ANALYSIS AND TECHNIQUES OF DATA COMPRESSION IN SMART GRIDS IN THE CONTEXT OF IEC 61850 COMMUNICATION PROTOCOL

by

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A thesis submitted to the
School of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the degree of

Master of Applied Science

in

The Electrical and Computer Engineering

Faculty of Engineering and Applied Science

University of Ontario Institute of Technology (Ontario Tech University)

February 2020

THESIS EXAMINATION INFORMATION

Submitted by: **Rizwan Ayub**

Master of Applied Science (MASc) in Electrical and Computer Engineering

Thesis title: ANALYSIS AND TECHNIQUES OF DATA COMPRESSION IN SMART GRIDS IN THE CONTEXT OF IEC 61850 COMMUNICATION PROTOCOL

An oral defense of this thesis took place on February 11th,2020 in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

Abstract

A smart grid is characterized by a two-way communication between the generation and the loads in addition to the distributed energy resources, which dictated the integration of smart monitoring devices to achieve full observability of the network. In smart grid operation, the monitoring and the measuring devices such as smart meters, phasor measurement units (PMUs) and the intelligent electronic devices (IEDs) typically record the data and share the information across each level of the grid. In distribution substations, the data and hence the information is then further transferred throughout the supervisory control and data acquisition (SCADA) and the data control center using the communication protocols. As a result, a large amount of data is transferred among different monitoring devices, data control centers, and SCADA within the smart grid, which calls for new requirements for the communication channels and the storage capacities. Data compression is considered promising techniques to reduce the burden on the communication channels as well as the storage in particular during the smart grid operation. This thesis focuses on studying the data compression techniques when applied to power system disturbances in the context of the IEC 61850 communication protocol, which is extensively used in smart distribution substation automation. A proposed approach for data compression is introduced in this work and it is based on a combined wavelet-surrogate binary regression tree and a hybrid thresholding method. The proposed approach for data compression is tested experimentally in real-time in the context of IEC 61850 communication protocol and the performance is compared to the existing approaches for data compression. The results have shown that the implementation of the proposed data compression approach may lead to significant reduction in the number and sizes of the Generic Object-Oriented Substation Event

(GOOSE) messages, which are exchanged between the IEDS and the SCADA within the smart distribution substation automation in smart grids.

AUTHOR'S DECLARATION

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STATEMENT OF CONTRIBUTIONS

- The main contribution of this thesis is to introduce a new data compression approach that can provide significant reduction in the number and sizes of the GOOSE messages
- In this research Important Features of Signals are preserved while decomposition and reconstruction as discussed in Chapter#4.
- A novel approach is introduced that combines the wavelet transform and a surrogate binary regression tree discussed in detail in Chapter#4.
- This work Demonstrates the effectiveness of the proposed approach through implementing it in real-time using OPAL-RT and in the context of the IEC61850 communication protocol, which is extensively used in smart grids. Discussed in Chapter#6.
- Part of the work described has been submitted and is in review:
- R.Ayub, W. G. Morsi, "A real time wavelet-based data compression Technique for Smart grid using OPAL-RT and IEC61850," *IEEE Trans. Ind. Appl.*, -In Review

Acknowledgements

First and foremost, I would like to thank Almighty God, the compassionate, the almighty merciful, whose guidance kindly lead me to complete my thesis.

I would like to express my gratitude to my supervisor Dr. Walid Morsi Ibrahim for his continuous support throughout my studies. Learned a lot from him and his support.

My appreciation and deep thanks to all the students within our Smart Grid and Electric Vehicles research group at Ontario Tech University for helping me out in difficult time.

Thanks, and love are also due to my sisters who stood by me and always encouraged me. A special thanks and gratefulness to my mother, father who constantly prayed for me and encouraged me in every step of my life.

“Talent is cheaper than table salt what separates the talented individual from the successful one is a lot of hard work.”

Stephen King

Dedication

This thesis is dedicated to my mother and my father.

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Nomenclature

db	Dauechies Wavelet Family
sym	Symlet Wavelet Family
h_0	Low-pass Filter Coefficients
h_1	High-pass Filter Coefficients
T_j	Threshold value
$d_i k$	Detail coefficients
μ	Range
$MSEn$	Mean Square error
PI_m	Predictor Importance
d_1	detail at scale 1
d_2	detail at scale 2
d_3	detail at scale 3
$c_0 n$	Original Disturbance Signal
$\tilde{c}_0 n$	Reconstructed Signal
$x[t]$	Discrete time representation of signal x
f	Frequency
$NMSE$	Normalized Mean Square error
CR	Compression Ratio
DWT	Discrete wavelet Transform
FT	Fourier Transform
MRA	Multi Resolution Analysis
WT	Wavelet Transform
CWT	Continuous Wavelet Transform
STFT	Short Time Fourier Transform
SLT	Slantlet Transform

EZWT	Embedded Zero tree Wavelet transform
SM	Master Subsystem
SS	Slave Subsystem
SC	Console Subsystem
SSD	System specification Description
ICD	Capability of IED
CID	Configured IED Description
GOOSE	Generic Object-Oriented Substation Event
IED	Intelligent Electronic Devices
RTU	Remote Terminal Unit
SCADA	Supervisory control and Data acquisition

1. Introduction

1.1. Background

Smart Grid is characterized by two-way communication between the distributed energy resources, loads, distribution substations and the smart monitoring and control devices. The smart grid is considered an evolution of the traditional power grids by integrating artificial intelligence, advanced monitoring and controlling tools and signal processing techniques. Smart grids are different from the traditional grids not only in terms of the bi-directional power flow and the seamless communication but also in two-way communication between the distribution substations and the loads through a communication infrastructure that integrates the intelligent electronic devices (IEDs), the supervisory control and data acquisition (SCADA) and the switchgear devices[1], [2]. The smart grid monitoring devices such as the IEDs, the phasor measurement units (PMUs) and the Remote terminal units (RTUs), are connected to a communication network to communicate with each other on a regular basis. The smart devices like PMUs, IEDs and RTUs are available at different locations of the smart grid to share the statuses and other information through the Generic Object Oriented Substation Event (GOOSE) messages across each level in real-time (see Figure 1.1) [3]. The data recorded using the digital fault recorders (DFR) and the IEDs often must be transferred across communication links throughout the smart grid to the SCADA and to the data control centers for further analysis and study. Moreover, during smart grid operation, the exchange of information using GOOSE messages, is performed in a cyclic manner even there are no change in the statuses, a phenomenon alike a heartbeat mechanism[4]. The widespread installation of Smart meters contributes to the smart grid operation because of the bi-directional communication capabilities of such digital meters to establish appropriate interactions between the customers and the utility, hence enabling the exchange of real time consumption of data, power quality data, electric parameters and the ability to connect or disconnect with grid operators[5], [6].

The outcome of such information exchange as part of the smart grid operation is a massive amount of GOOSE messages being published and received, which may lead to communication channels congestions and a limited storage space. The IEC61850 standard in [7] defines 355 different classes of data that can be exchanged between these devices to report 13 classes of system information, 11 classes of physical device information, 66 classes of measurands, 14 classes of metered values, 36 classes of controllable data, 85 classes of status information and 130 classes of settings. Sharing of such information across each level of the smart grid may be at the supervisory control and data accusation (SCADA), the smart meters, the Wide area monitoring systems (WAMSs), the RTUs as well as the IEDs and other monitoring devices in the field [8]. This massive amount of data circulates every Micro or Nano seconds to the electric utilities, the data control centers as well as to the customers in a real-time manner. This significant increase in the data exchange will need new sets of requirements regarding the use of the communication channels bandwidth and an increase in the storage space.

According to [9], the large number of smart monitors and meters will be installed in the distribution systems to allow real-time monitoring of the system operation in particular when considering the bi-directional power flow through exchanging GOOSE messages in real-time. For example, power quality monitoring devices can have voltage and current fault data at sampling frequency of 1msps and 250ksps.For this situation considering four channels for voltage and current recording the one sec of waveform can have 10MB of data which can reach to Giga and tetra bytes per day for one recording device.

Therefore, it is very important to compress this large amount of information, and transfer it without any loss during transmission process. Data compression techniques are considered a promising avenue to help alleviating such a problem

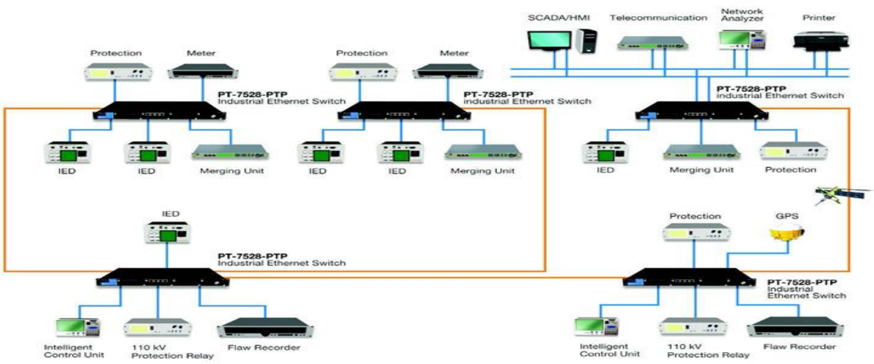


Figure 1.1 Smart Monitoring Devices Communication in Smart Grid [3]

1.2. Problem statement and Motivation

In smart grid operation, the information exchanged between the smart monitoring devices, the SCAD and the data control centers exponentially increases which leads to a massive amount of GOOSE messages being exchanged. Therefore, this calls for new set of requirements for the communication channels bandwidth and the need for increased storage space. Furthermore, one of the main issues that will be faced by the future smart grid power is to transfer these data exchanging GOOSE messages, statues from one monitoring devices to the other without loss of information in smart distribution systems.

Therefore, the use of data compression techniques may provide a solution to help reducing this burden, which can not only help reducing the transmission communication congestion but also compress the signal at the same time helps preserving the original features of the signal. The basic requirement of any data compression technique is to keep the salient features of the signal i.e. abrupt changes even after the compression and the data can be nearly reconstructed at the receiving end.

The main motivation of this research to introduce a more effective wavelet data compression approach, which could perform a more effective compression of the disturbance signals as well as reduces more bytes compared to the existing approaches. This thesis presents a new approach that uses hybrid thresholding (a combination of hard and soft thresholding) in performing the compression unlike in previous work in which only one type of thresholding is used. Furthermore, the proposed approach is implemented in real-time through experimentally assessing its performance by monitoring the GOOSE messages exchanged using OPAL-RT in the context of IEC61850 communication protocol.

1.3. Contributions

The main contributions of this thesis can be listed as follows:

- The main contribution of this thesis is to introduce a new data compression approach that can provide significant reduction in the number and sizes of the GOOSE messages exchanged while preserving the salient features contained in the analyzed disturbance signals.
- The work presented in this study aims to address such a problem by introducing a novel approach that combines the wavelet transform and a surrogate binary regression tree. The use of the surrogate binary regression tree is to predict the wavelet decomposition level(s) that retain the most salient features of the

disturbance following the signal decomposition and before applying the wavelet compression. A hybrid thresholding is then applied, which combines both soft and hard thresholding, in such a manner to preserve the prominent salient features identified by the surrogate binary regression tree. This will eliminate the need for the trade-off that must be made in traditional approaches between the compression ratios and the measured distortions and hence the salient features of the disturbances are kept in the reconstructed signal.

- This thesis demonstrates the effectiveness of the proposed approach through implementing it in real-time using OPAL-RT and in the context of the IEC61850 communication protocol, which is extensively used in smart grids.

1.4. Thesis Organization

This thesis includes seven chapters. Chapter 1 explains the importance of data compression techniques in smart grids followed by the problem statement and motivation. Finally, the thesis contributions towards this research are outlined.

Chapter 2 surveys different methods for data compression previously published in the literature. The advantages and the disadvantages of each method are presented and discussed. The main research gap of the existing methods is highlighted, and finally the main objective of proposed wavelet data compression approach is presented.

Chapter 3 is dedicated to the multi-resolution analysis and the Wavelet transform. This chapter explains the mathematical background of the Wavelet transform and its comparison with other transforms. Moreover, the wavelet functions and families are also discussed in detail. Additionally, the Decomposition and Reconstruction process using Multi-resolution analysis (MRA) are discussed in this chapter.

Chapter 4 Describes the methodology used to address the data compression process using the wavelet transform. Specifically, the hard and soft thresholding along with their advantages and disadvantages are discussed. Furthermore, the metrics used to assess the goodness of compression are presented and finally, a detailed description of the proposed wavelet-surrogate binary regression using hybrid thresholding is presented.

Chapter 5 discusses the real time experimental set-up and software used to experimentally test the proposed data compression approach in real-time. The chapter presents the RT-LAB simulation set-up, the blocks used, as well as the OPAL-RT. Furthermore, the chapter sheds the light on the basics of the GOOSE messages set-up, and how to implement in real-time using OPAL-RT in the context of the IEC61850 communication protocol.

Chapter 6 introduces the results of the simulation and the real time experiment with detailed extensive analysis. An in-depth introduction of the RT-LAB simulation is presented including methods of sending disturbances signals from PC to OPAL-RT mother board. The existing and the proposed data compression approaches using WT are implemented in real-time using OPAL-RT considering different disturbances signals. The results are presented and discussed to demonstrated the effectiveness of the proposed approach in data compression in terms of the number and sizes of the GOOSE messages received.

Finally, Chapter 7 presents the main conclusion and recommendation regarding the effect of data compression technique on the GOOSE messages exchanged in light of the IEC61850 communication protocol compared to other existing approaches. Finally, the future work that can be based on the work presented in this thesis is presented.

2. Literature Review

2.1. Introduction

The main goal of this literature review is to provide a review of the existing data compression methods applied to power systems signals. By reviewing the previously published work the readers should be able to understand the basics concepts of data compression methods and their application to power system disturbance signals. Moreover, this chapter will shed the light on a research gap in the literature which is relevant to the implementation of the data compression in real-time and its implications on the communication protocols used in smart grids. Furthermore, this chapter gives an insight on the advantages, disadvantages and limitations of the existing data compression methods. Finally, this chapter identifies the research gap that currently exists in the literature and pave the way towards the main contribution of the research work presented in this thesis.

2.2. Previous Work on Data Compression

This section presents the existing methods that are introduced in the literature for data compression. The previous work is classified into two different types non-wavelet methods [10]-[16]and wavelet-based methods [19]-[23] as discussed below.

2.2.1 Non-Wavelet Based Methods

In [10] combination of Wavelet Packet Transform and the minimum description length criterion are used to perform compression on signals from KEPCO Japan. Moreover, they used different kind of wavelet filters to carry out this compression methods the main limitation of this method is it required higher sampling rate and have usage of filters as well as it requires usage of several wavelet functions. In[11] Slantlet transform is used to compress the power quality signals. They used MATLAB Simulink to perform the disturbances like voltage sag swell and further used to compress them and reconstruction is done through slantlet transform inverse (SLT inverse). Moreover, to check the efficiency of their method they used NMSE (Normalized Mean square error) in decibels. Panda at al.[12] worked on a similar approach where they used the Spline wavelet and S-transform to perform compression. The Spline transform is explained in equation 2.1and ,2.2. Using this method, they achieve reasonable amount of compression ratio and NMSE as well.

$$\partial(x) = \sum_{k \epsilon z} c(k)\beta^n(x-k) \qquad (2.1)$$

$$\beta^n(w) = \left(\frac{\sin(\frac{w}{2})}{w/2}\right)^{n+1} \qquad (2.2)$$

Where $\beta^n(x)$ is center-symmetric B-spline of degree n and is used for compression and reconstruction of power quality data. In [13] a data compression method based on neuro fuzzy method was used. They used neural-network paradigms with supervised learning as well have used sugeono mechanism with in neural fuzzy method. In [14] a power system fault data compression technique using vector quantification is proposed. Huffman coding algorithms along with vector quantization. A similar modified approach is utilized in [15] where the Huffman coding along with the wavelet was used. They compared their proposed method results with a compression tool software WINZIP. Results shows that WinZip cannot achieve higher compression ratio as compare to wavelet compression. Moreover, while using WINZIP tool important features of the signal while compression is not kept under consideration as those are the important features and important abrupt changes of disturbance signals. It is worth noting that the previous work in [16]relied on

Embedded zero tree wavelet EWZT where simulated PMU signals and Real PMU signals were compressed and result were compared.

2.2.2 Wavelet Based Methods

Studies [17]–[19] were credited to introduce compression techniques based on the lossless coding in which the reconstructed signal becomes identical to the original signal. The main limitation of the lossless coding-based techniques is they suffer low compression ratio as well as the high requirement of sampling rates[17]. On the other hand, studies employed the wavelet-based compression to achieve higher compression ratios compared to the lossless-based compression. Santoso et al in [19] were pioneered in applying the discrete wavelet transform (DWT) to power quality data using the disturbance from New York Manhattan Building. The discrete wavelet transform was applied to four power quality disturbance signals to obtain the details and the compression was performed by applying hard thresholding to all detail levels. The hard threshold used is shown in equation below.

$$d_s(n) = \begin{cases} d_s(n) & |d_s(n)| > n_s \\ 0 & |d_s(n)| < n_s \end{cases} \qquad (2.3)$$

Despite the outcome of this process have shown compression ratios reaching 2.9 and 5.32 varies according to the type of signal, the application of the hard thresholding is usually associated with certain drawbacks and limitations such as discontinuity at reconstruction stage and many issues can be faced as discussed in Chapter 4 section 4.2.Furthermore, the study did not include any real-time implementation of the data compression method used and hence the effect of data compression on the GOOSE messaging in the context of IEC61850 could not be studied.

Jixian et al.[20] proposed a Wavelet based data compression and denoising technique where Daubechies of order 2 (db2) and 5 scale of decomposition were used for data compression. The study in IEEE-39 bus system to justify their approach where they used voltage and frequency disturbance signals. In[21] combination of Wavelet transform and Wavelet packet were used to compress and evaluate the actual Digital fault recorder signal (DFR). Which was then transferred through a simulated public switch telephone line (PSTN). The main drawback of this method is that it cannot be used to transfer the Actual Power Signals and is not applicable in real time manner where it is actually needed for. Jesim.et al.[22] a wavelet packet transform method with optimal tree function is used to compress and denoise the disturbance signal. They used different disturbance signals from Frequency fault recorders (FDR), Phasor measurement units (PMU). Optimal tree function is shown figure.2.1.

