AUTOMATIC FAULT ANALYSIS IN POWER SYSTEMS VIA APPLICATION SERVICE PROVIDER

A Dissertation

by

Mustarum Musaruddin

Submitted to the Office of Graduate Centre of

The University of Adelaide

in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

The School of Electrical and Electronic Engineering

The Faculty of Engineering, Computer and Mathematical Sciences

The University of Adelaide, Australia

February 2011

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February 2011

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Abstract

Automatic Fault Analysis in Power Systems via Application Service Provider

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This dissertation presents a new approach to automated fault analysis in electrical power systems. New contributions to the fault and disturbance investigation topic are automated fault analysis service (AFAS) via application service provider (ASP) and remote relay testing service (RRTS). The implementation of AFAS complies with the new international standard of communication network and system in substations (IEC-61850).

The signal processing approaches in an automated fault analysis service are based on the wavelet transform and empirical mode decomposition methods. Several case studies have been carried out to test the performance of the signal segmentation technique. The data for analyses are from simulated fault data and from real disturbance records obtained from the intelligent electronic devices (IEDs) in substations.

The implementation of AFAS and RRTS was developed using C# with .NET technologies, MATLAB and open source software. Signal segmentation, signal modelling, fault type classification, fault location service, a web-based COMTRADE viewer and remote relay test service have been developed in this dissertation. Such services are designed to enhance manual investigations performed by engineers. The services have been tested extensively using disturbance records from power utilities and a power system simulation model.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Mustarum Musaruddin

Date

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List of Abbreviations

ACSI	Abstract Communication Service Interface
AFAS	Automated Fault and disturbance Analysis Service
ANN	Annunciator elements
API	Application Program Interfaces
ASP	Application Service Provider
ATP	Alternative Transient Program
CB	Circuit Breaker
CBMA	Circuit Breaker Monitor Analysis
CFG	Configuration elements
COMTRADE	Common format for Transient Data Exchange
CON	Control elements
CT	Current Transformer
CWT	Continuous Wavelet Transform
DFRs	Digital Fault Recorders
DFRA	Digital Fault Recorders Analysis
DPRA	Digital Protective Relay Analysis
DFT	Discrete Fourier Transform
DPRs	Digital Protective Relays
DWT	Discrete Wavelet Transform
EJS	Easy Java Simulation
EMD	Empirical Mode Decomposition
EMS	Energy Management System
FAFL	Fault Analysis with Fault Location
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
GOOSE	Generic Object Oriented Substation Event
GUI	Graphical User Interface

HPF	High Pass Filter
ICA	Independent Computing Architecture
IEDs	Intelligent Electronic Devices
ISP	Internet Service Providers
ISVs	Independent Software Vendors
IA	Instantaneous Amplitude
IMFs	Intrinsic Mode Functions
IT	Information Technology
JIM	Java Internet Matlab
LAN	Local Area Network
LD	Logical Devices
LN	Logical Nodes
LPF	Low Pass Filter
MET	Metering and measurement elements
MMI	Man Machine Interface
MMS	Manufacturing Message Specification
MSD	Multi-resolution Signal Decomposition
OLE	Object Linking and Embedding
OPC	Ole for Process Control
PHP	PHP Hypertext Pre-processor
PRO	Protection elements
PSCAD	Power System Computer Aided Design
QMF	Quadrature Mirror Filter
RDP	Remote Desktop Protocol
RF	Fault Resistance
RMS	Root Mean Square
RPC	Remote Procedure Calls
RRTS	Remote Relay Testing Service
RTS	Relay Test System
SAS	Substation Automation System
SCADA	Supervisory Control and Data Acquisition

SD	Standard Deviation
SEL	Schweitzer Engineering Laboratories
SER	Sequence of Event Recorder
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
TimeSeg	Time Segment
TLI	Test Laboratories International
UDDI	Universal Description and Discovery Interface
VNC	Virtual Network Computing
VT	Voltage Transformer
WAN	Wide Area Network
WAP	Wireless Application Protocol
WCF	Windows Communication Foundation
XML	eXtensible Markup Language
WS-AFA	Web Services for Fault Analysis
WSDL	Web Services Description Language

Acknowledgments

Firstly, I want to thank ALLAH the Almighty, the most beneficent, the most compassionate, and the most merciful. I also want to express my deepest gratitude to so many people who had a tremendous effect and notable help, so that this dissertation could be well completed.

In particular, I am indebted to my advisors, Dr. Rastko Zivanovic and Assoc. Prof. Nesimi Ertugrul, for their guidance, nurturing, encouragement, and support in every stage of my study. Their knowledge, kindness, patience, open-mindedness, and vision have provided me with lifetime benefits.

AusAID Australian Development Scholarship provided me with a scholarship during my studies for which I am grateful.

I would like also to thank Dr. Bill Winser at the Centre for Learning and Professional Development, University of Adelaide, for his help in editing this dissertation.

I am grateful to every member of department, and staff of University of Adelaide International student centre, especially Niranjala Seimon, who has help me during my stay in Adelaide.

Acknowledgment is extended to ESKOM Transmission Network South Africa and Indonesian Power Utility for providing the experimental data.

Many thanks are also devoted to my family members: my mother, father, my beloved wife, my daughters, brothers and sisters, for all the support they provided and their patience with all frustration they encountered during my study.

Thanks must go to my friends and colleagues for the constant encouragement, helpful suggestions and the enthusiasm they have shown towards this research during its development.

List of Publications

Journal Papers:

1. M. Musaruddin & R. Zivanovic, "Web Services for Fault Analysis in Smart Grid Applications," *Australian Journal of Electrical and Electronics Engineering, AJEEE* Volume 8, Number 2, 2011, Australia.
2. M. Musaruddin & R. Zivanovic, "Web Services for Automated Fault Analysis in Electrical Power Systems," *International Journal of Advances in Information Sciences and Service Sciences, AISS* Volume 2, Number 3, September 2010, Seoul, Korea.

Conference Papers:

1. M. Musaruddin & R. Zivanovic, "Investigation of Power System Disturbances via Application Service Provider," in *Proceedings IEEE 13th International Conference on Harmonics and Quality of Power (ICHQP 2008)*, Wollongong, Australia.
2. M. Musaruddin , M. Zaporoshenko & R. Zivanovic, "Remote Protective Relay Testing," in *Proceedings IEEE Australasian Universities Power Engineering Conference (AUPEC 2008)*, Sydney, Australia.
3. M. Musaruddin & R. Zivanovic, "Web Services for Automated Fault Analysis in Electrical Power System," in *Proceedings IEEE International Conference on Networked Computing and Advanced Information Management and Services (NCM 2009)*, Seoul, Korea.
4. M. Musaruddin & R. Zivanovic, "Automated Fault Analysis in the Indonesian Power Utility: A Case Study of South Sulawesi Transmission System," in *Proceedings IEEE Australasian Universities Power Engineering Conference (AUPEC 2009)*, Adelaide, Australia.
5. M. Musaruddin & R. Zivanovic, "Signal Segmentation of Fault Records based on Empirical Mode Decomposition," accepted for publication in *IEEE International Technical Conference (TENCON 2011)*, Bali, Indonesia.

Chapter 1: Introduction

1.1 Background

The objectives of every electric power utility are to maintain network integrity and stability throughout, and to promote the higher reliability of their power supply to customers without interruption. With the increase in power supply demand and deregulation in many countries, power systems have been operating in a stressed condition. To increase power system reliability, many attempts have been made to enhance control and protection of power systems. However, it is inevitable that faults in power systems can happen due to factors such as lightning strikes and equipment failure. While for much of the time the grid will operate automatically, human operators will still need to be in the loop to both monitor the normal operation of the grid and deal with unexpected events that cannot be handled by the automatic controls. Thus fault and disturbance analyses will then be needed to provide protection engineers with a good situational awareness and to help them decide how to fix the inevitable operational problems. Consequently, automated fault and disturbance analysis tasks have become increasingly challenging and require more advanced techniques.

Automated fault analysis may be defined as the ability of a specialised computer program to correlate and analyse available data about faults and disturbances [1]. The users of the information extracted from automated fault analysis are: operating personnel, protection engineers and maintenance crews. Operating personnel need the fault event information to conduct restoration procedures for returning the system to normal service as quickly as possible. Protection engineers are responsible for analysing what caused the fault. Maintenance crews require information concerning what equipment is damaged or operating outside the normal parameters in order to repair, maintain and return outages equipment to service [2].

Data used for automated fault analysis are retrieved from substation intelligent electronic devices (IEDs) such as digital fault recorders (DFRs), sequence of event recorders (SERs), digital protective relays (DPRs), and phasor measurements units (PMUs). The analyses rely on data recorded during disturbances. Data recorded during faults in the transmission network are used by control centre personnel to analyze the protection system and to decide on actions that will increase system reliability.

In recent years, the volume of recorded data has increased due to the increasing number of recording devices in substations. The investigation and management of disturbance records takes considerable time and will require skilled personnel. Manual analysis of these records is both time-consuming and complex and for these reasons, many records may not be examined and much of their potential value would be lost. Determining how to effectively analyze these records is a challenge being faced by many power utilities.

The existing fault analyses in power systems are primarily desktop applications. With service-oriented architecture, everything is a service, encapsulating a function and providing the function through an interface that can be invoked for use by other services on the network. The fault analysis services proposed in this dissertation are post-event and not control functions. Fault analysis is performed by protection engineers who analyse faults in more depth and who will provide some results to system operators but not in real-time.

Recent advances in information technology (IT) have transformed the role of the internet from purely data and information delivery to the largest computing services delivery infrastructure. Service oriented architecture (SOA) together with web services has become the de-facto standard for architecting and implementing business collaborations within and across organisation boundaries [3]. However, the full potential of the application service provider (ASP) model has not yet been utilised in the process of fault and disturbance investigation in electrical power systems, where most analysis applications still conform to the standalone models and are not treated as distributed services.

To enhance such analysis, a standardized fault and disturbance investigation service provided via ASP is proposed in this dissertation. The services could be used in an automated way and in conjunction with the rule-based system that captures the knowledge of experienced investigation engineers [4]. Individual services can be used for semi-automatic analysis when we follow step-by-step investigation procedures and solve all required tasks using the investigation services.

In this dissertation we argue that one of the system operation tasks, namely post-event fault and disturbances investigation, can be significantly enhanced through the application of the ASP. In this model a service provider takes responsibility for the proper operation, upgrade and maintenance of investigation services leaving investigation engineers to focus on specific investigation, using the services when required [5]. The service provider can be an internal department of the utility or a third party company which specialises in providing such services.

1.2 Research Objectives

Automated fault analysis is a widely studied subject with many different approaches. The aim of this dissertation is to develop a system of automated fault analysis in power systems via application service provider technology.

The main goals of this dissertation can be summarized as follows:

- To develop automatic fault and disturbance recognition algorithms and test them extensively on the real disturbance signals, obtained from the intelligent electronic devices.

- To develop a software package for automatic fault and disturbance analysis via the application service provider.

- To integrate intelligent electronic devices and automated fault analysis services using the new standard for the communication network and system in substations (IEC 61850).

- To develop remote relay testing service for the web-based investigation of protection system performance.

1.3 Major Contributions

Several new methods or developments are introduced in this thesis. The major contributions are as follows:

- The introduction and development of power system disturbance investigation via application service provider model. It includes the development of web services for automated fault analysis in electrical power systems which complies with the IEC-61850.

- The development of data analysis for pre-processing services using wavelet analysis and empirical mode decomposition.

- The introduction and development of a remote relay testing system for online investigation of intelligent electronic devices.

- The development of a distributed triggering and recording system based on IEC-61850 standard.

1.4 Organisation of the Dissertation

The dissertation is organized as follows:

- Chapter 2 covers the necessary background information on transmission system fault analysis that uses signals recorded during events. First, the infrastructure for collecting fault data is overviewed, and then the fault investigation scenario is described. Fault analysis functions and techniques are also presented in this chapter. Furthermore, a review of existing fault and disturbance analysis tools is presented.

- Chapter 3 provides information about available technologies to develop web services for automated fault analysis in power systems. It covers an overview of the application service provider technologies including web services and thin client computing technologies. Then, a new standard of the communication network and system in substations (IEC-61850), one that especially deals with disturbance data recording, is presented. Furthermore, this chapter presents ole for process control (OPC) and manufacturing message specification (MMS) protocols as a communication solution in dealing with the IEC 61850 protocol.
- Chapter 4 describes the development of web services for automated fault analysis. In this chapter, the wavelet transform and empirical mode decomposition methods for signal segmentation in automated fault analysis service are described. Furthermore, illustrative examples of the use of the proposed technique are presented.
- Chapter 5 describes the development of a remote protective relay test service (RRTS). It covers the RRTS concepts, implementation and testing case studies.
- Chapter 6 highlights the conclusions of this dissertation and discusses directions for future research.

Chapter 2: Review of Transmission System Fault Analysis

2.1 Introduction

This chapter provides the background knowledge for the dissertation study. First, the infrastructure for collecting fault data in transmission substations is overviewed. Then, the existing fault investigation scenario is discussed. The fault analysis functions, including signal segmentation and modelling, fault type classification and fault location are reviewed. Furthermore, the existing fault analysis techniques and tools are overviewed.

2.2 Infrastructure for Collecting Fault Data

Transmission substations are utilized for voltage transformation and the routing of energy flow from power grids. In order to continuously control, monitor and protect power grids, the substations are controlled by substation automation systems (SAS). The purpose of SAS is to take decisions automatically with minimum user intervention and provide automation within the substation, and includes the intelligent electronic devices and communication network infrastructure [1]. Typically, the substation automation systems consist of a remote terminal unit (RTU), intelligent electronic devices (IEDs), substation communication infrastructure and a supervisory control and data acquisition (SCADA) system.

2.2.1 Remote Terminal Unit (RTU)

RTU is a stand-alone data acquisition and control unit. The function of the RTU is to control process equipment at the remote site, get data from the equipment, and transfers the data, such as measurements of voltage, current, power and circuit breaker positions, back to the SCADA system [6]. In other words, the RTU may work as an interface between the communication network and the substation equipment. However, some functions of an RTU may reside in one IED [7].

2.2.2 Intelligent Electronic Devices (IEDs)

An Intelligent Electronic Device is a device that incorporates one or more processors that can run an executable source and that provides a data communication interface, electronic multi-function meters, digital relays, a programmable controller, intelligent sensors, intelligent RTUs or a workstation PC are examples of such a device [7, 8].

In order to help users decide how to respond to the event and implement the necessary actions, raw data from IEDs must be transformed into knowledge [9]. Several examples of the operational data required during a fault on the power systems are: bus phase voltage, bus residual voltage, line phase voltages, line phase currents, control contact performance, alarm contacts, fault duration, clearing time and type of fault [9].

Much research has been dedicated to the integration of intelligent electronic devices (IEDs). For example, a concept of implementing and integrating (IEDs) recorded data was presented by several authors in [10 – 12]. The studies were conducted to enhance the functionality and reliability of an automated fault and disturbance analysis that can meet the new IEC standards such as IEC 61850, IEC 61970 and IEC 61968 [10]. In their studies, the authors focussed on several problems, such as how to design a new interface without changing the existing systems, how to handle input and output data or to program from various types of IEDs or programs, how to adapt the new IEC standards into the existing systems and how to approach new applications.

Moreover, Kezunovic et al. [9] introduced two stages of utilizing the IED-recorded substation data in an automatic way. The first stage is to download IED data to the substation PC using legacy software packages and the next stage is to convert the data into a common format for transient data exchange (COMTRADE) which is the standard format as specified by IEEE Standard C37.111 [13]. Finally, the data is stored in the database. The authors successfully described a new concept of the implementation and integration of IED-recorded data and provided an example scenario. Unfortunately, the authors did not provide enough results of the implementation and did not analyse the effectiveness of their new concept. It is clear that the IEC 61850, IEC 61970 and IEC 61968 standard [9] have to be followed in order to implement and integrate recorded data in substations and to secure automated fault analysis.

2.2.3 Substation Communication Infrastructure

In line with the development of the networking technology, substation communication has changed dramatically during the last decade. Several technologies that currently have been utilized in transmission substation are ethernet, TCP/IP, high-speed wide area networks and high-performance low-cost computers [14].

A new communication model was needed in order to be able to manage the large number of devices in substations and to improve communication within devices. That model has been developed and standardized as IEC61850 – communication networks and systems in substations [14]. This standard will have a significant impact on how electric power systems are designed and built in the future [15]. In addition, there are several benefits from implementing IEC 61850, such as: lower installation, transducer, commissioning, equipment migration, extension and integration costs, and the implementation of new capabilities [15]. More details about substation communication solutions based on IEC 61850 are discussed in Chapter 3.

2.2.4 Supervisory Control and Data Acquisition (SCADA) Systems

SCADA systems are now being widely deployed in many industries in order to control and monitor a plant or equipment in such areas as energy, oil and gas refining, telecommunications, water and waste control and transportation.

SCADA systems focus on the supervisory level used for control, operation and monitoring. The control system consists of a central host or master (MTU), remote units (RTU's or IEDs) and a collection of software used to monitor and control remotely located field data elements [14]. In order to support SCADA data transmission, a communication network is important.

Formerly, SCADA systems have made use of the private switched network for monitoring purposes. Today many systems are monitored using the infrastructure of the corporate local area network (LAN)/ wide area network (WAN) and wireless technologies [16].

The new development of the SCADA system was studied by several authors [17-20] for different purposes. Although all the authors have different objectives, most of them deploy information technology approaches, such as client/server techniques, internet-based and web services, in their studies.

Kalaitzakis et al. [19] investigated the development of a data acquisition system for remote monitoring of renewable energy systems based on the client/ server architecture without physical connection of the monitored systems to the data collection server. The authors argued that the proposed system was implemented successfully and can be extended to perform remote control of the renewable energy system for users authorized to control this function.

The application of web services in SCADA systems was explored by Kelapure et al. [17]. In their research, the authors successfully implemented .NET technology in dealing with the web services. They were also able to develop a web man machine interface (MMI) and a wireless application protocol (WAP) publisher. One of the benefits of the web MMI is that it does not need any client software installation. The user only needs internet ready computer systems and access rights.

2.3 Fault Investigation Scenario

Post-event investigation of faults and disturbances based on event records plays an important role in maintaining an acceptable level of power quality and reliability in electrical power systems. The main goal of an investigation is to find the cause of events of interest and consequences related to power system operation [1]. Nowadays, it is common practice in power utilities for a large number of disturbance records to be collected due to the increasing number of installed DFRs and other IEDs in substations. Engineers have more recorded data than can be analyzed within the time available. Manual analysis of these records is both time-consuming and complex and for these reasons, many records may not be examined and much of their potential value would be lost.

In the case of a fault happening on a transmission line, the protective relay will detect the fault and issue a command to the circuit breaker to open. After a pre-specified delay, the relay will issue a command to the circuit breaker to re-close. If the fault is permanent, the relay will detect the fault again and issue a command to open the breaker and to lock it in the open position. The SCADA system will get information on the status of that line if the line is disconnected due to protection action, but there is no information as to why this has happened. Furthermore, the exact location of the fault as well as the response time of the protection system and circuit breakers is not provided by SCADA. Control centre personnel who are in charge of controlling circuit breakers via the SCADA system 24 hours a day need more detailed information about the fault and the performance of circuit breakers and the protection system to make decisions on how to bring back the line into service in the shortest time possible. Several questions concern them, such as: where and what is the problem? Did the line re-close and stay in operation? Was everything working correctly? If so, can it be returned to service? If not, what needs to be isolated? The protection engineer will analyse the event and provide the system operator with the necessary information related to the fault on the network. Several issues that need to be answered by protection engineers are: did the right protection systems respond in the right way? Did the wrong protection systems respond in the wrong way? Did the right protection systems respond in the wrong way? In order to answer these questions, the protection engineers must perform the following manual procedures that will take at least fifteen minutes to complete, before the report can be sent to the control centre [21]:

- Write down details of the incident provided by the controller.
- Enter the IED software and select the appropriate IED to dial up.
- Scan the IED table of contents for the relevant fault records and select the disturbance files to retrieve.
- Start to download the selected recording.
- Once a record is available on the IED software, the protection engineer will analyse the record.
- Often, another record from the opposite end of the transmission line is also required before an accurate analysis conclusion can be finalised.

It has been argued [21] that the processing time is based on the assumption of only one transmission line being tripped and that two records are required. However, experience has shown that the average response time is approximately 30 minutes. With the increased complexity and dynamics of the transmission network, the demand for faster and better information for the network controllers has also increased.

2.4 Fault Analysis Functions

The first requirement for the fault analysis software is that it must be able to read a COMTRADE file. Then, the fault analysis function must extract from the COMTRADE file the following information [22]:

- Faulted phase/s
- Fault type
- Total fault duration
- Main 1 protection operating time
- Main 2 protection operating time
- Fault location
- Fault resistance
- DC offset parameters
- Breaker operating time
- Auto re-close time.

2.4.1 Signal Segmentation

The first stage in the analysis of non-stationary signals, recorded during a disturbance, is detection of abrupt changes. This information is used to segment signals in stationary parts for further analysis. These stationary parts correspond to the system's states, such as pre-fault, fault, circuit-breaker open and circuit-breaker re-close. Segmentation techniques have been studied by researchers in different areas, including image processing and signal processing. Although several authors studied the segmentation signals, only a few of them considered the abrupt change detection of disturbance records from IEDs. One of the segmentation techniques using abrupt change detection was investigated by Ukil and Zivanovic [23, 25] in their research article. They suggested that implementing the segmented recording and working on the specific segments, such as pre fault, fault and after circuit breaker opening, is crucial for improving the fault recognition rate and automatic analysis quality. The segmentation algorithms presented in their research article are proposed for off-line operation. However, they stated that the accuracy and speed of operation of the segmentation algorithms are acceptable. Furthermore, Bassevile and Nikoforov [24] summarises abrupt change detection techniques.

It is pointed out [23] that the result of the segmentation service can be used:

- to synchronize disturbance records from different recording devices, triggered by the same disturbance;

- to extract data required for performance evaluation of the protection system (e.g. fault duration, protection system operating times, breaker operating times, etc.).

2.4.2 Fault Type Classification

Many types of equipment may be destroyed if the fault is not cleared rapidly. Therefore, the fault must be cleared as quickly as possible. It is stated [26] that about 80-90 % of faults occur on overhead transmission lines while the rest take place on substation equipment and bus-bars combined. Typically, faults on transmission systems can happen due to several causes, such as the fault current, insulation ageing or external causes [26].

- Fault current

Healthy insulation in the equipment can be subjected to a transient over voltages fault of small time duration due to switching and lightning strikes, direct or indirect. Failure of insulation may happen, resulting in a very high fault current. This current may be more than 10 times the rated or nominal current of the equipment.

- Insulation aging

Aging of power equipment may cause its breakdown even at normal power frequency voltage.

- External causes

External objects such as a bird, kite string, or tree branch are considered as external causes of faults. These objects may span one conductor and ground causing a single line to ground fault (phase-earth) or span two conductors causing a phase-phase fault.

The fault type can be classified as shunt or series faults. Shunt faults are faults when one or more of the phases are short-circuited (possibly to earth), for example: single-line-to-ground (SLG) fault, line-to-line (LL) fault, double-line-to-ground (2LG) fault and three-phases (3Ø) fault. Series faults could be described as a fault for which the impedances of each of the three phases are not equal, usually caused by the interruption of one or two phases. Series faults can be due to a circuit breaker malfunction in one or several phases, a broken conductor or a fuse operation in one or two phases. More details about fault types in power systems are explained in reference [26, 27].

2.4.3 Fault Location

The subject of fault location has been of considerable interest to electric power utility engineers and researchers for many years. Finding the locations of transmission line faults has been the main goal of most of the research done to date. The main reason for this area of research is the impact of transmission-line faults on power systems and the fact that the time required to physically check the lines is much larger than that required for faults in the sub-transmission and distribution systems. The aim of fault location is to locate the fault with the highest possibly accuracy. Accurate fault location is needed for several reasons such as:

- Avoiding lengthy and expensive patrols.
- Expediting repairs and restoration.
- Detecting problems at an early stage.
- Reducing revenue loss caused by outages.

A fault location function can be implemented into [2]:

- Microprocessor-based protective relays.
- Digital fault recorders.
- Stand-alone fault locator.
- Post-fault analysis program.

The above list of fault location function implementations can be extended with the web services for fault location; this possible extension is one of the contributions of this dissertation.

In dealing with estimating fault locations, several methods are presently used in the field [26]:

- DFR and short circuit data match
- Travelling wave methods
- Impedance-based methods:

- One-ended methods without using source impedance data (Simple reactance, Takagi [28])
- One-ended methods using source impedance data

- Two-ended methods

In this study, only certain impedance-based fault location methods are considered. One–ended impedance based fault locators calculate the fault location from the apparent impedance seen when looking into the line at one end [29]. Figure 2-1 shows a single line diagram and circuit representation of a fault line on a transmission line with two sources S and R.

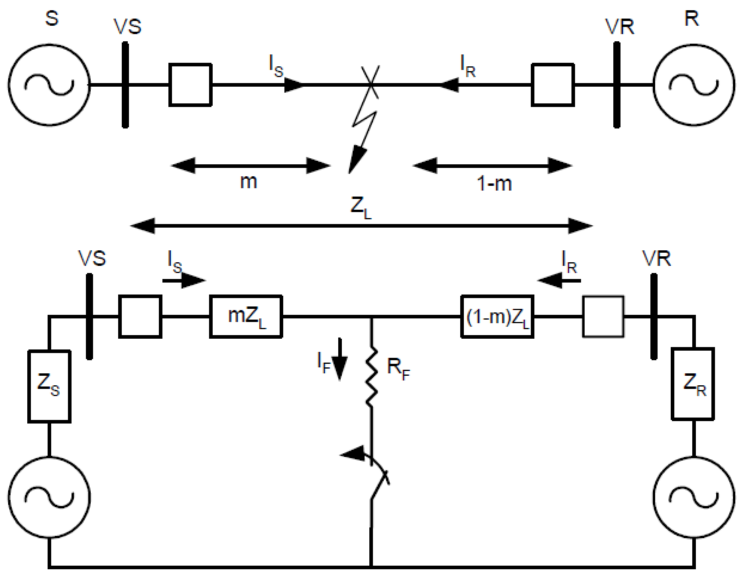


Figure 2-1. Single line diagram representation of line fault

From Figure 2-1, the voltage drop for three phase faults can be mathematically expressed as:

$$V_s = m.Z_L \,.\, I_s + R_F \,.\, I_F \qquad (2.1)$$

where:

V_s is the voltage at terminal S

m is the distance to the fault in per unit

Z_L is the line positive sequence impedance between terminals S and R

I_s is the line current from terminal S

R_F is the fault resistance

I_F is the total fault current.

The value of the impedance measured at terminal S may be found by dividing equation (2.1) by the measured current, I*s*.

$$Z_{FS} = \frac{V_s}{I_s} = mZ_L + R_F \frac{I_F}{I_S} \qquad (2.2)$$

where:

Z_{FS} is the apparent impedance to the fault measured at terminal S.

The Simple Reactance method compensates for the fault resistance by measuring only the imaginary part of the apparent line impedance. Therefore, the per unit fault location for three phase faults is given as [29]:

$$m = \frac{Im\left(\frac{V_S}{I_S}\right)}{Im\ (Z_L)} \qquad (2.3)$$

The fault location for single line to ground fault (a-g) is given as [33]:

$$m = Im\left[\frac{V_{Sa}}{(I_{Sa} + k_0 I_R)}\right] / Im(Z_L) \qquad (2.4)$$

where:

k_0 is $(Z_{0L} - Z_L)/3Z_L$ and residual current $I_R = 3I_0$

To improve the fault location calculation, the Takagi method uses the complex conjugate of differences between pre-fault (I_{PF}) and fault current (I_F). The Takagi method is given as [29]:

$$m_{(Takagi\,)} = \frac{I_m\left(V_S\, I_{T^*}\right)}{I_m\,(Z_L.I_S.I_{T^*})} \qquad (2.5)$$

where :

$I_{T^*} = I_F - I_{PF}$, and I_{T^*} is a complete conjugate of I_T

2.5 Fault Analysis Techniques

Previous research in fault analysis has been extensive. It has dealt with many different techniques, for example: signal processing and intelligent systems including expert systems, neural networks, fuzzy logic and support vector machines.

Signal processing techniques that have been commonly used in the past were based on the orthogonal transforms such as fast fourier transform (FFT). The reasons for this choice are that most of the analytic approaches were based on the extraction of phasors [2]. However, with the improvement of analytic techniques, several new signal processing techniques have been introduced, such as wavelets transform, Hilbert transform, S transform and some other digital filters [26]. The fault and disturbance analysis using signal processing has been documented in [30-40].

An expert system technique is well suited for the decision making process. Neural networks can be used in fault analysis [2]. Although neural networks have been shown to act as powerful pattern recognizers, some drawbacks to their use in the analysis, such as the issue of the selection of the training sets and methodology, need special attention [2]. Fault analysis using expert systems and neural network approaches were developed by the authors [41 - 55]. They argued that utilising these techniques can assist operators and protection engineers in analysing fault events and substation disturbances.

To be able to make a selection of the variables and their typical values in applying the theory of fuzzy logic to the analysis tasks, better understanding of the knowledge about the event/device being analysed is critical [1]. Most of the fuzzy logic applications to fault analysis proposed so far have been mainly related to power systems classification and equipment states; however, there is less information from the authors regarding the guidance and justification of the above mentioned selections [1]. More fault analysis studies using fuzzy logic are documented in references [56 - 58].

In order to enhance automated fault analysis functions, Kezunovic et al. [10] in their research introduced new integrated functions of fault analysis, for example: the integration of digital fault recorders analysis (DFRA), digital protective relays analysis (DPRA), circuit breaker monitor analysis (CBMA) and fault analysis with fault location (FAFL). The first three functions are IED specific while the one remaining is a system wide analysis. In a system wide concept, the software module is installed and executed on a server and only reports are sent to the clients. The benefits of this concept are that users can analyse the fault remotely and integrate different types of data input. However, it was not clear in the study what methods the authors were using to deal with the signal analysis. Although several techniques in automated fault analysis have been studied, none of those techniques were implemented as the application service provider (ASP).

2.6 Overview of the Fault and Disturbance Analysis Tools

There are several available software tools for fault analysis in power systems, such as DIGSI from Siemens, SEL-PROFILE from Schweitzer engineering laboratories (SEL), digital fault recorder assistant (DFR Assistant) from Test laboratories Inc., Wavewin from SoftStuf Inc. and TransView from Omicron. The following is an overview of the fault analysis tool.

