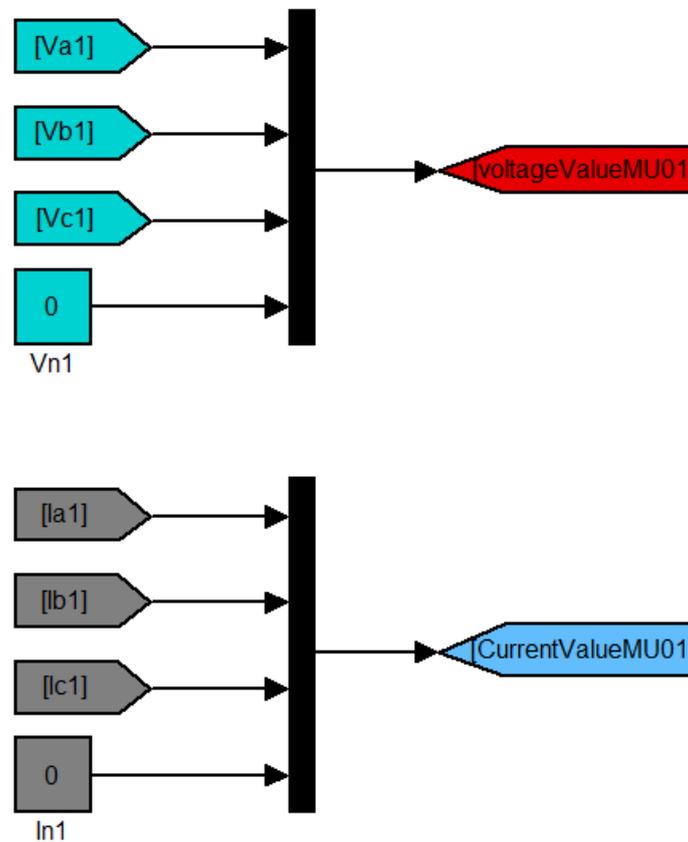


Figure 4.7 Managing NCITs Signals for Merging Unit 1

Output of MUX is the single vector forms of ECT and EVT, which includes four currents values and four voltage values. Same step is repeated for the Merging Unit 2 current and voltage input signals, which can be seen in Figure 4.8.

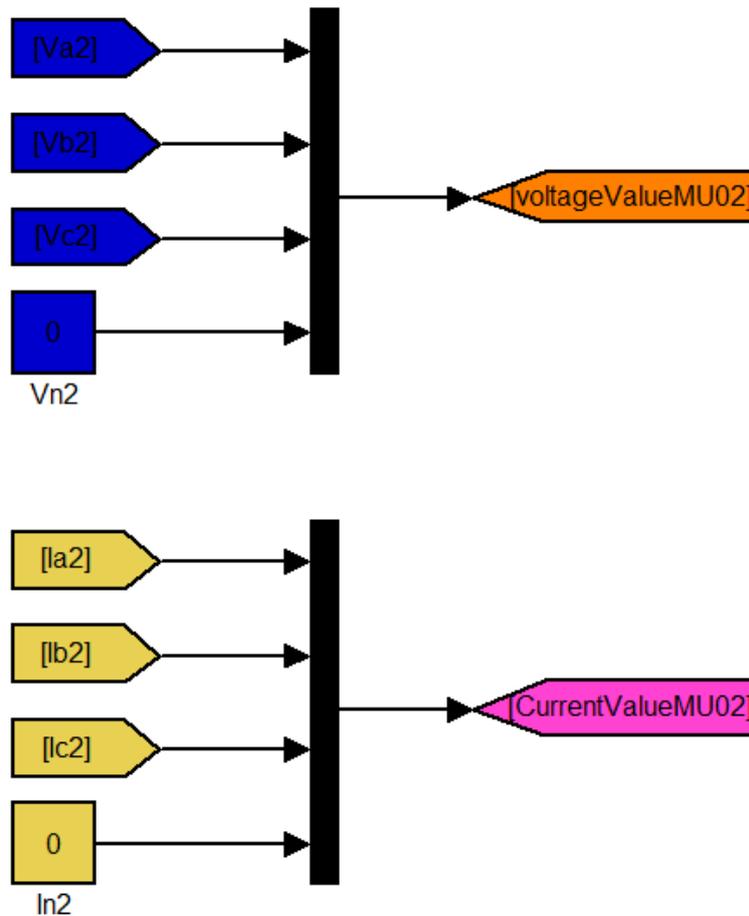


Figure 4.8 Managing NCITs Signals for Merging Unit 2

4.3.4 Connecting Merging Unit to System

Once the NCITs signals are converted into a single vector form, then the next step would be feeding signals into one of the Merging Units. Thus, a comparison study will conduct the following steps in order verify the correct functionality of the Merging Unit:

Chapter 4: Experimental Analysis, Results and Discussion

First, both the voltage and current measurement signals are connected to Merging Unit. The QA (quality attributes) is an eight element vector (each element represents a 16 bit value) used as the input quality attributes of the current/voltage dataset. In this case, Constant block is used to control the attributes. The input “Stop” is a flag enabler which starts the transmission of Sampled Values per the nominal line cycle. The “Stop” input is the output from “Err” output for other Merging Units. In this case Merging Unit 1’ Stop input is the Merging Unit 2’ Err output and Merging Unit 2’ Stop input is the Merging Unit 1’ Err output. Normally, “Stop” should operate with GOOSE message the Merging Unit has subscribed to in order to stop the operation. Figure 4.9 gives detailed configuration of Merging Unit 1.

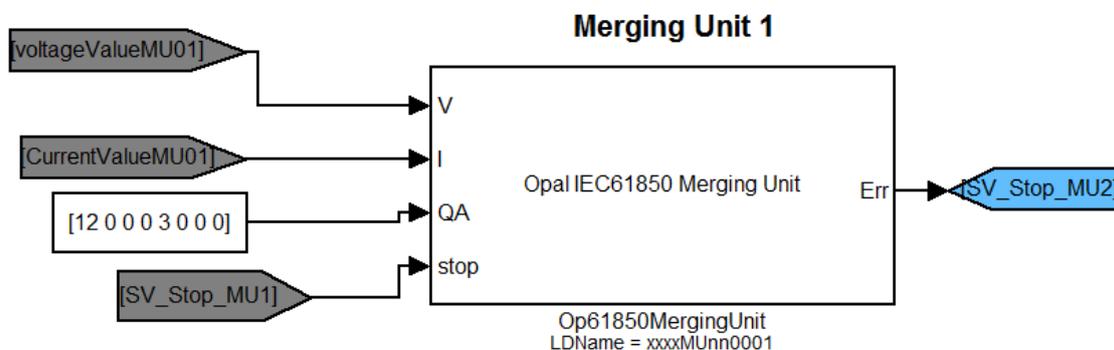


Figure 4.9 Merging Unit 1 Configuration

To check the Merging Unit 1 configuration and its working sample test run to see if Sample Value can be captured from Wireshark software. Simulation is run for 10 second and Wireshark also runs simultaneously in Microsoft windows environment without any specific target, it means Wireshark will capture all the

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data packets on Process Bus network. Sampled Value received and captured with the “svID: OPAL_MU001” by Wireshark can be seen in Figure 4.10.