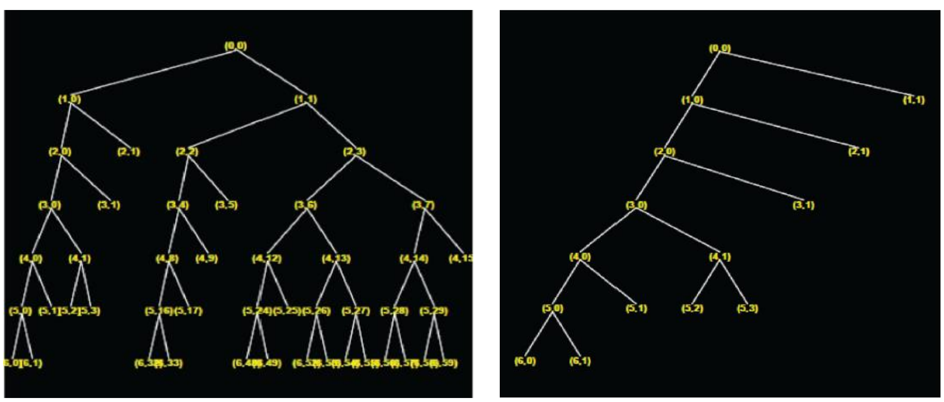


Figure 2.1: Example of Best Optimal tree [22]

Research in [23]used a waveform coding and enhanced athematic coding technique based on wavelet transform to compress power Quality disturbance signals. In most of the researches mentioned above a proper effective way of power disturbance data compression is not mentioned which can used to be implemented on real smart grids. Additionally, a real time implementation in the researches is lacking.

2.3. Research Gaps

Table 2.1 summarized the previous work that has been published in the literature. The following represents a summary of the research gaps identified in the previous work.

- The previous work published in the literature lacks the real-implementation of the data compression methods to experimentally testing their effects on the exchanged GOOSE messages in the context of IEC61850 communication protocol, which is extensively used in smart grids.
- The previous methods on data compression uses one of two thresholding types, either hard or soft thresholding, which results in several limitations to the outcome of the compression process a in depth comparison of both the threshold is done in Chapter 4 Section 4.2.
- The lossless coding-based techniques suffer low compression ratio as well as the high requirement of sampling rates while in the lossy-based coding a tradeoff must be made. The previous work lacks a systematic approach to get rid of the trade-off that must be made and hence avoid any compromise in retaining the salient features of the disturbances following the compression process.

Table 2.1: Literature Review of Wavelet based and Non-wavelet-based Data compression Approaches

Ref.	Wavelet type/Other Techniques	Function	Optimal decomposition scale	Type of Threshold	Real-time Implementation	Fault data type
[10]	Minimum Description Length Criterion and WPT	db5	3	Hard	×	Signal phase to Ground fault event
[11]	Slantlet Transform	db2	3	Hard	×	Voltage sag, swell, Harmonic Distortion Signal
[12]	Spline wavelet and S-transform	Db2	3	Hard	×	Impulsive transient, Variable frequency, Momentary Interruptions
[13]	Fuzzy Logic	N/A	N/A	N/A	×	Power Quality Disturbance
[14]	Huffman Coding and Vector Quantization	N/A	N/A	Hard	×	A phase Fault current
[15]	Enhancement data compression approach (EDCA)	N/A	N/A	N/A	×	PQ signals
[16]	Embedded Zero tree Wavelet	N/A	3	Hard	×	Real PMU signals
[17]	FFT (Fast Fourier Transform)	N/A	N/A	N/A	×	Data fault recorder from Texas A&M
[19]	DWT	db2	3	Hard	×	Power disturbance data
[20]	DWT(MRA)	db2, Sym2	5	Soft	×	Frequency, Voltage Drop
[21]	Both, LZW algorithm	db4, db20	3	Hard	×	Neutral current Signal
[22]	Wavelet Packet	Coif1-5, db2-14, sym2, sym13	Optimal Tree	Hard	×	FDR, PMU load Voltage Data

N/A Not Applicable, Detail Not Available, ×Not Performed

2.4. Research Objective

- The need for real time implementation and experimental testing to understand the effect of data compression on IEC61850 communication protocol.
- A need for hybrid method to benefit from the advantages of both thresholding methods and performing more effective compression.

- A need for a systematic approach to preserve the salient features in the disturbance signals when using the lossy-based techniques to avoid the trade-off hat must be made.

2.5. Summary

This chapter discusses the previously published work in the literature concerning data compression for smart grid applications. The concepts of lossless and lossy-based data compression were introduced and pros and cons of each were identified. Furthermore, the data compression methods were classified as wavelet-based and non-wavelet-based methods. In the lossless methods the main limitation of the lossless coding-based techniques was that they suffer low compression ratio as well as the high requirement of sampling rates and are less reliable. In case of the wavelet-based data compression it was concluded that all the previous published research was not implemented in real time and not being experimental tested to understand the effect of data compression on IEC61850 communication protocol in real life smart grid. Additionally, a there was not a proper approach to perform an effective comparison by using a hybrid threshold i.e. Hard and soft threshold and take benefit from the advantages of both thresholding methods.

On the other hand, in case of non-wavelet-based data compression for disturbance signal not much work has been done and existing approaches are impractical to implements those methods on real time smart grids. Lastly, This Chapter concludes by identifying the research gaps and proposes a modified approach to fill these gaps. The next chapter will explain the detail of Wavelet transform and its comparison with other analysis techniques.

3. Wavelet Based Data Compression ‘‘The Traditional Approach’’

3.1. Introduction

In wavelet transform, the original signal which is in the time domain is transformed into the time-scale domain. In this chapter the fundamentals of the Discrete wavelet transform (DWT) is presented, as well as a comparison with other transform analysis technique followed by a detailed explanation of the use of the multi-resolution analysis in extracting the features of the signals a decomposing the scales into approximation and details. The chapter concludes with an in-depth discussion of the decomposition, reconstruction process and traditional approach used.

3.2. Types of Wavelet Functions

In Transform analysis different kind of wavelet family are used and each of them have different properties. More about these Wavelet families and functions are discussed in Table 3.1 and [24].

Table 3.1: Properties Comparison of Different Wavelet Functions

Wavelet Function	General form	Members range	Orthogonal	Biorthogonal	Filters length	DWT	Vanishing moments numbers
Daubcechies	dbN	Db1-db45	✓	✓	2N	Possible	N
Symlets	symN	Sym2-31	✓	✓	2N	Possible	N
Biorthogonal	biorNr.Nd	Bior1.1-bior 6.8	×	✓	Max(2Nr,2Nd) +2	Possible	Nr
Coiflets	CoifN	Coif1-coif5	✓	✓	6N	Possible	2N
Discrete Meyer	Dmey	1	✓	✓	102	Possible	-

× Not Available,✓ Available

Each wavelet family and function described above have different energy and are used for different kind of application. The Daubechies (dbN) and the Symlets (symN) are the wavelet family members usually used in power quality detection. These two wavelets functions are mostly used to detect the discontinuity and sudden changes in any power quality disturbances signals [8], [19]

3.3. Discrete Wavelet Transforms

In this section a comparison of Discrete Fourier transform (DFT), the Short-time Fourier Transform (STFT) and the Wavelet transform is presented. Discrete Fourier transform can be mathematically described as (3.1).

$$x[f] = \frac{1}{N}\sum_{t=1}^{N-1} x[t]e^{-\frac{i2\pi ft}{N}} \qquad (3.1)$$

where, x(t) is the original target signal, $e^{-\frac{i2\pi ft}{N}}$ is the function to perform the Fourier transform, and X(f) is the frequency representation with t is time, f is frequency and N is the total length of the signal. There are some drawbacks of Fourier transform in signal processing that is the window size is always fixed, since the DFT window is computed assuming that there is no change in the signal outside of this window, which further creates different issue for non-stationary signals. Furthermore, The DFT only provides an amplitude-frequency spectrum of the signal and the time information of the signal is totally lost. To overcome such limitations, the STFT [25] was introduced and it is mathematically expressed as:

$$X[f,\tau] = \sum_{n=-\infty}^{\infty} x[n]g[n-\tau]\, e^{-i2\pi fn} \qquad (3.2)$$

The advantage of using the STFT is that it uses a moving window function $g[n-\tau]$ where τ is the amount in which the shifts at one time, x[n] is a time domain representation of original targeted signal, x[f] is frequency domain representation of original targeted signal and g[n] is window function with a fixed window size of τ. At the same time this moving window in time domain might create problem, as the moving window decreases the frequency resolution increases but at the expense of the time resolution. In order to address these pervious two complication of fixed window size, the Wavelet transform was introduced.

The wavelet transform is a time-frequency analysis representation, which is suitable for non-stationary signals. Unlike DFT and STFT, which uses sine and cosine functions as the base signals for analysis as well as have fixed window size to perform analysis, the wavelet transform uses a large numbers of wavelet functions from the wavelet library. Furthermore, the wavelet transform is characterized by a variable window length [26], which lead to better time-frequency resolution compared to STFT. This improvement was due to the variable window size that is offered by the wavelet transform, which mathematically expressed as:

$$X[f] = \frac{1}{\sqrt{v}} \sum_{t=-\infty}^{\infty} x[t] w \left[\frac{t-\varphi}{v}\right] \qquad (3.3)$$

Where x[t] is the original signal, w[t] is the wavelet function, v and φ are the scale and shift parameters respectively. More about the wavelet forming orthogonal basis and different compulsory conditions are discussed in [27], [28]

3.3.1 Multi Resolution Analysis

In discrete wavelet transform (DWT), the signal important features are represented in both time and frequency domain using the multi-resolution analysis (MRA) [29]. The Multi-resolution analysis apply successive decomposition to the approximation with no further decomposition to the details. In MRA, the original signal $x(t)$ is decomposed into low frequency and high frequency components, where the approximation represents the low frequency components and the details represent the high frequency components. The details resolution levels are the most important part of the decomposed signal since the transient features (i.e. sharp edges, abrupt changes) of the signal are usually contained within the details while the approximation usually contains a smooth version of the original signal. The approximation and the details form orthonormal basis and are connected to the low-pass and the high-pass filters by Equation (3.4) and (3.5). During the analysis decomposition stage, down sampling is performed while in synthesis reconstruction stage the up is performed. For more information on Multi resolution analysis (MRA) readers may refer to[30].

$$\emptyset(t) = \sum_{k} h_o\,(k)\sqrt{2V}(2t-k) \qquad (3.4)$$

$$w(t) = \sum_{K} h_1(k)\sqrt{2V}(2t-k) \qquad (3.5)$$

Where h_o is low pass filter, h_1 is a high pass filter coefficient, $\emptyset(t)$ is scaling function and $w(t)$ is wavelet function. [31], [32].

The MRA typically splits the signal into high and low frequency components in which the signal is represented by one approximation and more than one detail level. The number of decomposition levels is a function of the sampling frequency and the length of the signal. Each of these details and approximation contain different frequency ranges and an example of how the Multi resolution analysis is performed is as shown in Fig. 3.1 where a three-level decomposition for a target signal using db2 is performed. MATLAB toolbox was utilized to perform this decomposition[33].

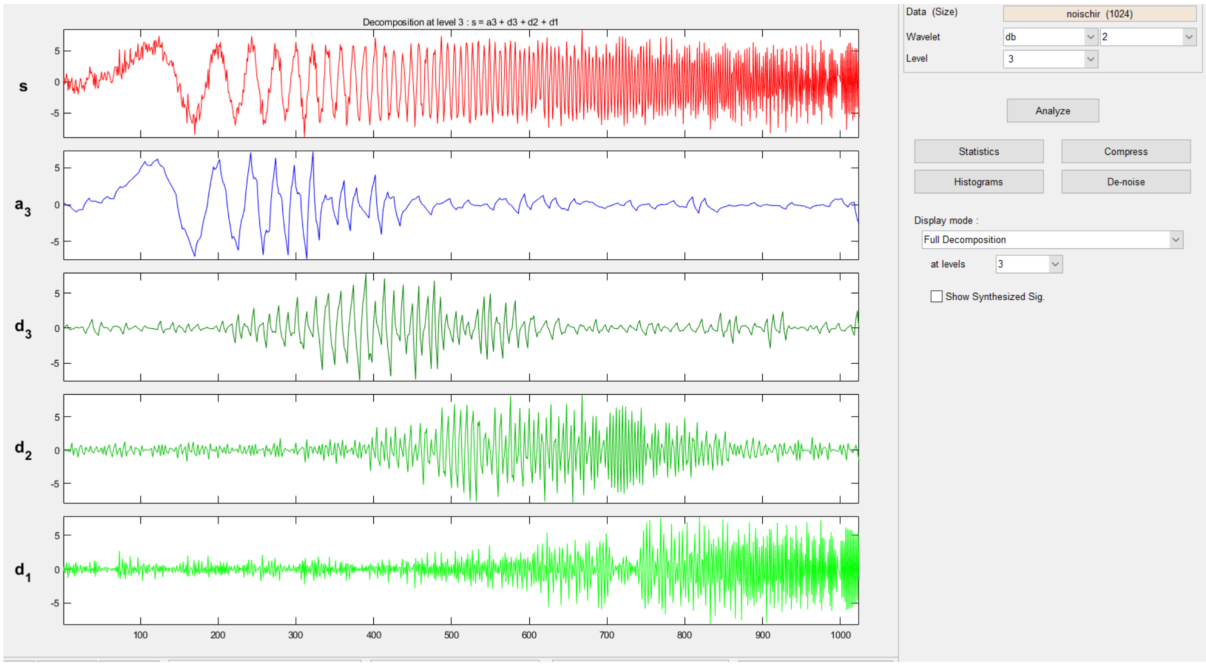


Figure 3.1: Example of Multi resolution Analysis

Where s is the signal to be decomposed, a3 is the approximation for three levels of decomposition and d_1, d_2, d_3 are the details.

3.3.2 Continuous Wavelet Transforms

The Continuous wavelet transform (CWT) represents a time scale representation and it can be mathematically expressed as [34]:

$$CWT(a,b) = \frac{1}{|a|^{1/2}} \int_{-\infty}^{\infty} x(n)\varphi\left(\frac{n-b}{a}\right) dn \qquad (3.6)$$

Where φ is the shifted and scaled mother wavelet, a and b are the scale and time shifts indices respectively More about CWT is discussed in [34].

3.3.3 Comparison of Different Transform Analysis Techniques

The main drawback of using DFT and STFT that they have fixed window size, which can result in having poor resolution, whereas CWT overcomes the limitation of the DFT and

STFT regarding the time-frequency resolution. However, in many power system applications, there is no need to represent the signal using every sample time and shift as in the CWT and hence the need for the concept of multi-resolution analysis emerges to provide different frequency sub-bands as in the DWT. Therefore, the work in this thesis focuses on the use of MRA and the DWT to perform the analysis using the wavelet toolbox in MATLAB. Moreover, table 3.2 shows the comparison result of different transforms i.e. (STFT, DWT, CWT). The table shows the DWT outperforming the other techniques by showing a smallest computational time value hence DWT is selected as signal; processing technique to extract the important features of the disturbance signals.

Table 3.2 Computational Complexity of Transform Analysis

Techniques	**STFT**	**DWT**	**CWT**
Computational time (sec)	0.1954	0.0049	0.2415

3.4. Decomposition Process

In the decomposition stage, the MRA provides the “Approximations” and “Details”. The Approximations represent the low-frequency components whereas the Details represent the high frequency components of this decomposing stage. The resolution of the Detail levels is the most important part of the decomposed signal because they contain the transient features (i.e. sharp edges, abrupt changes) of the signal, whereas the Approximation part contains the smooth version of the signal and represents almost the same shape as original signal. These details and approximation are obtained by passing the signal through filter banks(decomposition) i.e. high pass and low pass filters. Low pass filter removes low frequency components whereas a high pass filter removes the high frequency components of the signal this process is shown in Fig.3.2.In WT-based MRA as shown in Fig.3.2 a two-time down sampling rate is adopted to ensure the equivalence in the number of sampling points before and after whereas Nyquist rule is applied to sample any signal and sampling at each decomposed scale [35] this shows that WT have nonredundant property.

Let's suppose $c_o(n)$ is the original signal, the decomposition of this signal can be obtained by passing this signal through the low-pass filters i.e. $g(n)$ and $h(n)$. The coefficients $c_1(n)$, $d_1(n)$ are obtained after the decomposition of $c_o(n)$ and they are defined in equation 3.7 and 3.8.

$$c_1(n) = \sum_k h\,(k - 2n)c_o(k) \qquad (3.7)$$

$$d_1(n) = \sum_k g\,(k - 2n)c_o(k) \qquad (3.8)$$

The decomposition stage is depicted in Figure 3.2. and as discussed earlier in each of the decomposed level the length of the signal is half as compare to the former stage.

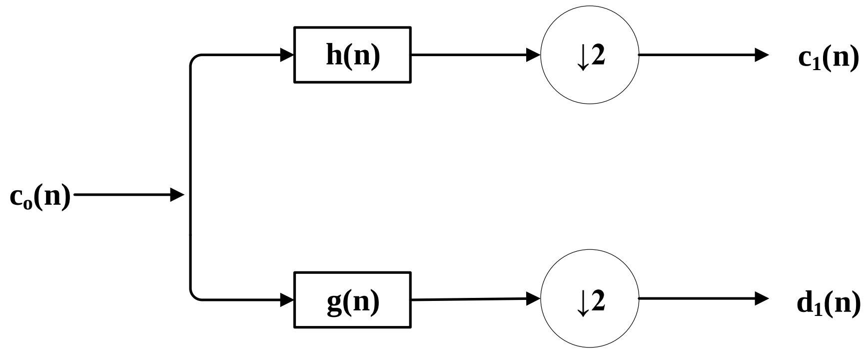


Figure 3.2: Decomposition Process During MRA

3.5. Reconstruction Process

In this stage, the approximations and details at each scale are passed through high-pass filters and are up-sampled by two and added at the end. This process is done at each scale as in decompositions to obtain the original signal, as shown in Fig.3.3. The reconstruction stage can be mathematically expressed as:

$$c_o(n) = \sum_k c_1(k)h(n-2k) + d1(k)g(n-2k) \qquad (3.9)$$

Where $c_o(n)$ is reconstructed signal from decomposed signals c_1 and $d1$ whereas $g, h(n)$ are high pass filters.