2.6.1 Wavewin

The Wavewin tool was developed by Softstuf Inc. [59]. Features of Wavewin such as the fault calculator (reactance methods with single end) can be integrated into devices, and it also has waveforms and phasor viewers. However, to calculate the fault, the user needs to manually input the parameters of positive and zero sequence then select the channel of faulty phase current and voltage. Wavewin is a standalone application where users have to install the Wavewin software into their computer before they can use it. Furthermore, Wavewin is not supported by the automatic abrupt change detection for signal segmentation in the waveforms viewer. In contrast to Wavewin, automated fault and disturbance analysis service (AFAS), which is developed in this study is a distributed application and provides automatic signal segmentation of fault and disturbances in the waveform viewer.

2.6.2 SIGRA

Siemens [60] has developed the SIGRA application program that supports the analysis of fault events in the power systems network. SIGRA offers a graphic display of the data recorded during the fault event and uses the values measured to calculate further variables, such as impedances, outputs or r.m.s. values, which make it easier to analyze the fault record. These variables can then be represented in any of the following diagrams of the views: time signal diagrams, fault locators, vector diagrams, circle diagrams and harmonics. Similar to wavewin, SIGRA is also a standalone application and not provide the automatic signal segmentation of the event changes.

An example of fault locator interface in SIGRA can be seen in Figure 2-2. Figure 2-3 presents the waveforms viewer of SIGRA. The COMTRADE data to test this tool is from the Poseidon substation in ESKOM South Africa and the fault locator technique used is the single end method. As can be seen from the figure, the fault is located at 23.4 km with the fault type being phase C to ground fault.

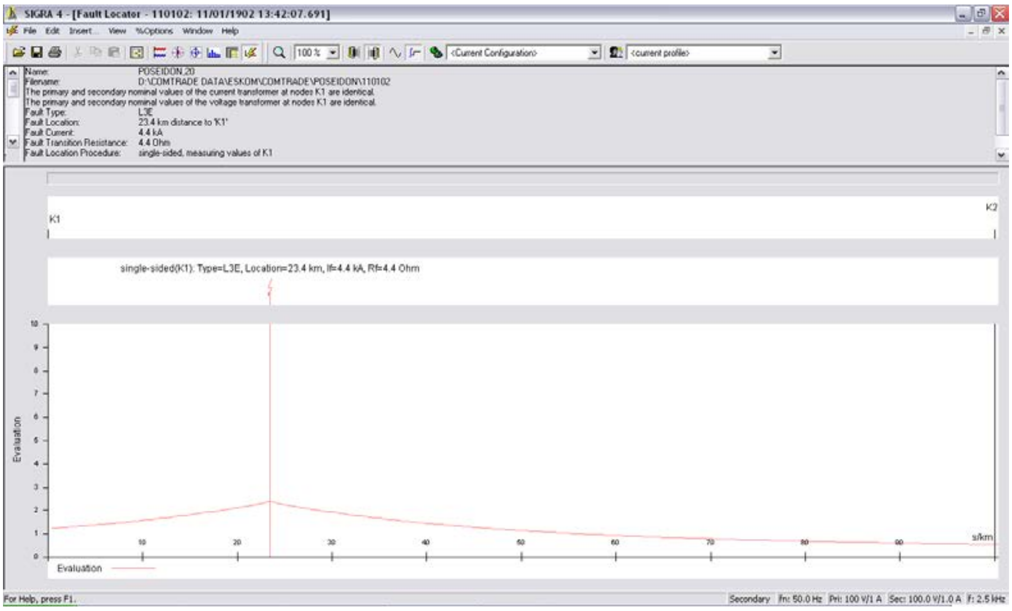


Figure 2-2. Fault locator in SIGRA

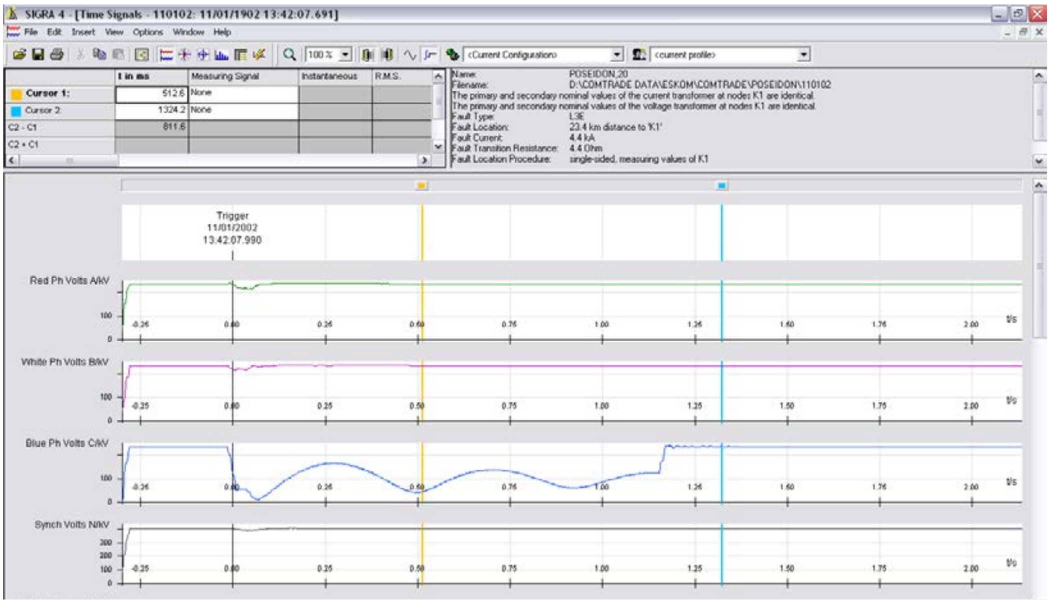


Figure 2-3. Waveforms viewer in SIGRA

2.6.3 SEL-PROFILE

SEL-PROFILE® was developed by Schweitzer engineering laboratories (SEL) [61]. This software allows users to see phase and sequence components at the bus and the fault. The SEL-PROFILE is running under disk operating systems (DOS)-based program which eliminates tedious hand calculations and quickly provides the answers for critical or special fault locating problems and system studies. Several features of the SEL-PROFILE are: it processes SEL relay event reports, recalculates fault locations, uses single and two-ended methods of analysis, handles phase and sequence components and accommodates manual entry of fault data. In terms of graphics, SEL-PROFILE is not user friendly because users have to entry data manually under DOS program and it is not supported the waveforms viewer. Figure 2-4 shows the interface of SEL-PROFILE running under the disk operating system.

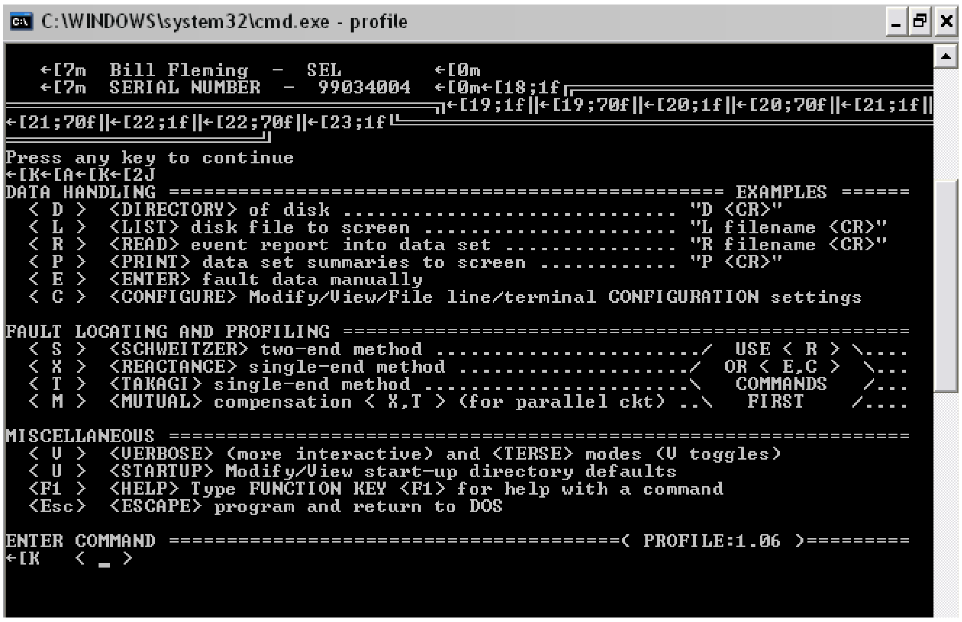


Figure 2-4. SEL-PROFILE software running under DOS

2.6.4 DFR Assistant

DFR Assistant™ software is developed by Test Laboratories International Inc (TLI Inc.) [62]. DFR Assistant tools perform automated analysis and classification of digital fault recorder (DFR) files. A wide range of DFR products from different vendors, as well as models and vintages from the same vendor, can easily be configured and customized to fit specific application requirements. Several features from DFR Assistant are: Integrating DFR Data, Automating Analysis and Reducing Restoration Time. DFR Assistant is a standalone application and not provides the automatic signal segmentation based on the abrupt change in the fault record.

2.6.5 TransView

TransView is a COMTRADE file analysis tool which is part of the test universe software package from OMICRON [63]. The TransView system supports the analysis of fault records. Using the measured values recorded in the fault record, TransView calculates additional values, such as positive-sequence impedances, r.m.s. values, etc. These measured and calculated variables and binary signals are graphically prepared for display in the following view(s): time signals, vector diagrams, circle diagrams, harmonics and fault locator. The signals can be displayed either as primary or secondary values. However, to use the Transview, users have to install the software into their computer and the COMTRADE viewer is not supported with the automatic signal segmentation of the abrupt change of events during fault and disturbances. Figure 2-5 displays the TransView fault locator and Figure 2-6 shows the waveforms of disturbance data in TransView. The features of TransView software are quite similar to the Sigra software as can be seen from Figure 2-6.

Although several fault analysis tools are available, all of the tools need to be installed and configured in the user's computer with the specific operating systems, and none of them implement as web services, which is loose coupling and multi-platform. Even though those tools can communicate with the devices, most of them are only suitable for the specific devices that come together with that software from the specific vendor. Not all of the available fault analysis tools are provided with the automated signal segmentation where the user can see the fault state in the COMTRADE viewer. In contrast to the available fault analysis tools, automated fault and disturbance analysis service (AFAS) provide the automated signals segmentation based on the abrupt change detection of event during fault and disturbance using wavelet and empirical mode decomposition (EMD) method. Furthermore, the existing fault analysis tools have not been considered in relation to the data source based on the IEC-61850 protocol. In contrast to the existing fault analysis tools, in this dissertation the proposed fault analysis functions is deployed via the application service provider and complies with the IEC 61850 standard as a new substation communication solutions for modern substations and smart grid applications.

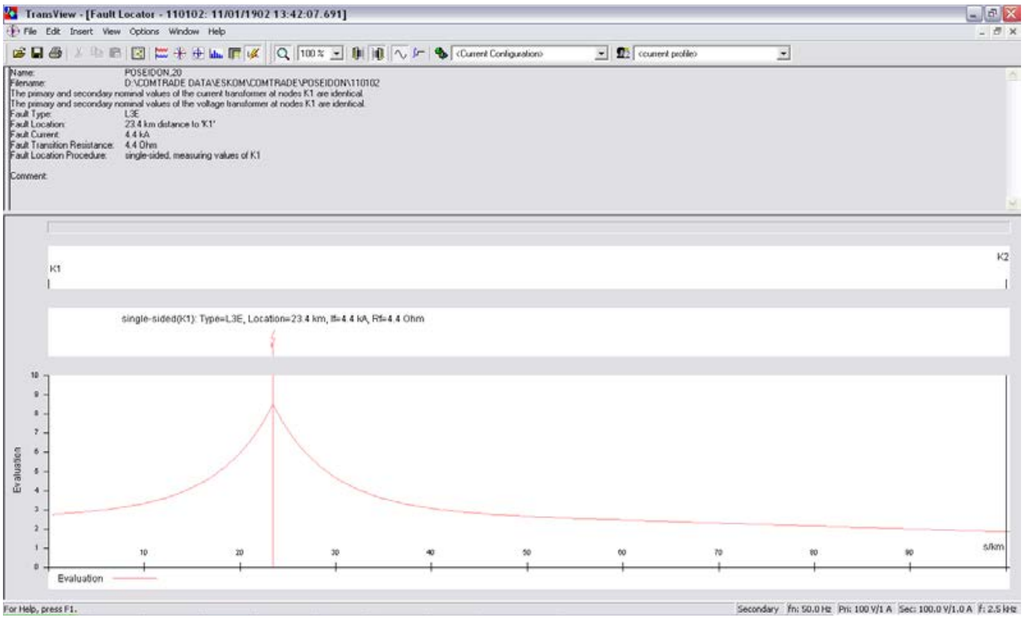


Figure 2-5. Fault locator in TransView

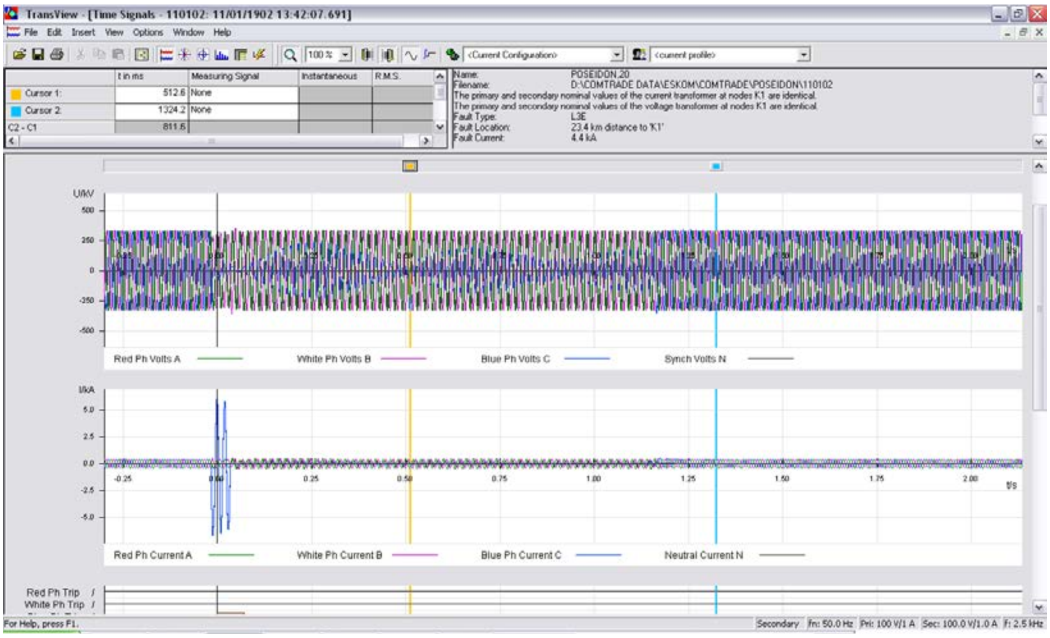


Figure 2-6. Waveforms viewer in TransView

2.7 Chapter Summary

The infrastructure for collecting fault data in transmission substation systems including SCADA system, intelligent electronic devices (IEDs) and substation communication infrastructure has been briefly described in this chapter. The background knowledge about a transmission system fault investigation scenario has also been presented. Furthermore, the existing techniques and tools for fault analysis have been briefly overviewed. In the next chapter, the application service provider technologies and the substation communication solutions for disturbance data recording based on IEC-61850 are presented.

Chapter 3: Application Service Provider and IEC 61850 Technologies

3.1 Introduction

This chapter presents the available technologies for automated fault analysis, with the emphasis on the service oriented technology approaches. Firstly, the concept of application service provider (ASP) is presented. Then, the web services and thin client computing as two of the key technologies of the ASP are overviewed. Furthermore, the new standard for communication networks and systems in substations (IEC-61850) for information relevant to disturbance recording is reviewed.

3.2 Application Service Provider (ASP)

The application service provider has emerged as a direct consequence of specific business and technology drivers that have materialized over the past decade. Several researchers [64 - 66] have explored the ASP technologies. Although they highlight the practical approaches of the ASP model for different purposes, all of the above authors agree that the role of the ASP is to manage applications and make them available to their customers from a central computer system over public networks such as the Internet.

ASPs are independent software vendors (ISVs) or internet service providers (ISPs) that use the internet as the delivery medium to make software applications available [64]. Obtaining these applications, services, and solutions from an outside supplier is a cost-effective solution to the demands of systems ownership. Hence, the ASP model is a promising innovation well suited to a cost-effective use in the investigation of faults and disturbances in electrical power systems.

The ASP gives its customers remote access to software applications and instead of downloading these applications, the customer actually logs on to the ASP's computer system and runs them on his own system, with only the results being downloaded [64]. There are many benefits associated with operating this ASP model. Some of them have been documented by Groves [66] and Ukil & Zivanovic [65]. For example, there is no need to purchase specialized applications for different operating systems, there is faster implementation and enhanced security. Another benefit is that software containing proprietary algorithms can be rewritten, so that it can only be run on an ASP network, and in this way competitors can use the software but not download it onto their own systems or modify it. Key technologies implemented in the ASP model are web services and thin client computing technology.

Although there are several studies of the ASP model application in various industries, only a few have considered use of the model in the electrical power delivery industry. The question of the need for ASP from the power utilities' perspective is discussed in [67]. Several services that are feasible to be implemented using the ASP model are introduced [67]: event annunciator, automated collection of disturbance reports, IED metering, one-line diagram display, electronic documentation storage and control commands. This list can be extended with additional disturbance investigation services suitable for ASP implementation such as: fault section estimation, signal segmentation and analysis, fault location, fault type classification, remote relay testing, etc.

3.3 Web Services

Web services was introduced in the mid 2000 with the introduction of the first version of XML messaging simple object access protocol (SOAP), WSDL 1.1, and an initial version of UDDI as a service registry [68]. This technology is independent of platform, programming language and the component model. A web service is a software application, accessible on the web through an URL that is accessed by clients using XML-based protocols, such as SOAP, and sent over accepted Internet protocols, such as HTTP. Clients access a web service application through its interfaces and bindings, which are defined using XML artefacts [69]. A web service consists of three basic components. They are service provider, service consumer, and service registry. The relationships among them are illustrated in Figure 3-1 and an example of web services can be seen in Figure 3-2.

Figure 3-1. Web services architecture model

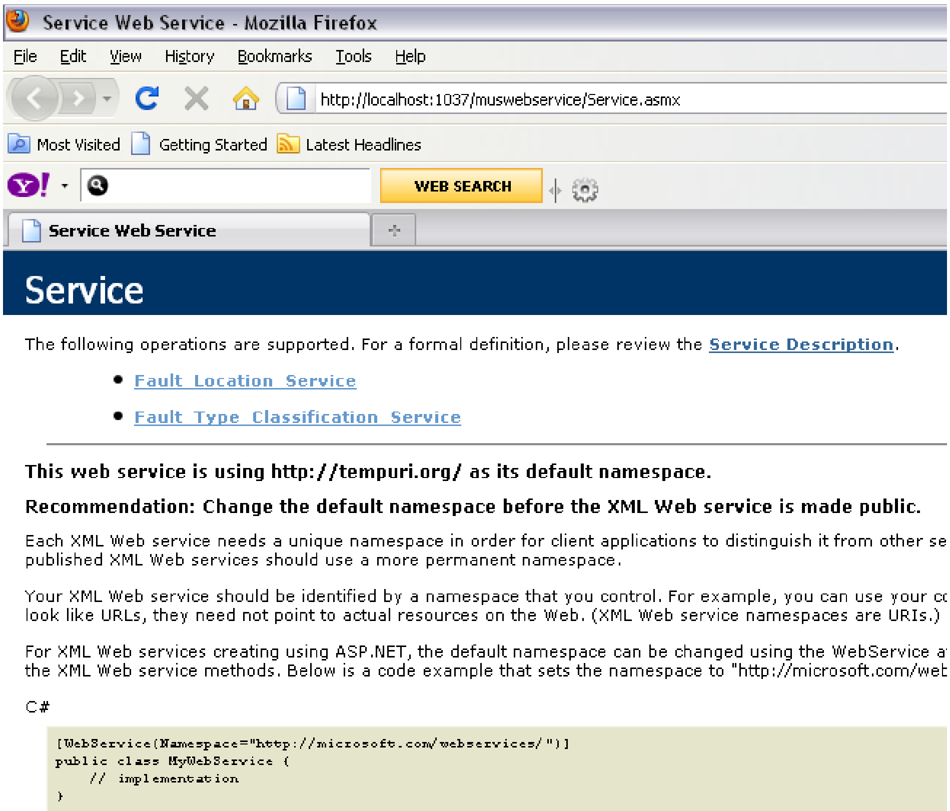


Figure 3-2. Example of web services

3.3.1 Extensible Markup Language (XML)

Extensible mark-up language (XML) and simple object access protocol (SOAP) are the fundamental technologies of web services. XML is a unified way to represent data [69]. Without XML, web services would not have been possible because every aspect of a web service uses XML. For example, sending a message to invoke a web service using SOAP is entirely built on top of XML.

3.3.2 Simple Object Access Protocol (SOAP)

SOAP is a lightweight XML-based protocol that supports remote procedure calls (RPC) and messaging over any network protocol but primarily over HTTP [70]. The SOAP specification provides standards for the format of SOAP messages and the way in which SOAP should be used over HTTP. SOAP was created to help provide the means to transport XML documents from one computer to another

SOAP itself is built using XML. SOAP can be defined as a standard mechanism for invoking web services. SOAP is used to call exposed methods of the web service. It describes how the data being passed to those methods is structured, and what the data is. If the client passes the web service a correctly formatted SOAP document as a web service request, effectively calling a method, the web service will return another SOAP document containing a response. A SOAP message consists of the three parts: an envelope, header and body.

The SOAP envelope is used to store the XML message. This envelope acts as a container to hold XML information, as shown in Figure 3-3. The envelope consists of two main parts: the SAP header and the SOAP body of message. The SOAP header can be used as a container for additional information about the SOAP message, for example, security credentials or message authentication information like message hash values. This information is then used to manage and or to help secure the package.

The SOAP body contains the XML message content. The body can contain information about the web service method that is about to be executed in a request. In a request the body would contain information about the method's parameters, the data type they expect, as well as the value that will be passed into those parameters. In a response the body of the SOAP message would contain the information on the data type that is being returned as well as the actual returned value. An example of SOAP can be seen in Figure 3-4.

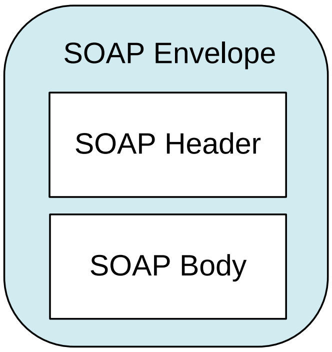
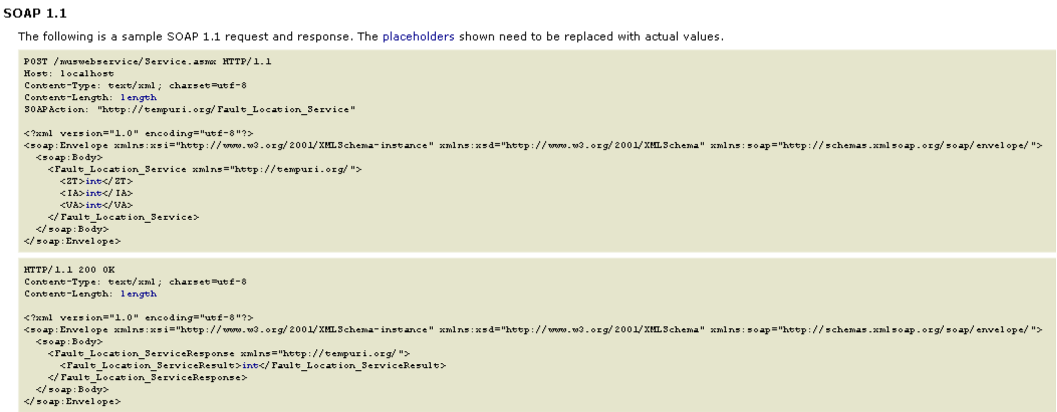


Figure 3-3. SOAP structure



SOAP 1.1

The following is a sample SOAP 1.1 request and response. The placeholders shown need to be replaced with actual values.

```
POST /muswebservice/Service.asmx HTTP/1.1
Host: localhost
Content-Type: text/xml; charset=utf-8
Content-Length: length
SOAPAction: "http://tempuri.org/Fault_Location_Service"

<?xml version="1.0" encoding="utf-8"?>
<soap:Envelope xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns:soap="http://schemas.xmlsoap.org/soap/envelope/">
  <soap:Body>
    <Fault_Location_Service xmlns="http://tempuri.org/">
      <ZT>int</ZT>
      <IA>int</IA>
      <VA>int</VA>
    </Fault_Location_Service>
  </soap:Body>
</soap:Envelope>
```

```
HTTP/1.1 200 OK
Content-Type: text/xml; charset=utf-8
Content-Length: length

<?xml version="1.0" encoding="utf-8"?>
<soap:Envelope xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns:soap="http://schemas.xmlsoap.org/soap/envelope/">
  <soap:Body>
    <Fault_Location_ServiceResponse xmlns="http://tempuri.org/">
      <Fault_Location_ServiceResult>int</Fault_Location_ServiceResult>
    </Fault_Location_ServiceResponse>
  </soap:Body>
</soap:Envelope>
```

Figure 3-4. SOAP example

3.3.3 Web Services Description Language (WSDL)

Web service providers describe their service interfaces using a web services description language (WSDL) and publish them to the service registry. WSDL is an XML-formatted language for describing the purposes of the web services [70]. In other words, WSDL can be defined as a standard mechanism for describing web services. Figure 3-5 shows an example of WSDL in the web browser.

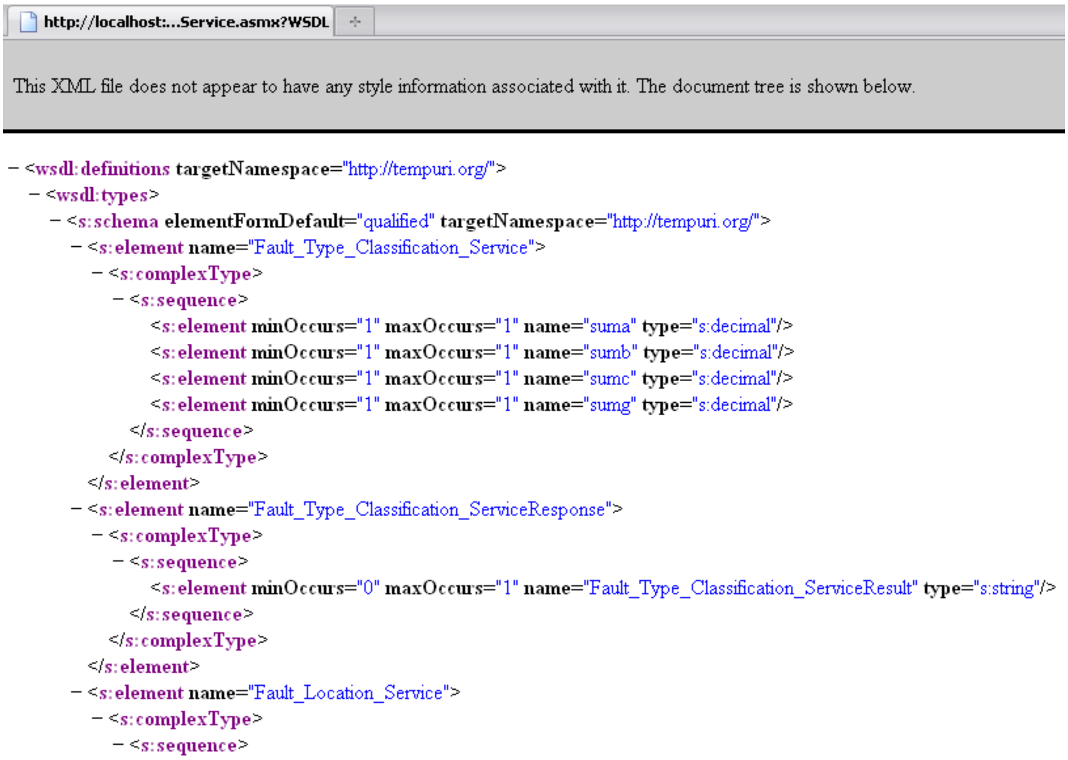


Figure 3-5. WSDL example

3.3.4 Universal Discovery, Description and Integration (UDDI)

UDDI is a distributed directory that allows businesses to list themselves on the Internet. The UDDI can also be defined as a standard mechanism for publishing and discovering web services [71]. Service consumers use the UDDI application program interfaces (APIs) to find, locate and point to a service.

The UDDI directory is the general standard used as a registry of web services that are available for use in a particular network [71]. The UDDI is like a Yellow pages for web services. If a user wants to find a web service for an enterprise application, the UDDI can be consulted. The UDDI would tell where to find the service, and it would direct the user to a WSDL document so the web service could be examined to make sure it was the one desired.

A UDDI registry is a central concept and constitutes one shift to a model that assumes a distributed, loosely coupled set of web service. The service that the consumer wants we want to consume could be anywhere at any given moment, and in fact the same function may be performed by a different service depending on changing criteria, such as availability or price. The magic of web services is that they are located at addresses to which any computer can connect. The web service's URL is the basis for its universality and network transparency. Universal transparency comes from the ability to use a logical name in the consuming application that the UDDI can than translate into the appropriate URL. If a service that provides fault location function is wanted, the logically named "FaultLocation" can be invoked thereby allowing the UDDI to resolve the name into a URL. Thus, if the location of a service changes, the application can still resolve to new URL location of required web service. This is the key to achieving the agility that web service technology promises [71].

3.4 Thin Client Computing

A thin client network is a server based network where the majority of the processing is done by the server rather than by the individual client machine(s) [72]. Software applications and programs are held and run on the server, and displayed on the client machine.

There are several solutions of thin client computing such as:

- Independent computing architecture (ICA) is a general-purpose distributed presentation protocol for Microsoft windows applications [73]. It was designed to provide a display export with emphasis on minimizing network traffic. ICA is the physical line protocol used to communicate between client and application server.

- Remote desktop protocol (RDP) [72] is a proprietary protocol developed by Microsoft. It is based on the T.120 protocol family standards. RDP supports virtual channels and can therefore be extended to support new data types in the same way as ICA. RDP supports various mechanisms to reduce the amount of data transmitted over the network connection. In terms of supported features, protocol efficiency and client platform support, RDP and ICA are very close. However, RDP is limited to Windows platforms whereas ICA runs on UNIX platforms as well.

- Tarantella (AIP) [74] allows clients to connect to server-based Windows (RDP), Web (HTTP), UNIX (telnet, SSH), Mainframe (3270) and AS/400(5250) applications. The main task of Tarantella is to manage users and applications centrally, provide for security, session management and load balancing and integrate protocol support into a single Java client. Tarantella uses adaptive internet protocol (AIP) which is socket-based and can be tunnelled over HTTP.

- Virtual network computing (VNC). The technology underlying VNC is a simple remote protocol with the concept of a remote frame buffer [75]. VNC protocol is totally independent of operating system, windowing system and application.