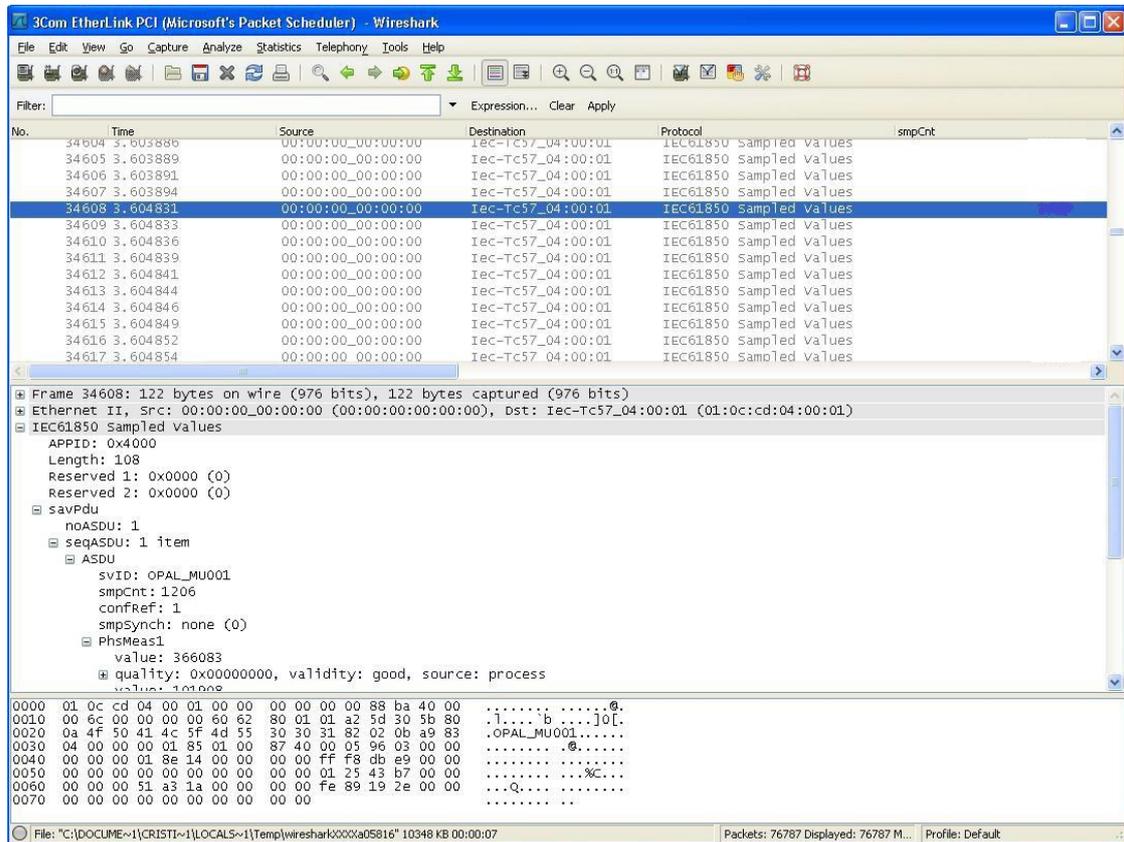


Figure 4.10 Window Environment Wireshark Sampled Values Capture.

Purpose of this test in Microsoft Windows environment is to confirm that similar task can also be performed in Window environment, as other researchers prefer to use the Linux. Linux is an open source operating system. Linux is a Personal Computer (PC) version of UNIX operating system. UNIX was designed to fulfill the various demands of researchers and students. Linux inherits many features of UNIX, such as the speed, efficiency, scalability and flexibility [35].

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The same test was also run in Linux flavoured version OS (Operating system) called Ubuntu with the same setting of simulation, except this time Wireshark is configured by filtering “SV” packets on Process Bus network. Wireshark only captures Sampled Value on Process Bus network. The captured Sampled Value by Wireshark can be seen in Figure 4.11.