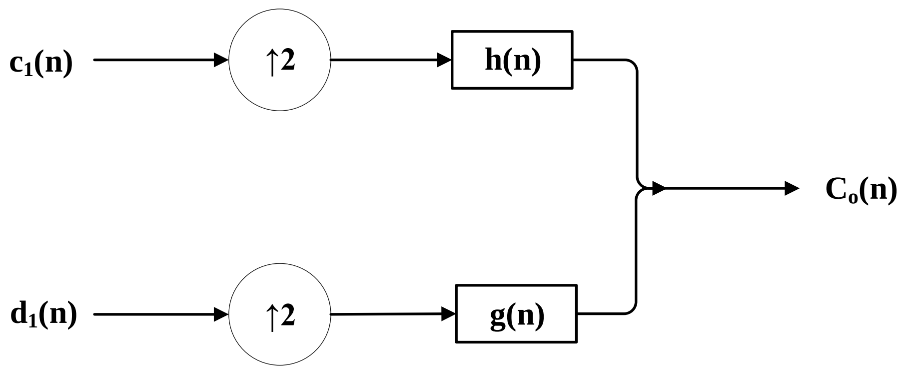


Figure 3.3: Reconstruction Process During MRA

3.6. Traditional Approach

The traditional approach starts with decomposition step through MRA which gives approximations and details. To all the details hard threshold is applied and is added at the end with the approximation to get back to the original signal in reconstruction stage. The block diagram below depicts the process of wavelet based traditional approach.

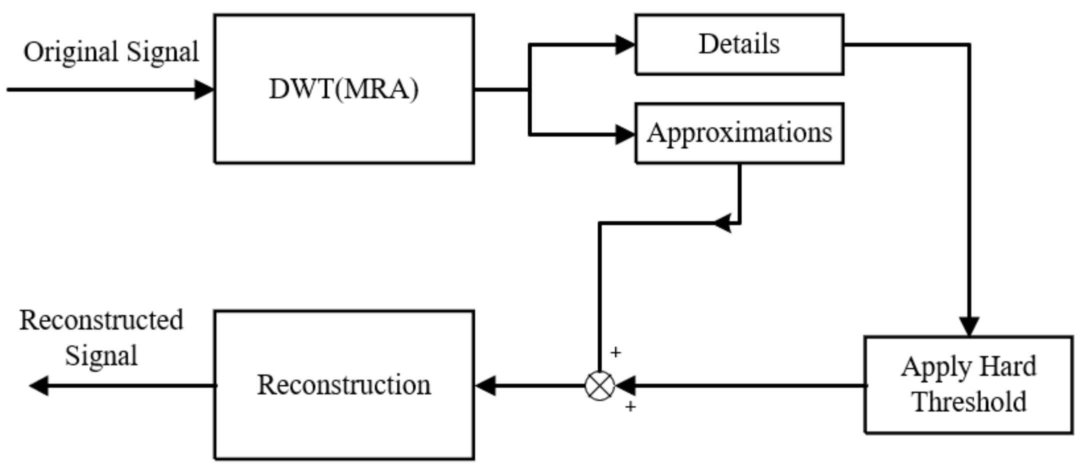


Figure 3.4 Procedure of Traditional Approach [19]

3.7. Summary

In this chapter, a comparison of different transform analysis techniques is presented. It was observed that both STFT and DFT suffer due to the fixed window size and hence the trade-off between the time and frequency resolution. The WT method overcome such limitations by introducing the variable window size and hence the MRA which provide different frequency sub-bands at different frequency ranges. Furthermore, the numerous wavelet functions available in wavelet transform and their properties help in detecting transients and power quality disturbance events. The decomposition stage using MRA is also discussed in this chapter as well as the reconstruction stage along with its implementation. Lastly the Traditional approach is explained in a block diagram.

4. Wavelet Based Data Compression ‘‘The Proposed Approach’’

4.1. Introduction

This chapter presents an overview of the proposed approach for data compression which is based on a combined wavelet-surrogate binary regression and hybrid thresholding. The proposed approach is then compared to the traditional approach for data compression that is based on wavelet transform. As discussed in [19], [20] the wavelet transform has an excellent performance in detecting and localizing the abrupt changes, discontinuity in any disturbance signal. The compression is accomplished in a wavelet domain low-amplitudes in detail scale retaining the coefficients which are related with the disturbance event because these are important part of signal and discarding those which are disturbance free or distortion. The approximation of any decomposed signal is an important scale as it represents the properties of original signal. The thresholding is applied to the details while the smoothed (approximation) signal is kept for reconstruction purposes. The reconstructed signal is usually characterized by less distortion, less in both size and length as compared to original signal.

4.2. Threshold

There are two kind of thresholds that can be used for wavelet data compression purposes. The main goal of implementing any of these thresholds is to remove the disturbance free events in any disturbance signal whereas keeping the abrupt changes in a signal without losing the original shape and form of the signal. In this way the disturbance free coefficients are discarded. The thresholding of the coefficients can be carried out in many different ways. One of the simplest methods is to eliminate the zeros and distortion below a certain threshold τ_j whose value may vary from scale-to-scale. The Threshold is selected based on absolute maximum value of certain scale and may differ depending on the wavelet coefficient scale. When compressing the details of any signal, a threshold value τ_j is selected by finding the maximum the absolute value of the detail coefficients $d_i(k)$ and eliminating the zeros and any noise below that threshold.

$$\tau_j = (1 - u) \times \max\{|d_i(k)|\} \qquad (4.1)$$

Where, the value of u ranges from 0 to 1 and it is recommended to be 0.9 according to[19].

4.2.1 Hard Threshold &Soft threshold

Hard threshold can be applied to the wavelet details by Equation. (4.2) as follows:

$$d_i(k) = \begin{cases} d_i(k) & |d_i(k)| \geq \tau_j \\ 0 & |d_i(k)| < \tau_j \end{cases} \qquad (4.2)$$

Whereas soft threshold is applied using Equation. (4.3)

$$d_i(k) = \begin{cases} d_i(k) - \tau_j & d_i(k) \geq \tau_j \\ 0 & |d_i(k)| < \tau_j \\ d_i(k) + \tau_j & d_i(k) \leq -\tau_j \end{cases} \qquad (4.3)$$

4.2.2 Comparison of Hard Threshold and Soft Threshold

Both these thresholds have different pros and cons. Both of these thresholds have different properties and are used for different purposes as well. An in-depth comparison between both of these thresholds is done below.

Hard Threshold

- Hard threshold is usually discontinuous at threshold points and it might produce oscillation and Pseudo-Gibbs phenomenon[36]and[37].
- Hard threshold eliminates all the values that are smaller than threshold and keep rest unchanged [38].
- It also produces discontinuity in the reconstruction stage [39].
- Mostly used to preserve edges and the local features of the signals [37].

Soft Threshold

- Soft threshold is continuous at the threshold point[40]
- Soft threshold deletes all the coefficients below threshold but scale those which are left [41].
- Soft threshold does not produce any discontinuity during the reconstruction stage [42].
- Abnormal spikes and distortion are reduced by using soft threshold.

As mentioned earlier, each threshold method has its own advantages and disadvantages when it comes to different aspects, therefore in order to benefit from the advantages of both methods, a hybrid thresholding approach is used in this research.

4.2.3 Selection of Wavelet Function and The Optimal Decomposition Scale

In order to apply WT-based MRA for data compression, it is very important to select best wavelet function and decomposition scale carefully. The best candidates of wavelet functions consist of the Daubechies (dbN) and the Sylmet(symN) wavelet. During this research db2 and level 3 decomposition scale is being utilized [19]. The main reason for choosing this wavelet function is that these wavelets have shown excellent performance in detecting discontinuity and abrupt changes more accurately[43].

4.3. Predictor Importance:

Predictor importance is applied in this research to provide a systematic approach to identify the wavelet decomposition level that retain the salient features in the disturbance signal. Basically, the predictor importance breaks the data set into tree sort of structure and grow a regression tree. After the calculation process, the predictor importance returns the importance of each data set that is given as input in form of numeric values. Each value represents the importance of each data set that is given as input. The importance of these details is predicted based on the value returned from the predictor importance tool. A regression tree made by this method has a decision rule that instance uniquely to child nodes of the actual node and at each of the leaf mode there is a target value made. In case of Wavelet decomposed details each of the details at different scales is inserted in to this tool and this tool make a surrogate regression tree. As a result, regression tree returns a value at leaf of each node representation the importance of each detail (d_1, d_2, d_3) against the original disturbance signal. That means the regression tree is created against the original signal versus the details at different scale for each disturbance signal. This data set is used to build a regression model that fits the details to the original signal. Surrogate Split tool is being utilized in this research. The main property of Surrogate split is the prediction property based on the missing attributes. It creates a new regression tree for missing attributes in the tree and give the prediction based on creating a new tree instead of that missing one which adds up improvement for each time the attribute is used [44].

4.3.1 Ranking of Wavelet Details Using the Predictor Importance

The process of ranking the details relies on computing the predictor importance (PI), which provides a numeric value for each detail level. These values rank the detail levels in terms of their importance in being the best predictor that strongly fits the original uncompressed signal. The process of computing the predictor importance (PI) starts by estimating the mean squared error (MSE) at each node m of the regression tree, which was obtained following Section above as the node error (i.e. prediction error) ε_m weighted by the node probability ρ_m.

$$MSEn = \varepsilon n \times pn \qquad (4.4)$$

The change in the ΔMSE for each detail at tree branch b is the difference between MSE of the parent node (np) and the total MSE of two children nodes (nc).

$$\Delta MSE_m = MSE_{np} - \sum\nolimits_{nc} MSE_n \quad (4.5)$$

For each predictor m , the changes in MSE for a tree with Q branches are

$$\Delta MSE_m = \sum_b \Delta MSE_b \qquad (4.6)$$

Therefore, the predictor importance for all the details input i.e. (d_1,d_2,d_3) attributes is then calculated as

$$PI_m = \frac{\Delta MSE_m}{Q} \qquad (4.7)$$

More about Predictor importance tool can be found in [45].

4.4. Evaluation Metrics for The Goodness of Compression

It is very important to assess the performance of the compression and reconstruction of signal after the compression is done. Furthermore, it is important to assess that either the signal is compressed properly and retained its original shape properly or not. After compressing the disturbance signal using the WT, it must be reconstructed properly for completeness. In order to ensure perfect compression and reconstruction, the following are the indicators which help indicating how accurate and good the compression is performed.

4.4.1 Normalized Mean Square Error (NMSE)

In order to evaluate the performance of the reconstructed signal $c_o\tilde{}n$,the normalized mean square error is calculated using Equation.4.8.

$$NMSE = \frac{\|c_0(n) - \tilde{c}_0(n)\|^2}{\|c_0(n)\|^2} \qquad (4.8)$$

Where $c_o n$ is the original signal and $\tilde{c}_0(n)$ is the reconstructed signal**.** On the other hand, the Normalized mean-square error (NMSE) helps finding out the effectiveness of compression. As this proposed approach is lossy approach and we lose in terms of NMSE. The smaller the NMSE, the higher the quality of the reconstructed signal. In order to get a high-quality reconstruction, the NMSE should be in between 10^{-4} to 10^{-6}[19].

4.4.2 Compression Ratio

In order to assess the goodness of compression, the compression ratio (*CR*) is computed by finding the ratio of the file size in bytes containing the original (uncompressed) signal to the size in bytes of the file containing the compressed signal[19].

$$CR = \frac{\sigma}{\tilde{\sigma}} \qquad (4.9)$$

4.4.3 Difference Between the Original Signal and the Reconstructed signal

The difference between the original signal and the reconstrued signal gives the distortion removed during compression. This is unwanted distortion that is being removed as a result of the application of the thresholding process. The difference between the original and the reconstructed signal for each disturbance signal is shown in Fig.6.6,6.10,6.14,6.18.

4.4.4 Reduction in Sample Points and Reduction in Overall Size of Signal:

After applying the threshold, the sample points that are below the threshold are removed which result in reduction of the size of the total signal in terms of bytes as can be seen in result section stem plots and Tables in Chapter#6. This is a major advantage since it is expected to help reducing the communication channel requirements with respect to the GOOSE messages exchanged during smart grid operation, which is discussed in chapter 6.

4.5. Combined Wavelet-surrogate Binary Regression and Hybrid Thresholding Approach

Proposed approach is a simple data compression approach using Wavelet transform (Multi resolution analysis). In this Proposed approach a combination of two threshold are used; namely the hard and the soft threshold. As shown in Fig.4.1, the implementation process of the proposed approach consists of four different stages. In the first stage, the disturbance signal is decomposed by applying the DWT-MRA. In the second stage, the predictor importance is applied to identify the wavelet detail level that has the highest PI value. In the third stage, the hybrid thresholding is applied by applying soft threshold to the detail level identified as the highest PI value while the hard thresholding is applied to the remaining wavelet details. In the final stage, the compressed signal is reconstructed using the approximation and the detailed levels after applying the hybrid thresholding.

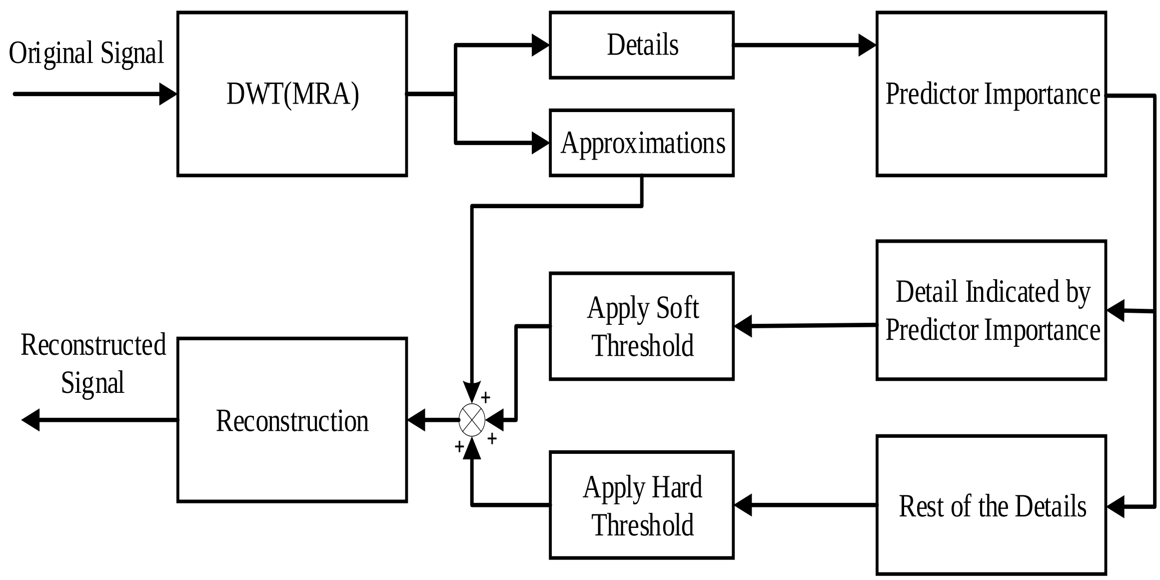


Figure 4.1: Procedure of Proposed Approach

4.6. Summary

This chapter comprehensively discuss the methodology used to address the data compression process using the wavelet transform. Specifically, the hard and soft thresholding along with their advantages and disadvantages are discussed. Furthermore, the metrics used to assess the goodness of compression are presented and finally, a detailed description of the proposed wavelet-surrogate binary regression using hybrid thresholding is presented.

5. Real Time Implementation Using OPAL-RT and IEC61850

5.1. Introduction

The main goal of this chapter is to present the real-time implementation using OPAL-RT and IEC 61850. The experimental set-up used in this research including the hardware description, is described and the details regarding the modeling of the publisher and the subscriber IEDs are described. The chapter also sheds the light on the software used in the real-time experimental testing of the GOOSE messages. Table 5.1 lists the hardware, software description and the requirements for the experimental system used in this thesis.

Table 5.1: Hardware and Software Requirement

Hardware	**Software**
OPAL-RT™ OP5031	Host operating system: Windows 10™
8 active cores	Target operating system: Red hat v2.66.29.6-opalrt-6.2.1
Motherboard	X10DRL-1 Supermicro mother board Dual intel® Xeon®(E5).
	RT LAB™ V2.0.19
	Matlab™v2011b Simulink™V7.9
Cisco Smart Switch SLM2048 48 Ports	N/A

5.2. Need for Real-time Simulation

In Smart grid operation, there is a large number of monitoring devices, which are communicating with each other to exchange a large amount of data. The implementation of the IEC61850 requires extensive testing before the deployment of the IEDs and the other smart devices which can be performed through real-time simulators such as OPAL-RT. The following are the benefits of the real-time simulator.

- **Saves Time**

  Helps performing engineering testing to find out any problem in earlier stages of design process.

- **Reduce Cost**

  It is capable to test any device without any physical modification in system. Moreover, it reduces the overall cost of the project.

- **Increase test functionalities**

  It helps testing all the real-life scenarios and condition in easy simulated environment.

  Able to modify all the parameters and signals of the test system at a glance.

- **Reduces risks**

  It reduces planted related risks.

  Therefore, it is very important to have all the monitoring devices in real time manner.

5.3. RT-Lab

RT-Lab is the software used to interface with Simulink MATLAB interface to perform any kind of power system related modeling, simulation and further can be used to run in real-time simulators (OPAL-RT). It has library and specialized blocks sets, which can be used for Hardware in loop test in real time as well to increase speed and precision of simulation. Most commonly used blocks in RT-LAB are discussed below. Figure 5.1 shows the main user interface of RT-LAB.

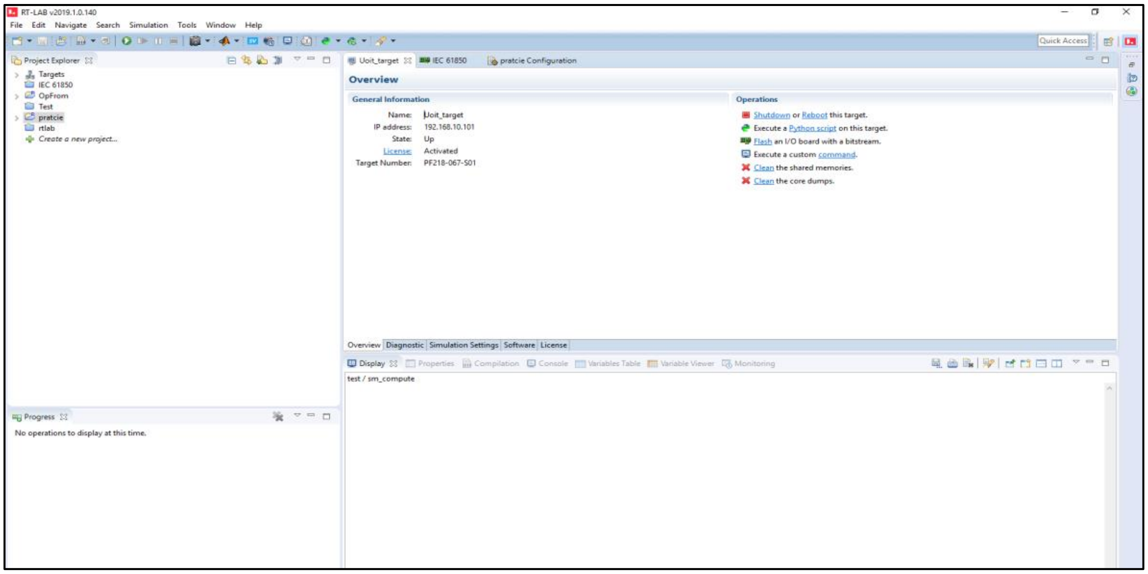


Figure 5. 1: RT-LAB Main User Interface.