3.5 Impact of the IEC-61850 Standard on Disturbance Recording

Standardization contributes significantly to building an intelligent future power system grid. A recently adopted standard for the communication networks and systems in substations (IEC 61850) defines a large data model of the substation domain and a set of services that operate on that data [7]. The IEC 61850 standard accompanying service oriented architecture and web services technology make it possible to build an open, flexible and scalable infrastructure for information integration. Figure 3-6 presents IEC 61850 according to the open systems interconnection (OSI) layer.

NOTE:
This figure is included on page 41 of the print copy of the thesis held in the University of Adelaide Library.

Figure 3-6. IEC 61850 according to OSI layer [7]

It is stated in IEC61850-5 [7] that the functions of a substation automation system (SAS) are to control, monitor and protect the equipment of substation and its feeders. All power system equipment and switchgear within substations are logically allocated onto the three different levels of architecture based on their functionality: station, bay/unit and process. The station level is responsible for collecting all the information within a substation for further application such as SCADA and energy management system (EMS), etc. It receives data either from the bay level or from a remote control centre via communication interfaces. The bay level mainly uses the data of one bay and acts on the primary equipment within it. The typical equipment at the bay level is the protective relays which are known as IEDs in IEC 61850. The process level functions are all functions interfacing the high voltage equipment and the protection and control devices. It obtains data from the process units, such as the current transformer (CT), the voltage transformer (VT) and the circuit breaker (CB) and delivers the data to the bay level.

Unlike other SCADA protocols that present data as a list of addresses or indices, IEC 61850 presents data with descriptors in a composite notation made up of components. Table 3-1 shows how the A-phase current expressed MMXUAphsA$cVal is broken down into its component parts.

Table 3-1. Example IEC 61850 descriptor components [7]

NOTE:
This table is included on page 42 of the print copy of the thesis held in the University of Adelaide Library.

The standardization expands over the information modelling of the target system and the communication protocol for communicating the data encapsulated in the information model. IEC 61850 defines several information models and information exchange approaches for events within substations.

3.5.1 Information Models of IEC 61850 for Disturbance Recording

The IEC 61850 standard focuses on the information models or what to exchange, and information exchange or how to exchange. The main feature of the information model is the logical node (LN). As stated in [76], it is about how 80 LN are defined in IEC 61850-7-4, which is composed of a group of related data objects, such as measurement or a status, and these are contained in the IED.

Figures 3-7 and 3-8 shows the group of logical devices (LD) and logical nodes (LN). Table 3-2 shows the description of logical device in SEL-421 [7].

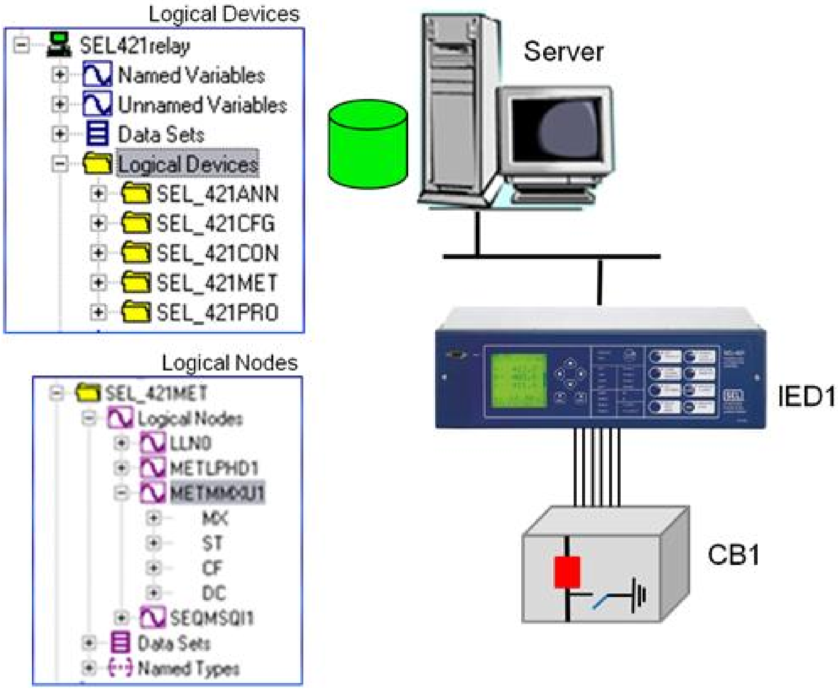


Figure 3-7. Example of logical devices and logical nodes from SEL421 relay

Table 3-2. Example of SEL-421 Logical Devices [7]

NOTE:
This table is included on page 43 of the print copy of the thesis held in the University of Adelaide Library.

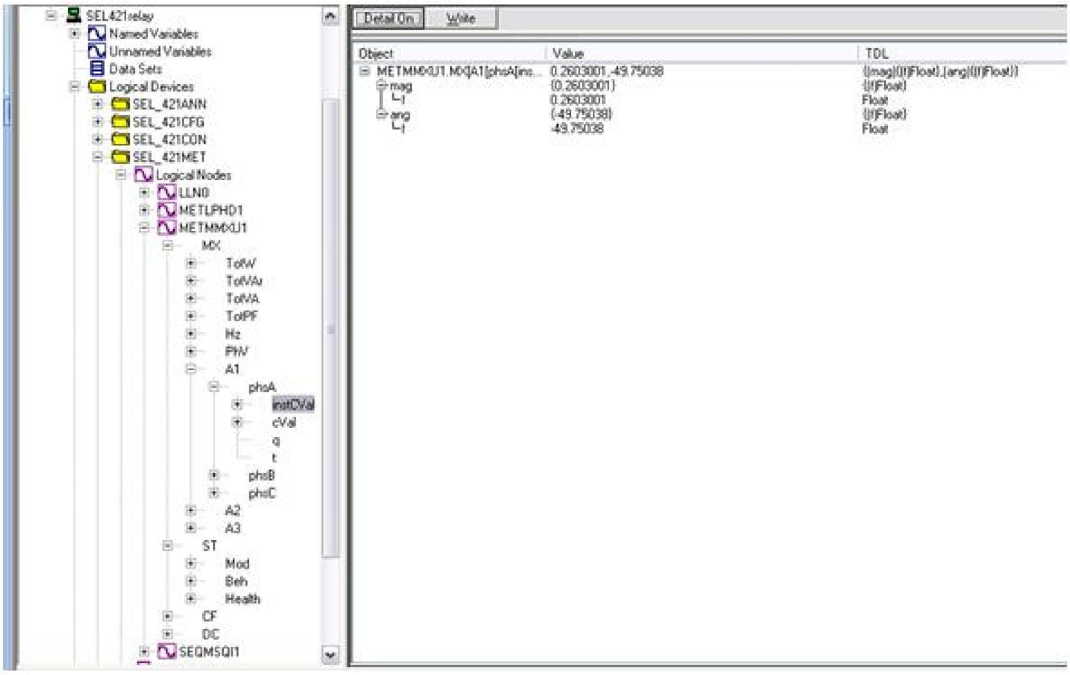


Figure 3-8. SEL-421 relay logical nodes

To design a fault analysis function that complies with the IEC 61850, a logical node that should be considered is a recording unit of the RDRE type. The disturbance records should be in COMTRADE format [13]. The RDRE is an acquisition function for voltage and current waveforms from the power process (CTs, VTs), and for position indications of binary inputs. It is also mentioned in the standard that a calculated value, such as power and calculated binary signals, may also be recorded by this function if applicable. Figure 3-9 presents logical nodes for disturbance recording.

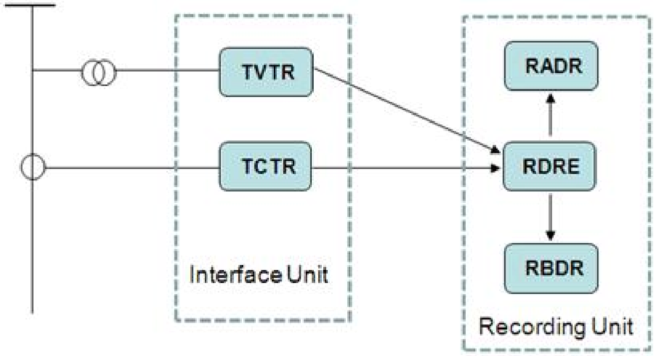


Figure 3-9. Logical Nodes for Disturbance record

Furthermore, the modelling of logical node for disturbance recording as defined in IEC61850-7-4 is composed of three functions: RDRE (basic functionality), RADR (analog channel) and RBDR (binary channel). It is mentioned in that standard that for consistent modelling, the disturbance recorder function described as a requirement in IEC 61850-5 is decomposed into one LN class for analogue channels (RADR) and another LN class for binary channels (RBDR). The output will refer to the IEEE standard format for transient data exchange (COMTRADE) for power systems (IEC 60255-24). Disturbance records are logical devices built up with one instance of LN RADR or LN RBDR per channel. However, since the content of logical devices (LD) is not standardized, other LNs may be inside the LD "disturbance recorder" if applicable. In addition to the channel number, all attributes needed for the COMTRADE file are provided either by data from the TVTR or TCTR or by attributes of the measured value (samples subscribed from TVTR or TCTR) itself.

3.5.2 Information Exchange Model

IEC 61850 describes the information exchange model which is implemented on the server enabling the client's system to access and modify data in the information model. The basic services that are used to mediate between the outside world and the real IED device are referred to as an abstract communication service interface (ACSI). The basic process of these services is described in detail in IEC 61850-7-1 and IEC 61850-7-2. The ACSI communication method is depicted in Figure 3-10.

NOTE:
This figure is included on page 46 of the print copy of the thesis held in the University of Adelaide Library.

Figure 3-10. ACSI communication method [7]

3.5.3 Mapping to Communication profile

The services defined in the information exchange model are mapped to standard web services. A detailed description of each service is provided together with the corresponding web service definition language (WSDL) describing the exact structure of the service methods. Each service defined for the various data models is mapped to simple object access protocol (SOAP) services making it possible to transfer data with the correct types and structure defined in the information exchange model.

3.6 Ole for Process Control (OPC)

Object linking and embedding (OLE) for process control (OPC) is one of the most common ways to exchange data between applications connected to real time systems from different vendors. OPC is widely used because its open standards support open connectivity. OPC technology is based on Microsoft COM/DCOM, which is a published protocol that links software applications [77]. These software applications include protocol drivers, databases and programmable logic. It is also suited for distributed and centralized monitoring, control and SCADA systems. Several advantages of OPC are mentioned in [77] such as flexibility in implementation and ease of implementation and configuration. OPC provides the means of transporting field data to computing systems through various communication infrastructures via an Ethernet local area network (LAN) or wide area network (WAN).

The OPC foundation promotes interoperability through the creation and maintenance of an open-standard specification and by adapting and creating standards to meet evolving industry need. Currently, there are eleven OPC standards existing or under development [78]:

- OPC .NET 3.0 (WCF)

OPC .NET 3.0 (WCF) is the result of collaboration among several OPC vendor companies to provide a simple .NET interface for OPC classic servers. It was developed to allow client applications to easily use the latest .NET features to access existing OPC classic servers. Windows communication foundation (WCF) is the .NET replacement for DCOM. WCF provides a framework for building service-oriented applications, decoupling the service interface from the underlying protocol. As a result, the methods of the server oriented application can be configured to use named pipes, TCP, HTTP, and HTTPs at the same time without any changes to the application code.

- OPC unified architecture (UA)

OPC UA is a new set of specifications that are not based on Microsoft COM that will provide standards based cross-platform capability.

- OPC XML-DA

OPC XML-DA provides flexible, consistent rules and formats for exposing plant floor data using extensible mark-up language (XML), leveraging the work done by Microsoft and others on XML SOAP and web Services.

- OPC data access

OPC data access moves real-time data from PLCs, digital control systems (DCSs), and other control devices to HMIs and other displays clients.

- OPC complex data

OPC complex data allow servers to expose and describe more complicated data types such as binary structures and XML documents. This standard specifies a companion specification to data access and XML-DA.

- OPC alarms and events

OPC alarms and events provide alarm and event notifications on demand (in contrast to the continuous data flow of OPC data access). These notifications include process alarms, operator actions, informational message, and tracking/auditing messages.

- OPC batch

OPC batch carries the OPC technology to the specialized needs of batch processes. This standard specifies interfaces for exchanging equipment capabilities (corresponding to the S88.01 Physical model) and present operating conditions.

- OPC data exchange

OPC data exchange transports data from client/server-to-server with communication across Ethernet networks. This standard provides multivendor interoperability, remote configuration, and diagnostic and monitoring/management services.

- OPC historical data access

OPC historical data access provides access to data that is already stored (in contrast to OPC data access, which provides access to real-time, continually changing data). From a simple serial data logging system to a complex SCADA system, historical archives can be retrieved in a uniform manner.

- OPC security

OPC security specifies client control access to plant process servers in order to protect this sensitive information and to guard against unauthorized modification of process parameters. All the OPC servers provide information that is valuable to the enterprise and, if improperly updated, could have significant consequences for plant processes.

- OPC commands

OPC commands specifies a new set of interfaces that allow OPC clients and servers to identify, send, and monitor device control commands.

3.7 Manufacturing Message Specification (MMS)

Manufacturing message specification (MMS) is an internationally standardized messaging system for exchanging real time data and supervisory control between networked devices and/or computer applications [79]. It is designed to provide a generic messaging system for communication between heterogeneous industrial devices. In theory, it is possible to map IEC 61850 to any protocol. However, it can be quite complicated to map objects and services to a protocol that only provides access to simple data points via registers or index numbers. MMS supports complex named objects and flexible services that enable mapping to IEC 61850 [77].

3.8 Chapter Summary

The available technologies to support automated fault analysis have been presented in this chapter. The concept of application service provider technologies including the key components of ASP such as thin client and web services has been overviewed. IEC-61850 as a new substation communication solution for automated fault analysis in power systems has been presented. In this chapter, the IEC-61850 is more focussed on the information model for disturbance recording and service oriented solutions. The technologies that support implementation of IEC-61850 in substations, such as OPC and MMS, have been overviewed. The applications service provider model for automated fault analysis has been discussed. Detailed information regarding the development of automated fault analysis service will be explained in the next chapter.

Chapter 4: Automated Fault and Disturbance Analysis Service (AFAS)

4.1 Introduction

This chapter describes the development of web services for automated fault and disturbance analysis (AFAS). The signal processing methods for automated fault and disturbance analysis are presented. Wavelet transform and empirical mode decomposition (EMD) are the methods chosen in dealing with the signal segmentation process. The segmentation is important for deciding the fault states, such as pre-fault, fault and after circuit breaker reclosing. Then the signal modelling service, which analyzes each of the individual segments, is discussed. Also discussed are the fault type classification and fault location services. Furthermore, the implementation of AFAS is presented in this chapter.

4.2 AFAS System Overview

As indicated in Figure 4-1 the traditional approach would be manual analysis, but the proposed new approach of fault analysis would be through automatic or semi-automatic use of the fault investigation services provided through an ASP. The ASP based fault and disturbance investigation is a solution that will speed up the investigation process in order to find out the root cause of faults and disturbances and to provide a report to control centre personnel in a timely manner. One of the advantages of fault investigation via the ASP is to ensure a more consistent analysis of faults and disturbances. In an organisation, when several engineers with different experience are investigating events it is very likely that different standards and tools are being used. As a result it is possible to have very different disturbance reports and even false conclusions. This situation can clearly be prevented if all investigative engineers follow the same procedure and use the same services that are organised and provided via ASP.

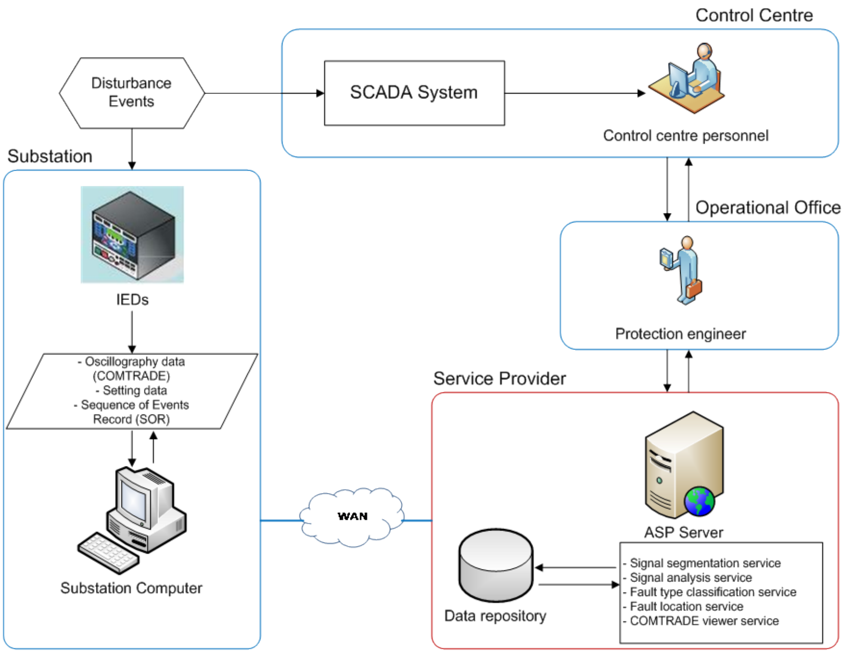


Figure 4-1. Fault analysis scenario

An example of the disturbance investigation process is presented in Figure 4-2. The analysis goes through a number of hypotheses which are tested using the services provided in the ASP. In Figure 4-2 we show only a few possible hypotheses to illustrate how this process is organized. The whole investigation can be automated using an expert system technology. The output of the automated system will be the final report. However we believe that for many complex cases, investigation will be performed step-by-step following the process shown in Figure 4-2 in a semi-automatic way, using the services to complete tasks in each step. The services currently implemented and tested in the ASP demonstration system are discussed in this chapter.

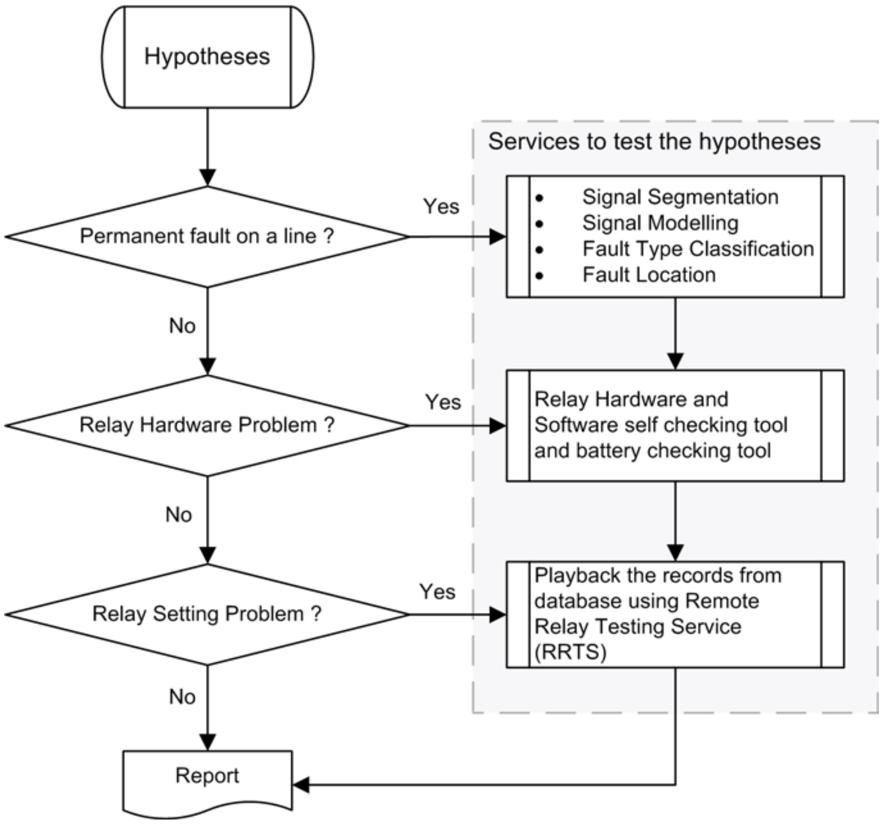


Figure 4-2. An example of the investigation procedure and required services

The AFAS model via ASP has a 3-tier architecture. The bottom tier is the data storage tier, which is optionally implemented either as DBMS (for easy data management) or as a custom file system (to achieve efficiency). The middle tier is a query processing module comprising a set of web-services developed in the C# and Microsoft .NET framework. Finally, the top tier consists of a web-accessible graphical user interface (GUI) implemented in PHP hypertext pre-processor (PHP).

The system architecture for automated fault analysis via the ASP model is depicted in Figure 4-3. In this model, the fault analysis application will collect the disturbance data from the IEDs in a substation via OPC. In order to collect these data, the AFAS server is designed to comply with IEC-61850 by considering the information model, information exchange and mapping to communication profile. The AFAS server is integrated with the OPC server that supports IEC 61850. In this study, a Matrikon OPC server for IEC 61850 [80] and AX4-MMS OPC server [81] are deployed to deal with data retrieval from IEDs in a remote location from the AFAS server. Figures 4-4 and 4-5 display an example of the interface of the Matrikon OPC server with the IEC 61850 and AX4-MMS OPC servers respectively. From these figures we can see how the values of logical devices (LD) and logical nodes (LN) from the SEL 421 relay in the remote area can be explored. To display the data in the web interface, the web client for IEC 61850 explorer is developed in this project. The goal of this web client development is to get the real-time data including LD and LN from remote IEDs via the web browser without having to install the software in the client computer. The development of the web client for the IEC 61850 explorer is implemented using PHP hypertext pre-processors (PHP) [82], jQuery [83] and the library from OPC labs [84]. Furthermore, the real time data from IEDs also can be recorded into a MySQL database [85] by utilising the OPC data logger [86]. Figure 4-6 shows an example of interface of the web client for IEC 61850 explorer.

The AFAS server also provides several services for the analysis function, such as signal segmentation, signal modelling, fault type classification and fault location. These services are useful in helping the protection engineer work faster during the investigation of fault event than would conventional analysis because the AFAS will send the report automatically when there is a fault event in the substation. One of the advantages of the AFAS application is that it does not use a big bandwidth to transfer the huge disturbance data to the control centre because only the analysis report will be sent to the control centre. Thus the control centre personnel can make a quick decision whether to reclose the line or not if there is a fault on the transmission line.

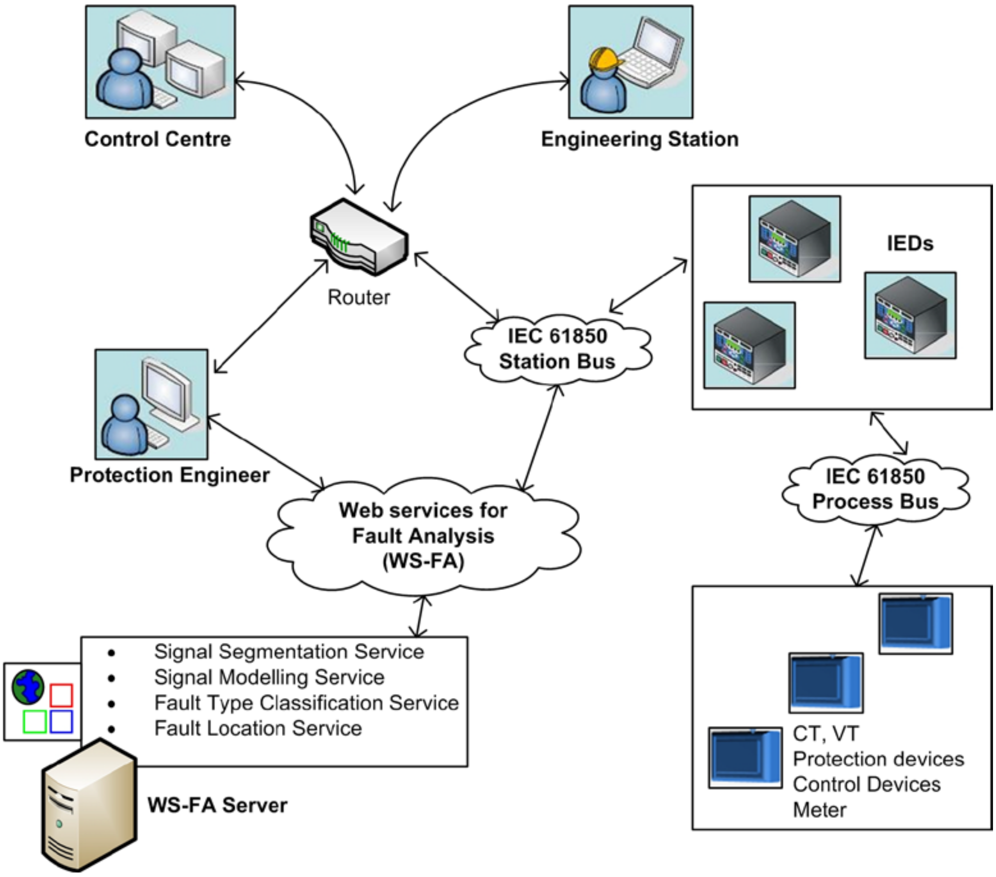


Figure 4-3. Architecture of AFAS model complying with IEC 61850

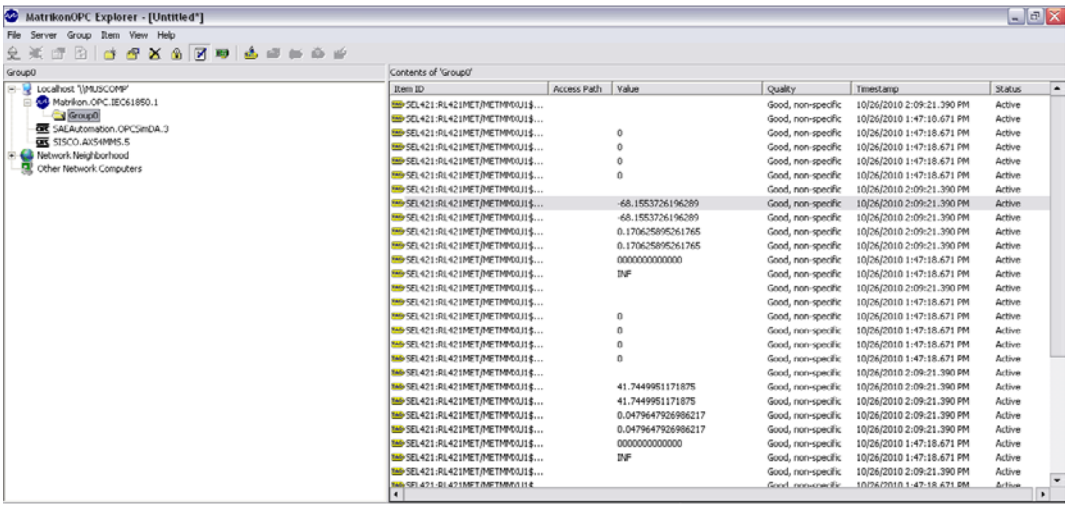


Figure 4-4. Matrikon OPC server for IEC61850

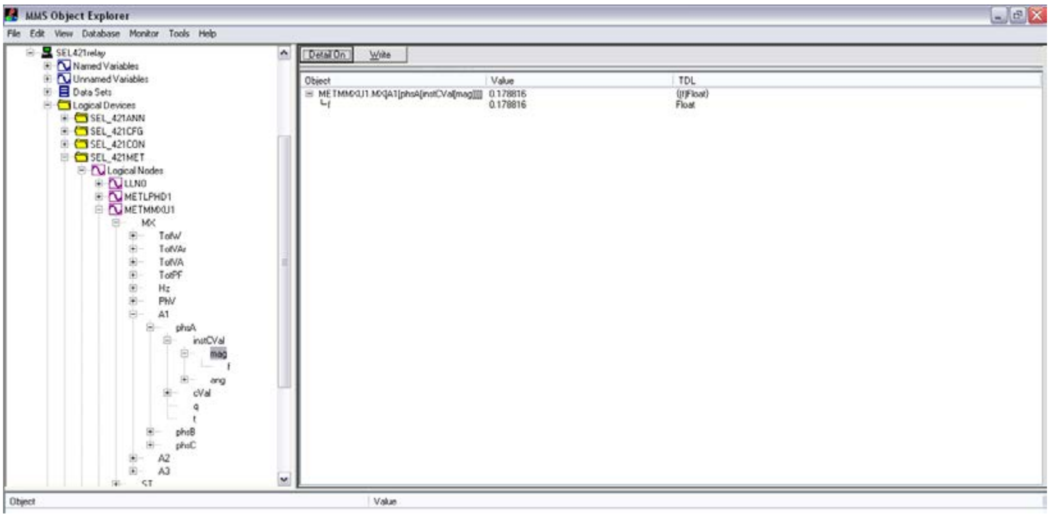


Figure 4-5. AX4-MMS OPC server

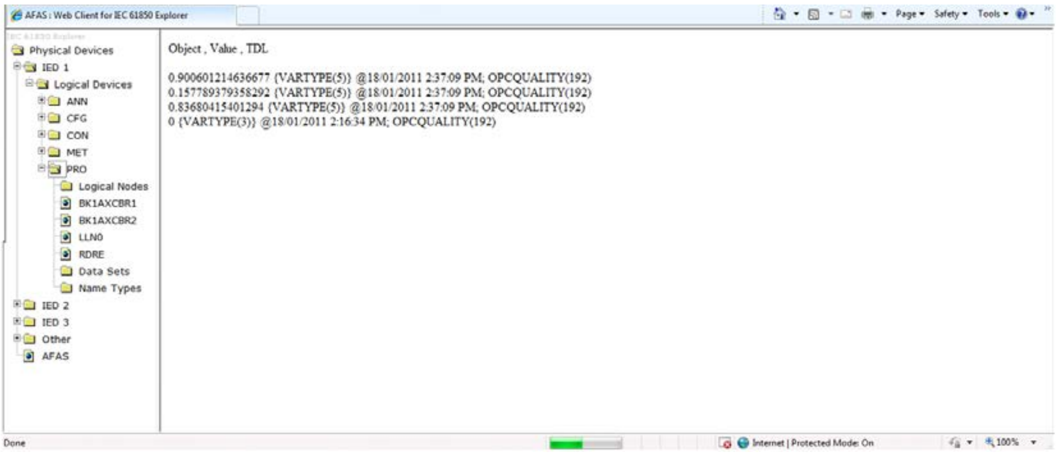


Figure 4-6. Web client for IEC 61850 explorer

4.3 Signal Segmentation Service

In order to enhance the segmentation process, this study dealt with two methods of analysing the fault and disturbance data, namely wavelet transform and empirical mode decomposition (EMD). The concept and a brief mathematical summary of both wavelet and EMD are discussed in the Appendix A.