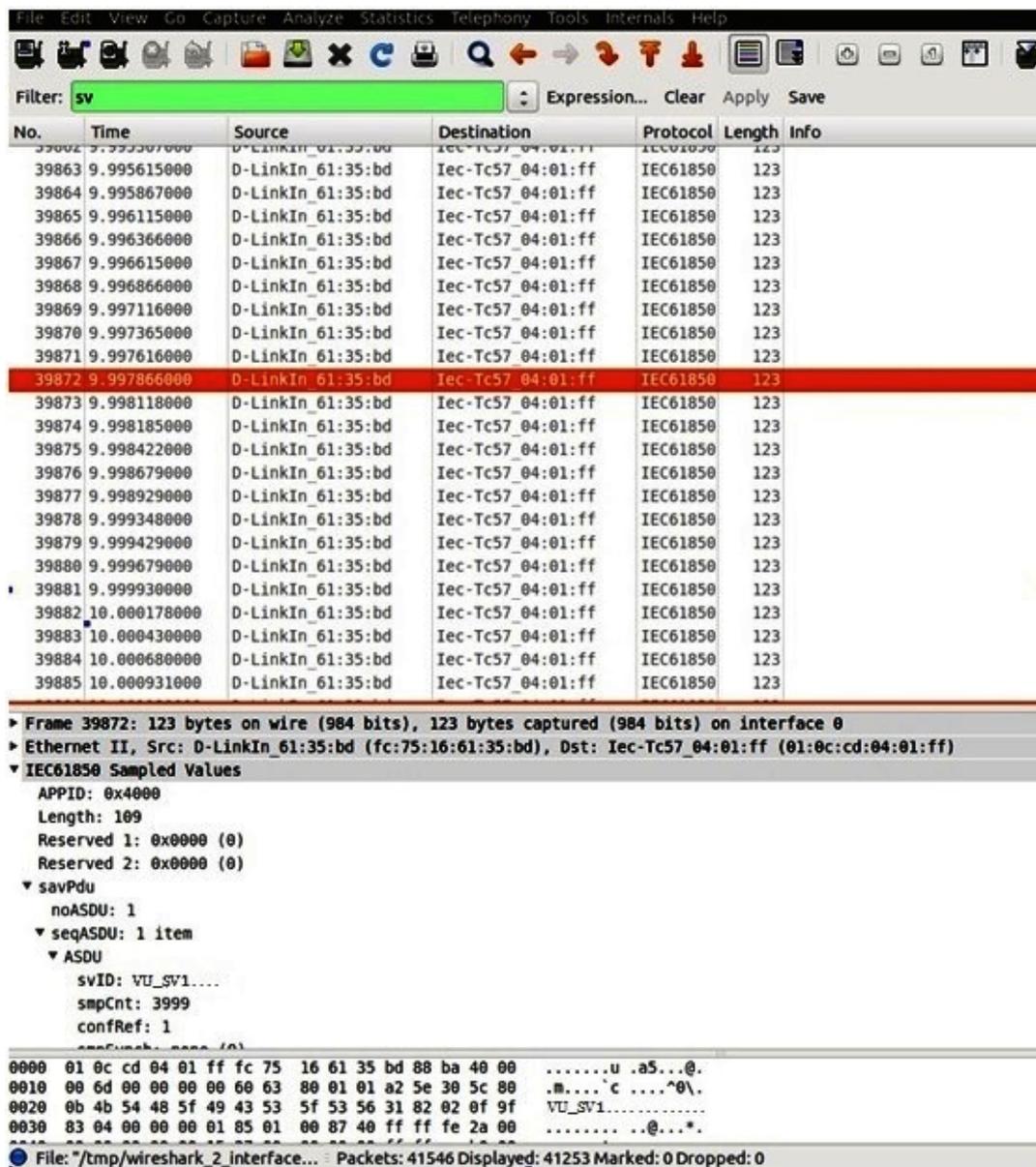


Figure 4.11 Linux Environment Wireshark Sampled Value Capture

Chapter 4: Experimental Analysis, Results and Discussion

Wireshark captured packets of Sampled Value as shown in Figure 4.11 have time difference or time delays, but these delays are not always $250\mu\text{s}$. Also by sending 4000 samples the total time should be within 1 second, which explains why the errors are increasing. After 10 seconds, the packet with “smpCnt=3999” on the time when it was captured is about 9.997866s. “smpCnt” starts from “0 to 3999” and loops back to initial 0, it means that more than 2 milliseconds errors already accumulated. These inaccuracies indicate jitters because the code is not running in high priority. According to the IEC 61850-9-2 LE this algorithm is still accurate enough to make the bay level protection devices recognise the Sampled Value Stream and read the data correctly.

Same steps are taken to configure Merging Unit 2. Figure 4.12 shows both the Merging Units and its configuration.