5.3.1 Master Subsystem (SM)

Every Model in RT-LAB™ must have at least one SM subsystem as this is the main subsystem. It includes all the computational elements of the designed model, the mathematical operator and I/O blocks, signal generators. No changes can be made to this block while the simulation is running. as shown in figure.5.2

5.3.2 Slave Subsystem (SS)

This block consists of all the mathematical operations, I/O Block and Scope etc. Whereas this subsystem is only required if the computational elements need to split across several modes.

5.3.3 Console Subsystem (SC)

The SC subsystem is available to the user while the simulation is executed. It allows the user to do any changes if any and interact with the system while the simulation is running. The SC subsystem is shown in figure.5.2.

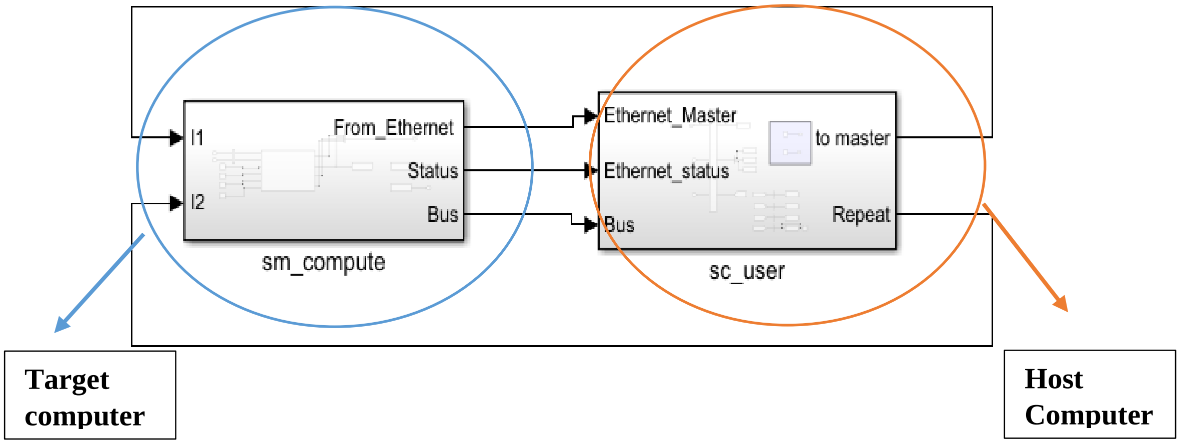


Figure 5.2: SM and SC Blocks

5.3.4 OpComm Block

It is an important block in RT-LAB as it enables the communication between all the subsystems where every subsystems input must first go through an Opcomm block before any operation is performed.

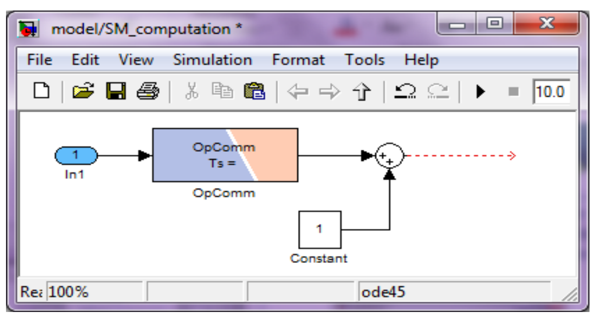


Figure 5.3: OpComm Block [46]

In any designed simulation in RT-LAB all the subsystems must first go through Opcomm before any predation is performed, Opcomm block must be placed after the subsystem creation.

5.3.5 In the real-time Subsystem (SM or SS)

Opcomm receives real-time synchronized signals from other real-time subsystems Moreover this block receives asynchronous signals from the console subsystem.

5.3.6 In the Console Subsystem (SC)

One or more Opcomm blocks can be used in the SC to receive signal from the real-time subsystems.

5.3.7 OpInput, Opout and OPConfiguration:

OpInput allows user to interconnect the model and make a connection between two subsystems whereas the Opout has similar property of connecting the two subsystems together. These two blocks can be simply used for IEC61850 purpose where two subsystems are connected together. On the other hand, Opconfiguration allows a user to configure the environment in which the model will be complied. OPInput and OPOutput blocks are shown in Fig.5.4.

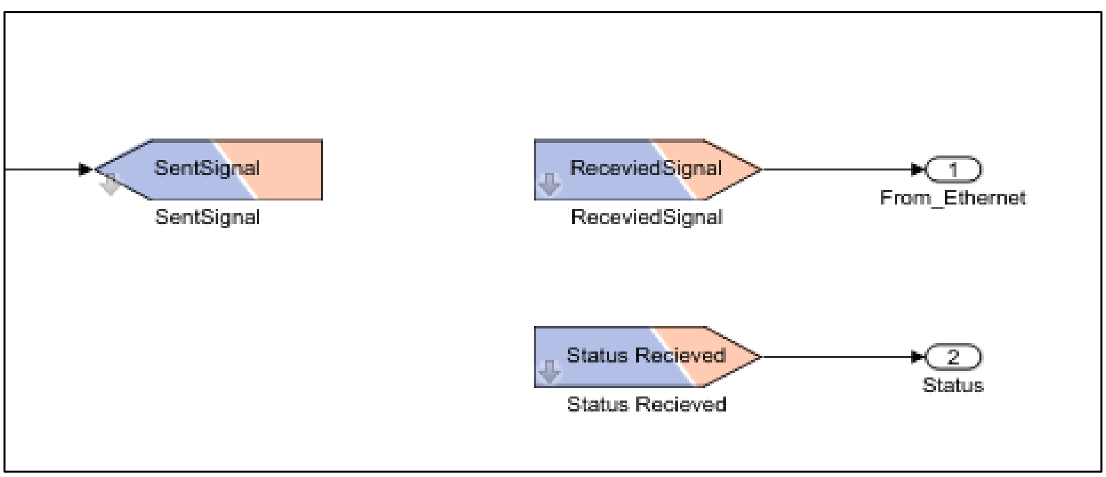


Figure 5.4: OPInput/Output Block

5.3.8 Simulation Parameters

Fixed-step mode is always used in OPAL-RT real-time models. It is very important to choose real-time step-size precisely because it will affect all the necessary calculations, algorithms, and the code that are read by the processors. The fixed-time step used by OPAL-is usually 5ms to feed all the inputs and the processing files to processor.

5.4. IEC61850

The IEC61850 is a communication protocol standard. The issue of interoperability was first addressed by the IEEE where there were working on a similar project called Utility communication architecture (UCA)[47]. However, in 1997 IEEE and IEC joined together to work for a universal protocol that can be used internationally in every electric utility automation [48], [49]. In 2004, these both organizations came up with an international standard protocol that was made to solve problems related to interoperability and interchange ability named as IEC61850[50]. The second edition of IEC61850 standard was published in 2014 summarized in pairs of 20 documents in ten parts. The summary is shown in Table5.1[51], [52], [53, p. 61850]

Table 5.2: IEC61850 Arrangement [49,50,52]

Part	Content
1	**Introduction:** Summary of IEC61850 using texts, figures from other parts of standards
2	**Glossary:** Collection of particular definitions from other standards and terms defined in different part of IEC61850 protocol
3	**General Requirements**: Basic of this protocol such as system requirements, availability, security and more.
4	**System and Project Management:** Different challenges in Substation such as documentation, factory tests, system test procedure and quality assurance.
5	**Substation Automation System Configuration Language:** SCL very important part of any protocol
6	**Communication requirements:** Communication requirements linked with logical nodes, or for communication purpose etc.
7	**Communication layout for substations and feeder equipment:** This part is divided in to four sub sections that defines all the abstract models used in IEC61850 to meet all the requirements and usage based on substation and automation
7-1	**Principle and modes:** Basic concept of modeling
7-2	**Communication services interface:** Models and services that are required during usage for substation automation and Protection systems purposes
7-3	**Common Data classes:** it is compulsory to implement the concept of hieratical object model
7-4	**Technical Report:** Explain the usage of logical nodes of various special domain
7-5	**Compatibility of Logical mode classes and Data classes:**92 Logical nodes that can be used for different classes for basic substation functions.
8	**Specific Communication Service Mapping (SCSM):** Mapping of models to selected MMS or ISO/IEC 8802-3 protocols
8-1	**Guideline for mapping IEC61850 to IEC60870-5-101/-104**
9	**Process Bus Mapping:** This is divided in to two different sub sections that explains different implementation of IEC6150 process bus.
9-1	**Sample values over serial Uni-directional Multi Drop point to Point links:** Mapping of core elements the transmission of Sample values in point to point manner
9-2	**Sample Values over ISO/IEC8002-3:** mapping of Generic object-oriented systems events (GOOSE) and sampled measured values.
9-4	**Usage of IEC61850 for monitoring of Power devices and equipment**
9-5	**Usage of IEC61850 to transmit synchrophasor information**
10	**Process for conformance testing of IEC61850 required documentation, device related conformance testing and quality assurance.**

The IEC61850 works on an Ethernet technology connection to meet the high-speed communication criterion. The use of such connection helps replacing copper wires, which cover the whole space. Moreover, by replacing these wiring, a virtual kind of scenario is created where same testing can be performed with much more extra features and high speed. The reduction of these wires is replaced by the Generic object-oriented substation event (GOOSE) messages, Sample values, trip/fault data sets that are received by all over IEDs available in the field. More about these features is discussed in section 5.6. These unique features of this protocol have direct impact on the cost, the communication and the design in any power utility system.

5.4.1 Comparison with Other Existing Protocol

An in-depth comparison between IEC8150 and other existing communication protocol for use in substation automation are discussed in table 5.3.

Table 5.3: Comparison with Other Protocols [55]

Properties	MODBUS	IEC60870-5-103	IEC61850
Communication Speed	9.6 Kbs,19.2 Kbps maximum	9.6 Kbs,19.2 Kbps maximum	100MBPS
Disturbance Record Uploading	✗	✗	✓
Control over circuit breaker	✗	✗	✓
Type of Communication	Master-Slave Technique	Master-Slave Technique	Publisher-Subscriber Technique
Time accuracy Synchronization	✗	±1 msec	±1 msec
Peer to Peer Communication	✗	✗	✓
Interoperability	✗	✗	✓

✗-Not Available,✓ Available and Supported

5.4.2 Key Advantages of IEC61850

Some major key advantages of using IEC61850 communication protocol in substation automation and the smart grid are summarized as follows:

- IEC 61850 is specifically designed to reduce the fault recovery time, much more security, and can be easily configurable.
- Works on Object orientation programming which worldwide know language and engineers can easily work on in case of difficulties.
- Instead of heavy bundle of copper wires GOOSE messages works virtually by sending trip messages, statues and Booleans within the smart monitoring device inside the substation.

- It uses a Standard configuration language (SCL) which can help easily connecting any monitoring devices with each other.
- IEC61850 is extensible enough to support new system evolution

5.5. Interoperability and SCL Language

5.5.1 Substation Configuration Language (SCL):

Before the standardization of IEC61850 protocol is was very difficult for different vendors to connect their devices, IEDs and communicate with each other[56].This was because each manufacture design their product in a way that it was difficult to interoperate with the other devices in the station if one equipment in a station stopped working or failed due to some reason whole surrounding devices that were connected with it had to change as well. This was considered as a major drawback for any kind of substation.

IEC61850 introduces XML-based substation configuration language (SCL) which solved the issues discussed above [57]. It achieved the interoperability between other surrounding devices in a network without any further hustle. Moreover, it specifies substation configuration language using the four different files. These files are listed as follows [50], [58]:

- (SSD)System specification Description
- (ICD)Capability of IED
- (CID) Configured IED Description
- (SCD) Substation Configuration Description
- (SED) Description of System Exchange

In order to configure two or different IEDs in a Field all the Devices are connected with each other in a network using their Capability of IED(ICD) files. Whereas for Configuration of GOOSE the SCD file is used which contain all the GOOSE configuration and mapping. In order to have the flow of GOOSE messages and Sampled values the SCD files of different IEDs are mapped to each other. For example, if there are different manufactures devices are available in the substation each of theirs ICD, SCD files are used to connect them together in a network. In this research the ICD file was already inserted by the OPAL-RT. Figure5.5 shows an example of IEC 61850 configuration process [48].

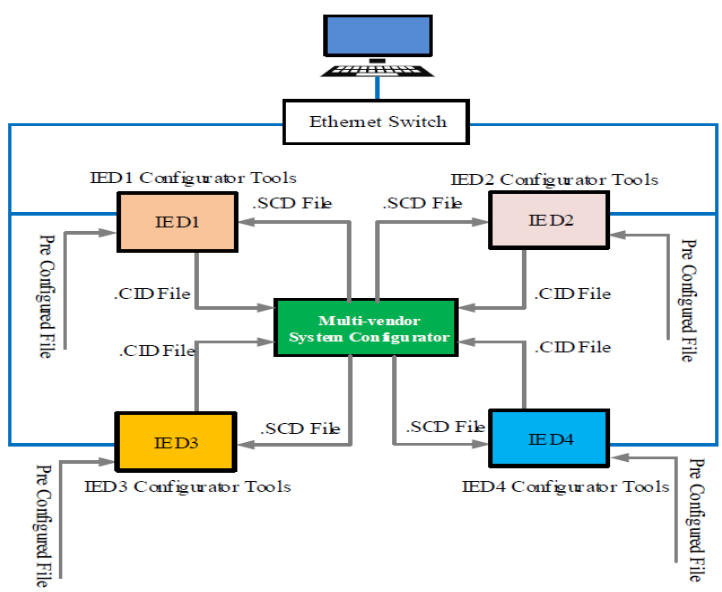


Figure 5.5: IEDs and System Configuration in IEC61850 Protocol [48]

Last but not least, due to a wide range of different manufacture monitoring devices it might be a considerable challenge for engineers and technicians to connect all the devices in a field to together in to a network.

5.6. GOOSE Messaging

The GOOSE messages is one of the most important features of IEC61850 Protocol [59].It is basically the mapping of time critical messages on ethernet to make it faster. These are bi directional messages that are transmitted in Smart grid from one monitoring devices to other devices. GOOSE messages help the replacing the old wiring system with these virtual wires. The GOOSE messages are faster compared to hard wires and can help communicating faster. The fast response, the quick status transfer and trip messages are uniqueness of this technology [60]. The main purpose of these messages is to indicate any change in substation and the smart grid operation. The GOOSE messages are sent from one IED to other IED in a cyclically loop order even when there is no change in status or communication failure. This cyclical movement of these message between monitoring devices confirms that all the devices are connected in field and there is no further fault or trip. These messages may contain data sets, analog or binary data sets of trip signal, breaker signal and statues which are all broadcasted to other monitoring devices over ethernet whereas the fault signals are sent to main SCADA system in the field. Some of the additional feature of GOOSE are as follows.

- Any monitoring device has a capability of being a publisher and subscriber at the same time which mean these IED devices can publish and subscribes to other IED at same time.
- Data transfer is much faster between IEDs in the field.
- Data can be sampled value, trip status, Boolean or analog signal.
- Best usage in protection and control field.

- Even if there is no event occur messages are sent to all the IED (Monitoring devices) which acts as an indicator of future failure

5.6.1 Publish Subscriber Communication Services and Configuration setup

The Publisher-subscriber models are used in IEC61850 to broadcast the GOOSE messages to all the IEDs and the monitoring devices, which are in the range of the publisher. The subscribers, which are subscribed to the publisher, can receive the GOOSE messages. This works in a way that the publisher broadcasts the messages containing the trip data sets, the statues and all the subscribed monitoring devices can receive these messages [60] and [61]. Each IED is a publisher and a subscriber at the same time, which means they can receive the messages and publishing them. The Publisher and the subscriber are configured providing SCL/CID/ICD file, creating connection pint for every attribute comprised within the selected GOOSE message. The configuration set-up is basically done by dropping the SCL file into the required columns and connecting them virtually with each other so the GOOSE can transfer. Basically, the subscribers SCL file is virtually connected to the Publishers whereas the publishers SCL file is virtually connected to the subscriber by dropping them in to drop down list. The publisher-subscriber configuration setup is shown in Fig.5.6.

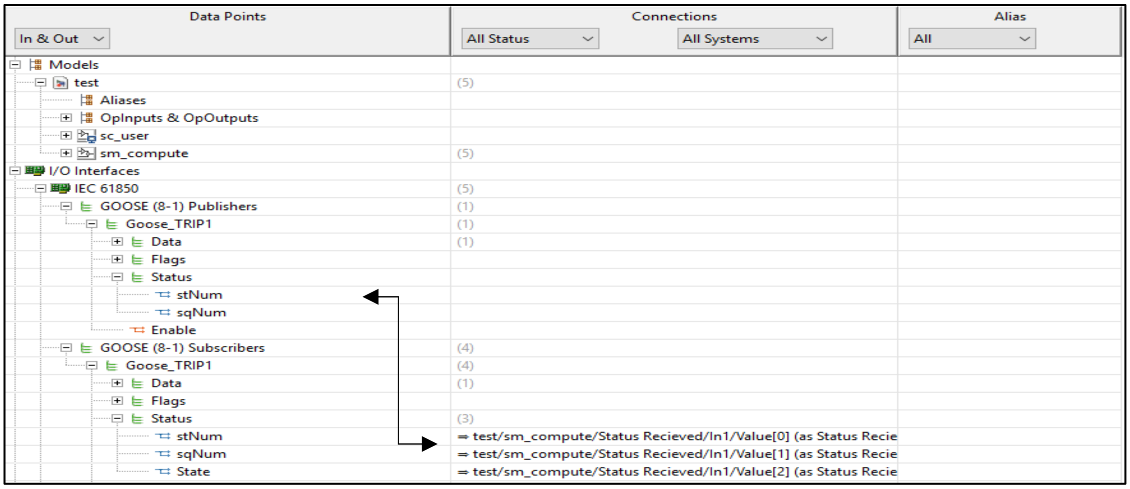


Figure 5.6: GOOSE Messages Configuration

5.6.2 Status Transferred over GOOSE in IEC61850

Whenever the GOOSE messages are transferred over the ethernet using IEC-61850 protocol and in order to check whether the signal is received or not at the receiving end, the status display in terms of values is used. These statuses are also used to check if there is any kind of interruption or trouble in transmission of GOOSE messages. These statuses are built-in in the IEC-61850 protocol and are also used for safety purposes. These statuses consist of StNum, SqNum and different States. The StNum value is incremented starting from '0' with every change of whichever objects contained within the GOOSE message whereas SqNum is the value started from '0', with every GOOSE message received without any modification of its object value. If any change is detected for whichever of the object this count restarts from 0.