The wavelet transform method is used to decompose the original fault signal into finer wavelet scales, followed by a progressive search for the largest wavelet coefficients on that scale. Large wavelet coefficients that are collocated in time across different scales provide estimates of the charges in the signal parameter. The change of segmentation time can be estimated by the time-segments when the wavelet coefficients exceed the first-order approximation of the threshold [87]. The mathematical descriptions of the wavelet transform can be found from the references [88 - 91].

In this project, *Daubechies* 1 (*db1*) and 4 (*db4*) wavelets were selected as mother wavelets instead of other choices because they are compactly supported wavelets with an external phase and the highest number of vanishing moments for a given support width [92].

The abrupt change detection algorithm has been developed using a wavelet signal decomposition technique and quadrature mirror filter banks [23]. The technique decomposes recorded signals into smoothed and detailed (localized) components represented by wavelet coefficients. The abrupt change time segments can be estimated by the instants when the wavelet coefficients exceed a given threshold. The signal segmentation algorithm using wavelet method can be seen in Figure 4-7.

Wavelet transform was used to decompose the analogue signals into the wavelet coefficients. Figure 4-8 shows the original disturbance signal and its wavelet coefficients where *db4* is chosen as a mother wavelet. The threshold method is then used to check whether the wavelet coefficient exceeds the first order approximation. When the wavelet coefficients of the faulted signal exceeds the threshold, the time segmentation will display the number 1 as an indicator in the AFAS database, and if the wavelet coefficient is under the threshold, then it will display the indicator as 0. If the time segment (TimeSeg) value is equal to one, it means that that there is an abrupt change in the specific signal.

Figure 4-9 shows a picture of an AFAS database in MySQL where the indicator of TimeSeg value is equal to one. As can be seen from Figure 4-9, the abrupt change happened when the sample numbers are equal to 674, 822 and 3618. The information from the database then can be plotted together with the waveform in the web-based COMTRADE viewer. The resulting segmented phase current signal using the wavelet method can be seen in Figure 4-10.

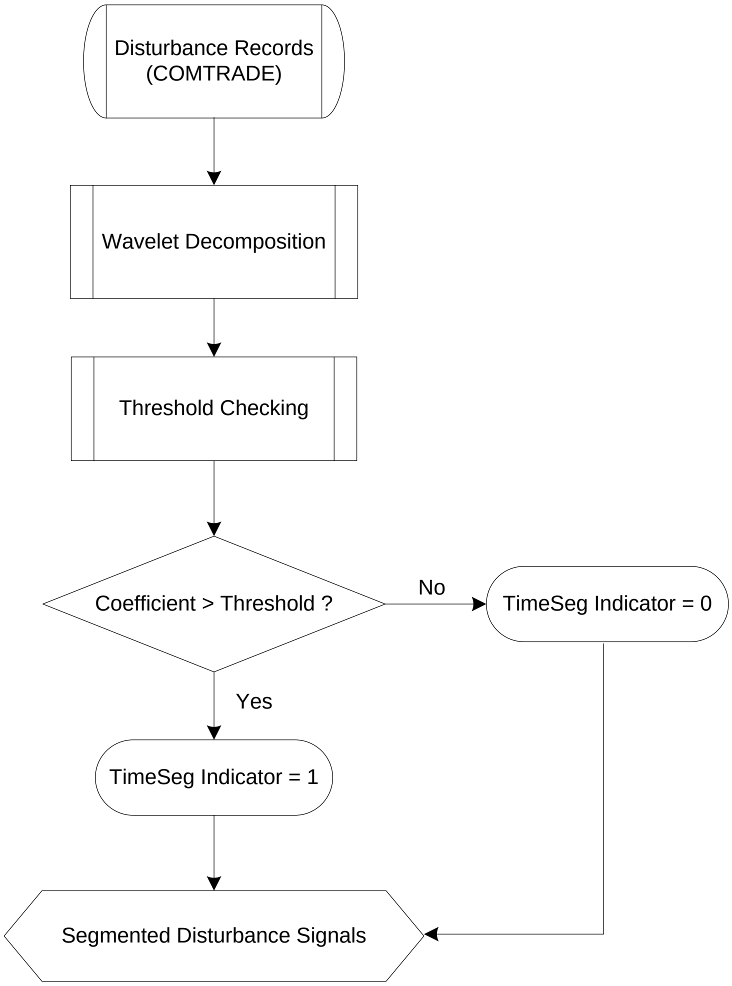


Figure 4-7. Signal segmentation algorithm using wavelet

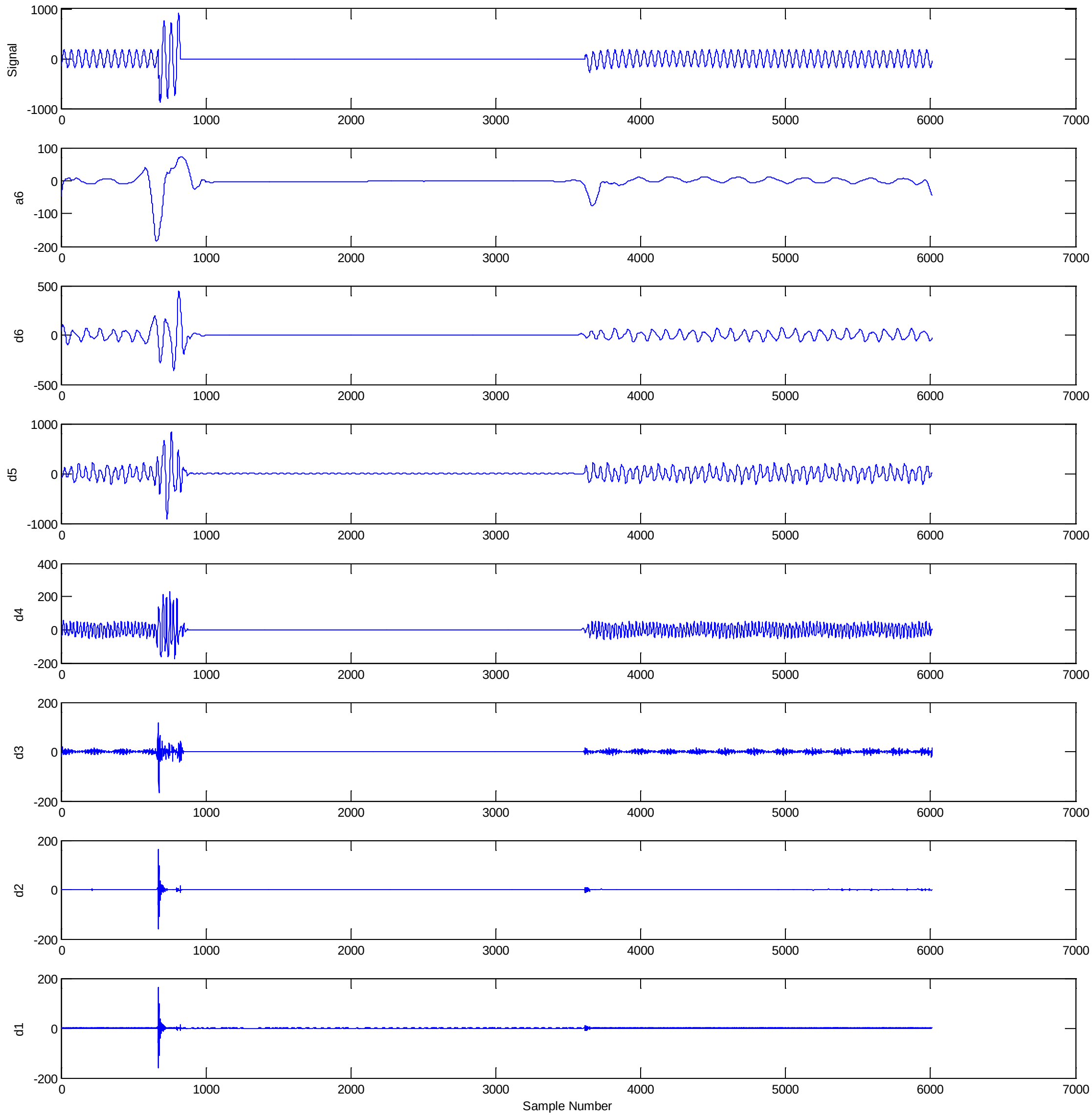


Figure 4-8. Signal decomposition using wavelet method with *db4* as a mother wavelet, the original Blue phase current and its approximation coefficient (*a6*) and detail coefficients (*d1* to *d6*), signals recorded at Delphi substation on 11/01/2002.

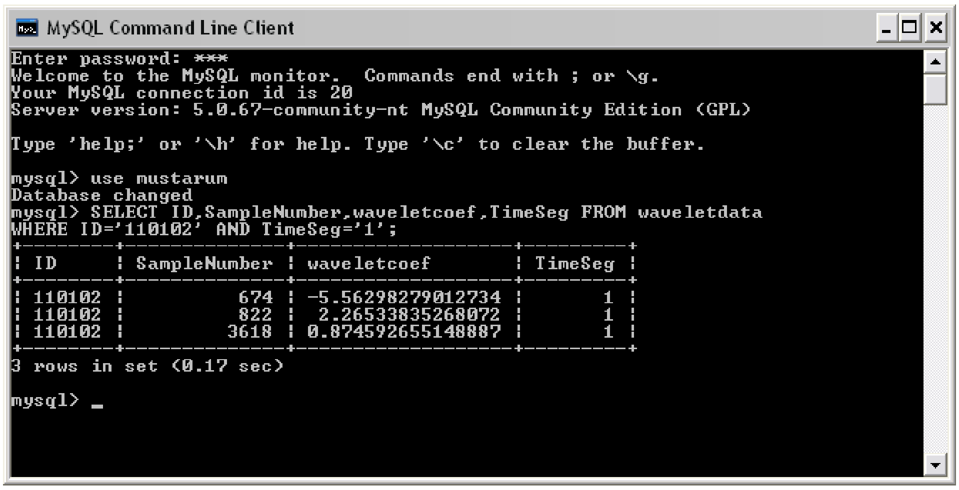


Figure 4-9. AFAS database (table: waveletdata)

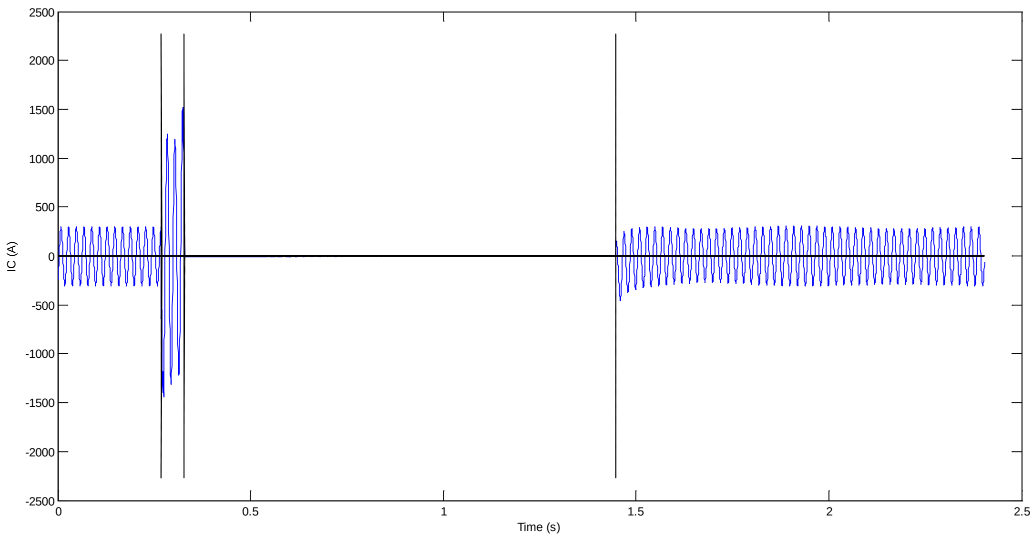


Figure 4-10. The segmented disturbance signal (Ic) using wavelet method (signals recorded at Delphi substation on 11/01/2002)

In contrast to conventional decomposition methods such as wavelets, which perform the analysis by projecting basis vectors, EMD expresses the signal as an expansion of basic functions that are signal-dependent and are estimated via an iterative procedure called shifting [93]. The signal segmentation algorithm using empirical mode decomposition method can be seen in Figure 4-11. The process of signal segmentation using the EMD method is as follows:

1. Read disturbance records in COMTRADE (configuration (*.cfg) and data (*.dat) files.
2. Identify all extremes of the original signal *x(t)* of each phase (I_a, I_b, I_c, V_a, V_b, V_c).
3. Interpolate between minima, ending up with some envelope of x(t) and compute the mean value *m(t)*

$$m(t) = \frac{e_{up} + e_{low}}{2} \qquad (4.1)$$

4. Calculate the detail of *d(t) = x(t) – m(t).*
5. *d(t)* is seen as a new value of *x(t)* so repeat step 3, the result is a new *d(t)*
6. Calculate the standard deviation from the two consecutive sifting results as

$$SD = \frac{[d_{k-1}(t) - d_k(t)]^2}{d_{k-1}^2(t)} \qquad (4.2)$$

7. If the value of *SD* is less than the threshold then extract an IMF component, otherwise repeat step 3 and 4.
8. Calculate residual *r(t) = xt – IMF(t).*

9. $r(t)$ is seen as new $x(t)$ so repeat step 7, the result is a new $r(t)$.

10. Calculate the standard deviation from the two consecutive sifting results.

11. If the result is less than threshold then the second IMF is obtained, otherwise repeat step 7 and 8.

12. Repeat step 7 to step 10, determining all IMF components. Residual is a monotonic function from which no more IMF can be extracted.

13. Apply the Hilbert transform to the decomposed IMF and construct the time-frequency-energy distribution, which is designated as the Hilbert spectrum, from which the time localities of events will be preserved.

14. Apply the threshold checking by comparing the change of energy with the threshold, if the coefficient is more than the threshold then produce pulsation signal. This is indicated by the value of TimeSeg indicator being equal to one or zero. When the TimeSeg is equal to one, it means that there is an abrupt change in the signal.

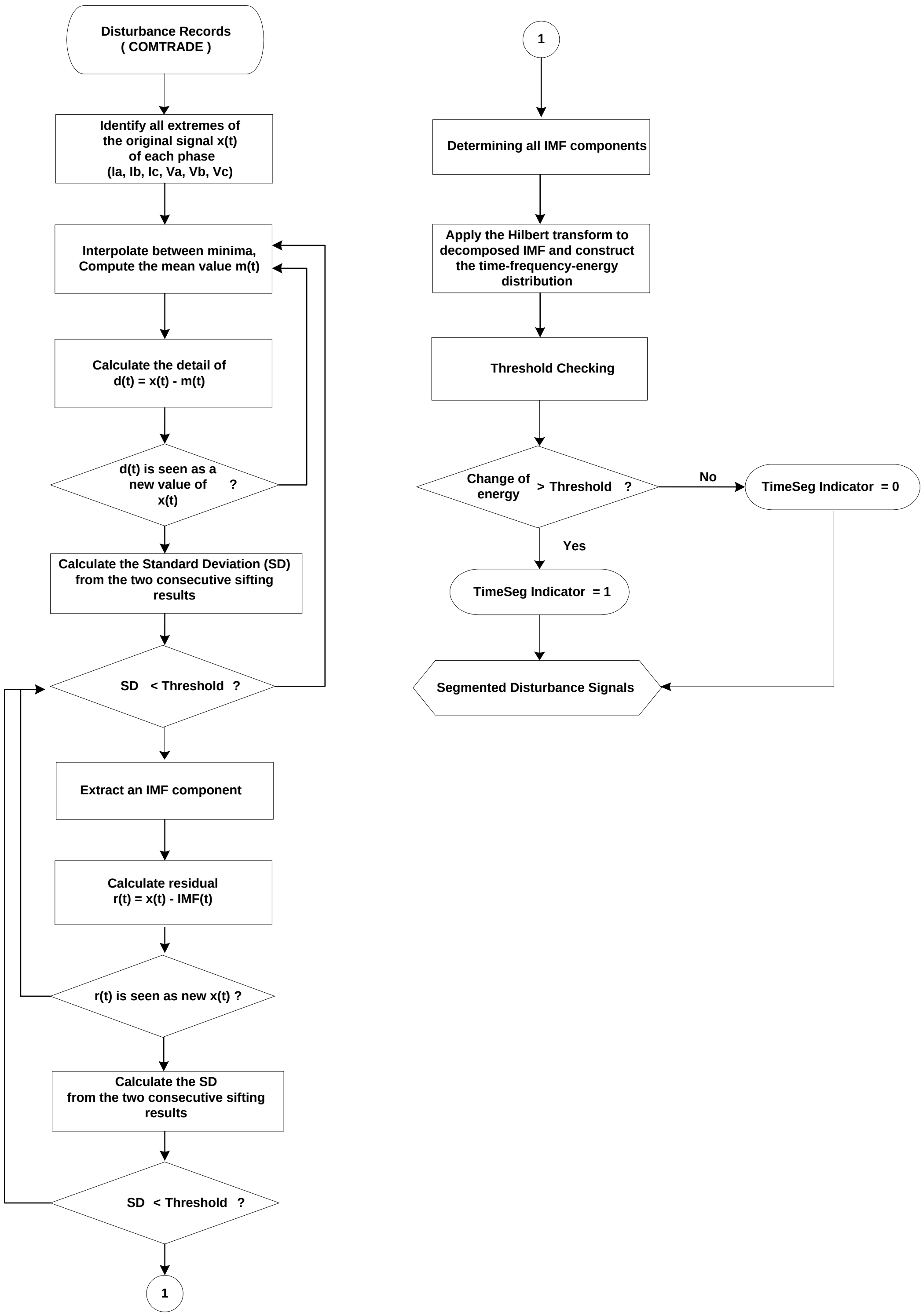


Figure 4-11. Signal segmentation algorithm using EMD

Figure 4-12 shows an example of signal decomposition using the EMD method. As can be seen from the picture, the original signal is decomposed into several IMFs (*d1* to *d11*). The *d1* and *d11* is the highest and the lowest frequency of IMF respectively. In this signal example, sample frequency (Fs) is 2.5 KHz and data length (L) is 6010. The instantaneous amplitude (IA) corresponding to each of IMF can be seen in Figure 4-13. Figure 4-14 shows the Hilbert spectrum of *d1*-*d11* IMFs. Furthermore, the segmented disturbance signal using the EMD method can be seen in Figure 4-15. Based on the experiment with several disturbance signals from power utilities and the power system simulation model, the signal segmentation service using the EMD method was found to perform with a good level of accuracy in response to the abrupt change in the disturbance records.

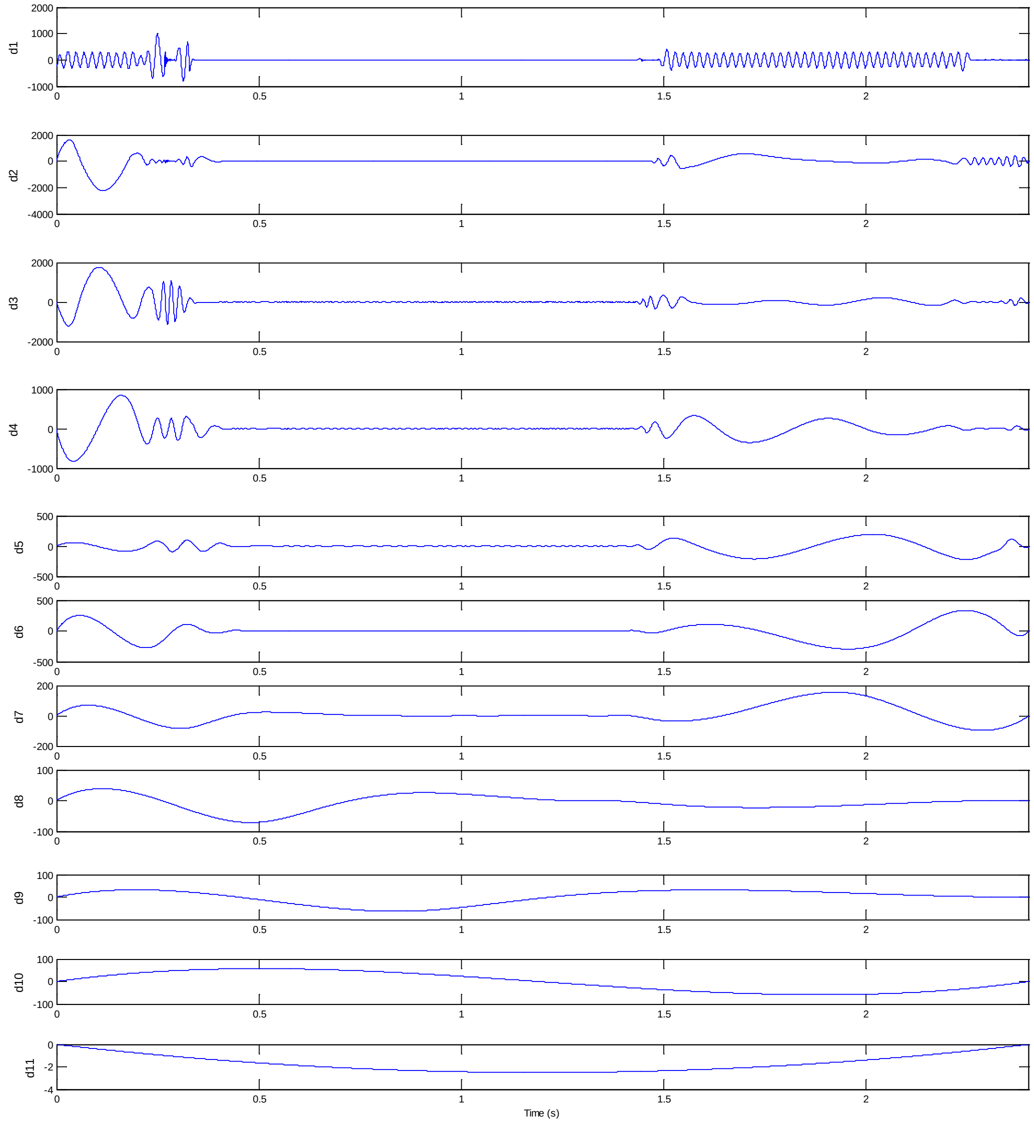


Figure 4-12. IMF components of Blue phase current in the single-phase-to-ground fault, signals recorded at Delphi substation on 11/01/2002.

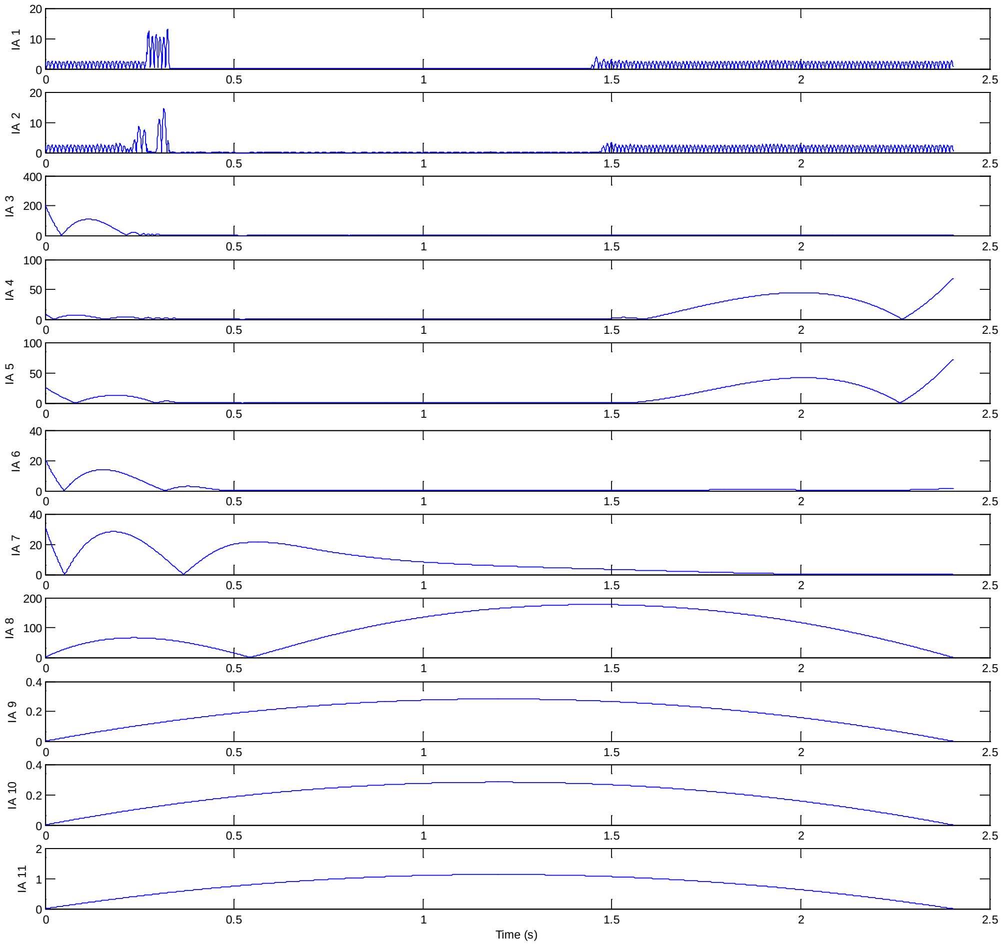


Figure 4-13. Instantaneous Amplitude (IA) corresponding to each IMF

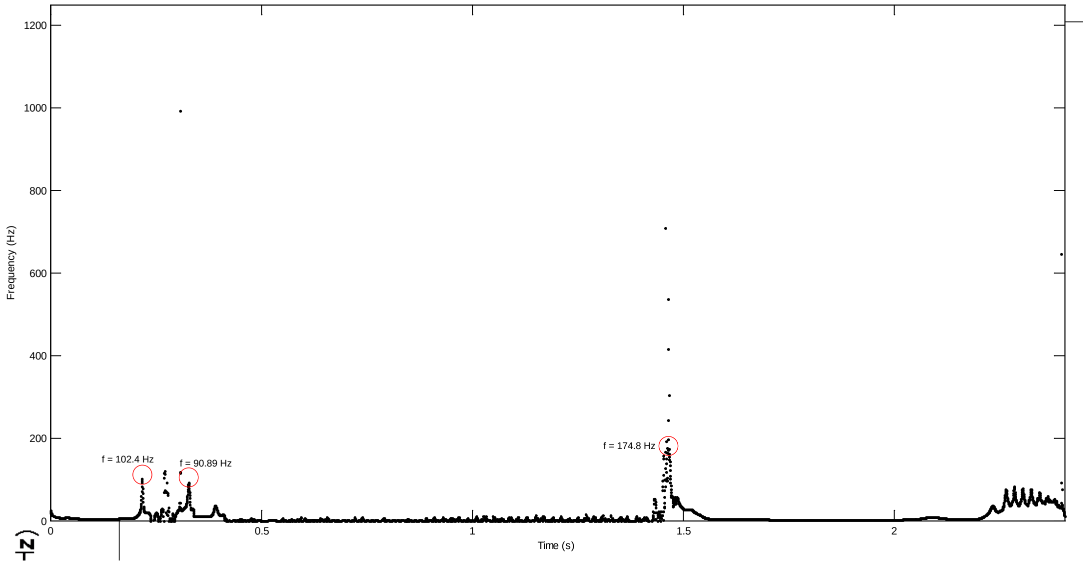


Figure 4-14. Hilbert spectrum of *d1-d11* IMFs

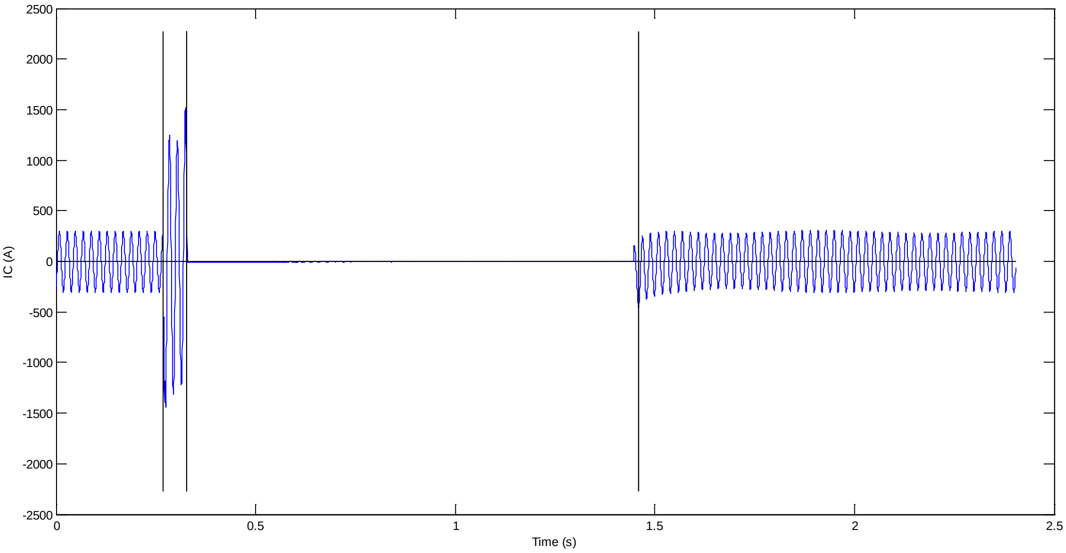


Figure 4-15. The segmented Blue phase current (Ic) using EMD method (signals recorded at Delphi substation on 11/01/2002)

4.4 Signal Modelling Service

After the segmentation step, we need to analyse all stationary signals linked to individual segments. This analysis will determine the parameters for all frequency components contained in each stationary signal. For each segment we apply fast fourier transform (FFT) to find the frequency components [94]. FFT is used to extract harmonically related voltage and current phasor magnitudes and angles from the recorded analogue signals. The results of this signal modelling will be used in the process of fault type classification and to calculate fault location.

4.5 Fault Type Classification Service

The purpose of fault type classification is to identify the type of fault that occurred on a transmission line. Is it a phase to ground, phase to phase, phase to phase to ground or a three phase fault? It should also determine which phases are involved in the fault. This service requires the following information about segments in all analogue recorded signals: start and end times for each segment, and fundamental frequency RMS value. This information is provided by signal segmentation and signal analysis services.