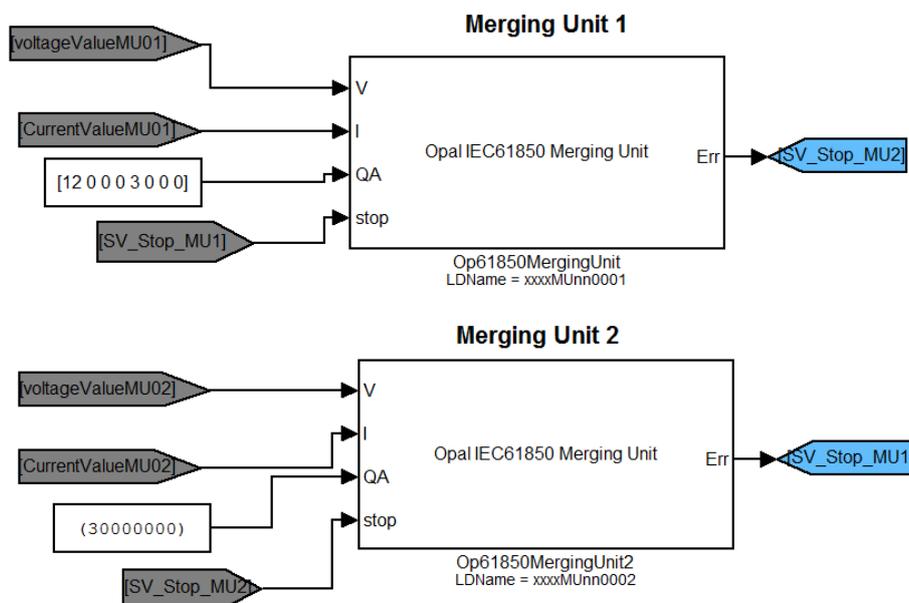


Figure 4.12 Configuration of Merging Units 1 and 2

4.4 Complete System Integration

This Section provides a detailed procedure for testing the different protection functions, using the developed models with the following steps:

1. The NCIT model is connected to the developed power system. ECT and EVT models are connected to different nodes of power system in order to convert high voltages and currents analogue to the low level voltages and currents
2. ECTs and EVTs are connected to the Merging Unit to convert analogue signals to digital signals form and also transmit the digitize data to Ethernet port
3. The Sampled Value stream is fed to the Process Bus network
4. The results are demonstrated

The complete developed power system is shown in Figure 4.13.

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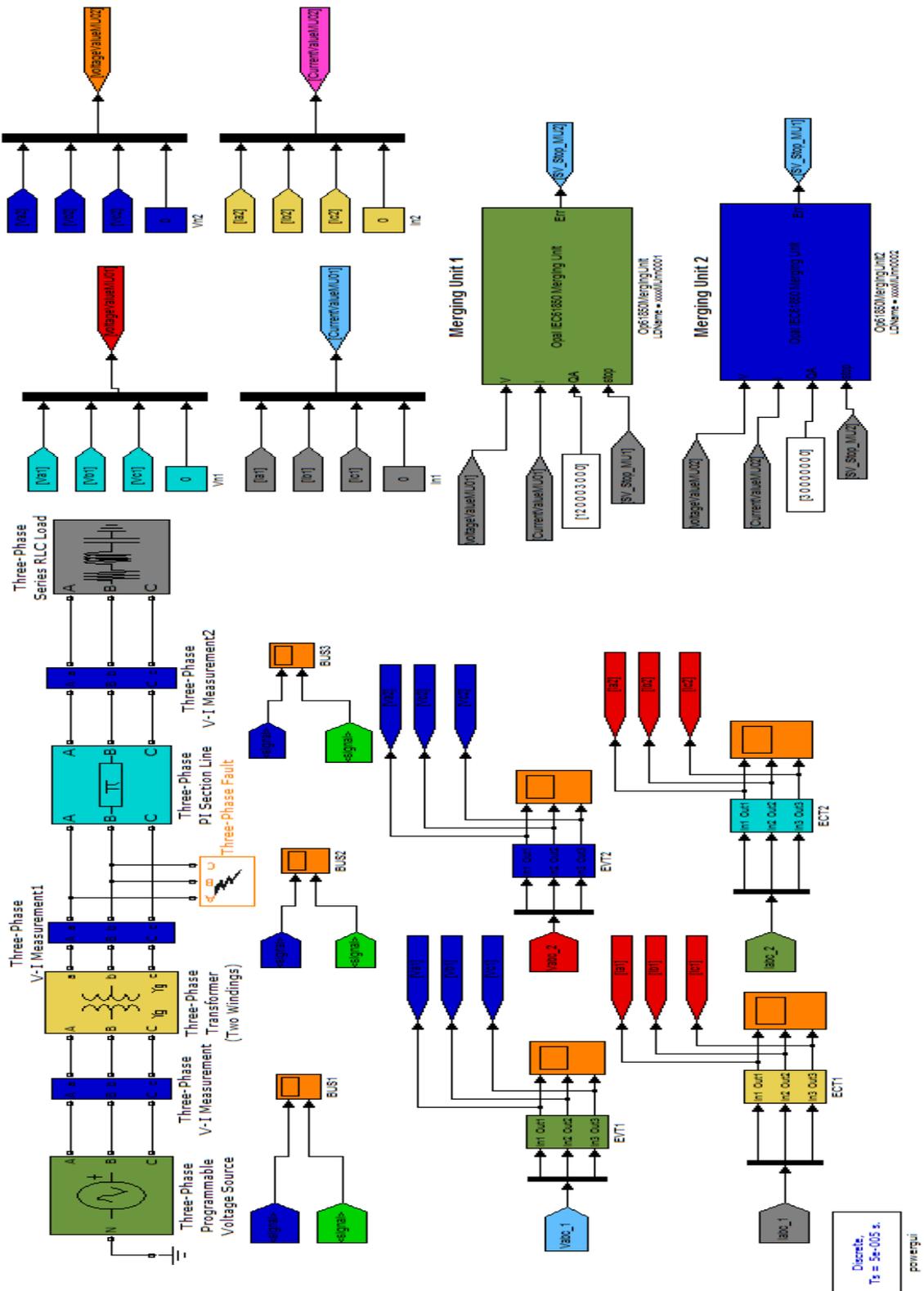