On the other hand, the states consist of values displayed, which represents statuses. If '0' is displayed, this means the messages have not been received or the message reception has stopped working, whereas if '1' is displayed, then this means the transfer of GOOSE messages is operational and there is no error. Similarly, if '-14' is displayed on the status display then this means the presence of an error in the communication protocol IEC-61850 or in Ethernet as shown in Table 4 below. All these statues are implemented in this thesis and are shown in result section.

Table 5.4: Status in IEC61850 [46]

Values	Properties
0	Message Reception has been Stopped working error indicated
1	Reception is Operational
-4	Message Lost: time frame between Two Consecutive GOOSE has over passed
-5	Message Out of Order
-14	Error in configuration of IEC61850 network.

5.7. Wireshark

Wireshark is a network packet analyzer software used to analyze packets transmitted over Ethernet in any network[63]. The GOOSE messages are published over the Ethernet in IEC-61850.In the IEC- 61850 standard, the GOOSE messages that are transmitted over the Ethernet can be examined and all the details related to any GOOSE can be seen on this software. Moreover, it can also create various statics for each message received over the Ethernet using IEC61850 protocol. A Wireshark user interface is shown in Fig.5.7

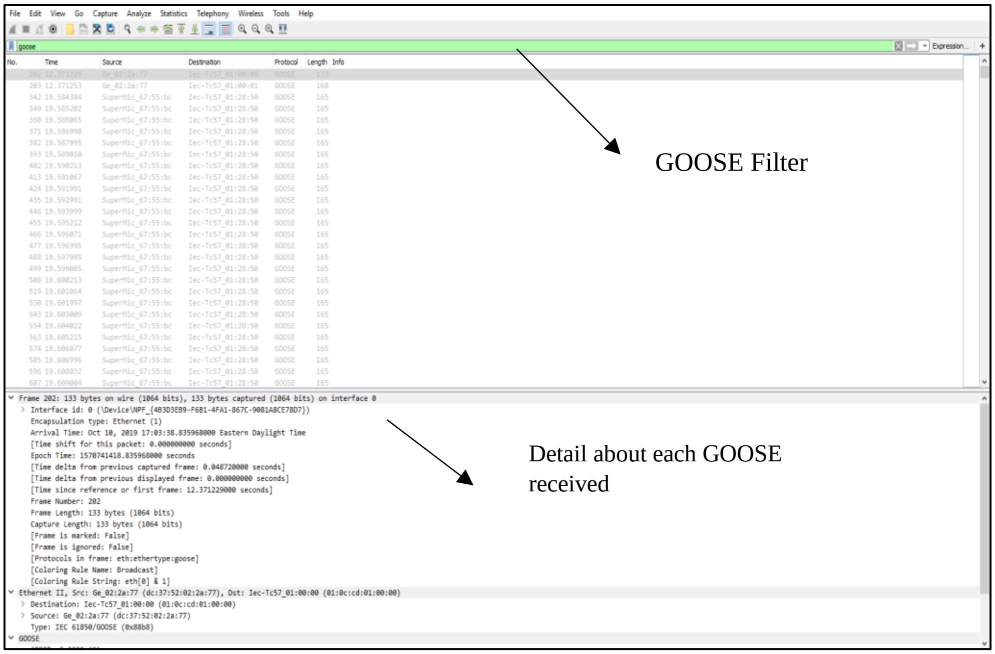


Figure 5.7: Wireshark User Interface [63]

5.8. Summary

In this chapter, the real-time set-up using the OPAL-RT and RT-LAB is discussed with all the details about the Simulink implemented in Simulink, which runs on RT-LAB software platform. Furthermore, this chapter presents a comprehensive discussion about the communication protocol using i.e. IEC61850 along with the functionality of GOOSE in it which is implemented in RT-LAB and OPAL-RT hardware. The Statuses properties are also discussed, which are used as built-in properties within GOOSE messages and represent an important part of these messages in real-time. Lastly the Wireshark software is discussed, which is used to analyze the properties of GOOSE received on the subscriber's end.

6. Results and Evaluation

6.1. Introduction

In this chapter , the performance of the proposed data compression approach will be assessed and compared to the Traditional approach. The data set related to the power disturbance signals used in this research data base repository of power system events[64].MATLAB is used in this research to apply the Multi resolution analysis (MRA), the discrete wavelet transform to perform the signal decomposition and reconstruction and for the data compression. Furthermore, the predictor importance using the surrogate binary regression tree was implemented in MATLAB. proposed

6.1.1 Experimental setup

For real-time implementation the OPAL-RT Model OP4520 is used and the IEC61850 is used as communication protocol using Ethernet. In order to test the transmission of GOOSE messages, the OPAL-RT mother board is used to model the IED, which publishes the GOOSE messages in IEC61850 configuration over Cisco Ethernet switch. On the other hand, the PC is used as the subscriber, which receives GOOSE messages. The disturbance test signal will be fed to the simulation model in RT-LAB, which will be send to the OAPL-RT mother board (IED) via IEC61850 protocol. The main purpose of this modeling is to create a smart grid scenario where the disturbance signal is sent from PC to OPAL-RT mother board and see the outcome on GOOSE messages published for each kind of compressed and uncompressed disturbance signal. In order to send the signal from the PC the Opfrom block from RT-LAB Simulink library is utilized, which is the part of the SM (Master Subsystem) as shown in fig. 6.14. Once the signal is captured by the specialized

Block (Op In and Op out) it is then transferred to IED (OPAL-RT mother board supermicro). In order to transfer the signal, the RT-LAB blocks OpIn and OpOut, which are part of the SC(Console) subsystem and are responsible for sending and receiving the signal, must be configured. The Configuration between these two blocks is done based on IEC61850 standard settings in OPAL-RT. Moreover, these SM and SC blocked are connected to each other using Opcomm block, which is responsible for communication between SM and SC block. First the uncompressed signal is sent, which results in publishing specific number and size of GOOSE by OPAL-RT mother board. Similarly, the compressed signals obtained after applying the traditional approach and proposed approach are sent over ethernet using IEC61850 to OPAL-RT mother board and the number and size of the GOOSE messages are recorded. The GOOSE messages published over Ethernet are then analyzed on Wireshark and all the detail, statistics are examined i.e. Total numbers of Goose ,size of Goose ,total bytes of Goose The diagram of overall process is depicted in Fig.6.1. Results are further discussed in this Chapter. The front and the rear views of the real-time set-up are shown in Fig.6.2 and 6.3.

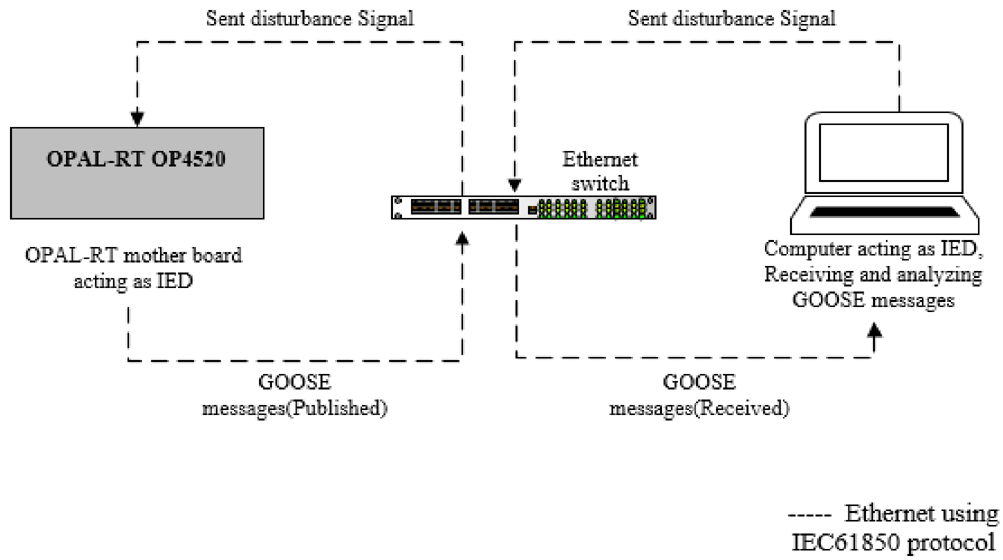


Figure 6.1: Diagram of Real Time Setup

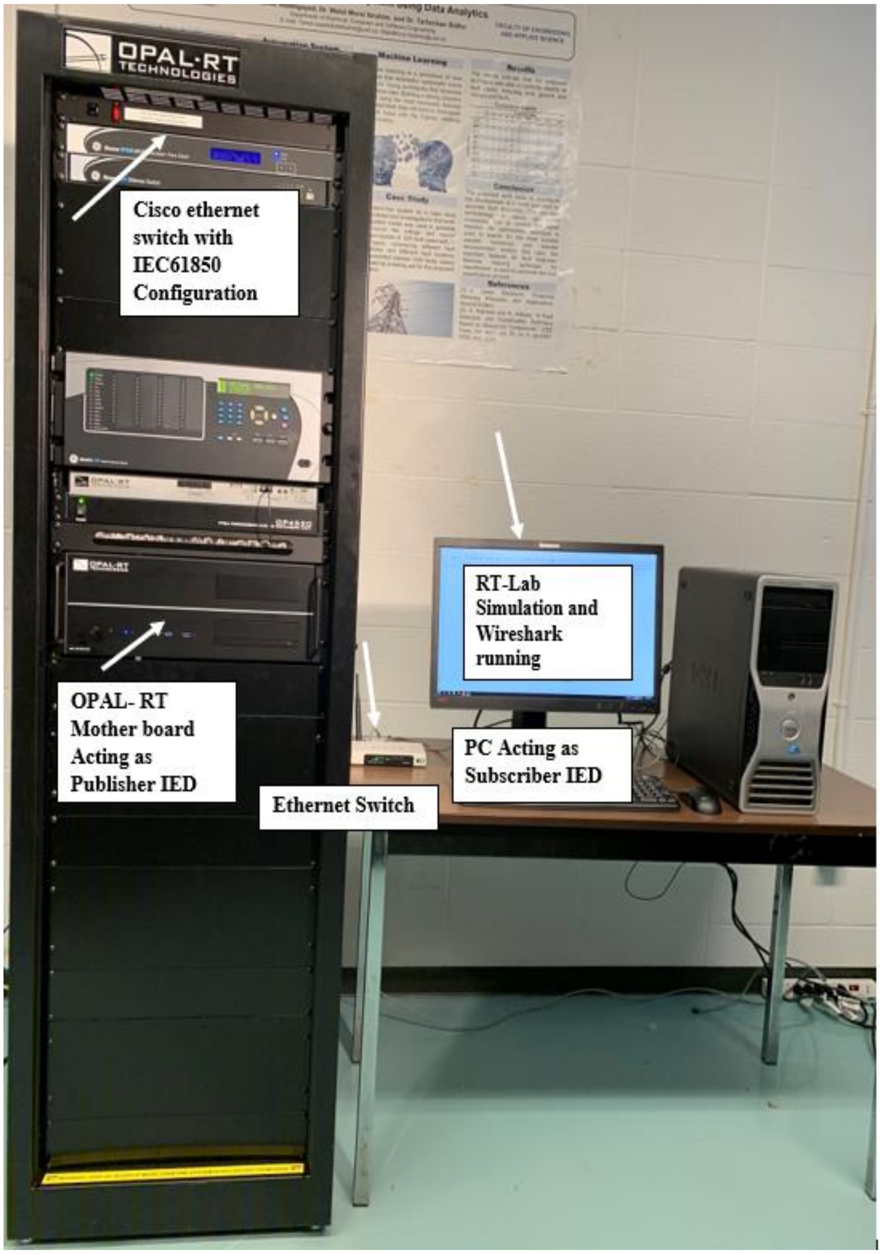


Figure 6.2: Front View of Experimental Setup

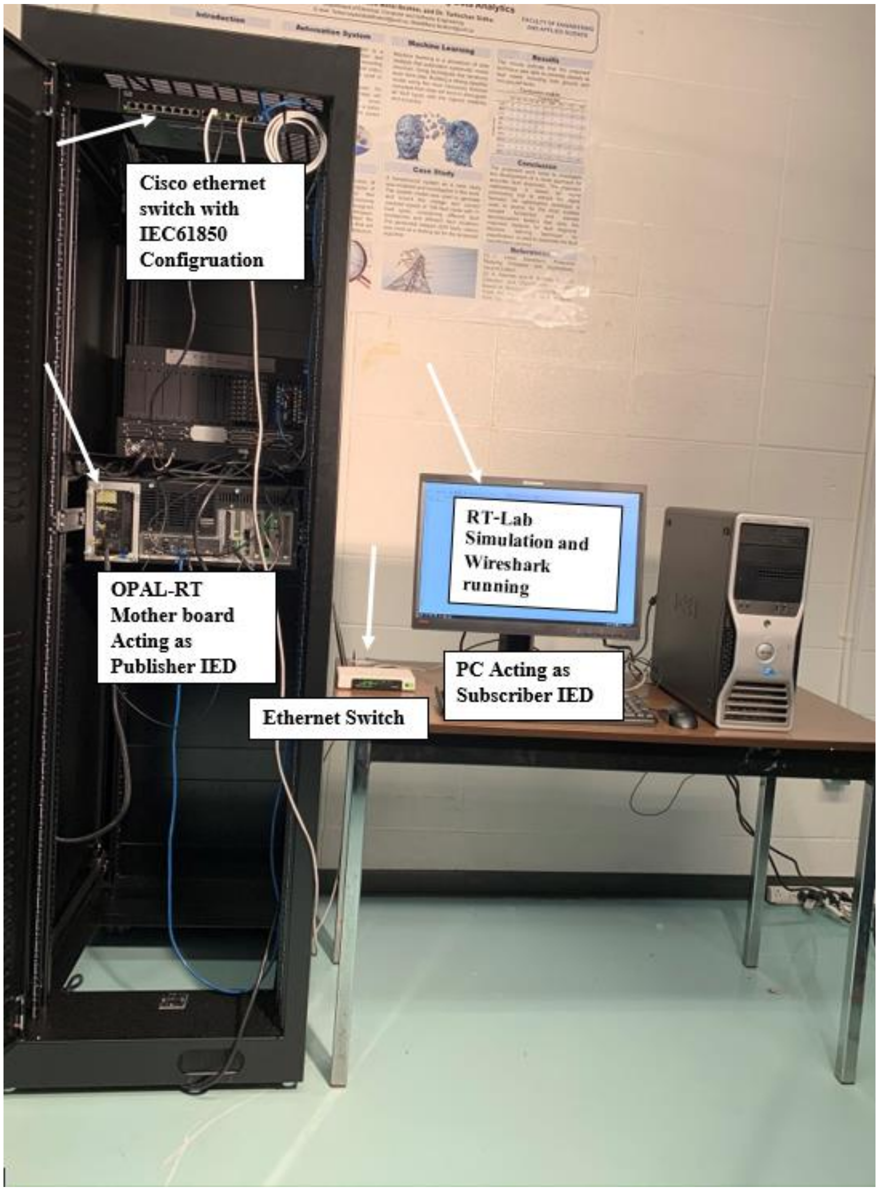


Figure 6.3: Rear View of Experimental Setup

6.2. Data Compression Result

In order test the performance of the proposed data compression approach, different disturbance test signals from the US DoE database are used. The Multi resolution analysis (MRA) is applied in MATLAB where wavelet tool box is used as well to get best results[33].Furthermore, the Daubechies wavelet function of Order 2 and with 3 wavelet decomposition levels are used as for the decomposition-reconstruction process [19]. The results are presented and discussed in the following subsections.

6.2.1 Traditional Approach (Event#1)

To compress the signal, the hard thresholding is applied to all the details i.e. $d1, d2, d3$ following the application of the Multi resolution analysis of the Event#1 is shown in Fig.6.4 As mentioned in Chapter 4, the selection of threshold τ_j depends on the maximum absolute value of each wavelet detail and may vary for each scale. For the Event#1, the application of equation (4.2 ,4.3), leads to the threshold values for each wavelet detail level to be: τ_1=57.15 for detail 1(d_1), τ_2=173.74 for detail 2(d_2), τ_3=395.16 for detail 3(d_3). The values below the threshold are discarded, whereas those which are above the threshold will be saved as these values will be the values, which represent the features contained within the decomposed signal. The Event#1 signal is decomposed as shown in fig.6.4 using the MRA, with db2 and three wavelet decomposition levels.