The fault type algorithm is applied based on wavelet entropy. The three phase current signals (I_a, I_b and I_c) and the ground current ($I_g = I_a + I_b + I_c$) are inputs to the algorithm. The faulted phases are determined and decomposed using wavelet transform. The signal being transformed at instant k and scale j consists of a high-frequency component coefficient $D_j(k)$ and a low-frequency component coefficient $A_j(k)$. It is stated in [95] that the original signal sequence $s(n)$ can be represented by the sum of all components as:

$$s(n) = D_1(n) + A_1(n) = D_2(n) + D_2(n) + A_2(n) \quad (4.3)$$

$$= \sum_{j=1}^{j} D_j(n) + A_j(n) \quad (4.4)$$

Various wavelet entropy measures were defined in [96]. In this study, the non-normalized Shannon entropy is chosen. The non-normalized Shanon entropy can be defined as [96]:

$$E_j = -\sum_k E_{jk} \log E_{jk} \quad (4.5)$$

where E_{jk} is the wavelet energy spectrum at scale j and instant k and it is defined as:

$$E_{jk} = |D_j(k)|^2 \quad (4.6)$$

The entropies of wavelet coefficients of the four currents (Ia, Ib, Ic and Ig) is calculated, then the sum of absolute entropies of the wavelet coefficients of each current (Sum A, Sum B, Sum C and Sum G) is calculated. To determine the type of fault, if-then-else function for Sum A, Sum B, Sum C and Sum G is applied. After determined the fault type, location of fault can be calculated. Figure 4-16 shows a fault type classification algorithm for automated fault analysis.

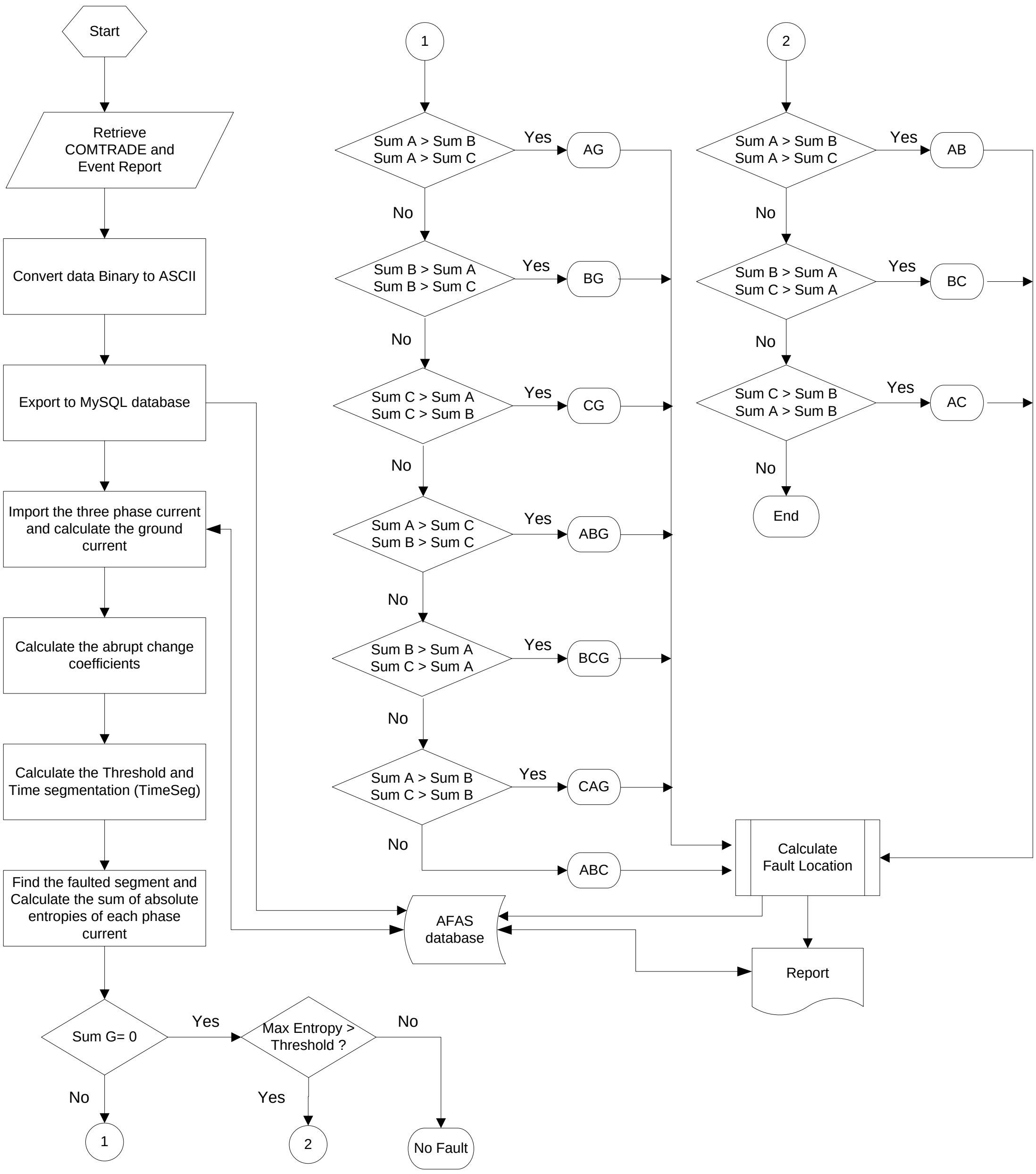


Figure 4-16. Fault type classification algorithm

4.6 Fault Location Service

The purpose of the fault location service is identification of the position of a fault on a transmission line using disturbance records. Accurate information on the fault location will reduce search time and operating cost. Maintenance teams can be sent directly to the site of the fault location, and in this way, the availability of the system will be increased. Based on the review of fault location discussed in section 2.4.3, the fault location algorithm implemented in the current version of this service is based on Simple reactance [29].

4.7 Illustrative Examples of Using Services

This section discusses how the signal segmentation techniques are tested using simulated fault data from PSCAD/EMTDC and from disturbance record obtained from IEDs in the ESKOM transmission network of South Africa and the South Sulawesi transmission system, Indonesia. PSCAD/EMTDC enables the user to schematically construct a circuit, run a simulation, analyse the results, and manage the data in a completely integrated, graphical environment.

4.7.1 Simulated PSCAD Fault Records

To demonstrate the performance of the wavelet and EMD segmentation services, we built the 230 kV transmission line model to generate fault signals. Sampling frequency is 2500 Hz. The total transmission line length is 100 km. Several types of short circuit fault single phase to ground, two phase to ground, phase to phase and balanced three phase faults were simulated in PSCAD/EMTDC. Different fault location and fault resistance values were used in these simulations.

4.7.1.1 Case Study of Single-phase-to-Ground Fault (AG Fault)

Figure 4-17 shows an example of a disturbance signal in the single-line-to-ground fault generated from power systems simulation model. The dashed line in Figure 4-17 indicates the abrupt change detection for segmentation using the EMD method. To test the signal segmentation algorithm between the wavelet and EMD methods, we simulated several cases when the location of the fault varies from 10 to 90%. Table 4-1 presents the signal segmentation estimation time between the wavelet and EMD methods. We found that the time segment start and end from both of the wavelet and EMD methods remains stable for all locations of faults. The time segment start in this case means the time when the algorithm detect the first abrupt change or fault. The time segment end means the time when the algorithm detects the next abrupt change or fault clearing. In the wavelet method, the first abrupt change is detected at 0.1204 second and the second abrupt change is detected at 0.1564 second. The first abrupt change is detected at 0.1208 second and the second abrupt change is detected at 0.154 second in the EMD method. Figure 4-18 shows the comparison of time segmentation using wavelet and EMD Methods in the single-phase-to-ground Fault (AG fault) where the fault resistance (R_F) = 0.001 Ω. It can be seen from Figure 4-18 that the time segmentation start and end using wavelet and EMD methods remains constant for all fault locations.

The time segmentation start using both methods is 0.12 second while for the time segmentation end using both methods is about 0.15 second.

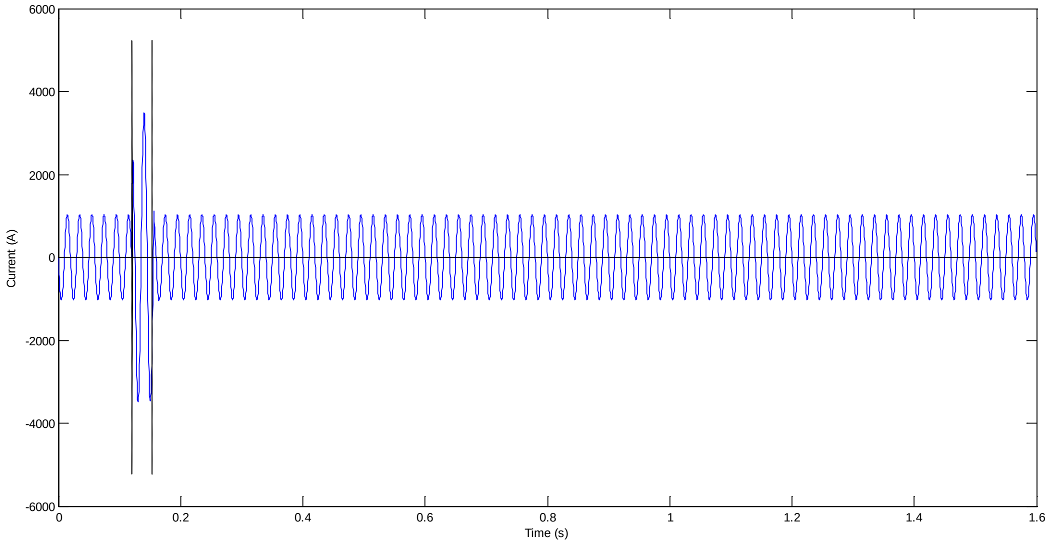


Figure 4-17. Example of segmented signal using EMD Method in the single-phase-to-ground Fault (AG fault) where the fault resistance (R_F) = 0.001 Ω and 20% fault location.

Table 4-1. Segmented signal estimation based on wavelet and EMD when fault resistance (R_F) is 0.001 Ω.

Fault Type	Fault Location (%)	Time Segment using Wavelet (s)		Time Segment using EMD Method (s)	
		Start	End	Start	End
AG	10	0.1204	0.1564	0.1208	0.154
AG	20	0.1204	0.1564	0.1208	0.154
AG	30	0.1204	0.1564	0.1208	0.154
AG	40	0.1204	0.1564	0.1208	0.154
AG	50	0.1204	0.1564	0.1208	0.154
AG	60	0.1204	0.1564	0.1208	0.154
AG	70	0.1204	0.1564	0.1208	0.154
AG	80	0.1204	0.1564	0.1208	0.154
AG	90	0.1204	0.1564	0.1208	0.154

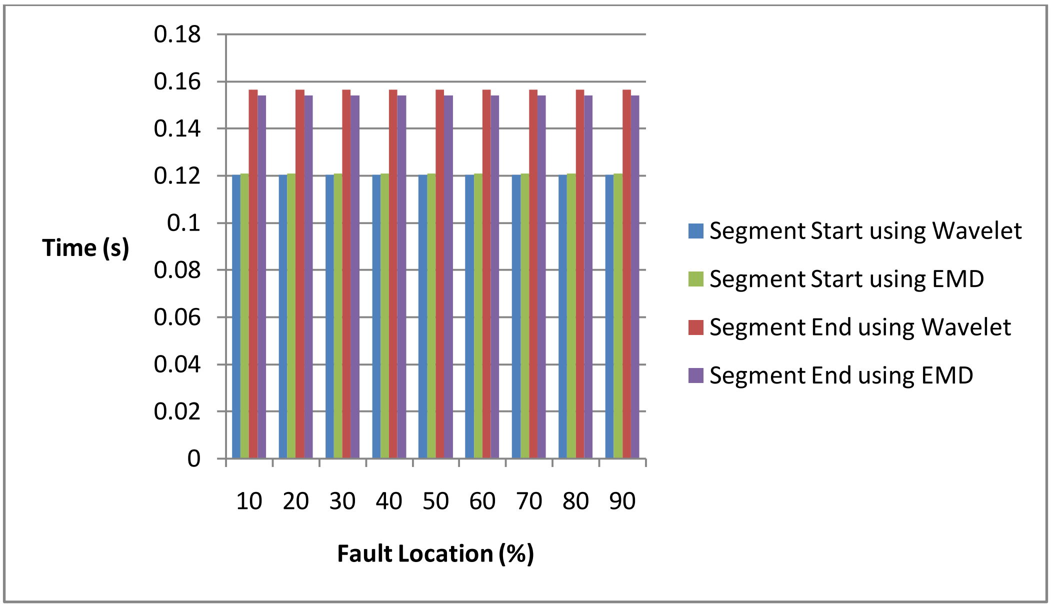


Figure 4-18. Comparison time segment using wavelet and EMD methods in the single-phase-to-ground fault (AG fault) where the fault resistance (R_F) = 0.001 Ω.

4.7.1.2 Case Study of Two-Phase-to-Ground Fault (ABG Fault)

Table 4-2 shows the estimated segmentation time between wavelet and EMD methods in the two-phase-to-ground fault (ABG fault) where the fault resistance (R_F) is 0.001 Ω. To test the performance of signal segmentation algorithm based on wavelet and EMD methods, the power system simulation model was tested by varying the fault location from 20 to 80%. We found that the estimated segmentation time based on the wavelet and EMD method is constant over the change in the fault location as can be seen in Figure 4-19.

Table 4-2. Segmented signal estimation based on wavelet and EMD in the two-phase-to-ground fault (ABG Fault) where fault resistance (R_F) is 0.001 Ω.

Fault Location (%)	Time Segment using Wavelet Method (s)				Time Segment using EMD Method (s)			
	Phase A		Phase B		Phase A		Phase B	
	start	end	start	end	start	end	start	end
20	0.1004	0.1548	0.1004	0.1556	0.1012	0.1532	0.1056	0.1524
40	0.1004	0.1548	0.1004	0.1556	0.1012	0.1532	0.1056	0.1524
60	0.1004	0.1548	0.1004	0.1556	0.1012	0.1532	0.1056	0.1524
80	0.1004	0.1548	0.1004	0.1556	0.1012	0.1532	0.1056	0.1524

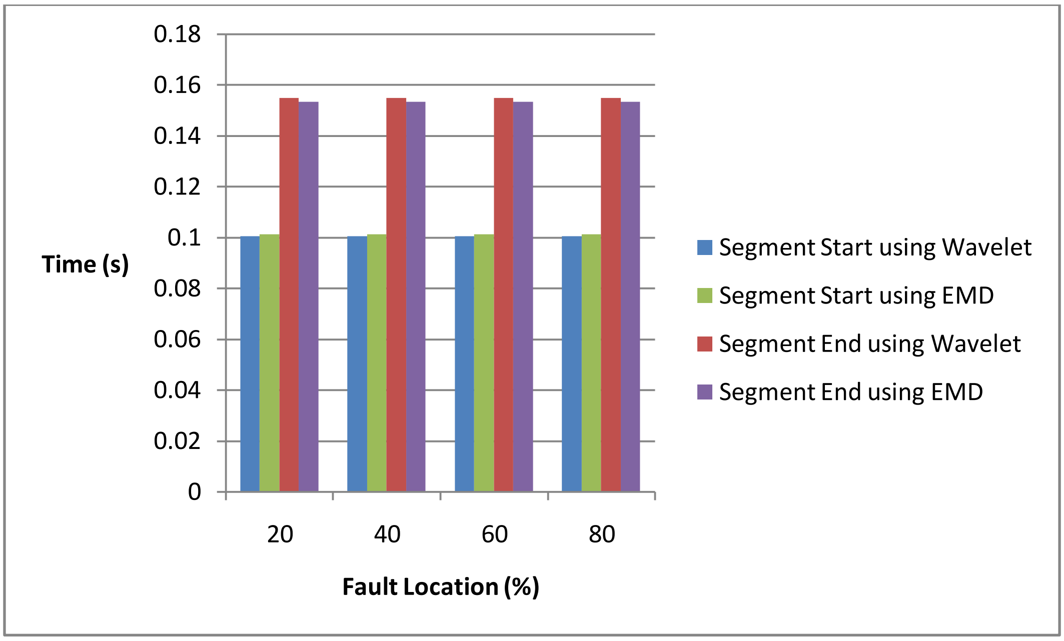


Figure 4-19. Comparison of time segment between wavelet and EMD methods in the phase A for the case of an ABG fault.

4.7.1.3 Case Study Three-Phase Fault (ABC Fault)

Table 4-3 shows the estimated segmentation time between wavelet and EMD methods. The type of fault is a three-phase fault (ABC fault) where the location of the fault used in the simulation is 50 % from Substation B. In this case, various fault resistance (R_F) from 20 to 100 Ω is used in the power system simulation model. We found that the time segment start and end using the Wavelet method remain stable for different R_F in all phases. Figure 4-20 shows the time segment using wavelet and EMD methods for variations in R_F in the three-phase fault where the fault location is 50 %. It can be seen from the chart that although there is a variation in R_F, the time segment using wavelet and EMD methods remains stable.

Table 4-3. Segmentation time of disturbance record using wavelet and EMD methods for variation of fault resistance in the three-phase fault where fault location is 50 %

R_F (Ω)	**Time Segment using Wavelet Method (s)**					
	Phase A		**Phase B**		**Phase C**	
	start	end	start	end	start	end
20	0.1004	0.1564	0.1004	0.1556	0.1004	0.1572
40	0.1004	0.1564	0.1004	0.1556	0.1004	0.1572
60	0.1004	0.1564	0.1004	0.1556	0.1004	0.1572
80	0.1004	0.1564	0.1004	0.1556	0.1004	0.1572
100	0.1004	0.1564	0.1004	0.1556	0.1004	0.1572
R_F (Ω)	**Time Segment using EMD Method (s)**					
	Phase A		**Phase B**		**Phase C**	
	start	end	start	start	end	start
20	0.1012	0.1536	0.1052	0.1516	0.1008	0.1552
40	0.1012	0.1536	0.1052	0.1516	0.1008	0.1552
60	0.1012	0.1536	0.1052	0.1516	0.1008	0.1552
80	0.1012	0.1536	0.1052	0.1516	0.1008	0.1552
100	0.1012	0.1536	0.1052	0.1516	0.1008	0.1552

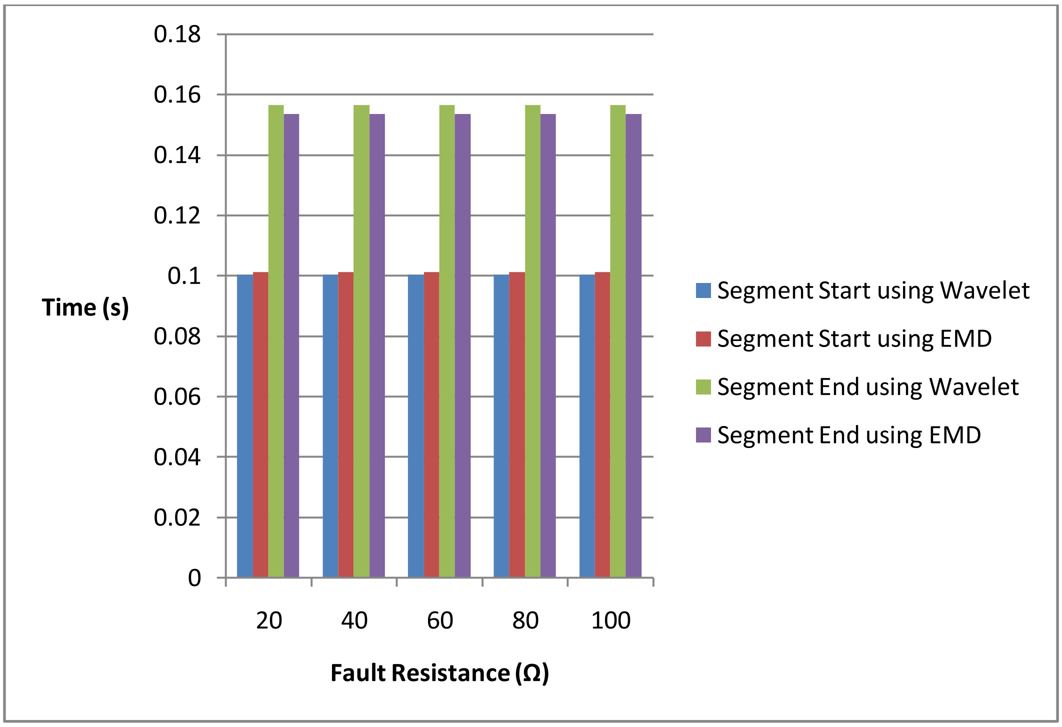


Figure 4-20. Time segment in phase A using wavelet and EMD methods for variations in fault resistance (R_F) in the three-phase fault where the fault location is 50 %.

4.7.2 Real Disturbance Records from Power Utilities

To test the validity of our signal segmentation service, we utilised real disturbance records from two different power utilities: ESKOM South Africa and the Indonesian power utility. Eskom transmission network is 400 kV and South Sulawesi transmission line is about 150 kV.

4.7.2.1 Case study of ESKOM Transmission Network, South Africa

- Case: Cleared Single-Phase Fault

In this case study, an example of disturbance record during single line to ground fault from the Delphi substation South Africa is utilised. The event happened on

11/01/2002 with 2500 Hz frequency sampling and 50 Hz fundamental frequency. Table 4-4 shows the time of the segmented signal based on wavelet and EMD methods in the single phase to ground fault. Figure 4-21 shows the segmented current signal from the Delphi substation. The abrupt change detection in the current signal is indicated by the vertical dashed line as seen in Figure 4-21. The different signal segment caused by different events during the fault is indicated in Figure 4-21. For example, segment A indicates the pre-fault section and the fault inception segment B the fault, while segment C indicates the opening of the circuit-breaker and segment D the auto-reclosing of the circuit breaker and system restoration. Comparison of signal parameter values of segment A and D shows that the fault was successfully cleared. From Table 4-4 we found that the fault duration (segment B) was 0.0592 second for both segmentation service (wavelet and EMD) methods.

Table 4-4. Segmented signal estimation based on wavelet and EMD method in the Blue phase current (I_C) obtained from Delphi substation on 11/01/2002.

Fault Type	**Signal Segmentation using Wavelet Method**			**Signal Segmentation using EMD Method**		
	First time segment (s)	Second time segment (s)	Third time segment (s)	First time segment (s)	Second time segment (s)	Third time segment (s)
CG	0.2692	0.3284	1.447	0.2688	0.328	1.458

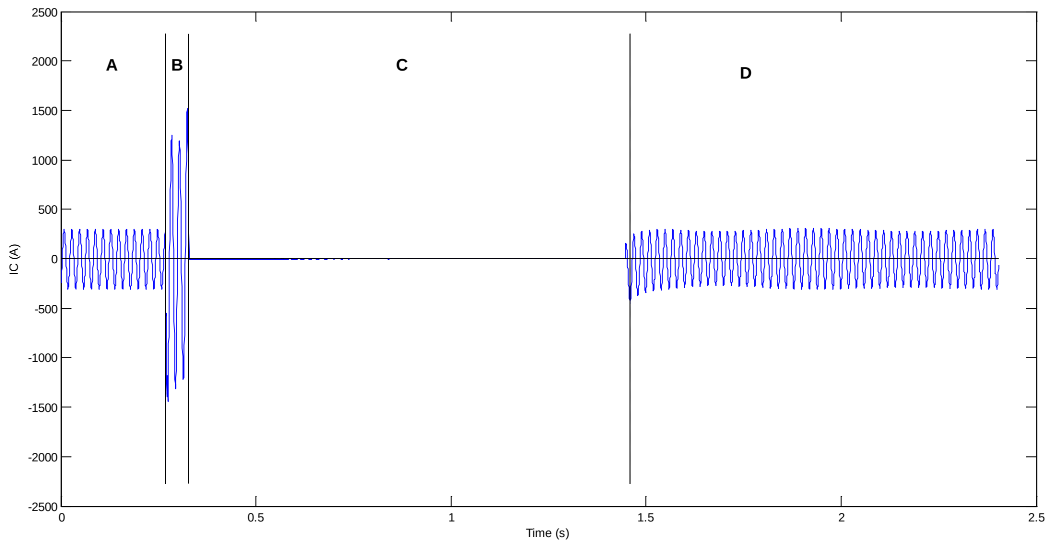


Figure 4-21. The segmented current (I_C) signals in the faulty phase, (signals recorded at Delphi substation on 11/01/2002).

4.7.2.2 Case Study of South Sulawesi Transmission System, Indonesia

- Case: Uncleared Two-Phase-to-Ground Fault

On 16 September 2008 a two-phase-to-ground fault occurred on a 150 kV South Sulawesi transmission line (Bulukumba substation). Table 4-5 presents the segmentation time of the disturbance record using wavelet and EMD methods. Figures 4-22 and 4-23 shows an application example of how the uncleared fault can be evaluated using the signal segmentation service using wavelet and EMD methods. Segment A indicates the pre fault section and the inception, segment B the fault and segment C the opening of circuit breaker. In this case, the fault duration is 0.059 second for signal segmentation using wavelet and 0.055 second for the EMD method.

Table 4-5. Segmented signal estimation based on wavelet and EMD, disturbance record obtained from Bulukumba substation Indonesia on 16/09/2008.

Fault Type	Segmented Signal using Wavelet Method			Segmented Signal using EMD Method		
	Time Segment Start (s)	Time Segment End (s)	Fault Duration (s)	Time Segment Start (s)	Time Segment End (s)	Fault Duration (s)
AB	1.184	1.243	0.059	1.186	1.241	0.055

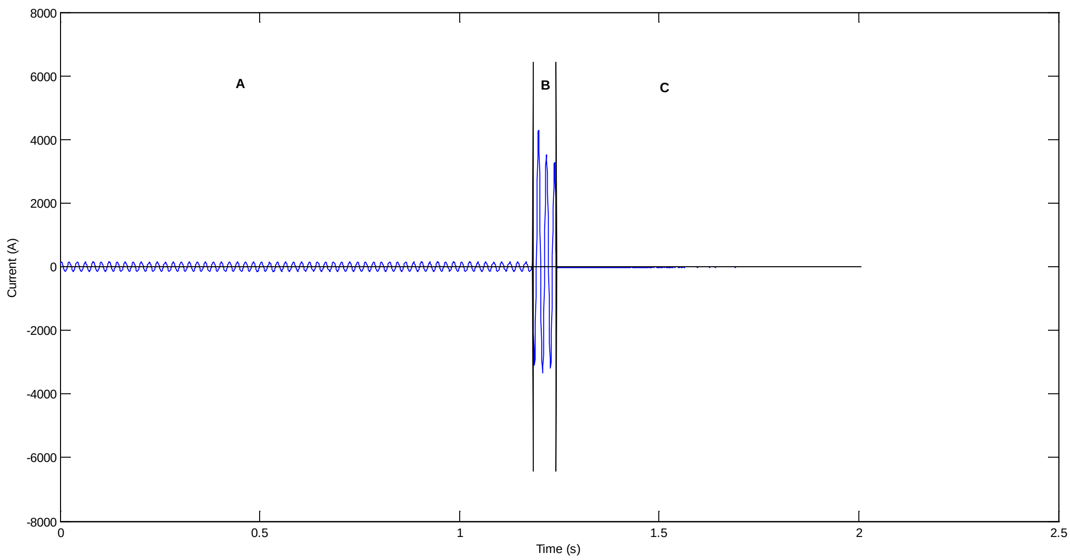


Figure 4-22. The segmented disturbance signals using wavelet method (signal recorded from Bulukumba substation on 16/09/2008)

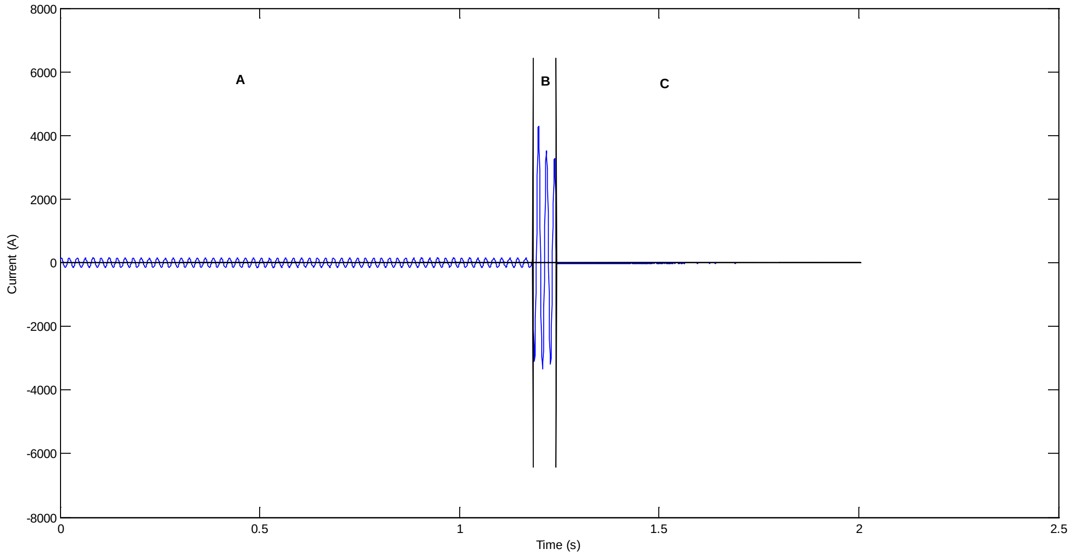


Figure 4-23. The segmented disturbance signal using EMD method (signal recorded from Bulukumba substation on 16/09/2008)

4.8 Implementing the AFAS

In line with the need to implement the automatic fault and disturbance analysis service, several requirements have to be considered including obtaining information related to the extent of the analysis, data integration and information exchange, organising databases, the dissemination of analysis results, user interface and implementation. With the integration of these aspects, the final goals of automatic fault analysis, such as providing better service to the customers and reducing the operating cost, will be achieved.

Figure 4-24 shows the implementation process of automated fault and disturbance analysis service (AFAS). It can be seen from Figure 4-24 that there are three main groups in the AFAS implementation environment. Group A is the development of abrupt change detection for signal segmentation and signal processing functions in Matlab 2008b. Then the results of group A as a dynamic link library (*.dll) file will be integrated into group B which is developed in visual studio 2008 using C# and .NET environment. Group C is mainly developed using open source application such as PHP hypertext pre-processors (PHP), MySQL and jQuery.

Several modules have been developed using C# programming language under the .NET framework. Figure 4-25 presents the scheme of the automated fault analysis service model. The explanation of each module is presented in the following sub sections.