Figure 4.13 Complete Power System Model

4.5 Experimental results and Analysis

Subsequent section presents the results and analysis conducted for the simulations after following the experimental procedures in previous simulation case:

1. Run the first test simulation to check if NCITs are getting the measured values and converting high voltages and currents values to low level, also detecting the fault applied in the power system
2. Run second simulation test to check the Merging Unit sending sampled vales stream on to Process Bus network

Both simulation tests were successful, the results and analysis have also been provided in subsequent sections. The final simulation test is carried out with complete power system model, where both Merging Units send the Sampled Value Stream to Process Bus network. The initial task is to verify if both Merging Units are on the Process Bus network and sending Sampled Value messages to the network. The “tcpdump” command is used to confirm the connectivity of the Ethernet interface of both Merging Units.

The *tcpdump* command, is used to capture the header of Ethernet packets of Sampled Value messages received by a specific interface to verify they have been sent onto the Process Bus network. The Figure 4.14 shows a screen shot

Chapter 4: Experimental Analysis, Results and Discussion

of successfully detected Sampled Value packets received from both Merging Units.

```
#@localhost: tcpdump -i eth1
10:44:18.079303 00:00:00:00:00:00 (oui Ethernet) > 01:0c:cd:04:00:01 (oui Unknown),
  0x0000:  4000 006c 0000 0000 6062 8001 01a2 5d30  @..1....`b....]0
  0x0010:  5b80 0a4f 5041 4c5f 4d55 3030 3182 0212  [...OPAL_MU001...
  0x0020:  9a83 0400 0000 0185 0100 8740 0005 be8a  .....@....
  0x0030:  0000 0000 0001 462b 0000 0000 fff8 fb4b  .....F+.....K
  0x0040:  0000 0000 0000 0000 0000 0000 012d 9371  .....-..q
  0x0050:  0000                                     ..
10:44:18.079306 00:00:00:00:00:00 (oui Ethernet) > 01:0c:cd:04:00:01 (oui Unknown),
  0x0000:  4000 006c 0000 0000 6062 8001 01a2 5d30  @..1....`b....]0
  0x0010:  5b80 0a4f 5041 4c5f 4d55 3030 3282 0212  [...OPAL_MU002...
  0x0020:  9a83 0400 0000 0185 0100 8740 0007 a120  .....@....
  0x0030:  0000 0000 0007 a120 0000 0000 0007 a120  .....
  0x0040:  0000 0000 0007 a120 0000 0000 000f 4240  .....B@
  0x0050:  0000                                     ..
```

Figure 4.14 *tcpdump* output

4.6 Sending Sampled Value Stream from Two Merging Units

One of the major advantages of the logical Merging Unit environment is that, it is easy to set up the scenario with multiple Merging Units in a single system. It will be very expensive and inflexible if physical Merging Units were set up such as in Figure 3.2 (physical Merging Unit experimental setup). In order to assess the performance of sending out multiple Merging Units, Wireshark software is used to capture Sampled Value messages and evaluation related to the Process Bus network communication interface is reported.

Chapter 4: Experimental Analysis, Results and Discussion

The principle of process level protection is introduced in Chapter 2 according to UCA International Users Group and it published in the user convention IEC 61850-9-2LE (Implementation_Guideline_for_Digital_Interface_IEC_61850). In particular, Sampled Value dataset comprises of four CTs/VTs transmitted using 80 or 256 sample per cycle. The Merging Unit block input data is computed by the sample rate and also the nominal frequency of the block. The line differential protection scheme needs measurement from both side of the transmission line so two Merging Units are required to measure both sides. The final simulation is run and Wireshark capture of Sampled Value stream is shown in Figure 4.15.