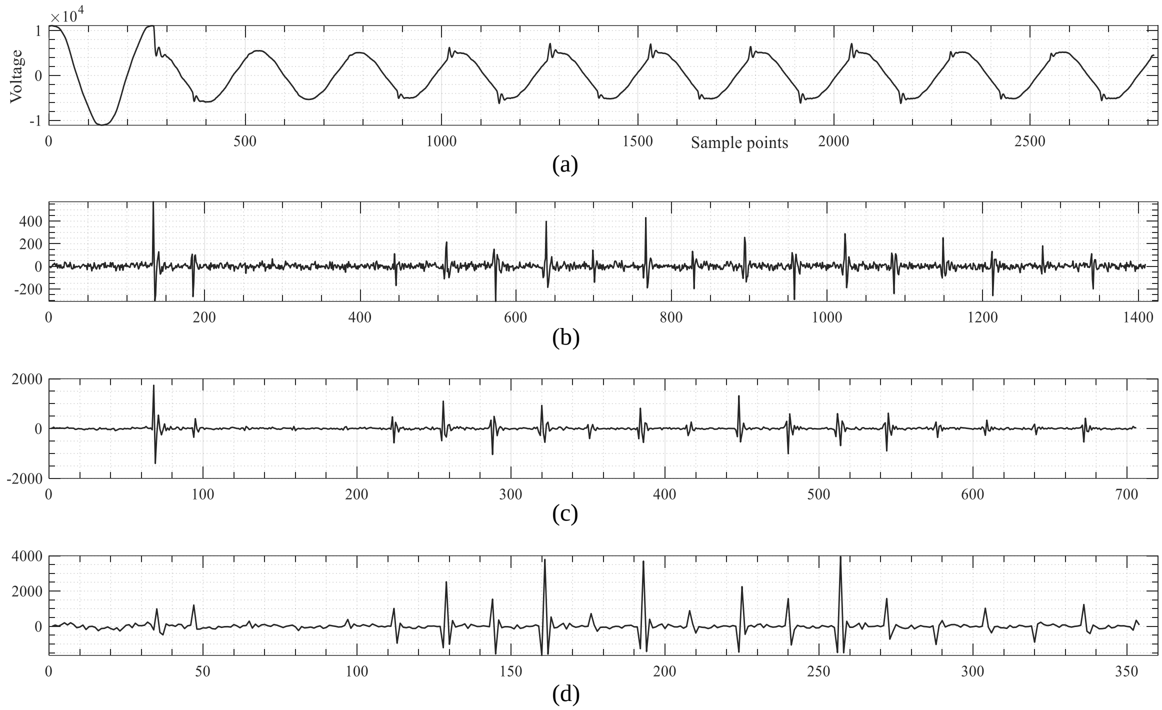


Figure 6.4: Event#1 (a) Original signal, (b) detail 1, (c) detail d2, (d) detail d3

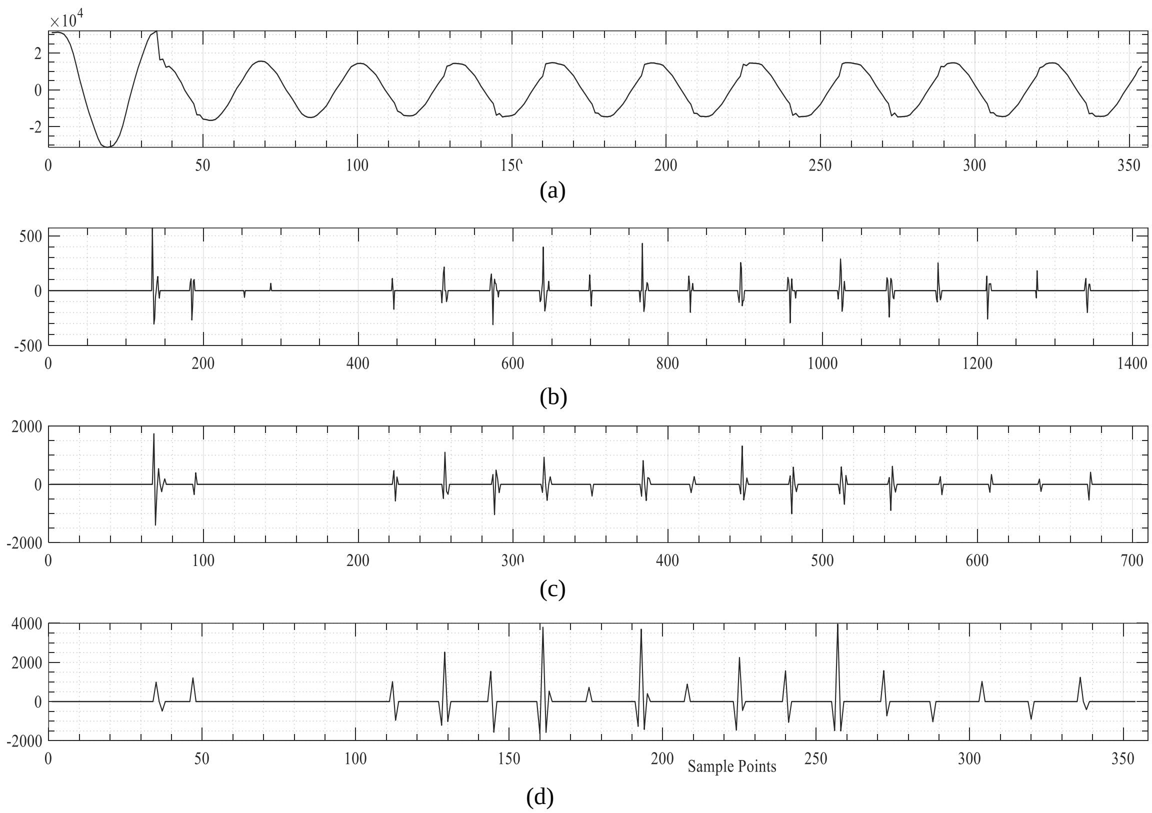


Figure 6.5: Event#1 (a) Smooth Approximation signal, (b) detail 1, (c) detail 2, (d) detail 3 after applying hard threshold

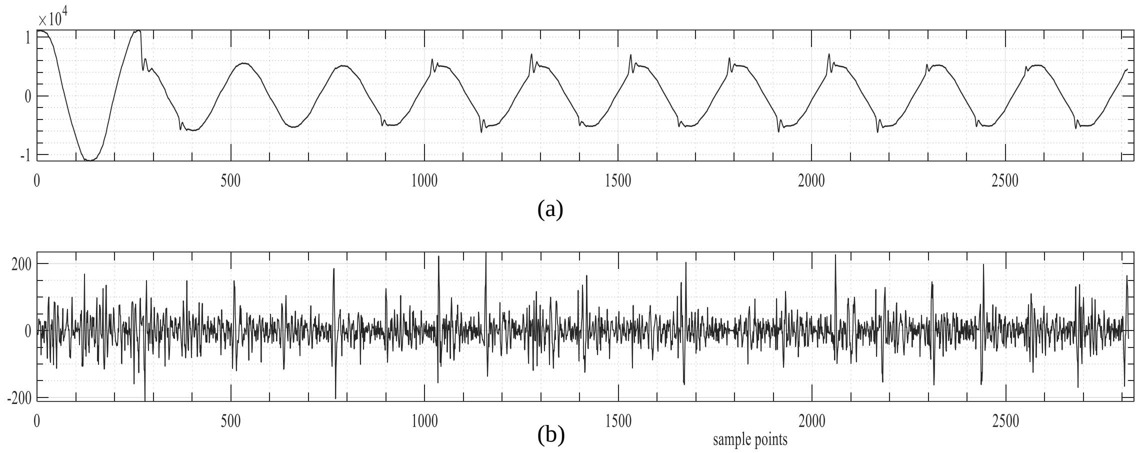


Figure 6.6: (a) Event#1 reconstructed signal and (b) difference between the original and the reconstructed signal.

Number of sample points for each level before applying the hard thresholding in (a), (b), (c), (d) and (e) are 2816, 1409, 706, 354 and 354.The total file size of the original signal is 22,528 bytes. After applying the hard thresholding to d_1, d_2, d_3 the sample points are reduced to 97, 57, and 35 samples as shown in Fig.6.5 (b), (c), (d). The total numbers of samples needs to be stored are 2 × (97+57+35) + 354 = 732 samples. Where Both magnitude and position of the signal are stored. The bytes required for these samples are 4,344 leading to the compression ratio of 22,528/4,344 = 5.18. The reconstruction is performed using the detail d_1, d_2, $d_3$and the approximation $A3$. Since the difference between the original signal and the reconstructed signal is difficult to visualize by visual inspection, the difference between the two signals can be used to quantify the amount of the information lost, which can take the form of noise and distortion as shown in Fig.6.6(b). The Normalized mean square error (NMSE) is is used to assess the goodness of reconstruction and using equation (9.5×10^{-5}.

6.2.2 Proposed Approach (Event#1)

The main purpose of using the predictor importance is not only to keep the important features of the signal after compression but also to reduce the file size and increase the compression ratio. More about predictor is explained comprehensively in chapter 4.

The use of the predictor importance as in eqs (4.5,4.6,4.7) indicates that detail level d_2 has the highest importance among all the details as shown in Fig.6.7. The hybrid thresholding is then applied by applying soft threshold to d_2 and the hard threshold is applied to the remaining detail levels. Table 6.1 list the measures used to assess the performance of both the traditional and the proposed approaches. Visual inspection of table 6.1 reveals that the implementation of the proposed approach leads to an increase in the CR from 5.18 in the Traditional approach to 5.24 in the proposed approach. Furthermore, the file size was reduced from 4344 in the Traditional approach to 4300 in the proposed approach. As a result, this approach helps reducing the bytes of signal more as compare to old Traditional as well as increasing compression ratio. Whereas, normalized mean square error (NMSE) is a bit high but is still in acceptable range. The comparison of both approaches is shown in table 6.1.

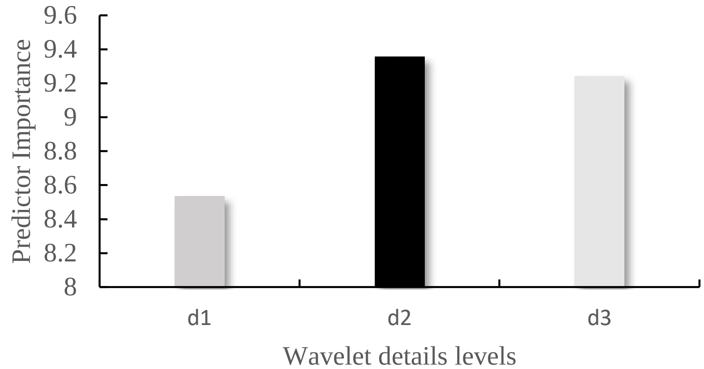


Figure 6.7: Predictor Importance for Event#1

Table 6.1: Comparison of Traditional and Proposed Approach for Event#1

Event#1	
Traditional Approach	**Proposed Approach**
Original signal Bytes:22528	Original signal Bytes:22528
Bytes After Compression: 4344	Bytes After Compression:4300
Compression ratio:5.1860	Compression ratio:5.24
NRMSE:9.5×10^{-5}	NRMSE:1.628×10^{-4}

6.3. Traditional Approach (Event#2)

A second example used to verify the data compression approaches is Event#2 as shown in Fig.6.8. Threshold is applied to decomposed scales where τ_1=415.5646 for detail1 (d_1), τ_2=328.2122 for detail 2(d_2), τ_3=232.27 for detail 3(d_3). After applying the threshold decomposition at different levels and reconstructed signal is shown in Fig.6.9,6.10.

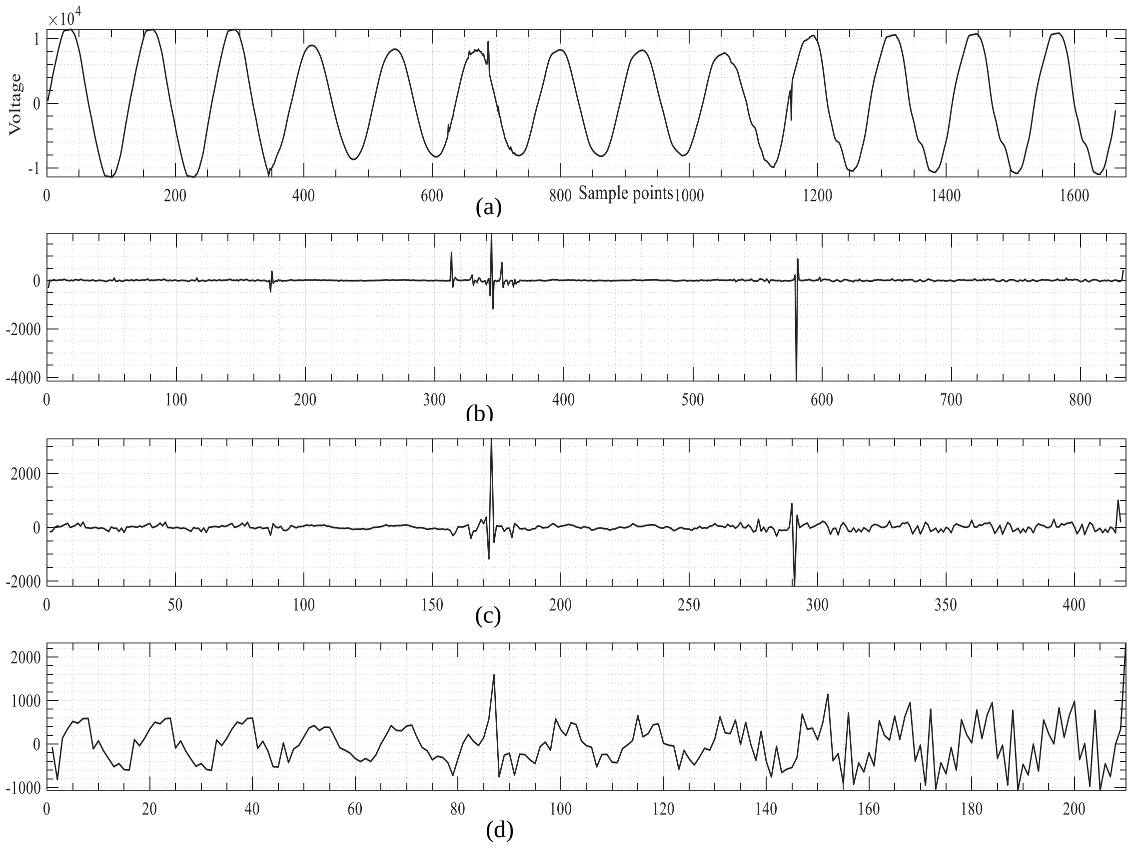


Figure 6.8: Event#2 (a) Original signal, (b) detail 1, (c) detail 2, (d) detail 3

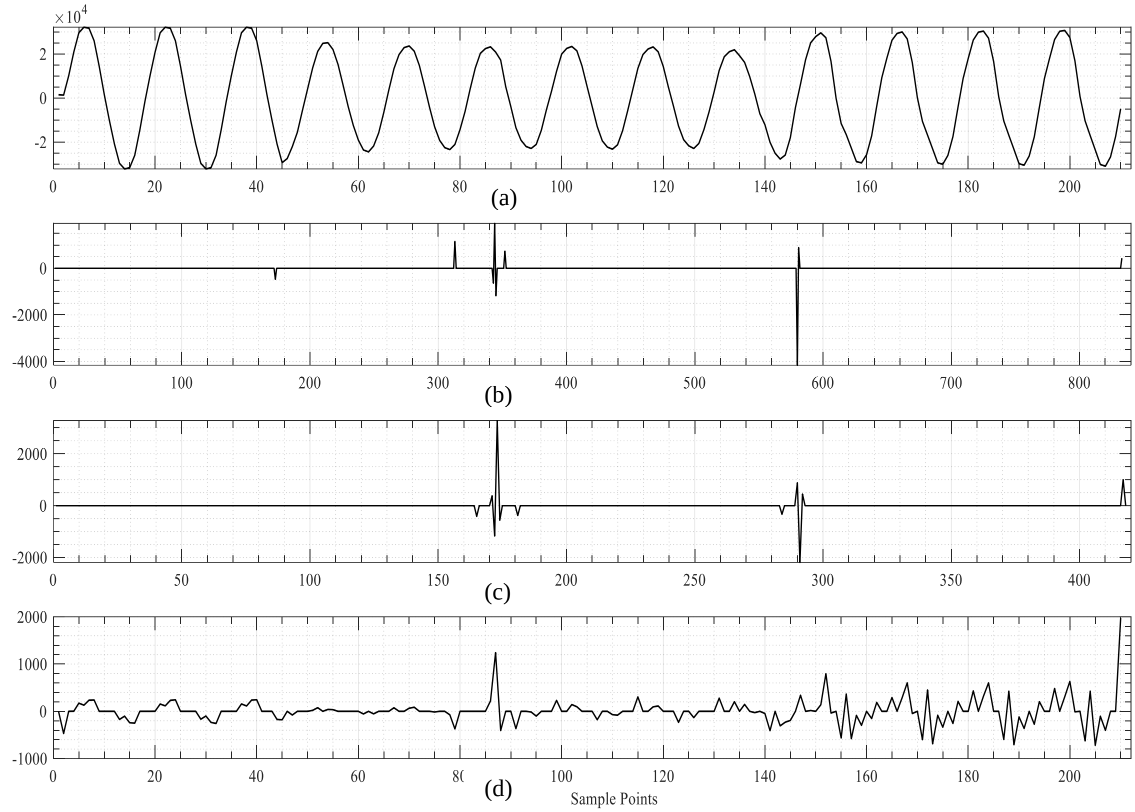


Figure 6.9: Event#2 (a) Smooth Approximation signal, (b) detail 1, (c) detail 2, (d) detail 3 after applying hard threshold

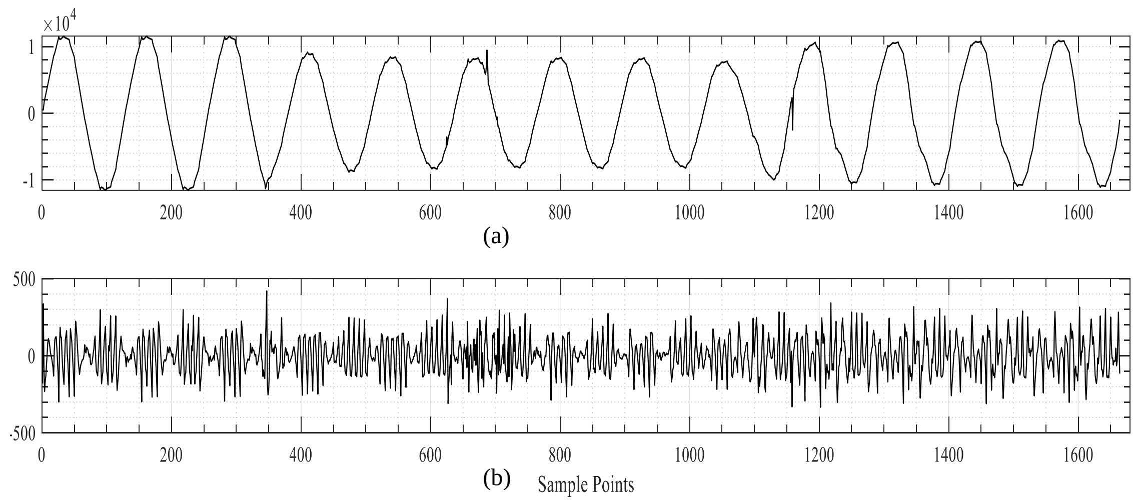


Figure 6. 10: Event#2 (a)Reconstructed signal and (b) difference between the original and the reconstructed signal.

Number of sample points for each level before applying the hard thresholding in (a), (b), (c), (d) and (e) are 1664, 833, 418, 210 and 210.The total file size of the original signal is 13312 bytes. After applying the hard thresholding to d_1, d_2, d_3 the sample points are reduced to 9, 11, and 135 samples as shown in Fig.6.9 (b), (c), (d). The total numbers of samples needs to be stored are 2 × (9+11+135) + 210 = 365 samples. Both magnitude and position of the signal stored. The bytes required for these samples are 2920 leading to the compression ratio of 13312/2920=4.55. The reconstruction is performed using the detail d_1, d_2, d_3 and the approximation $A3$. Since the difference between the original signal and the reconstructed signal is difficult to visualize by visual inspection, the difference between the two signals can be used to quantify the amount of the information lost, which can take the form of noise and distortion as shown in Fig.6.10(b). The Normalized mean square error (NMSE) is used to assess the goodness of is 7.459×10^{-5}.