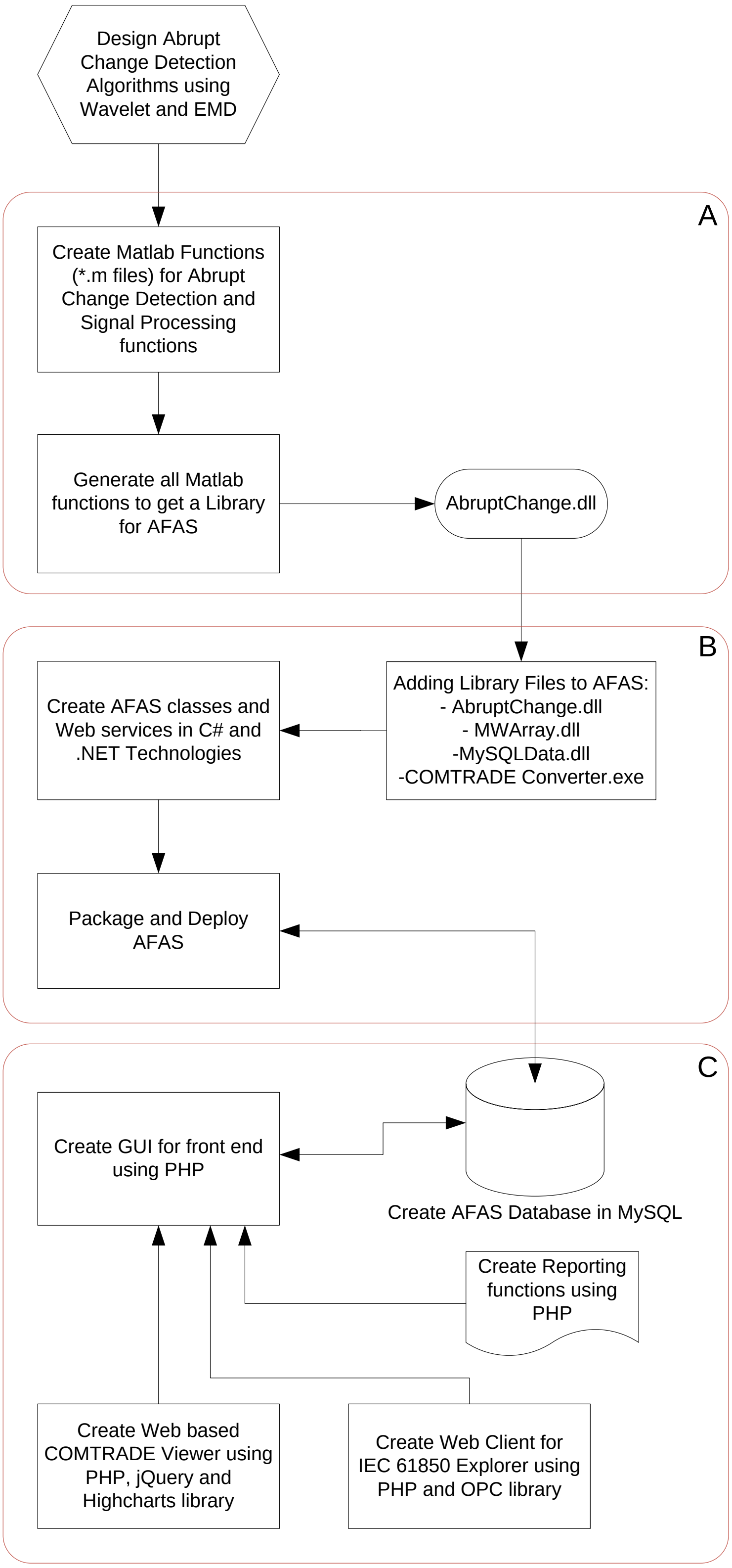


Figure 4-24. AFAS implementation process

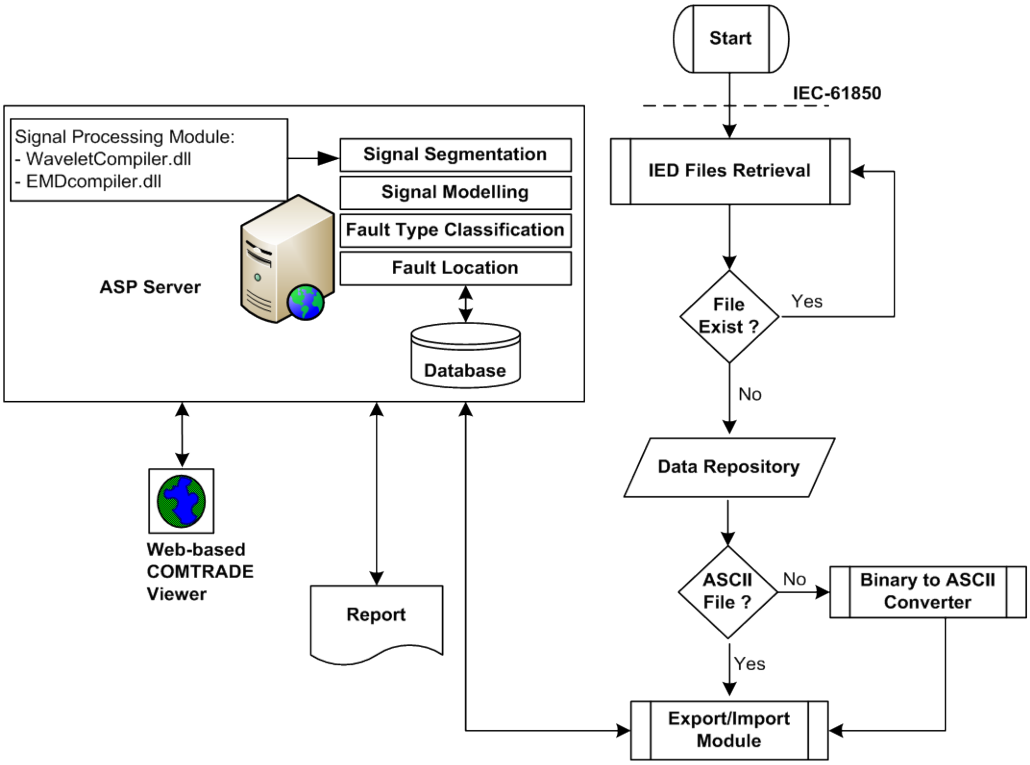


Figure 4-25. Automated fault analysis service model

4.8.1 The ASP Server

The purpose of the application service provider server is to host the application and services that can be accessible through the Internet. .NET framework is utilized in the development of the ASP server. .NET technology provides the richest level of integration among presentation technologies, component technologies, and data technologies ever seen on a Microsoft platform [98]. This includes COM+ component services, a commitment to XML and object-oriented design, and support for new web services protocols such as SOAP, WSDL, and UDDI.

The programming language of choice for .NET platform is C#. The C# language is powerful, productive, type safe, has a rich and clear syntax and provides a conceptually appealing implementation of the object-oriented paradigm. It is designed to give the optimum blend of simplicity, expressiveness, and performance, pushing beyond the limitation of Java, C and C++ [98]. Web services, report generation services and ASP.NET (C#) services are the main parts of the ASP server. The Apache web server is used as a web server because Apache provides a highly reliable and manageable WEB application infrastructure. To deal with fault analysis functions, we have tested and developed our algorithm using the Matlab program and compiled as a dynamic link library (.dll) files. All of these dll files then integrate into the fault analysis system.

4.8.2 Signal Processing Module

To enable the automated fault analysis service to calculate the fault, it is important to extract the value of the COMTRADE data and process the signal based on the algorithm that has been developed in the previous section. The following are procedures to create dynamic link libraries (*.dll) of the signal processing module using wavelet transform and empirical mode decomposition methods:

- Design the algorithm for signal segmentation functions and create functions in *.m files, then test signal segmentation functions in Matlab [99]. Several *.m files have been developed in Matlab using wavelet transform and empirical mode decomposition methods.

• The next step is compiling all *.m files using .NET builder tool which is available in Matlab R2008b. Once the compilation process is successful, the signal processing functions will be combined as a dynamic link library (*.dll) file. In this project a library file has been created for signal segmentation called AbruptChange.dll. Figure 4-26 shows the compilation process of the signal processing module. The signal processing module (AbruptChange.dll) has been set to process the input COMTRADE data and calculate the abrupt change detection of the currents and voltages, then produce the signal coefficient and segmentation time as the output of signal segmentation process.

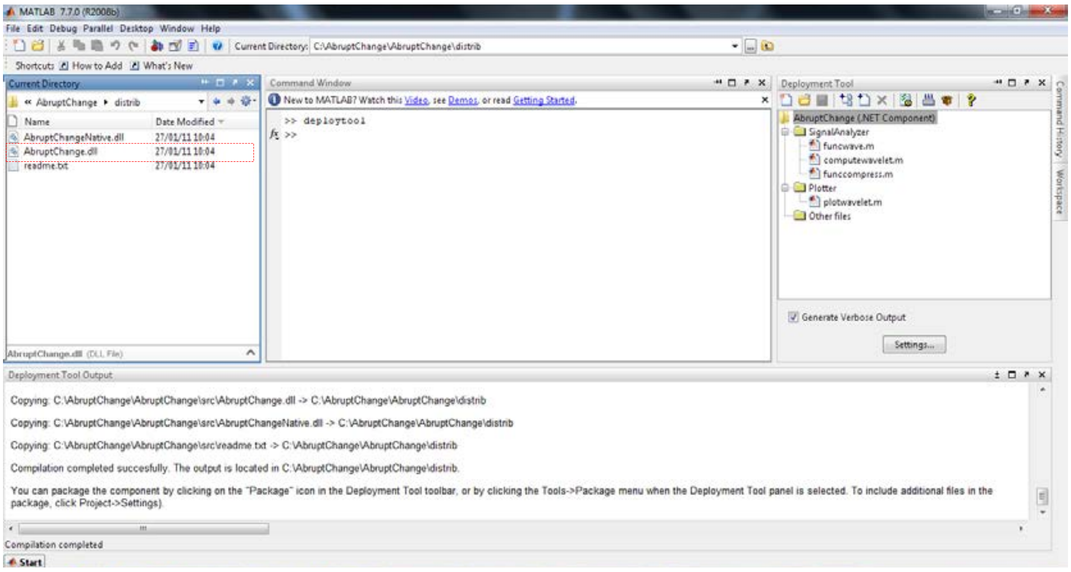


Figure 4-26. Successful compilation of signal processing module (AbruptChange.dll)

• In visual studio (VS) 2008 with C# programming language, create a class file to process the AbruptChange.dll. In this example, the class name is SignalProcessing.cs. In the VS 2008 then add the reference and use the library that has been created in the previous stage (AbruptChange.dll). Figure 4-27 presents the integration of signal processing module into the AFAS application.

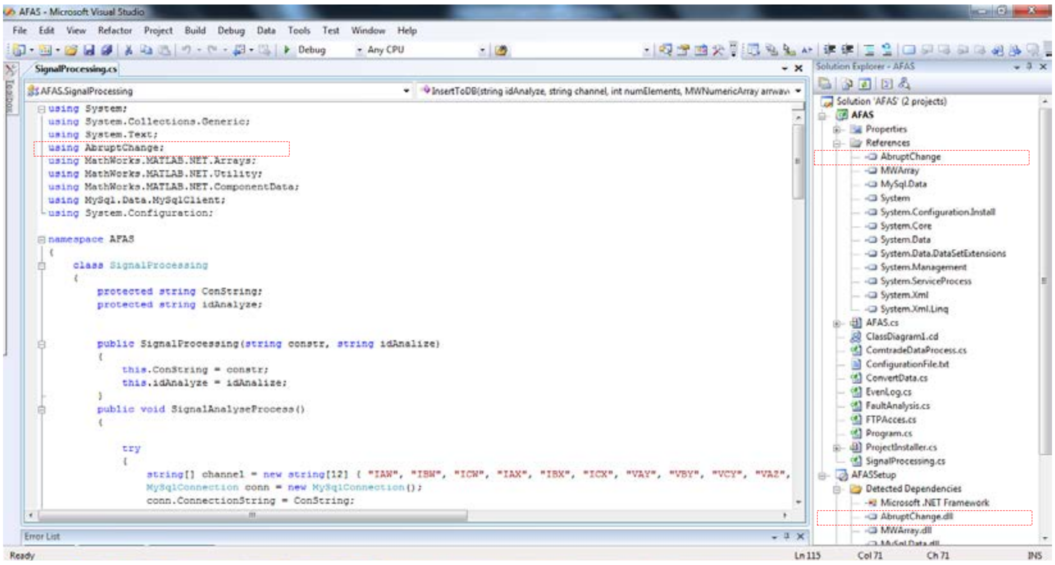


Figure 4-27. Integrate signal processing module (AbruptChange.dll) to AFAS application

Figure 4-28 presents the AFAS running on the local server which is connected to the IEDs. This service will automatically handle all data retrieval from IEDs, analyse faults and disturbances and store data into the database. The AFAS service is set to run automatically when the computer server is on.

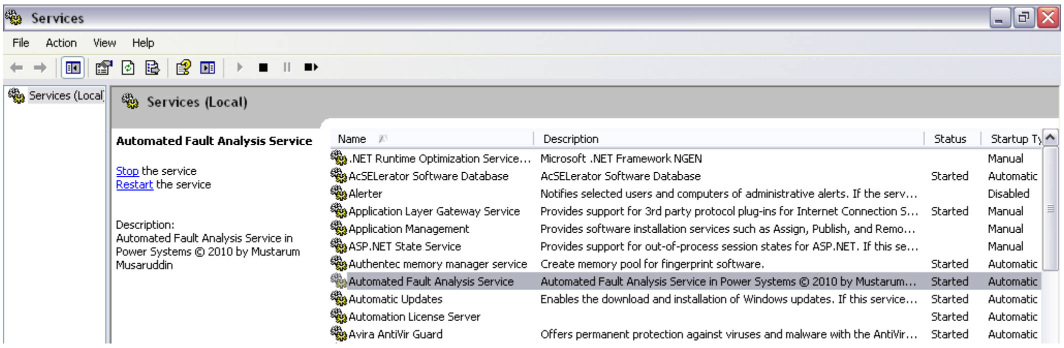


Figure 4-28. Automated fault analysis service running on server.

4.8.3 Automated IED File Retrieval

The first stage in the process of fault analysis is providing files that need to be analyzed. These files are retrieved from the IEDs, such as a digital fault recorder or a digital protective relay. Many digital relay vendors provide a PC software program that can communicate to their relay for relay settings, file retrieval and real-time data view. For example, Siemens has DIGSI software [100], General Electric has EnerVista software [101] and SEL has AcSELerator software [102] for most of its relay series. However, most of that software needs user intervention to manually initiate the file retrieval process. Therefore, we developed an automated file retrieval class using C# in the AFAS server, which can retrieve all the necessary files for automated fault analysis without user intervention. In the case of the relay not being supported by the IEC 61850 protocol, then the file transfer protocol is utilised to retrieve the useful data for analysis such as COMTRADE or event recorded data. Furthermore, for the purposes of monitoring IED's performance in remote areas, the web client for IEC 61850 was developed in this project. Figure 4-29 shows an example of the AFAS web client for IEC 61850 explorer. This web client retrieved real time data as well as logical devices (LD) and logical nodes (LN) from IEDs in the remote area.

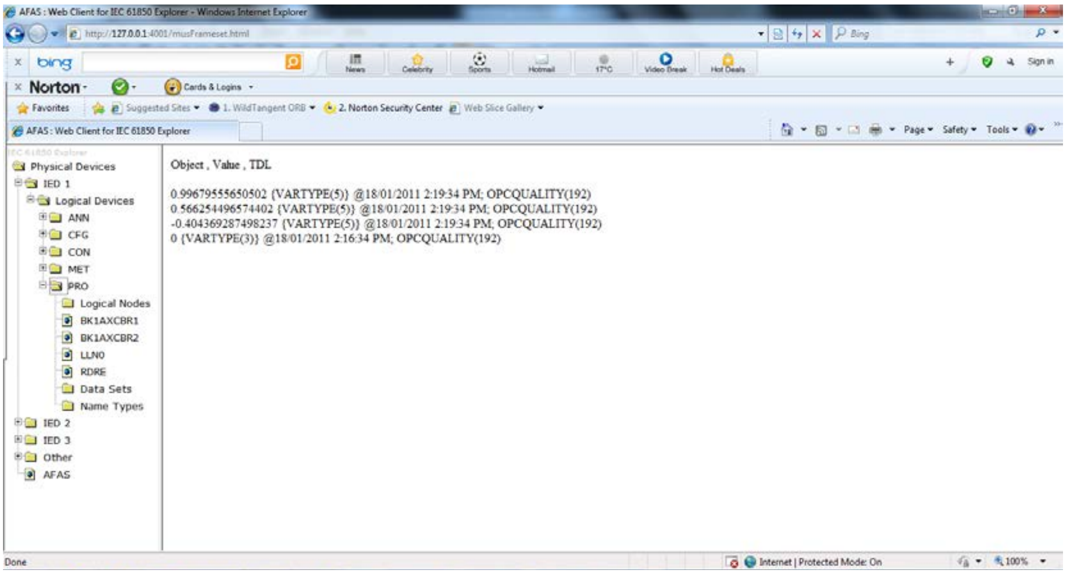


Figure 4-29. Example interface of AFAS web client for IEC 61850 explorer

4.8.4 Triggering Method using GOOSE message

Triggering is one of the important methods to detect the occurrence of an event. It is mentioned in [103] that triggering may be used to identify the beginning and the end of the event. Four triggering methods are mentioned in [103]:

- Simplest methods such as changes in RMS and waveforms.

In this method, the event that is associated with sudden changes in voltage or current waveform is an important event class. For example, voltage dips or swells, over current and sudden loss of load. The triggering point for this kind of event can be reached by utilizing a time dependent RMS sequence. A time dependent voltage or current RMS sequence is an approximation of the time dependent voltage or current magnitudes at the power system frequency.

- High-pass filters

This triggering method is simple and based on the idea that a high-pass filter can detect quick changes caused by most system events.

- Detecting singular points from Wavelet transforms

Singular points are those points where signal discontinuities are present. A significant singular point is often associated with sudden change in the system. Therefore it can be considered as a candidate for triggering. It is stated in [103] that discrete wavelet transforms (DWT) are particularly attractive in automatic detection of singular point.

- Prominent residuals from models

This method calculates the residual of each sample instance between the measured value and the value as predicted by the model.

In the substation automation system, two or more relays are installed on each end of a transmission line. One is the main protection relay and another one is a backup protection relay. If there is a fault in the transmission system, the relay will trip and trigger a recording of the disturbance events. However, if both main and backup protections relays that are supposed to be tripped cannot detect the disturbances in the transmission line, then the relay will not produce important files for analysis, such as high resolution data in COMTRADE or event recorded data. Thus, it is difficult to analyze the event without the disturbance information from the relay. Therefore, in this study we introduce the distributed triggering system from the AFAS server to automate the recording system based on the real time voltages and currents.

In the AFAS server, the OPC module that continuously monitors the value of the IED will get the real time values of current or voltage. The values are then stored directly in the MySQL [85] database via OPC data logger [86]. These values then calculated and compared to its threshold. When the values of currents or voltages are over the threshold then the AFAS server will send a command to trigger the relay connected to the faulted line or to the line neighbouring to the faulty line, even if the relay does not detect the disturbances. Sending the triggering command to the relay can be done through the generic object oriented substation event (GOOSE) message or via telnet for the relay without IEC 61860 enabled. It will then enable the relay to produce the COMTRADE data in the buffer.

The new triggering mechanism based on IEC 61850 has three different types: local, substation wide and system wide triggering. In local triggering, if the server detects the disturbances in the transmission line but the relay does not trip, the server will send a GOOSE message or command to the relay to trigger the event. In this case, only the relay integrated with the line will be triggered. In substation wide triggering, if the disturbances from another line can be seen by the server but the relay does not trip then the server will send the GOOSE message to the entire relay within the substation for triggering. In system wide triggering, the server will trigger all relays within the power system by sending the GOOSE message if the server detects the disturbances. The advantage of using the IEC 61850

GOOSE message as the trigger signal is that GOOSE messages can be sent to one specific device or group of devices, or they can be sent to all devices on the system [79]. A typical test set up configuration is shown in Figure 4-30.

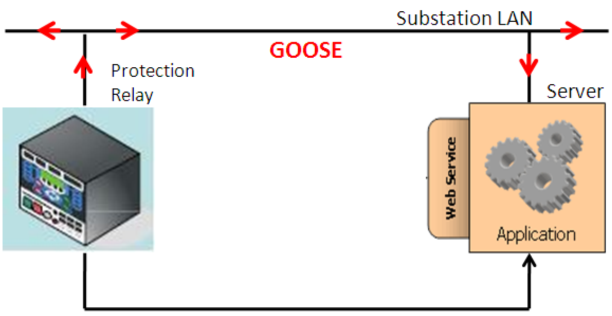


Figure 4-30. Typical system configuration

After the relay is triggered then the AFAS server will start to retrieve the COMTRADE data from the relay buffer. If the protective devices are not compliant with IEC 61850, the COMTRADE data can be retrieved via the file transfer protocol (FTP). The retrieved COMTRADE files are then stored in the file repository. It is common that the retrieved COMTRADE data from IED are in the binary format. Therefore the AFAS will automatically convert all the data into the ASCII format and export the data into the MySQL database. After all the necessary data are stored in the database then the service will calculate the wavelet coefficient of each phase current. The next step is for the signal segmentation and signal modelling services to process the signals based on the abrupt change detection. With the detection of abrupt change, segmentation of the signals such as pre-fault, fault and post-fault condition can be achieved. The segmented signals are necessary for further automated fault analysis process, such as fault type classification and fault location service. All the analyses' results will be stored back in the database for future use or just for the historical data. Users also can view the result on the web and display the waveforms of the COMTRADE data. The process of disturbance data retrieval and pre-processing for automated fault analysis can be seen in Figure 4-31.

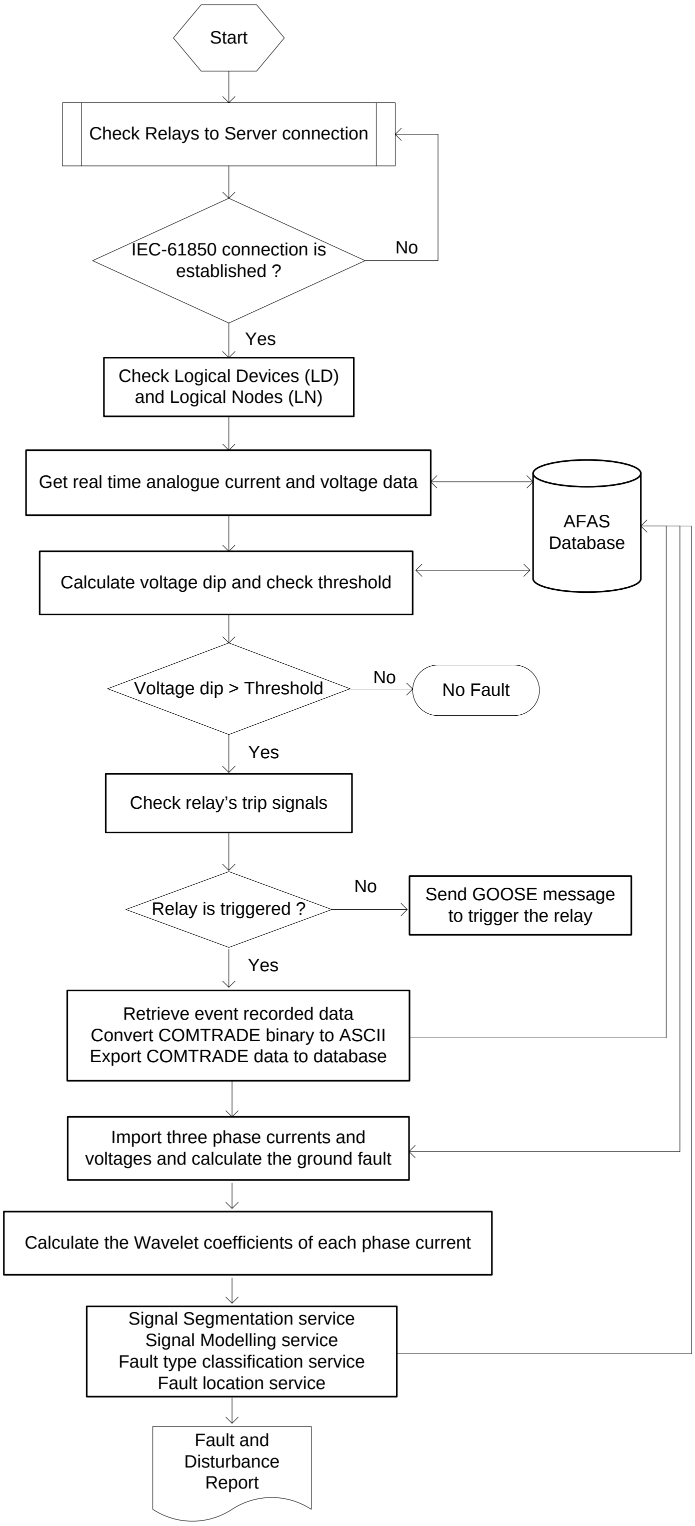


Figure 4-31. Disturbance data retrieval and pre-processing for automated fault and disturbance analysis

4.8.5 Database for System and Event Related Data Storage

The retrieved data from the IEDs in the substation are stored in the master PC in the COMTRADE format. We have utilized the MySQL database to store the COMTRADE data and other necessary information from the IEDs that would be useful for fault and disturbance investigation analysis. MySQL is an open source SQL server. MySQL is popular with internet service providers (ISPs) and web application developers because of its speed, reliability and flexibility of its access control system [85].

In the AFAS application, it is necessary to add a library reference to support mysql database (mysql.dll). The library for MySQL is downloaded from [104]. Figure 4-32 presents the graphical user interface (GUI) of AFAS Database.

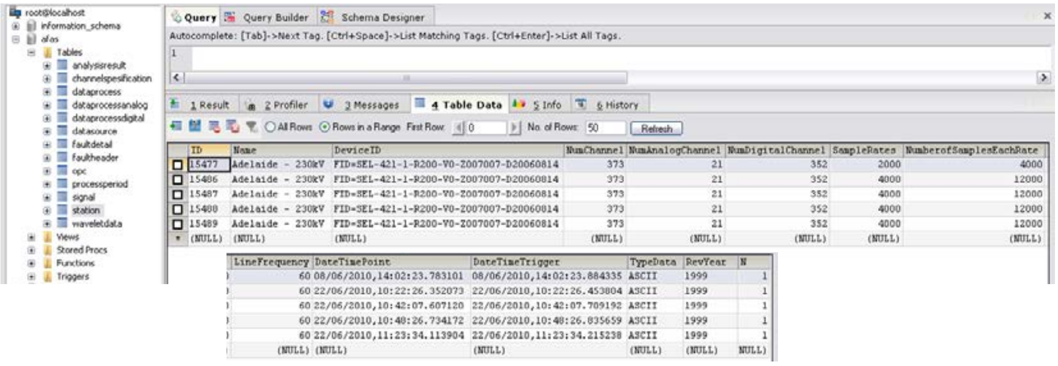


Figure 4-32. AFAS database (Table: Station)

4.8.6 Development of COMTRADE viewer

The available technologies to develop a web-based COMTARDE viewer have been investigated and tested in this study. The main idea is to develop a COMTRADE viewer that will be available in the web browser and that can be integrated with the AFAS database. Therefore, in choosing the suitable library for the COMTRADE viewer, several requirements are need to be considered, such as whether the viewer tool is able to support the MySQL database, and whether it is dynamic and has zooming and tool tip functions. The viewer tool should support the database because all of the data from COMTRADE and analysis results are stored in the MySQL database. Several useful tools that have been investigated for the development of web-based COMTRADE viewer are: Easy Java Simulation and Java Internet Matlab (JIM) to create viewer as a Java applet, .netCHARTING library to create a viewer in the .NET technology environment and Highcharts library to create a viewer using java script and jQuery framework.

- Easy Java Simulation (EJS)

Easy Java Simulation (EJS) [105] is an open source software tool that helps users to create interactive simulations in a Java Applet. EJS has the functionality to be integrated with Matlab functions. By using EJS, user can create their graphical user interface (GUI) model and Matlab functions, then EJS can generate the application as a Java applet which is ready to be put in the web server. Although EJS can be integrated with Matlab functions, these functions cannot work when users invoke the applet from the remote computer. This problem can be solved by utilizing the Java Internet Matlab (JIM) in the server.

- Java Internet Matlab (JIM)

Java Internet Matlab (JIM) is a tool that enables Matlab functions that are embedded in Java Applet interface to be invoked remotely [106]. In order to run the functions remotely, we embed the application code into our designed XML file which also contains the IP address of our web server. The XML file is generated using the EJS package. As a result, it produces the Java interface that can be integrated in our web server. Moreover, every time clients connect to the application services via web browser, the JIM server will detect and display their IP address in the ASP server engine. Figure 4-33 displays an interface of JIM server.

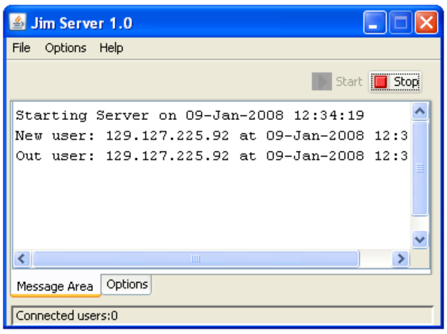


Figure 4-33. Java Internet Matlab (JIM) server interface

- .netCHARTING Library

Since its introduction in 2002, .netCHARTING has pioneered a number of unique technologies, which have subsequently become industry standards [107]. In today's dynamic, data-centric web environments, traditional charting implementations are faced with a number of scenarios they are unable to accommodate. The .netCHARTING’s smart features and automated handling elegantly address these requirements, ensuring charts are clear and visually stunning, even as the data they represent continues to change. Figure 4-34 shows a web-based COMTRADE viewer that displays the voltages and phase currents as well as the binary signals. These signals are retrieved from SEL 421 relay.