Chapter 4: Experimental Analysis, Results and Discussion

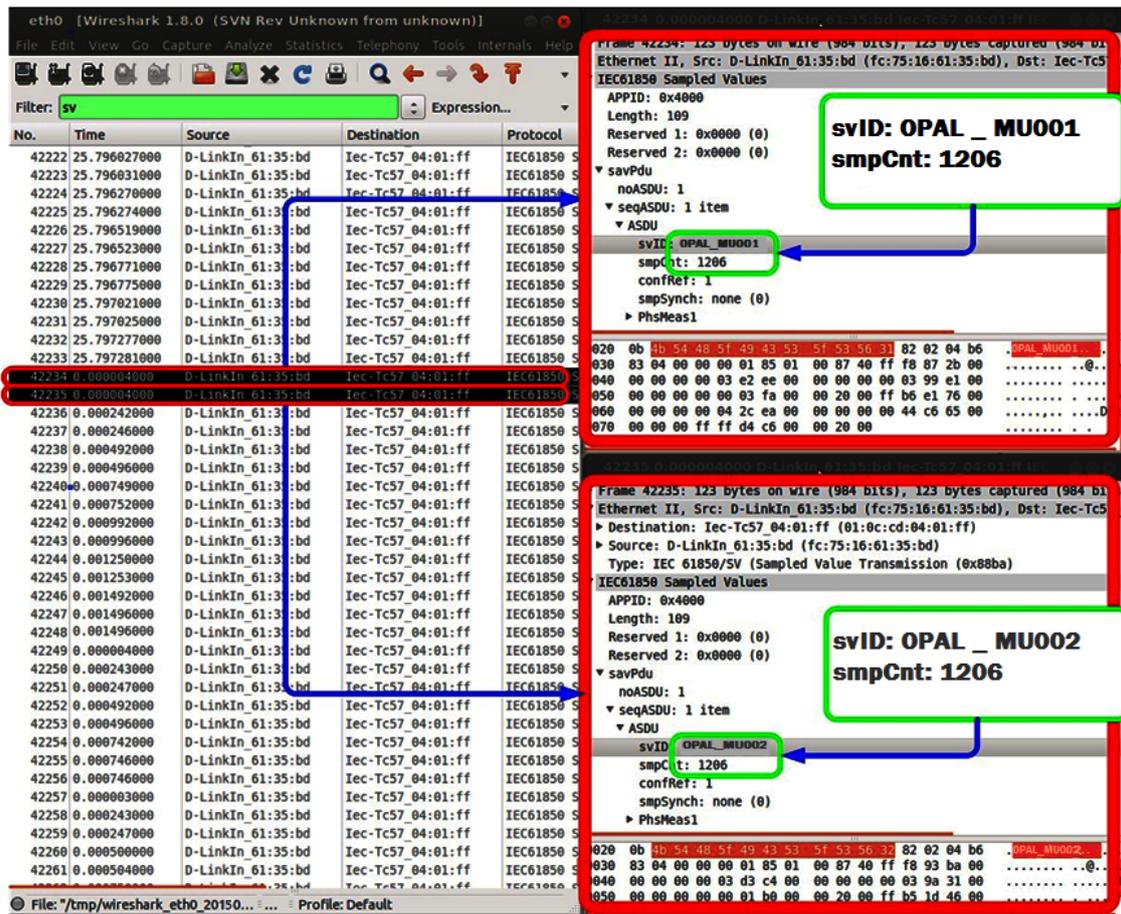


Figure 4.15 The Wireshark Capture of Send Sampled Values of Both Merging Units

Successfully captured Sampled Value Stream from both Merging Units, shows the time difference between two Sampled Value packets of both Merging Units is about $4\mu\text{s}$. According to the line differential protection under normal operation, these several microseconds do not affect functionality. Due to limited access to measurement tools, communication and protection scheme with the bay level IEDs are not performed, which may be very interesting, and this is mentioned in the future work section (Section 5.3).

Chapter 5: Conclusion and Future Work

5.1 Introduction

During the course of this research, new ideas cropped up. However, due to the time limitation and lack of access to measurement tools, only some of the new ideas have been studied but those unimplemented interesting ideas have been proposed for future work in this Chapter (Section 5.3).