6.3.1 Proposed Approach (Event#2)

The use of the predictor importance as in eqs (4.5,4.6,4.7) indicates that detail level d_3 has the highest importance among all the details as shown in Fig.6.11. The hybrid thresholding is then applied by applying soft threshold to d_3 and the hard threshold is applied to the remaining detail levels. Table 6.2 list the measures used to assess the performance of both the traditional and the proposed approaches. Visual inspection of table 6.1 reveals that the implementation of the proposed approach leads to an increase in the CR from 4.55 in the traditional approach to 4.933 in the proposed approach. Furthermore, the file size was reduced from 2920 in the traditional approach to 2696 in the proposed approach. As a result, this approach helps reducing the bytes of signal more as compare to old approach as well as increasing compression ratio. Whereas, normalized mean square error (NMSE) is a bit high but is still in acceptable range. The comparison of both approaches is shown in table 6.2.

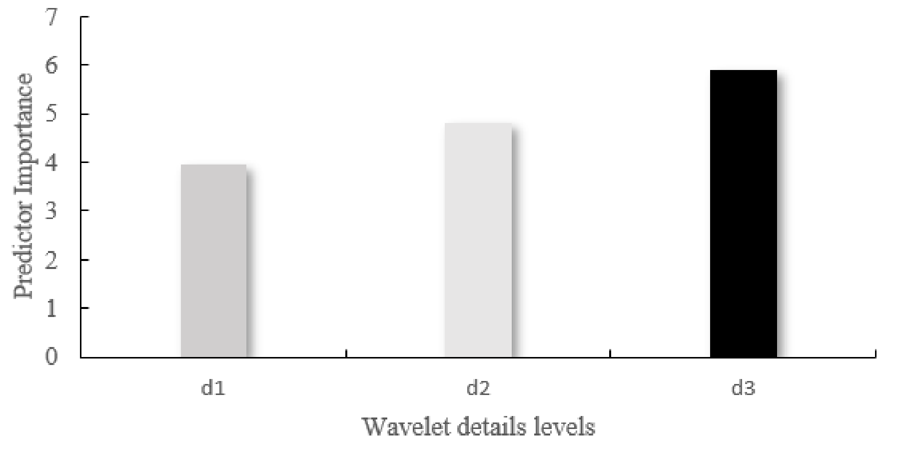


Figure 6.11: Predictor Importance for Event#2

Table 6.2 Comparison of Traditional and Proposed Approach for Event#2

Event#2	
Traditional Approach	**Proposed Approach**
Original signal Bytes:13312	Original signal Bytes:13312
Bytes After Compression: 2920	Bytes After Compression: 2696
Compression ratio:4.55	Compression ratio:4.93
NRMSE:7.459×10^{-5}	NRMSE: 2.582×10^{-5}

6.4. Traditional Approach (Event#3)

A third Example Event#3 is used to investigate both the compression approaches is shown in fig 6.12. Threshold varied for each scale in this signal. τ_1=151.2822, τ_2=224.6423, τ_3=207.708 were the threshold for Details d_1, d_2, d_3. After Implementation of the threshold on event#3 signal decomposition at different levels and reconstruction is illustrated in fig.6.13,6.14.

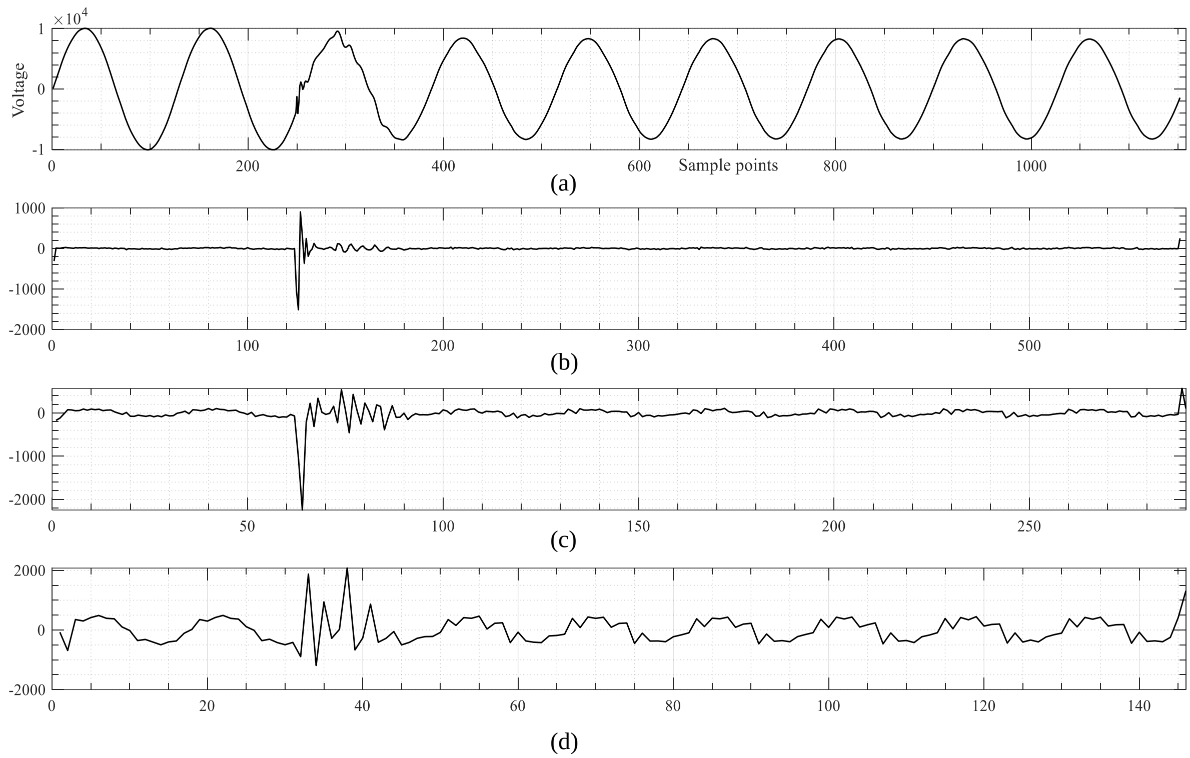


Figure 6.12: Event#3 (a) Original signal, (b) detail 1, (c) detail 2, (d) detail 3

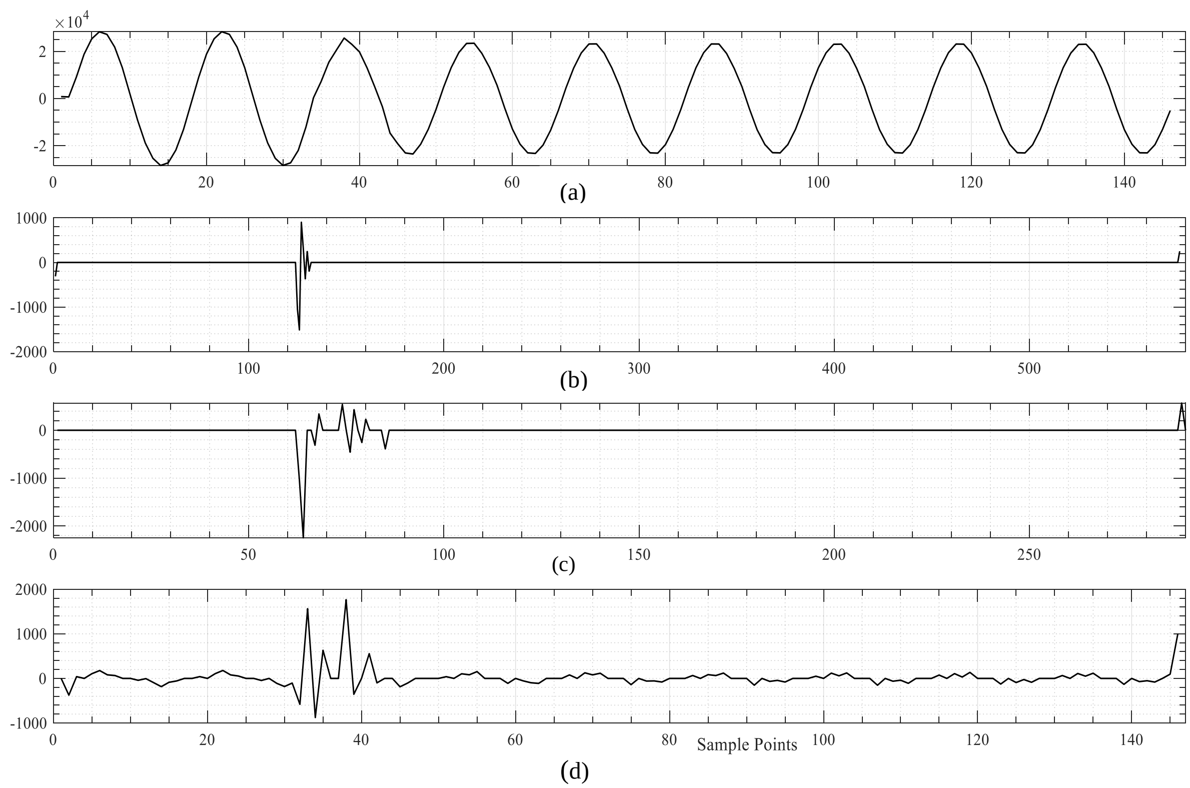


Figure 6.13: Event#3 (a) Smooth Approximation signal, (b) detail 1, (c) detail 2, (d) detail 3 after applying hard threshold

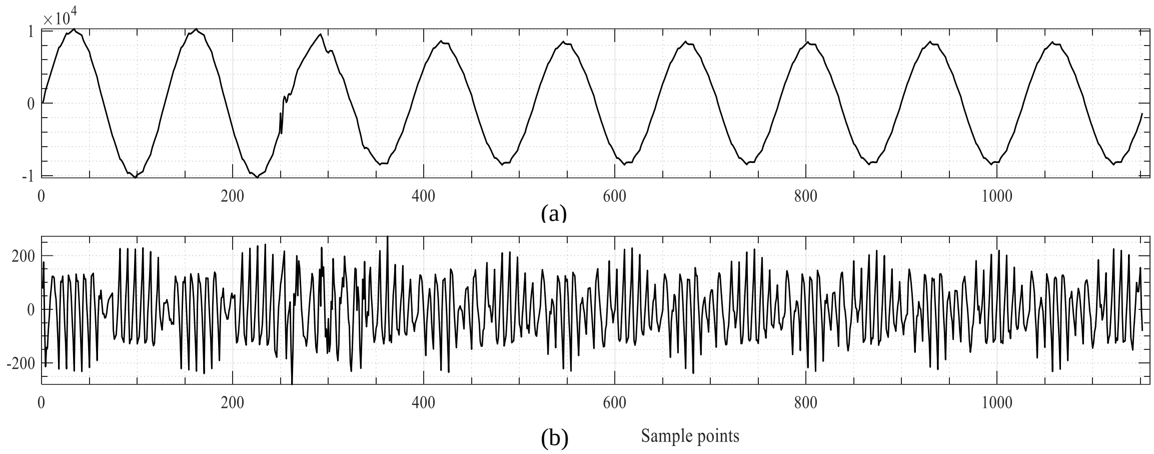


Figure 6.14: (a) Event#3 Reconstructed signal and (b) difference between the original and the reconstructed signal.

Number of sample points for each level before applying the hard thresholding in (a), (b), (c), (d) and (e) are 1152, 577, 290, 146 and 146.The total file size of the original signal is 9216 bytes. After applying the hard thresholding to d_1 , d_2 , d_3 the sample points are reduced to 9, 11, and 101 samples as shown in Fig.6.13 (b), (c), (d). The total numbers of samples needs to be stored are 2 × (9+11+101) +146=388. sam Both magnitude and position of the signal stored. The bytes required for these samples are 2136 leading to the compression ratio of 9216/2136=4.31. The reconstruction is performed using the detail d_1 , d_2 , d_3 and the approximation $A3$. Since the difference between the original signal and the reconstructed signal is difficult to visualize by visual inspection, the difference between the two signals can be used to quantify the amount of the information lost, which can take the form of noise and distortion as shown in Fig.6.14(b). The Normalized mean square error (NMSE) is used to assess the goodness of reconstruction and using equation (4.8) it was found to be 7.879×10^{-4}.

6.4.1 Proposed Approach (Event#3)

The use of the predictor importance as in eqs (4.5,4.6,4.7) indicates that detail level d_3 has the highest importance among all the details as shown in Fig.6.15. The hybrid thresholding is then applied by applying soft threshold to d_3 and the hard threshold is applied to the remaining detail levels. Table 6.3 list the measures used to assess the performance of both the traditional and the proposed approaches. Visual inspection of table 6.3 reveals that the implementation of the proposed approach leads to an increase in the CR from 4.31 in the traditional approach to 4.66 in the proposed approach. Furthermore, the file size was reduced from 2136 in the traditional approach to 1976 in the proposed approach. As a result, this approach helps reducing the bytes of signal more as compare to traditional approach as well as increasing compression ratio. Whereas, normalized mean square error (NMSE) is a bit high but is still in acceptable range. The comparison of both approaches is shown in table 6.3.

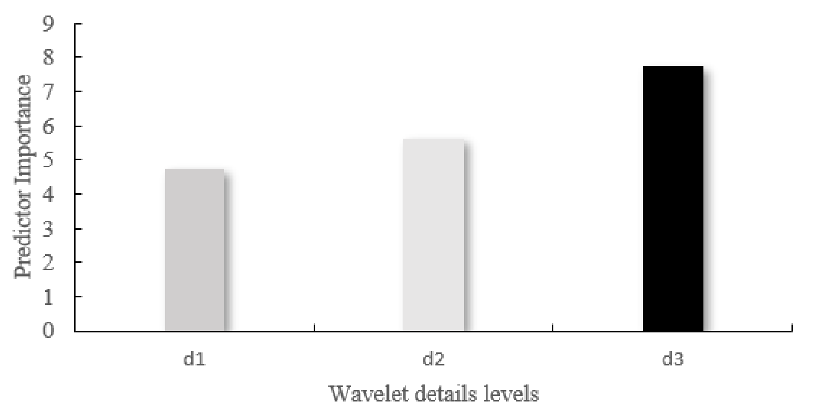


Figure 6.15: Predictor Importance for Event#3

Table 6.3 Comparison of Traditional and Proposed Approach for Event#3

Event#3	
Traditional Approach	Proposed Approach
Original signal Bytes:9216	Original signal Bytes:9216
Bytes After Compression: 2136	Bytes After Compression: 1976
Compression ratio:4.31	Compression ratio:4.66
NRMSE:7.879×10^{-4}	NRMSE: 2.52×10^{-4}

6.5. Traditional Approach (Event#4)

A fourth signal used to verify approach is Event#4 as shown in Fig.6.16. Threshold varied for each scale in this signal. τ_1=139.2746, τ_2=189.8248, τ_3=222.295 were the threshold for Detail d_1 ,d_2 ,d_3 . After Implementation of the threshold on Event#4 decomposition at different levels and reconstruction can be observed in fig. 6.17,6.18.

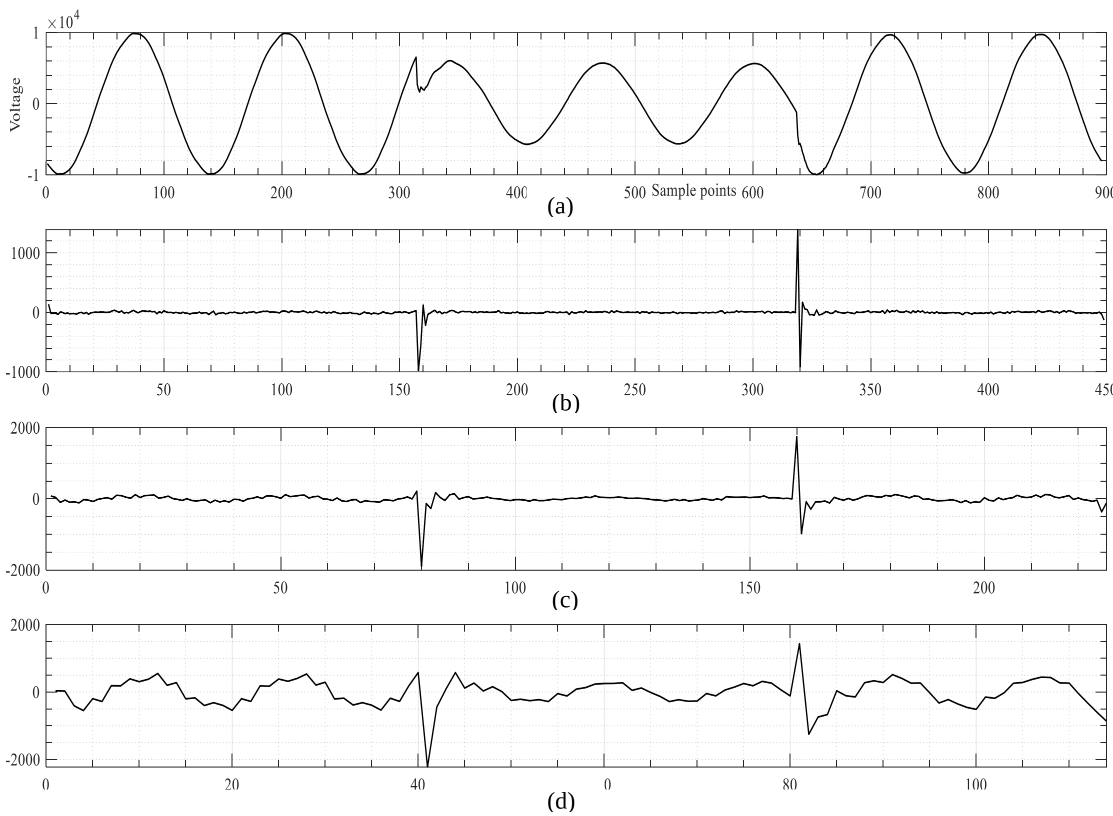


Figure 6.16: Event#4 (a) Original signal, (b) detail 1, (c) detail d2, (d) detail d3