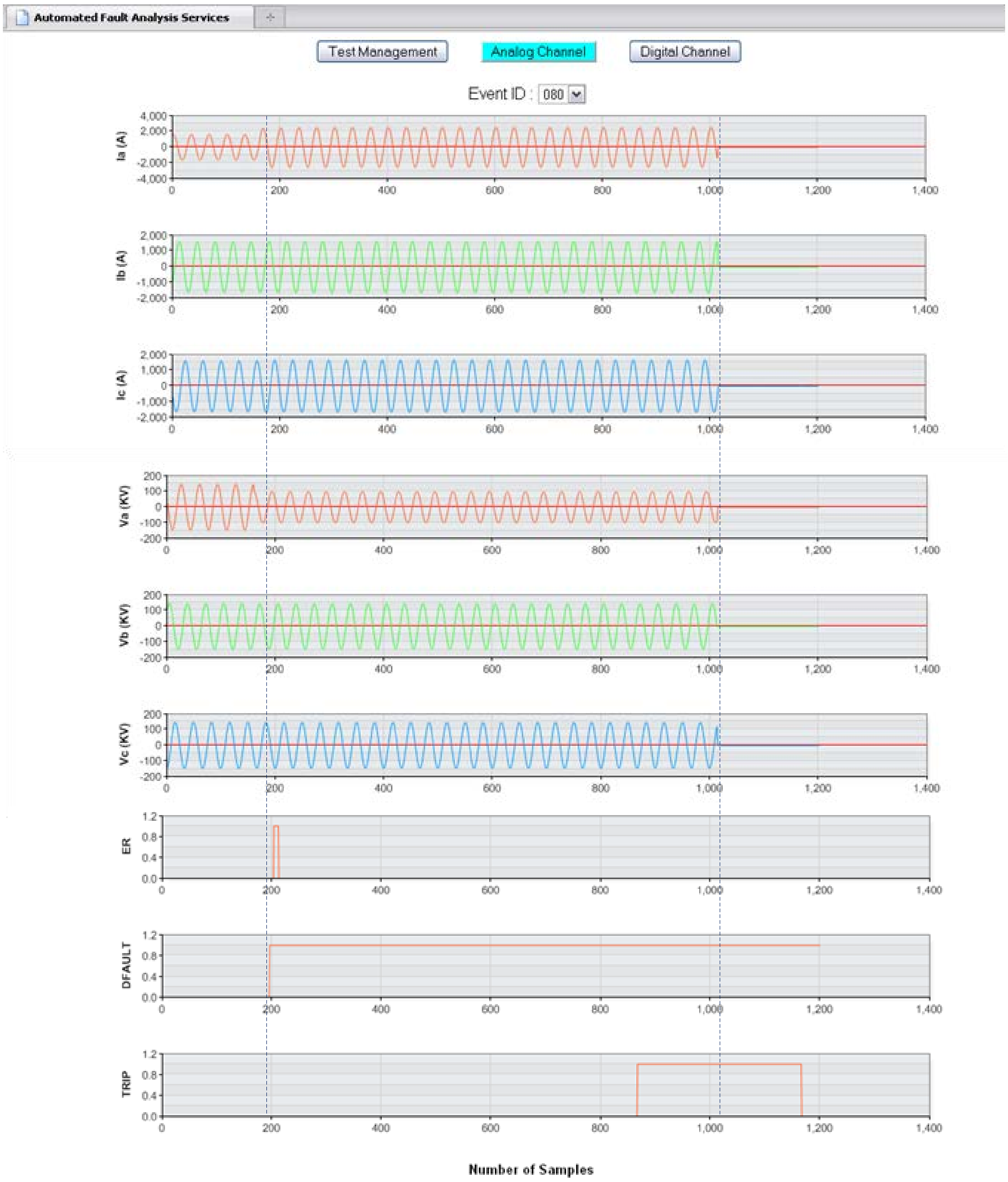


Figure 4-34. Example of web based COMTRADE viewer interface

- Highcharts Library

There are several charting libraries available on the Internet, but not all of the libraries support the functionalities that we required in the development of a web based COMTRADE viewer. One of the best charting libraries we found is Highcharts, which is free for non-commercial use. Highcharts is a charting library written in pure Java script and runs with jQuery framework. Highcharts is solely based on native browser technologies and does not require client side plugins like Flash or Java [108]. Furthermore, it does not need to install anything on the server. Highcharts has all functionalities that are required in the development of the AFAS COMTRADE viewer, including integration to MySQL database, zooming, tooltip label, export and print. With the exporting module enabled, users can export the chart to PNG, JPG, PDF or SVG format at the click of a button, or print the chart directly from the web page. Having considered all of those features, the Highcharts library was chosen for the development of AFAS COMTRADE viewer.

Figure 4-35 shows an interface of the AFAS COMTRADE viewer with the automated signal segmentation. As can be seen from Figure 4-34, users can select the available COMTRADE record from the drop down list, and then the chart will be displayed in three groups: phase current (I_A,I_B,I_C), Voltage (V_A, V_B, V_C), and the time segmentation (TS). The time segmentation will be displayed automatically when there is abrupt change in the signals. Users can zoom the chart to see the details of their disturbance signals interest and can print the chart or export the chart to other formats such as PNG, JPG, PDF or SVG. Figure 4-36 shows an example of zooming functions in the specific disturbance of voltage signal for two phase fault (AC fault). The zooming current at the first and second time segmentation (TS) can be seen in Figures 4-36a and 4-36b respectively. The zooming voltage around the first and the second time segment is shown in Figures 4-36c and 4-36d respectively. As can be seen from Figure 4-36a and 4-36c, the first TS is detected when the sample number is 178 and the second TS is detected when sample number is 1178 as shown in Figure 4-36b and 4-36d.

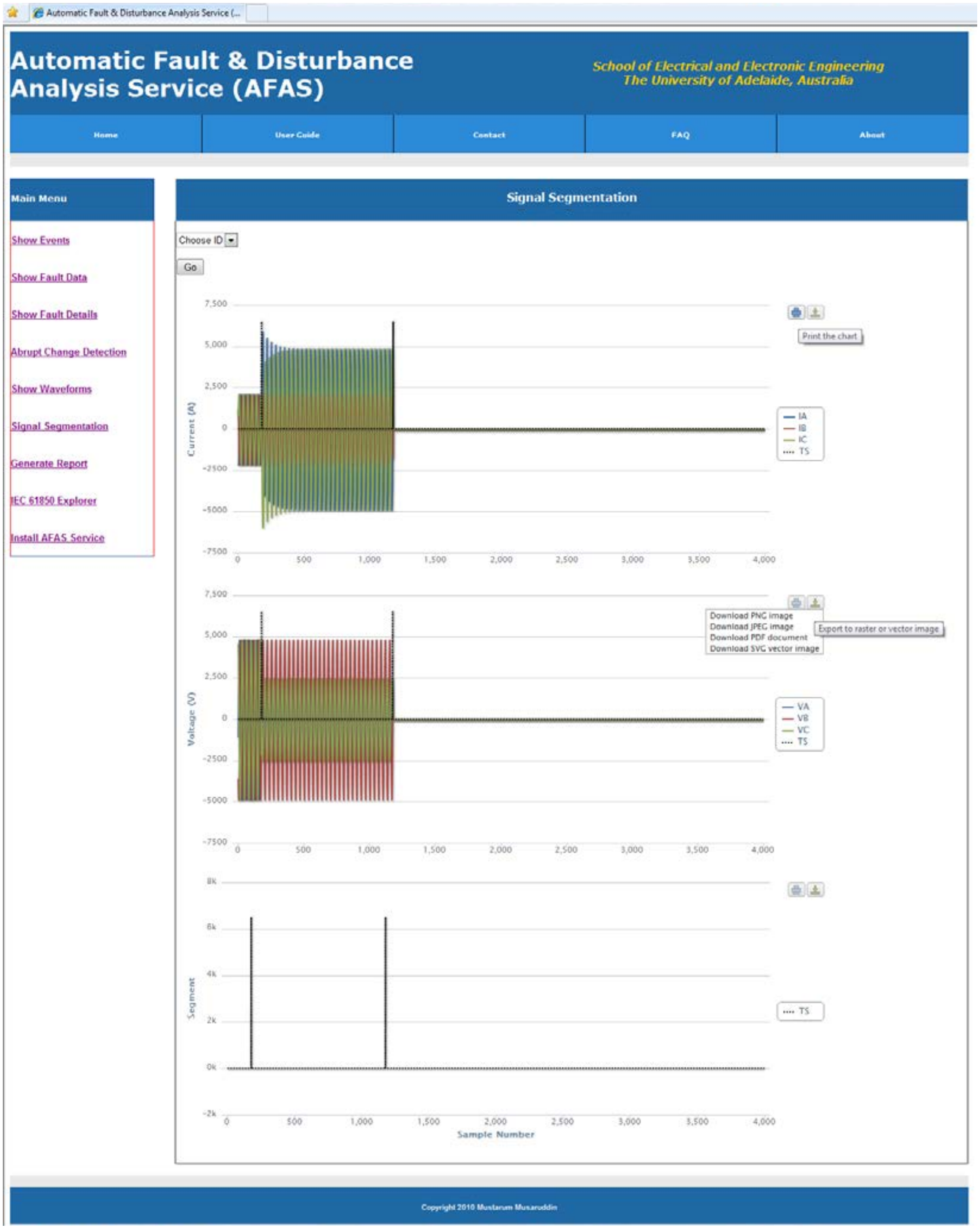
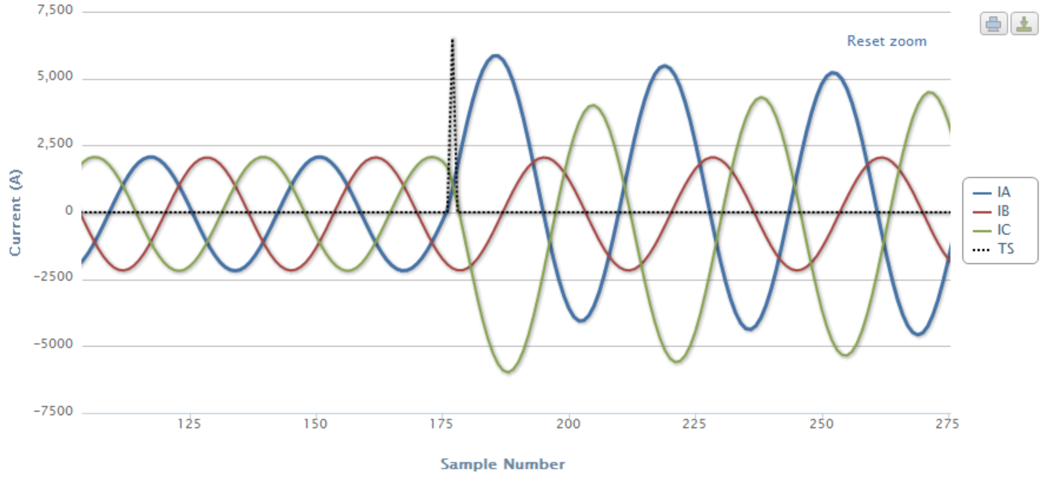
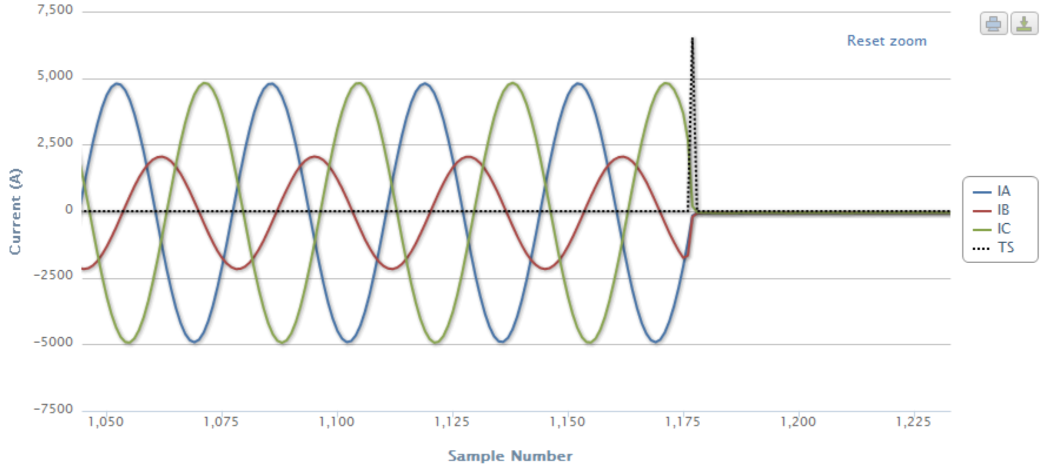


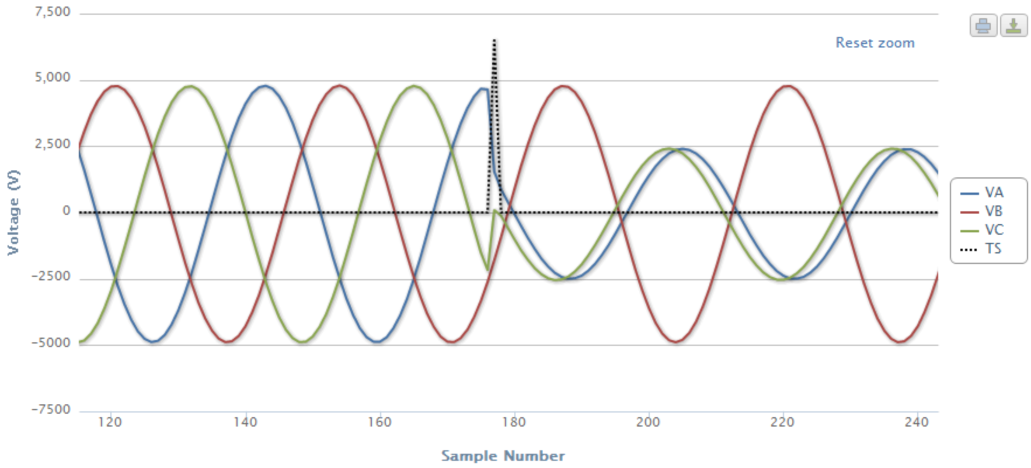
Figure 4-35. Example of AFAS COMTRADE viewer interface with the automated signal segmentation for two-phase fault (AC fault).



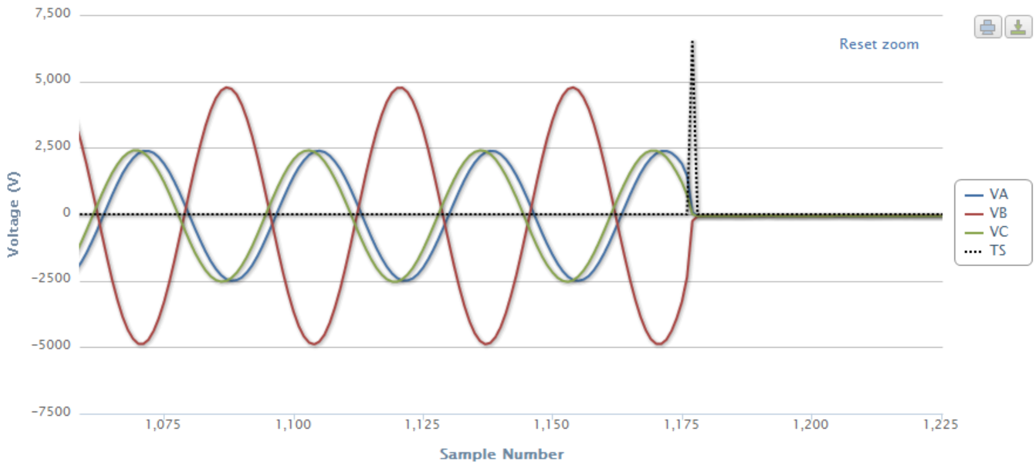
(a) Zooming current (I_A, I_B, I_C) at the first time segment (TS)



(b) Zooming current (I_A, I_B, I_C) at the second time segment (TS)



(c). Zooming voltages (V_A, V_B, V_C) at the first time segment (TS).



(d). Zooming Voltages (V_A, V_B, V_C) at the second time segment (TS).

Figure 4-36. Example of zooming functions in the AC fault.

4.8.7 The Automated Fault Analysis Client

The following are some examples of how the client can use this system:

a) The client can select the event ID of the fault and disturbance record, which is retrieved from IEDs. Then user can click the certain signals to view the waveforms in web-based COMTRADE viewer and proceed through investigation steps by analyzing the displayed signals using the services provided. All intermediate results of the investigation will be displayed and stored in the report. The user can also decide to activate automated use of services. This will result in the complete final report containing all information automatically created. The report can be edited and additional text added, and forwarded in different forms using email, fax, or SMS. Figure 4-37 shows an example of a simple AFAS report. As can be seen from Figure 4-37, the report can be converted to document or spread sheet file format, forwarded using email or can be printed directly.

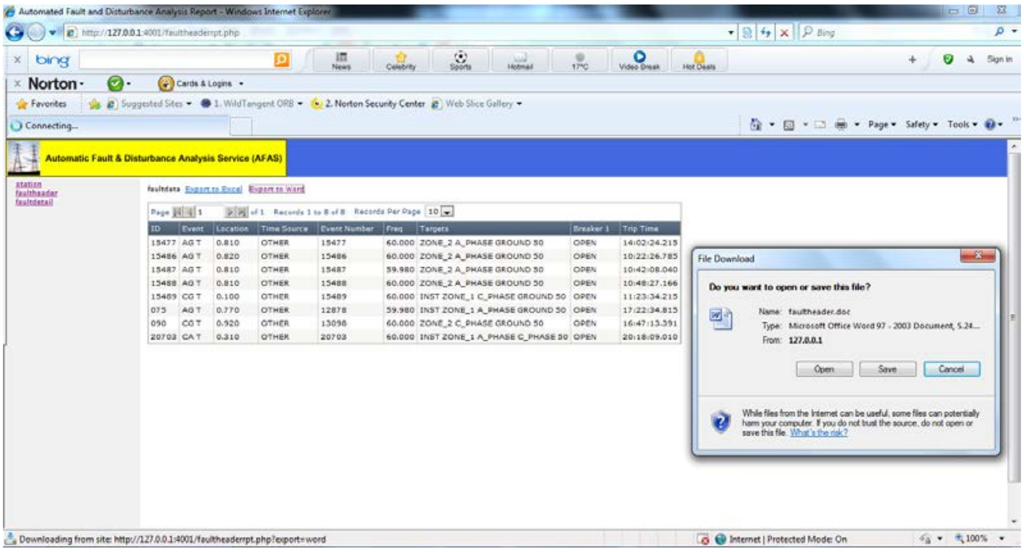


Figure 4-37. Example of simple AFAS report

b) If a fault is permanent and a line is not in service, the investigation engineer can test the relay remotely using the remote relay test service provided through the AFAS. The user can input test data from the web interface or select data from the data base on the server and upload to the relay test system which is located in the substation. The user can remotely control the relay test system. The system provides for test results to be retrieved from the relay under test and from the test system. Furthermore, if the problem is in the relay settings, users can change the settings remotely and redo the testing sequence. A detailed overview of these remote relay test service is presented in the Chapter 5.

4.9 Chapter Summary

The development of automated fault and disturbance analysis service has been presented. The signal processing methods implemented in the AFAS including the wavelet transform and EMD methods have been discussed in this chapter. The technique for signal segmentation based on wavelet and EMD has been tested using simulated fault data and disturbance records from power utilities. Test results for single-phase-to-ground, two-phase-to-ground, phase-to-phase and balanced three-phase faults have been presented. Fault resistances used in simulation ranging from 0.001 to 100 Ω and variation of fault location from 10 to 90 % were used in these studies. The studies show that the signal segmentation service using wavelet and EMD methods was quite stable over the variation of fault type, fault location and fault resistance. The development of a remote relay testing service (RRTS) is presented in the next chapter.

Chapter 5: Remote Relay Testing Service (RRTS)

5.1 Introduction

The purpose of testing protective relays is to ensure correct operation of the relay for all possible power system conditions and disturbances, such as transmission line faults. If a fault is not detected early, personal injuries and serious damage can occur. Hence, it is imperative that the protective devices in these systems are reliable. The only way to verify this is through testing, involving operating under various fault conditions.

It is common practice that protection engineers have to go to the substation to do troubleshooting testing to find out why a relay has performed unexpectedly in relation to a specific disturbance. This method is time consuming and costly. With the implementation of the remote relay testing service [109], a protection engineer can check the performance of a relay remotely, through remote playback of disturbance records and simulated data.

5.2 Relay Testing Overview

With the advent of modern computing, relays are now fed voltages and currents, which are stepped down to very low levels and passed through analog to digital converters. The resulting signals are then utilized by microprocessors to monitor the system. This has opened the door for greater flexibility in computation and made it possible for one relay to perform multiple protective functions rather than having multiple relays, each performing a specific function. A digital protective relay consists of the following main parts: processor, analog/digital input system, digital output system and independent power supply [110].

A digital protective relay has many special features. Some of the features are [111]:

- Its ability to perform self-diagnostic tests to detect component failures.
- The possibility of changing relay settings by using a communication interface, making adaptive relaying possible.
- The programming of a digital protective relay in order to do multiple protective functions within a single unit.
- The ability of digital relays to generate files which contain detailed data about power system fault disturbance and the corresponding responses of protective system components.

The generated data from a protective relay can be classified into four categories, namely: oscillography data, setting data, fault data and event record data [112]. Oscillography data is generated by the fault recording function of a digital relay and contain the records of what the relay sees during a disturbance event. Setting data specify configuration parameters of relays so as to set the relay response. Fault data present fault disturbance information calculated by the relay. Event data provide information as to how the relay and associated protection components respond to the disturbance event.

Protective relays must meet general requirements, such as correct diagnosis of trouble, quickness of response and minimum disturbance to the power system [110]. Protective relay testing generally consists of three categories: acceptance testing, commissioning testing, and troubleshooting testing [112]. Each testing category differs in terms of the testing goals, the timing of the test and the relay functions that need to be tested. An acceptance test performs detailed acceptance testing on all new relay models and versions. Commissioning testing involves performing a complete functional check and calibration of each relay during commissioning so that the relay operates correctly and accurately. Troubleshooting testing uses extensive self-testing routines and features detailed metering and event reporting functions. The remote protective relay test service that we proposed in this dissertation is focused on troubleshooting testing. Three factors need to be considered to perform the troubleshooting testing: time, goals and tests [111].

- Time: test at scheduled intervals or when there is an indication of a problem with the relay or power system.
- Goals:

    a) confirm that the relay is measuring ac quantities accurately.

    b) check that scheme logic and protection elements function correctly.

    c) verify that auxiliary equipment functions correctly.

- Tests: test all relay features that did not operate during an actual fault.

5.3 RRTS Architecture

The remote relay testing service (RRTS) that was implemented in this project is suitable for low level testing [113]. The low-level playback system which is remotely controlled through ASP can be installed in the same rack with intelligent electronic devices (IEDs) in a substation. The IED's should have low-level input and internet-based communication. The advantages of low level testing are lower costs and simplified design where amplifiers are not used. The amplifiers can distort transient signals used for troubleshooting tests. The advantage of avoiding amplifiers is that more realistic signals are injected [113]. The remote troubleshooting testing can be performed in the case of permanent fault when a transmission line is not operating.

The overall architecture for the remote relay test system is shown in Figure 5-1. The system was realized using an application service provider approach that allows the concurrent execution of multiple experiments using separate testing set-ups. Testing that requires the same relay setting is queued and executed in the order of the incoming requests.

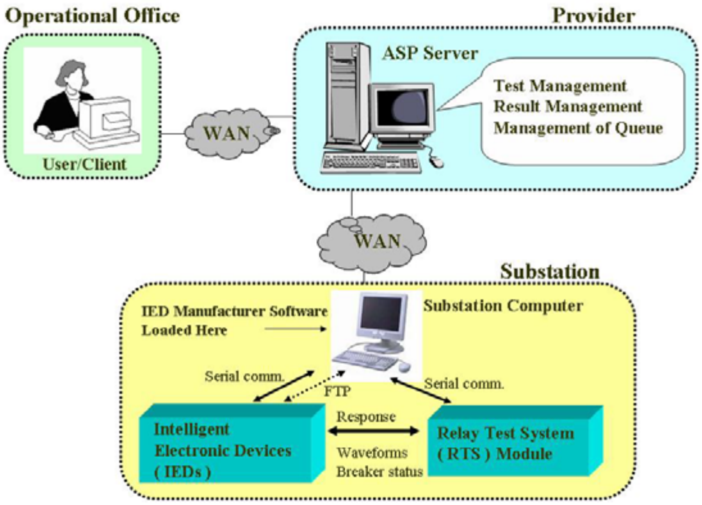


Figure 5-1. Remote relay testing system via ASP

The RRTS architecture includes user authentification, test management and result management. After a successful authentification at the remote relay test (RRT) server, the user can start testing the relay. The next stage is that the user can upload new setting files, case study files and fault records. The setting files are uploaded via the file transfer protocol (ftp) to the remote relay in the substation. The case study files and fault records are inputs to the relay test system (RTS) module. Once the relay is tripped, all internal relay files are automatically transferred to the database system. The database system is needed because of the limitations of the memory on the IEDs, and to back-up the necessary data for future analysis. When testing is finished the user gets an email and logs on to the server and downloads all report files. The user then can analyze relay report files, the sequence of events and the COMTRADE files. Figure 5-2 shows the architecture of remote protective relay test system.

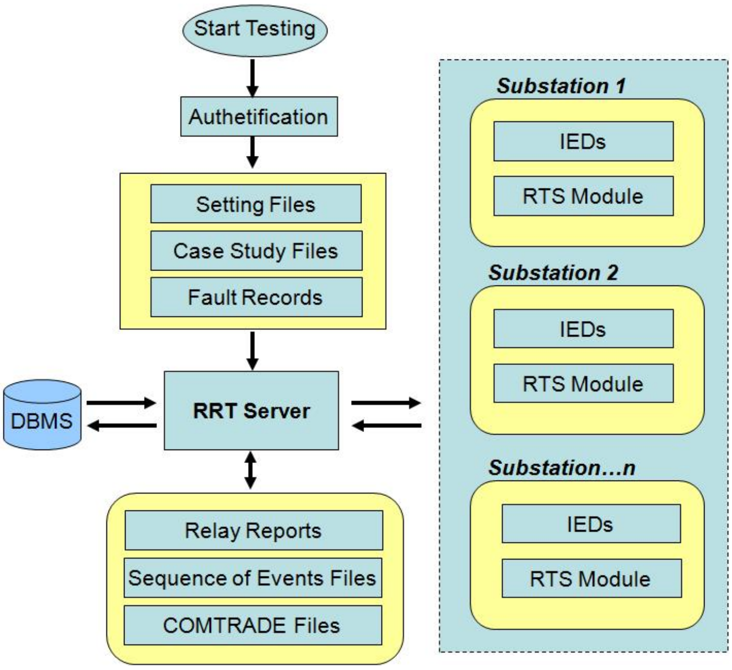


Figure 5-2. Remote relay testing architecture

There are two main functions in the remote relay test system: test and result management. Test management has several functionalities such as uploading of settings, test cases, disturbance records, and queue management. Result management deals with data retrieval from the IEDs to the file repository in the server, data conversion from binary to ASCII COMTRADE format, data export-import from file repository to the database system, the COMTRADE viewer, reporting services and notification services.

5.4 RRTS Procedures

5.4.1 Client

In the client computer, the first step is to create relay setting files for the 230 kV transmission line using AcSelerator Quickset software which can be downloaded from the Selinc website [114]. After creating and saving the setting files in the user computer, the users can export all setting files from the relay database to the client folder using a database manager. In the next step, the user can create a model using PSCAD/EMTDC or ATP EMTP software. In the ATP setting, a value of the time step length (delta T) of 0.00005 seconds was used while the total duration of the test (Tmax) was set to 1 second. Simulated signals were re-sampled at 2 kHz. The low-pass filter was used in this down sampling. After creating the model, users can generate fault signals using a batch generator. Eleven fault cases beginning with 75 % and ending at 85 % of the line are used to test the relay’s operation around the edge of zone 1. Then, users can create a case study file in *.RTA or .RTP format using SEL-5401/SELTEST software [115]. In SEL-5401/SELTEST, users can input the generated fault records into the case study files in order to generate COMTRADE files from the relay. Once all the setting files, case study files and fault records are ready, the user can upload those files to the server via RRTS web interface.

5.4.2 Server

The RRT application service will always run to establish the connection between Web server, SEL-421 relay, Relay Test System (RTS) module and Database server. The RTS module is designed for testing protective relays having low-level test capabilities. The system consists of the SEL-AMS Adaptive Multichannel Source and either the SEL-5401 or SELTEST software [115]. Once all the required files are uploaded into the database server, the RRT service will command the RTS module to run and will trigger the SEL-421 relay. When the relay is tripped, the system will retrieve the testing results from the relay, such as relay reports, sequence of events files and COMTRADE files, which will be transferred automatically into the database system and can be downloaded by the users. Finally, users can analyze the testing results using tools such as the web based COMTRADE viewer [5].

5.5 RRTS Implementation

Most of the tools used in the RRTS implementation are open source which is free and platform-independent. The implementation of the RRT server is developed using WampServer 2 [116]. WampServer is a software package that contains several tools for the web development and database management system, which include Apache web server, MySQL database and phpMyAdmin. The benefit of WampServer deployment is that there is no need to install and configure any other software which is time consuming. The following are the tools that were utilized in the development of RRT system.

- Apache web server: Apache web server is part of the Apache software foundation's Jakarta project [117]. This server makes all services accessible by clients via internet-connected computers.

- MySQL database: MySQL is an open source SQL database. MySQL is popular with ISPs and web application developers because of its speed, reliability and the flexibility of its access control system [85]. We have utilized MySQL to store relay reports, sequence of event files and COMTRADE files.

- Open database connectivity (ODBC): Open database connectivity (ODBC) is a connector to be used in the ASP to communicate with a database application [118]. It is used to retrieve, update or delete database information using ASP forms.

- Microsoft visual studio 2008: The deployment of RRTS is mainly implemented using the .NET technology with C#.NET programming language to integrate vendor specific software modules for testing the system and relay communication. Microsoft visual C# 2008 and visual web developer 2008 Express [119] are used to develop the service application. Figure 5-3 shows an interface of the RRTS console running on a server. From this console interface, users can see the status of the RRTS at every stage of the remote testing process, including uploading file settings to the relay and downloading investigation results from the relay, as well as sending emails to users. An example of automated email notification from RRTS once the testing of relay is finished can be seen in Figure 5-4.