5.2 Conclusion

Simulink module of NCITs are developed and tested. Simulink model of logical Merging Units are also tested, the Process Bus network communication interface for logical Merging Unit testing environment has been developed. To finish the research in a manageable way, iterative research pattern has been applied. Simulation power system has been developed to evaluate the capability of this Process Bus interface. The evaluation results shows that the Merging Units process the NCITs measurements and the Process Bus network capture the Sampled Value messages from communication interface and protection function operate correctly. Instead of purchasing the expensive physical Merging Units testing equipment, electrical engineering students, researchers and electric utility integration engineers can just use this soft Merging Unit

Chapter 5: Conclusion and Future Work

testing environment for basic testing and demonstrating the Process Bus technology concept and also interface the Process Bus with bay level which is in high demand by the industry. The beauty of the whole environment is that it can be easily run on any PC with normal processing power which is ideal for electrical students and researchers. The only software required is MATLAB which is a commonly used and accessible software tool. The OS (operation system) should be Linux which is free open source for anyone and also a commonly used OS among researches. But the best part is that, it also be run on Windows platform which is also considered an achievement in this research. Some interesting ideas have been implemented to make the Process Bus testing environment able to simulate the Process Bus more accurately and provide more functions.

5.3 Future Work

The Process Bus technology has been around for a couple of years but still is not largely adopted by the electrical protection industry. Only few countries have implemented Process Bus for few selected stations. Therefore, there is a large space for the developing testing tool. Even big branded companies in the protection testing tools industry, especially in Australia do not offer Process Bus interface testing environment and only few of them are offering Sampled Value strictly capturing tools to monitor the Process Bus interface. The Process Bus simulation interface has been developed in this research and is a part of the

Chapter 5: Conclusion and Future Work

Process Bus testing environment. This Process Bus soft Merging Unit testing environment is simple and cannot reach industry level testing accuracy and it cannot act as a professional testing tool but it does have a potential to improve in order to become a professional mature testing tool. Also further study and improvement on this environment will make it a valuable testing tool in an educational setup. Some suggestions for the continuous work are given in subsequent sections.

5.4 Time Synchronization

The Sample Value traffic is time critical communication so, the time synchronization between Process Bus devices is important. It is observed in this research that, there are different data sets from several Merging Units that need to be sent out, this result in time difference between each data set about several microseconds (around $4\mu\text{s}$). The standard IEC 61850-9-2 and results presented in Chapter 4 shows that the protection function can operate normally and $4\mu\text{s}$ is acceptable. Hence, in two Merging Unit case, time synchronization between both Merging Units is not necessary. However, synchronization between Merging Unit and switch is not required. The IEDs support IEEE 1588 synchronization protocol. The IEEE 1588 synchronization implementation is highly suggested for future work to improve the testing environment.

5.5 Interoperability

The interoperability is one very big advantage of IEC 61850 standard which ensures that IEDs from different vendors can work together in a single environment. Since the ABB, Siemens and Areva IEDs which are present in our lab are not up to date IEDs, and they do not support Process Bus function, the interoperability of Process Bus with bay level IEDs devices has not been evaluated in this research.

It is suggested to test a few IEDs from different vendors to be connected to Process Bus and configured with Process Bus protocol enabled. Each IED should be configured with different protection function and subscribes different measurement from the Merging Unit testing environment. Some interlocking function could be setup by GOOSE. The operation status of single or mixed IEDs protection system can be investigated and documented.

5.6 Stand Alone Merging Unit.

The evolution of Electronics and Microcontroller in electrical engineering in the near future will get more complex but will perform standalone function. In process level, Merging Unit only sends Sample Value and only takes trip information from bay level devices to stop its function. A Merging Unit with the

Chapter 5: Conclusion and Future Work

capability of not only sending Sample Values but also receiving Sample Values and also capability of sending and receiving GOOSE messages to communicate with bay level and self-protect with capability of CB trip functionality could be investigated. These are only possible with the help of microcontrollers. Initially Merging Unit itself is not compatible with all these functions and there may be need of other small microcontroller based circuits which works with the Merging Unit and perform standalone function and if there are proper measurement tools and IEC 61850 open source technology to develop the system, single standalone Merging Unit can be developed.

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