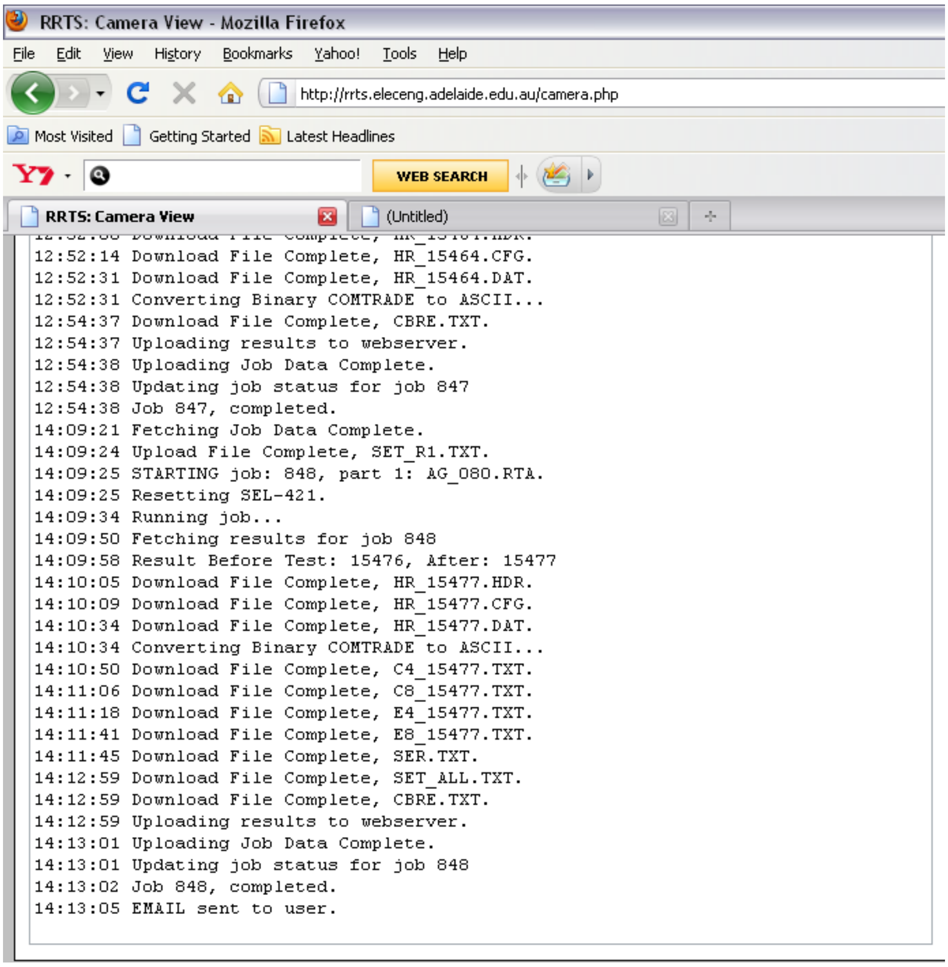


Figure 5-3. RRTS console running on server

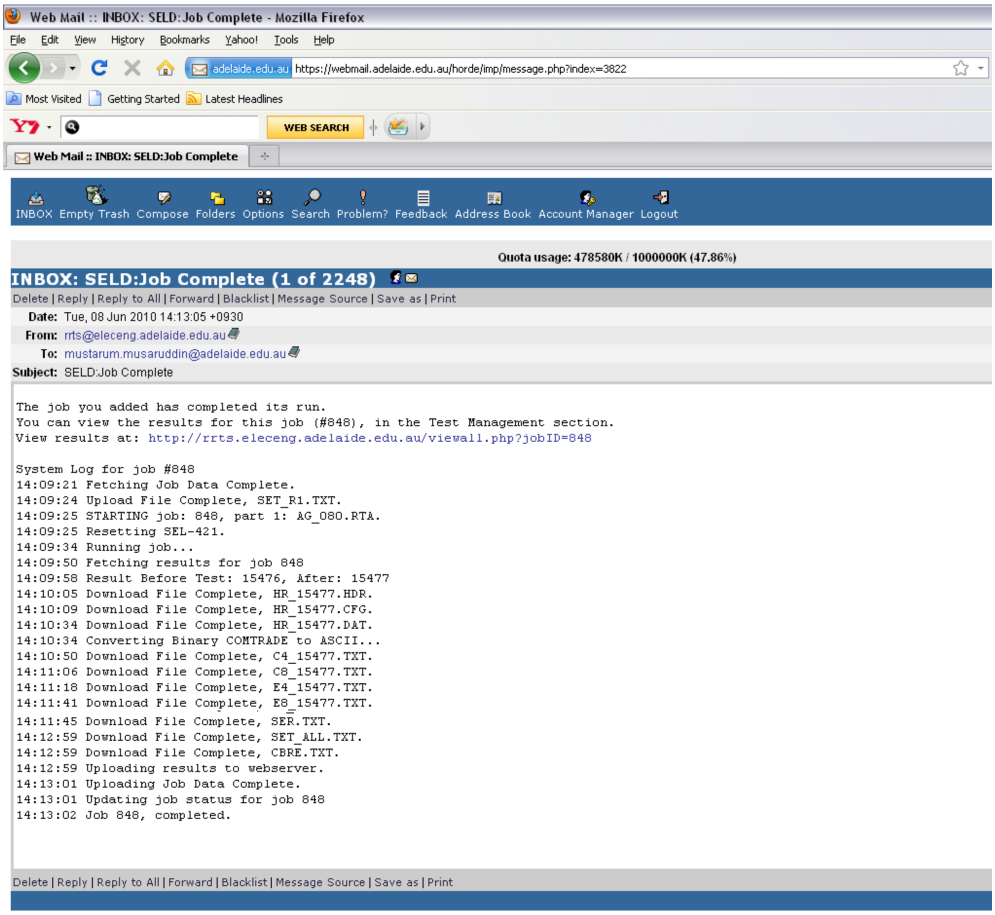


Figure 5-4. RRTS job notification sent to user via email

5.6 RRTS Case Study and Application Results

As an example of the RRTS case study, the performance of the SEL-421 protective relay at 230 kV overhead transmission line was tested. The simulation of power system model was created using power system computer aided design (PSCAD) software [120]. Figure 5-5 presents the power system simulation model in PSCAD. Different fault location and fault resistance values were used in these simulations. To change the variables of simulation, fault control module in PSCAD (see Figure 5-6) is integrated to the power systems model. Furthermore, all the fault and disturbance data are recorded in PSCAD COMTRADE recorder as can be seen in Figure 5-7. The COMTRADE data from PSCAD simulation were integrated into the SEL 5401 software. SEL 5401 is the software to simulate the SEL 421 relay by using SEL Relay Test System (RTS) module.

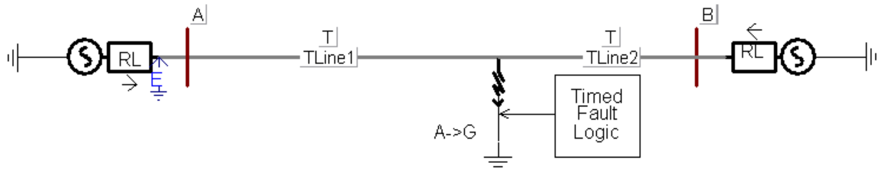


Figure 5-5. Example of power system simulation model using PSCAD

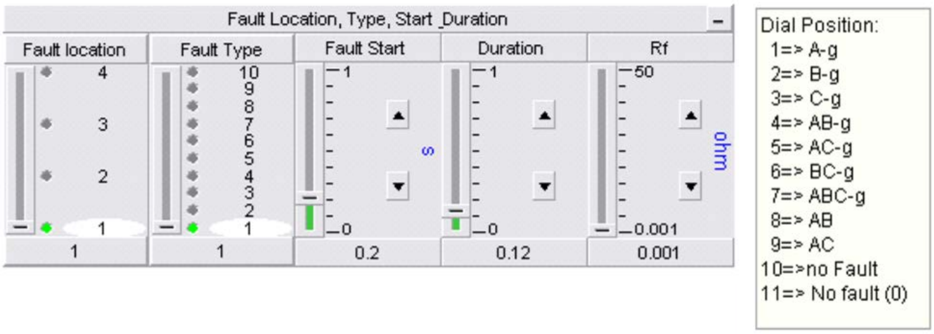


Figure 5-6. Fault control in PSCAD

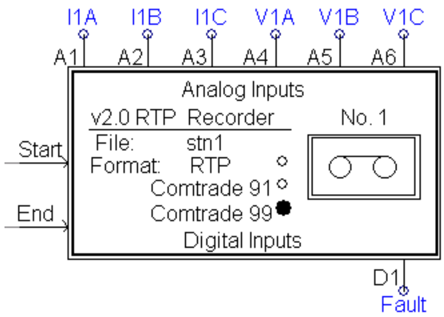


Figure 5-7. COMTRADE recorder model in PSCAD

The relay was set for single circuit breaker, three-pole tripping with the following functions [121]:

- Two zones of mho distance protection:
  - Zone 1, forward-looking, instantaneous under reaching protection.
  - Zone 2, forward-looking, time-delayed tripping.
- Inverse-time directional zero sequence over-current backup protection.
- Switch-Onto-Fault Protection Logic (SOTF). It is a logic that provides tripping if a circuit breaker closes into a zero voltage bolted fault.

In practice the impedance values can be obtained from a network authority, however the following line data was provided:

Positive sequence (Z_{1L}) = $39\Omega\angle 84°$

Zero sequence (Z_{0L}) = $124\Omega\angle 81.5°$

The tests were conducted, using increments of one per cent, ranging from 75 % for the line, to 85 % for fault locations. Using the above system, all combinations of fault types were created including phase-to-phase, phase-to-ground, two phases to ground as well as three phases shorted. These tests were first conducted using a value of phase-to-phase and phase-to-ground impedance of almost zero (0.001Ω), then impedance was increased to 1 Ω and then even further to 10 Ω.

Using the above system, all combinations of fault types were created (i.e. phase-to-phase, phase-to-ground, two-phases-to-ground as well as three-phases shorted). These tests were first conducted using a value of phase-to-phase and phase-to-ground impedance 0.001 Ω, then impedance was increased up to 10 ohms.

A table of relay response times for all test cases is presented in Table 8. It can be seen from Table 5-1 that the response time does not vary significantly for increased fault impedance. It should be emphasized that any faults to ground usually took longer to detect; this can be attributed to the way the relay's microprocessor analyses various faults, whereby some calculations take longer to process than others.

Table 5-1. Relay response times

BOLTED		MED R		HI R	
Fault Type/ Location	Relay Response (ms)	Fault Type/ Location	Relay Response (ms)	Fault Type/ Location	Relay Response (ms)
ABC_075	26.3	ABC_075	27.5	ABC_075	28.3
ABC_076	25.9	ABC_076	28.1	ABC_076	29.9
ABC_077	28.5	ABC_077	28.7	ABC_077	28.5
ABC_078	28.1	ABC_078	29.1	ABC_078	30.1
ABC_079	19.6	ABC_079	19.4	ABC_079	28.7
ABC_080	20.2	ABC_080	20.6	ABC_080	32.3
ABC_081	20.4	ABC_081	20.2	ABC_081	21
ABC_082	21	ABC_082	20.4	ABC_082	22.4
ABC_083	20.2	ABC_083	20	ABC_083	22.8
ABC_084	20.8	ABC_084	21.2	ABC_084	22.2
ABC_085	20.9	ABC_085	19.8	ABC_085	22.6
Average	22.9	Average	25.5	Average	26.25
ABG_075	27.7	BCG_075	26.1	BCG_075	28.9
ABG_076	30.1	BCG_076	27.7	BCG_076	30.3
ABG_077	28.7	BCG_077	26.3	BCG_077	30.9
ABG_078	32.3	BCG_078	29.9	BCG_078	32.3
ABG_079	21	BCG_079	20.4	BCG_079	20.6
ABG_080	22.4	BCG_080	21.6	BCG_080	22.2
ABG_081	21.8	BCG_081	21.2	BCG_081	21.4
ABG_082	23.2	BCG_082	22.4	BCG_082	23
ABG_083	21.6	BCG_083	21	BCG_083	21.2
ABG_084	23	BCG_084	20.2	BCG_084	22.8
ABG_085	22.4	BCG_085	21.8	BCG_085	22
Average	24.93	Average	23.51	Average	25.05
AG_075	28.3	AG_075	28.3	AG_075	23.4
AG_076	27.5	AG_076	29.7	AG_076	24.8
AG_077	27.1	AG_077	28.3	AG_077	24.2
AG_078	29.7	AG_078	29.9	AG_078	24.6
AG_079	23.4	AG_079	24.4	AG_079	23.7
AG_080	23.6	AG_080	23.8	AG_080	25.4
AG_081	24.2	AG_081	25.2	AG_081	24.8
AG_082	23.4	AG_082	23.6	AG_082	25.2
AG_083	23.8	AG_083	25	AG_083	24.6
AG_084	24.4	AG_084	24.4	AG_084	25.4
AG_085	24.6	AG_085	24.8	AG_085	26
Average	25.45	Average	26.13	Average	24.74

5.7 Chapter Summary

The Remote relay testing service (RRTS) has been described in this chapter. The deployment of RRTS has been implemented using C#, .NET technology and WampServer package. The implementation of the proposed service enables users to enhance the troubleshooting testing that is performed by engineers on remote locations. The next chapter presents the conclusions of this thesis and discusses directions for future research.

Chapter 6: Conclusions

6.1 Expected Benefits

This dissertation has focused on three fundamental problems in fault analysis in power system, namely automated fault analysis service (AFAS) and remote relay testing service (RRTS), signal pre-processing analysis and Monitoring and Triggering intelligent electronic devices (IEDs) based on IEC 61850. Although there are existing solutions to these problems, new approaches proposed in the dissertation have their unique strength in solving these problems and have demonstrated their advantages. The expected benefits to be achieved from the proposed approaches are summarized as follows:

1. Automated Fault Analysis Service (AFAS)

Development of automated fault analysis via ASP enable user to investigate fault and disturbance online without having to install the fault analysis software and because it is available via the application service provider, so it is multi platform without having to worry about the operating systems installed in client computers.

2. Remote Relay Testing Service (RRTS).

Investigation of protective relay in substation using remote relay testing service will help the protection engineer and the maintenance crew to test the relay if there is a permanent fault or to change the setting of the relay remotely without having to go to the substation. So, the remote protective relay testing can possibly reduce the outage time and cost therefore it will also increase the reliability of the power system.

3. Signal pre-processing algorithm using wavelet transform and empirical mode decomposition methods have shown the strength of signal segmentation and modelling of fault and disturbance records. With the high segmentation accuracy of fault condition such as pre-fault, fault and post-fault event enable the automated fault analysis gain the more accuracy in the next stage of analysis functions. It will provide protection engineer a fast and reliable tool for identifying fault in the restoration process.

4. Monitoring and Triggering IEDs based on IEC 61850

With the integration of AFAS, GOOSE and the IEC 61850 protocol, it enables the IEDs to trigger the records when it achieves the threshold value, and without having to wait until the relay is tripped. The benefit is protection engineer can analyse the event record even the relay is not tripped. Furthermore, all the values from IEDs can be monitored via the web browser.

6.2 Future Work

Although significant achievements have been made in the dissertation study, due to limitation of time, many research topics still remain to be explored. Some further work is suggested as follows:

1. Deployment of automated fault analysis service (AFAS) in a microcontroller board. The board should support the web server, web services, Ethernet, MMS, OPC, TCP/IP and IEC 61850 protocol. The AFAS board can be connected directly to the IEDs using Ethernet to automatically retrieve event records or using MMS and OPC technologies to retrieve data via IEC 61850 protocol. Client will be able to see the graphical user interface because all the front end application will be stored in the web server of the board. This module can be integrated as part of the smart grid applications.

2. Development of AFAS with the utilising of intelligent system techniques such as particle swarm optimization (PSO) techniques, etc. For example, the implementation of PSO method to find the optimum fault type classification or fault location. PSO method can be developed in Matlab then compile as a library to integrate into the AFAS application which can be developed in C# and integrated into the AFAS.

3. The development of remote relay testing service (RRTS) in this study is only implemented using relay from Schweitzer engineering laboratories (SEL) such as SEL 421. However, the RRTS is designed to be compatible to all type of relays. Therefore, the future work will be the integration of RRTS with several types of relays from different manufacturer.

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Appendix A. Wavelet and Empirical Mode Decomposition

A.1. Wavelet Transform Method

The wavelet transform has drawn much attention from scientists and engineers over the years due to its ability to extract signal time and frequency information simultaneously [122]. By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. Wavelets have been successfully applied in a wide variety of research areas such as signal analysis, image processing, data compression and de-noising, and the numerical solution of differential equations.

Wavelet analysis represents the next logical step since it is a windowing technique with variable-sized regions [92]. It also allows for the use of long time intervals where more precise low frequency information is needed, and shorter regions where high-frequency information is required. One major advantage of wavelets is the ability to perform local analysis – to analyze a localized area of a larger signal.

It is argued in [122] that calculating wavelet coefficients at every possible scale requires a moderate amount of work, and it generates a considerable amount of data. It is also mentioned that if we choose scales and positions based on powers of two then our analysis will be much more efficient and just as accurate.

In the continuous wavelet transform (CWT), the analyzing function is a wavelet, ψ. The CWT compares the signal to shifted and compressed or stretched versions of a wavelet. Stretching or compressing a function is collectively referred to as scaling (dilation) and translation (time shift). If the wavelet is complex-valued, the CWT is a complex-valued function of scale and position. If the signal is real-valued, the CWT is a real-valued function of scale and position. The definition of CWT for a given signal *x(t)* with respect to a mother wavelet $\psi(t)$ is defined as

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\ \psi^*(\frac{t-b}{a})\ dt \qquad \text{(A.1)}$$

where a is the scale factor and b is the translation factor respectively, and ψ is the wavelet function. Not only do the values of scale and position affect the CWT coefficients, the choice of wavelet also affects the values of the coefficients. By continuously varying the values of the scale parameter, *a*, and the position parameter, *b*, the CWT coefficients *C(a,b)* can be obtained.

The application of wavelet transform in engineering areas usually requires a discrete wavelet transform (DWT), which implies the discrete form of *t, a,* and *b* in (A.1). The representation of DWT is given by

$$DWT(m,n) = \frac{1}{\sqrt{a_0^m}} \sum_k x(k)\ \psi^*(\frac{k-nb_0\ a_0^m}{a_0^m}) \qquad \text{(A.2)}$$

where the original a and b parameters in (A.1) are changed to be the functions of integers m and n. k is an integer variable and it refers to a sample number in an input signal.

Gaouda et al. [123] documented that, compared with continuous wavelet transform (CWT), the discrete wavelet transform (DWT) is sufficient to decompose and reconstruct most power quality problems. The DWT differs from the CWT with clear steps in the time-frequency plane that are considered as a multi-resolution wavelet analysis [123]. The purpose of the multi resolution signal analysis is to decompose the signal in multiple frequency bands, in order to process the signal in multiple frequency bands differently and independently.

Figure A-1 presents the DWT algorithm. Starting from an original signal *s*, two sets of coefficients are computed: approximation coefficients CA_1, and detail coefficients CD_1. These vectors are obtained by convolving *s* with the low-pass filter Lo_D for approximation, and with the high-pass filter Hi_D for detail, followed by dyadic decimation. More precisely, the first step is given by Daubechies [92] as can be seen in Figure A-2. The length of each filter is equal to $2N$. If n = length(*s*), the signals F and G are of length $n + 2N - 1$, and then the coefficients CA_1 and CD_1 are of length.

NOTE:
This figure is included on page 148 of the print copy of the thesis held in the University of Adelaide Library.

Figure A-1. DWT algorithm [122]

Multiresolution signal decomposition (MSD) can be realised with the cascaded quadrature mirror filter (QMF) banks [91]. A QMF pair consists of two finite impulse response filters, one being a low pas filter (LPF) and the other a high pass filter (HPF). The output of the low pass filter is the smoothed version of the input signal and is used as the next QMF pair's input. The output of the high pass filter is the detailed version of the original signal. Detailed description of the QMF can be found in reference [91]. Let $x[n]$ be a discrete-time signal, then MSD technique decomposes the signal in the form of WT coefficients at scale 1 into $c_1[n]$ and $d_1[n]$, where $c_1[n]$ is the smoothed version of the original signal, and $d_1[n]$ the detailed version.

$$c_1\ [n] = \sum_k h[k - 2n]\, x[k] \qquad \text{(A.3)}$$

$$d_1\ [n] = \sum_k g[k - 2n]\, x[k] \qquad \text{(A.4)}$$

where $h[n]$ and $g[n]$ are the associated filter coefficients that decompose $x[n]$ into $c_1[n]$ and $d_1[n]$ respectively. The next higher scale decomposition will be based on $c_1[n]$. Thus, the decomposition process can be iterated, with successive approximations being decomposed in turn, so that the original signal is broken down into many lower resolution components.

The MSD [91] technique decomposes a given signal into its detailed and smoothed versions. Let $x[n]$ be a discrete-time signal, then MSD technique decomposes the signal in the form of WT coefficients at scale 1 into c1 [n] and

$d_1[n]$, where $c_1[n]$ is the smoothed version of the original signal, and $d_1[n]$ the detailed version.

NOTE:
This figure is included on page 150 of the print copy of the thesis held in the University of Adelaide Library.

Figure A-2. Multiresolution signal decomposition realised by QMF [91].

Several types of wavelet in wavelet families are:

- Haar: is the first and simplest type of wavelet. It discontinues and resembles a step function. It represents the same wavelet as Daubechies db1.
- Daubechies: is one of the brightest stars in the world of wavelet research. The names of the Daubechies family wavelets are abbreviated dbN, where N refers to the order, and db to the surname of the wavelet.
- Biorthogonal: This family of wavelets exhibits the property of linear phase, which is used for signal and image reconstruction.
- Coiflets: The wavelet function has 2N moments equal to 0 and the scaling function has 2N-1 moments equal to 0.

- Symlets: The symlets are nearly symmetrical wavelets proposed by Daubechies as modifications to the db family.

- Morlet: The wavelet has no scaling function, but is explicit

- Mexican hat: This wavelet has no scaling function. It is derived from a function that is proportional to the second derivative function of Gaussian probability density function.

- Meyer: The Meyer wavelet and scaling function are defined in the frequency domain.

In this study, the universal threshold method [87] is implemented; the universal threshold T can be written as:

$$T = \sigma \sqrt{2 \log_e n} \quad \text{(A.5)}$$

where σ can be the median absolute deviation of the wavelet coefficients, or standard deviation, and n is the number of samples of wavelet coefficients.

A.2. Empirical Mode Decomposition Method

The empirical mode decomposition (EMD) method is a relatively new, data-driven adaptive technique for analyzing data from non linear and non-stationary processes, which was originally introduced by N. E. Huang et al. in 1998 [124].

The wide ranging applications of the EMD method that have been applied in the past few years have varied from analyzing climatology data for climate variability to the study of white noise characteristics in biological data [125]. The goal of EMD is to decompose a time series into a finite number of intrinsic mode functions plus a residual which is conventionally termed as the time series trend. It is stated in [94] that an IMF is a function that satisfies two conditions: (1) The number of extrema and zero-crossings of the function along the domain of interest must be equal or differ by no more than one; (2) The mean at any point of the envelope defined by the local maxima and local minima is zero.

Let *x(t)* be a time series defined on an interval [0,T]. We wish to decompose *x(t)* into a number L of elementary and termed intrinsic mode functions (IMFs) $d^{(i)}(t)$, $1 \leq i \leq L$

$$x(t) = \sum_{i=1}^{L} d^{(i)}(t) + r(t) \qquad \text{(A.6)}$$

where r(t) is a residual function that is a non-zero-mean slowly varying function with only few extrema. Each one of the IMFs, say, the *i* th one $d(i)$ (t), is estimated with the aid of an iterative process, called sifting, applied to the residual multicomponent signal

$$x^i(t) = \begin{cases} x(t), & i = 1 \\ x(t) - \sum_{j=1}^{i-1} d^j(t), & i \geq 2 \end{cases} \qquad \text{(A.7)}$$

The EMD facilitates calculation of physically meaningful instantaneous frequencies by using the Hilbert Transform [124]. The Hilbert transform can be used to define the instantaneous amplitude and phase of an arbitrary time series $X(t)$. The Hilbert transform of $X(t)$ yields a time series Y(t) can be written as

$$Y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{X(\tau)}{t-\tau} \, d\tau \qquad \text{(A.8)}$$

The inverse transform is given by

$$X(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{Y(\tau)}{t-\tau} \, d\tau \qquad \text{(A.9)}$$

x(t) and *y(t)* form a convolution pair, which constructs decomposed signal:

$$Z(t) = X(t) + jY(t) = a(t)e^{j\theta(t)} \qquad \text{(A.10)}$$

Where *a(t)* is instantaneous amplitude and *θ(t)* is the phase.

$$a(t) = \sqrt{X^2(t) + Y^2(t)} \qquad \text{(A.11)}$$

$$\theta(t) = \arctan\frac{Y(t)}{X(t)} \qquad \text{(A.12)}$$

The instantaneous frequency can be computed as:

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \qquad \text{(A.13)}$$

Where *f(t)* is the singular value function of time t.

It can be seen from the above that a general method of EMD requires two steps. The first is to pre-process the data by the empirical mode decomposition method, in which the data are decomposed into a number of intrinsic mode function (IMF) components. The second is do a Hilbert transform to the IMFs and construct the time-frequency-energy distribution, which is designated as the Hilbert spectrum, from which the time localities of events will be preserved.

The sifting process of the given signal *X* can be illustrated as follows. First, identify the local extrema in Figure A-3, and generate the two functions called the upper envelope and lower envelope by interpolating local maxima and local minima respectively, as can be seen in Figure A-4. Second, take their average, which will produce a lower frequency component than the original signal as in Figure A-5. Third, by subtracting the envelope mean from the signal *X*, the highly oscillated pattern *d* is separated. Huang et al. [124] defined an oscillating wave as an intrinsic mode function if it satisfies two conditions: 1) the number of extrema and the number of zero-crossings differs only by one and 2) the local average is zero. If the conditions of IMF are not satisfied after one iteration of the aforementioned procedure, the same procedure is applied to the residue signal as in Figure A-6 until properties of IMF are satisfied. This iterative process is called sifting.

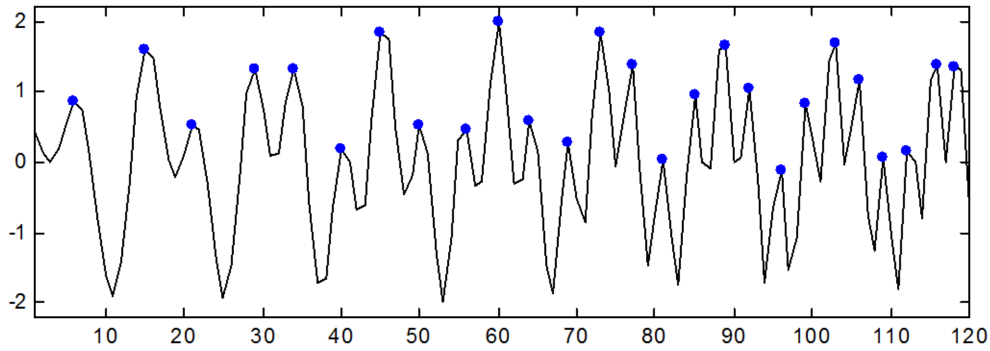

Figure A-3. Signal *X* with the local extrema identification

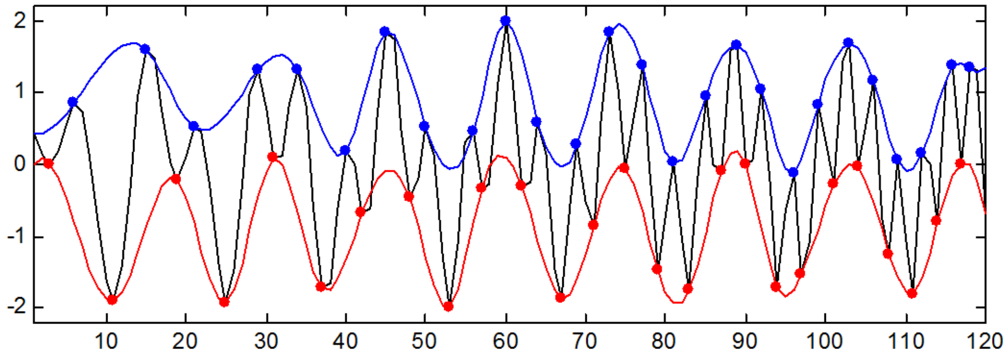

Figure A-4. Signal *X* with the upper and lower envelope

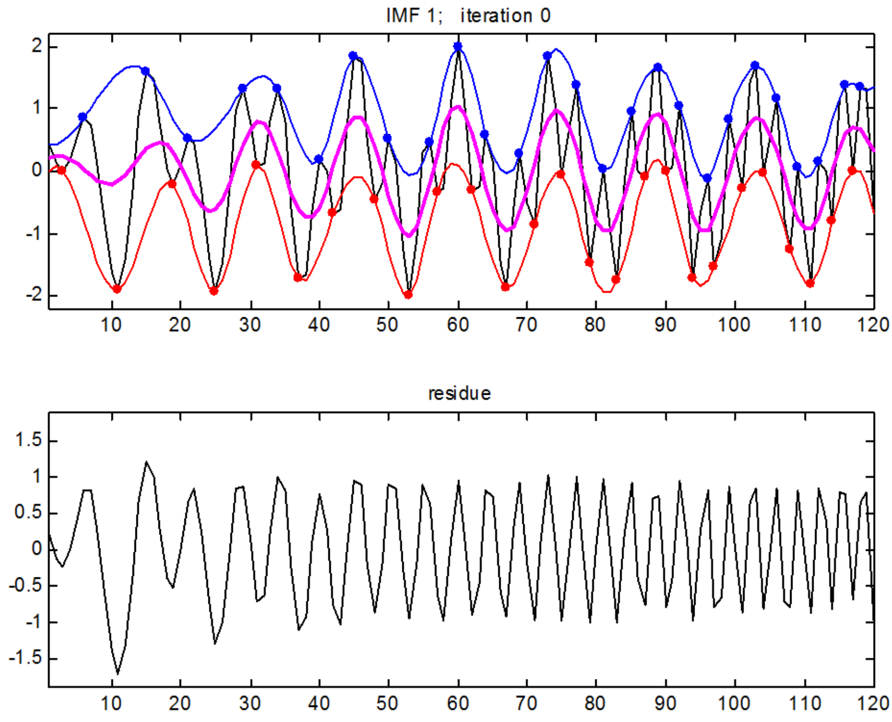

Figure A-5. Signal *X* with the average value and residual

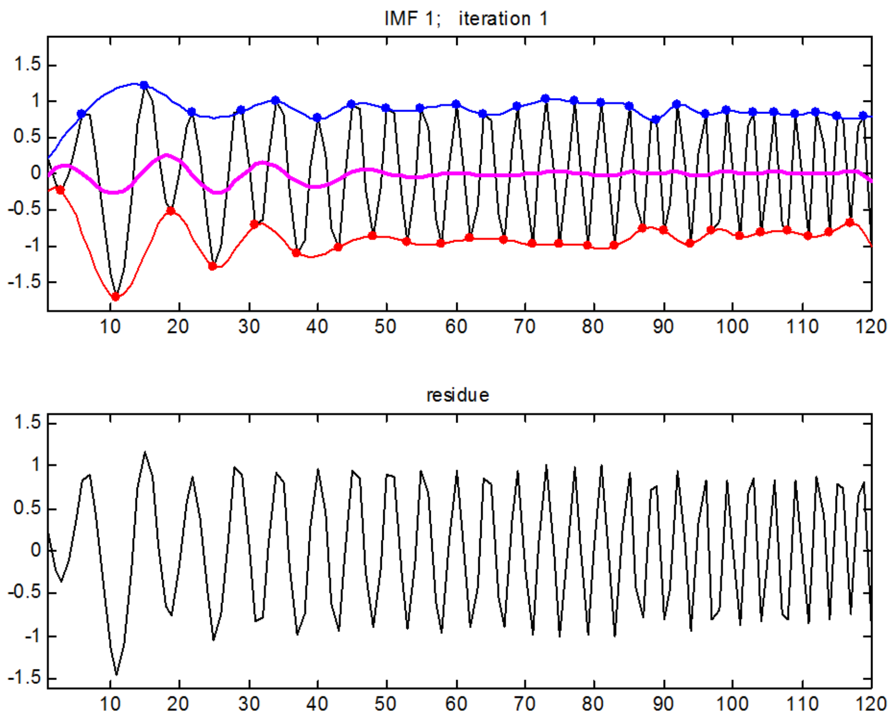

Figure A-6. Iteration 1 with the average value and residual