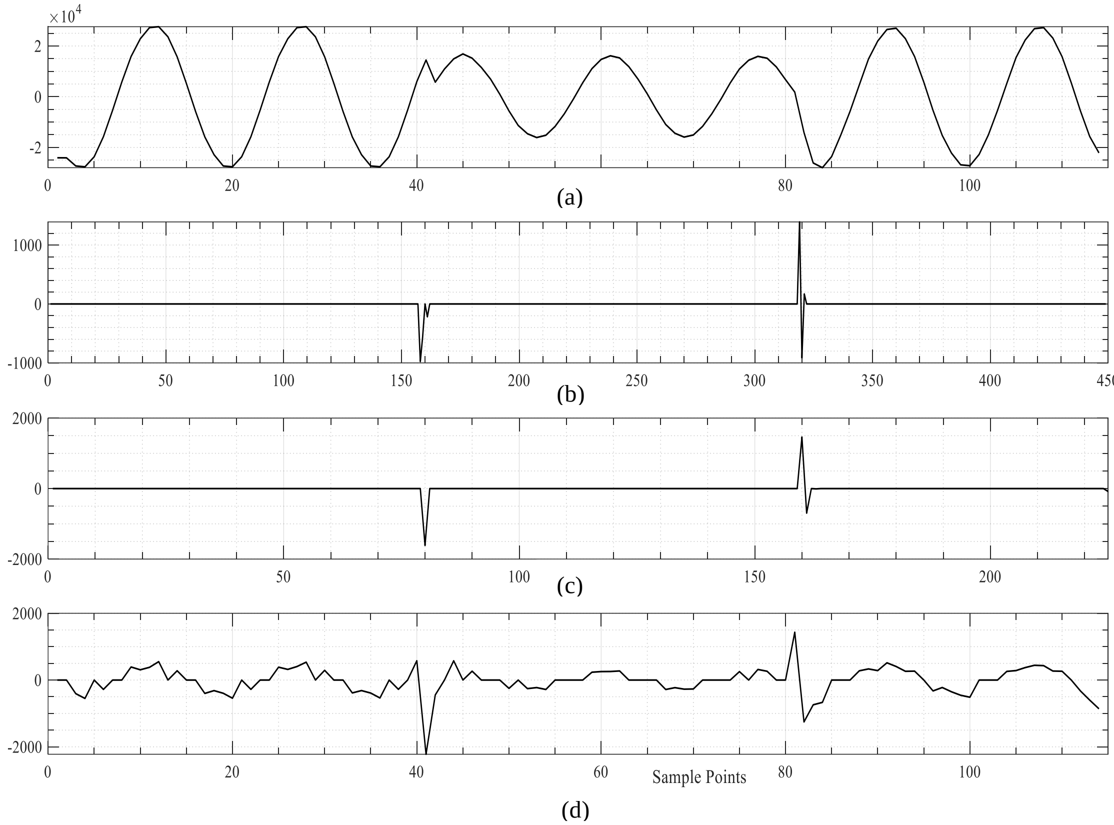


Figure 6.17: Event#4 (a) Smooth Approximation signal, (b) detail 1, (c) detail d2, (d) detail d3 after applying hard threshold

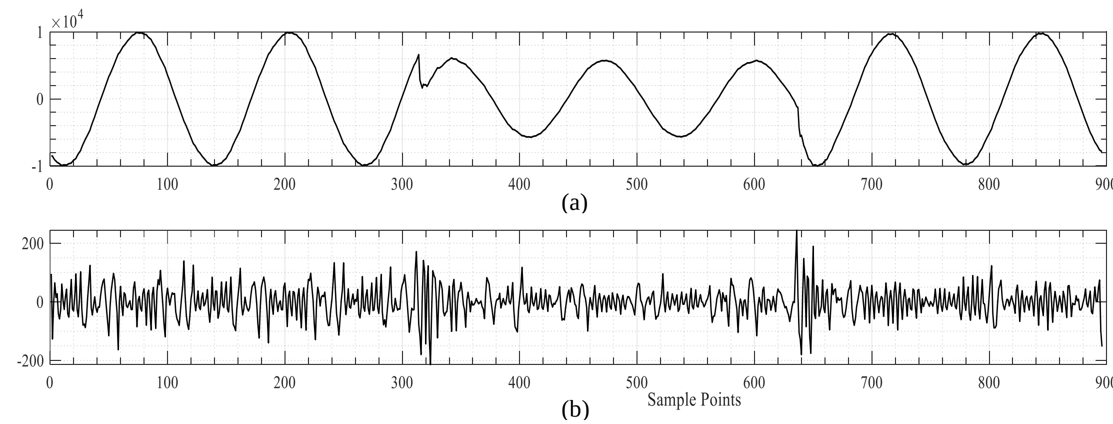


Figure 6.18 Event#3 (a)Reconstructed signal and (b) difference between the original and the reconstructed signal.

Number of sample points for each level before applying the hard thresholding in (a), (b), (c), (d) and (e) are 896, 449, 226, 114 and 114. The total file size of the original signal is 7168 bytes. After applying the hard thresholding to d_3 the sample points are reduced to 6, 7, and 69 samples as shown in Fig.6.17 (b), (c), (d). The total numbers of samples needs to be stored are 2 × (6+7+69) +114=158 samples. Both magnitude and position of the signal stored. The bytes required for these samples are 1568 leading to the compression ratio of 7168/1568=4.5714. The reconstruction is performed using the detail d_1 , d_2 , d_3 and the approximation $A3$. Since the difference between the original signal and the reconstructed signal is difficult to visualize by visual inspection, the difference between the two signals can be used to quantify the amount of the information lost, which can take the form of noise and distortion as shown in Fig.6.18(b). The Normalized mean square error (NMSE) is used to assess the goodness of reconstruction and is 6.584×10^{-5}.

6.5.1 Proposed Approach (Event#4)

The use of the predictor importance as in eqs (4.5,4.6,4.7) indicates that detail level d_2 has the highest importance among all the details as shown in Fig.6.19. The hybrid thresholding is then applied by applying soft threshold to d_2 and the hard threshold is applied to the remaining detail levels. Table 6.4 list the measures used to assess the performance of both the Traditional and the proposed approaches. Visual inspection of table 6.4 reveals that the implementation of the proposed approach leads to an increase in the CR from 4.5 in the traditional approach to 4.92 in the proposed approach. Furthermore, the file size was reduced from 1568 in the traditional approach to 1548 in the proposed approach. As a result, this approach helps reducing the bytes of signal more as compare to old approach as well as increasing compression ratio. Whereas, normalized mean square error (NMSE) is a bit high but is still in acceptable range. The comparison of both approaches is shown in table 6.4.

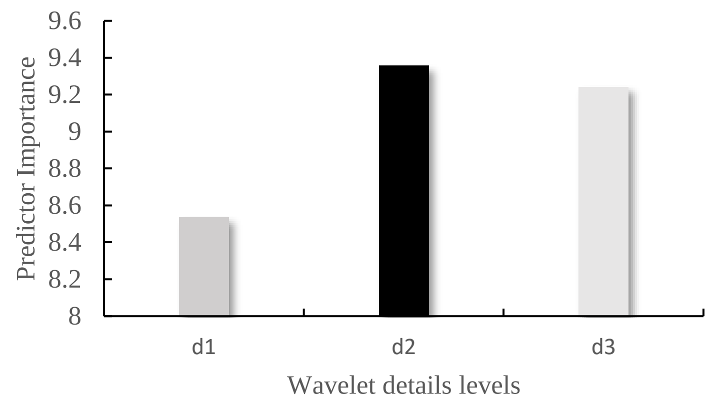


Figure 6.19: Predictor Importance for Event#4

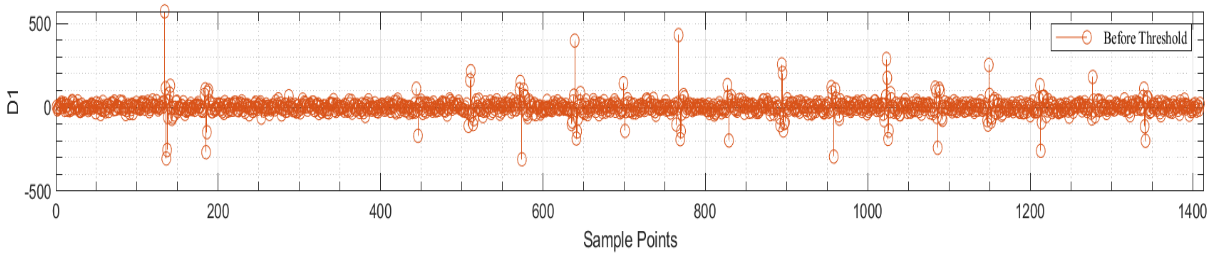
Table 6.4: Comparison of Traditional and Proposed Approach for Event#4

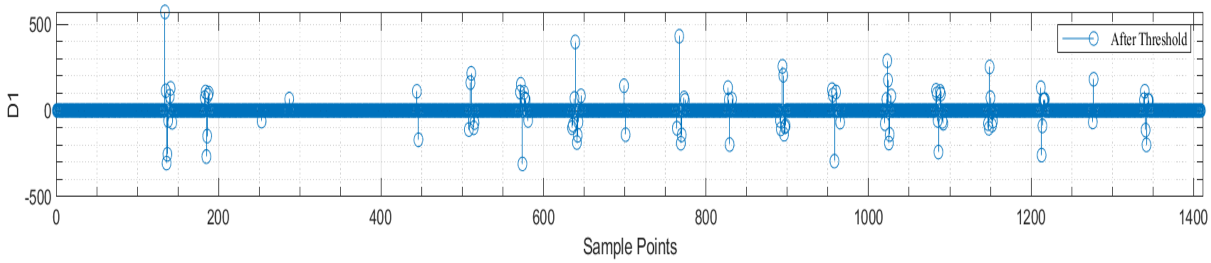
Event#4	
Traditional Approach	**Proposed Approach**
Original signal Bytes:7168	Original signal Bytes:7168
Bytes After Compression: 1568	Bytes After Compression: 1548
Compression ratio:4.5	Compression ratio:4.92
NRMSE:4.36$\times 10^{-4}$	NRMSE: 6.584×10^{-5}

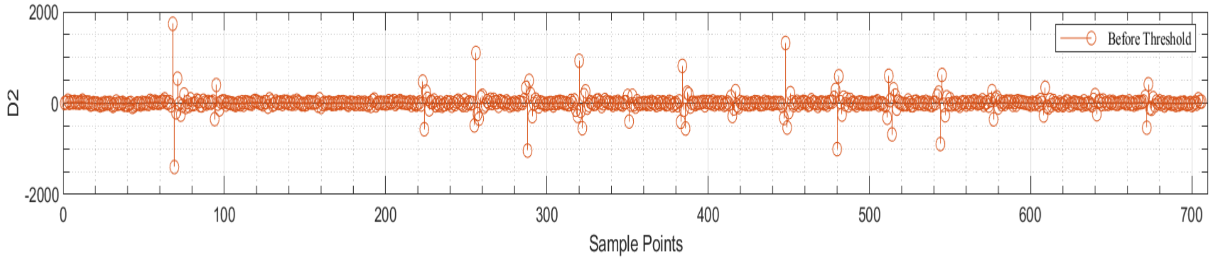
6.6. Discussion on the Effect of Compression on The Signals' Sample Points

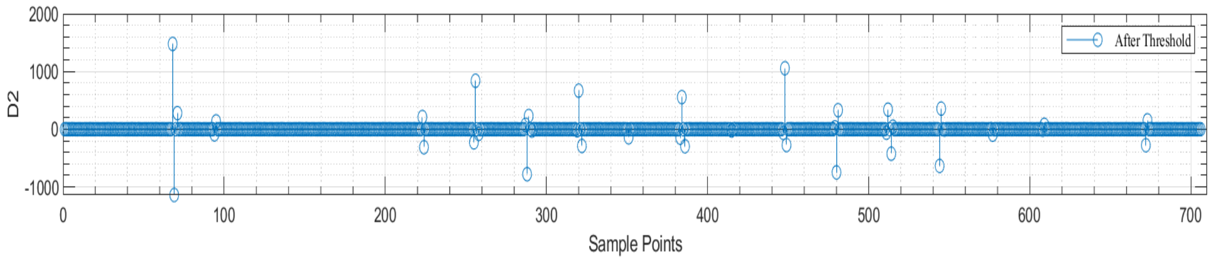
Figure 6.20 - 6.23, depicts the effect of compression on reducing the number of sample points. During the process of applying thresholding, all the sample points that is less than the threshold is set to zero while only the sample points that are related to some kind of disturbances or abrupt changes in the signal is kept. Moreover, those sample points that contain important features and discontinuity of the signal are also kept. The plots in orange represent the signals before applying the thresholding process while the plots in blue are for the signals after applying the thresholding process.

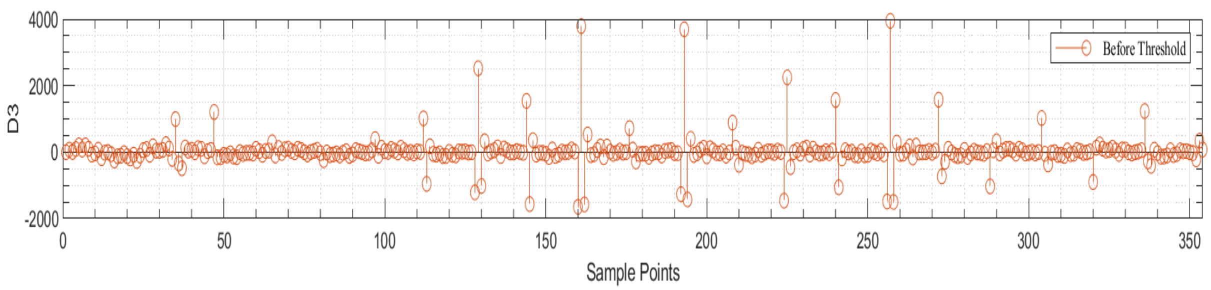
6.6.1 Event#1


Before Threshold
D1
500
0
-500
0
200
400
600
800
1000
1200
1400
Sample Points


After Threshold
D1
500
0
-500
0
200
400
600
800
1000
1200
1400
Sample Points


Before Threshold
D2
2000
0
-2000
0
100
200
300
400
500
600
700
Sample Points


After Threshold
D2
2000
1000
0
-1000
0
100
200
300
400
500
600
700
Sample Points


Before Threshold
D3
4000
2000
0
-2000
0
50
100
150
200
250
300
350
Sample Points

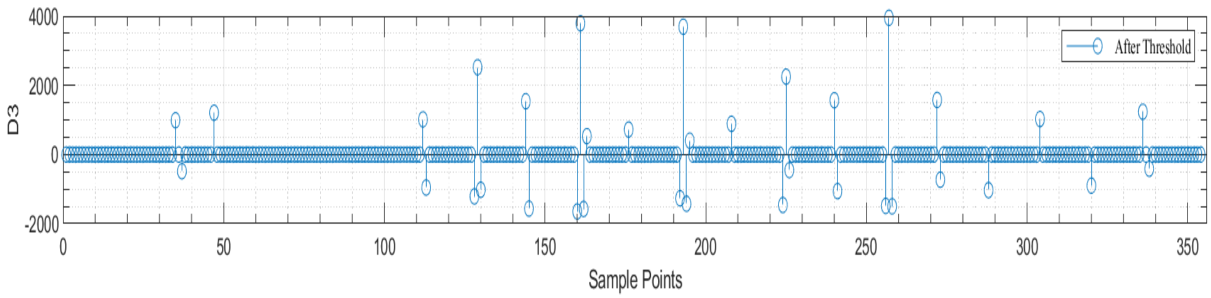
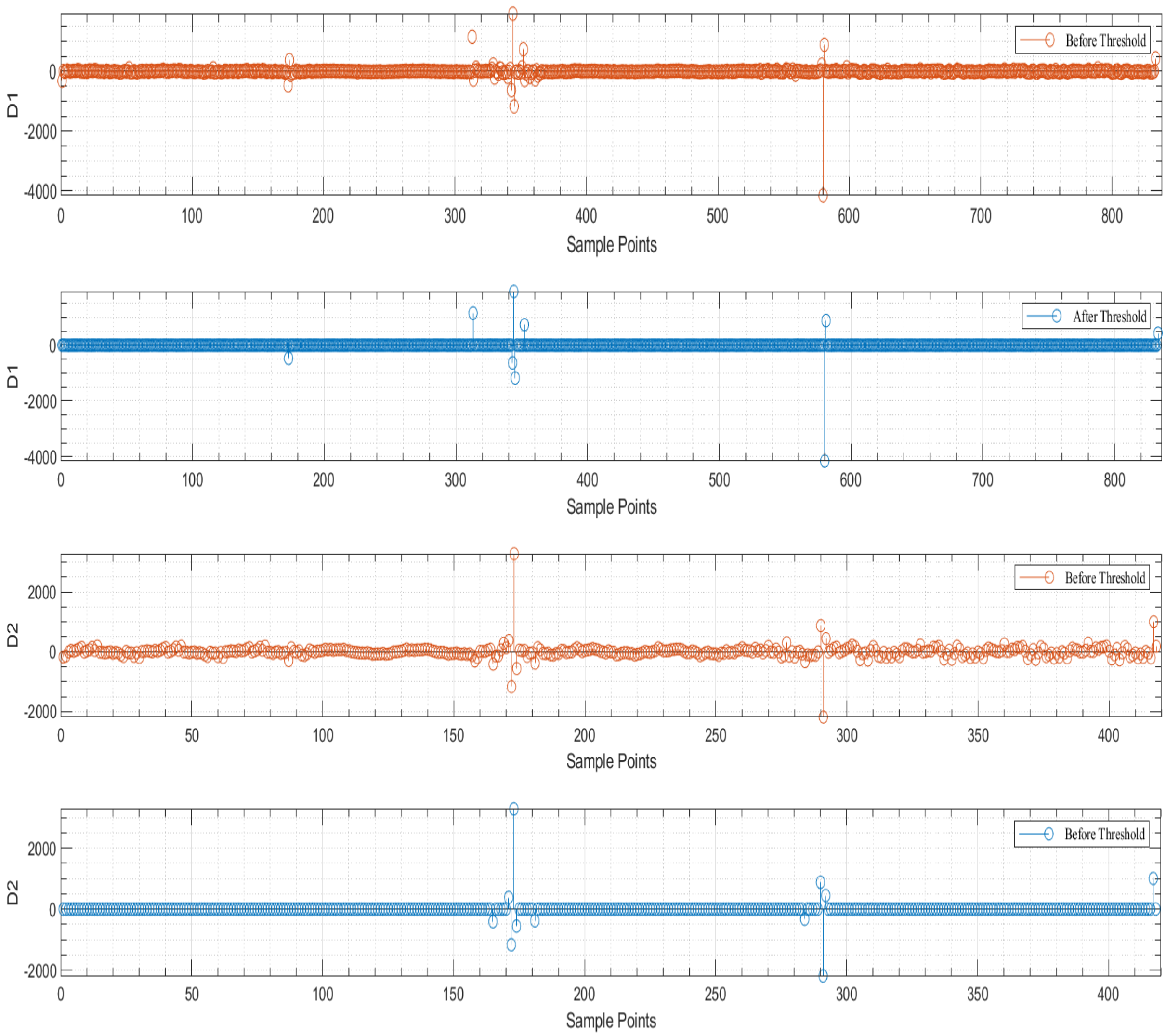


Figure 6.20: Sample Points Reduction Visuals for Event#1

6.6.2 Event#2



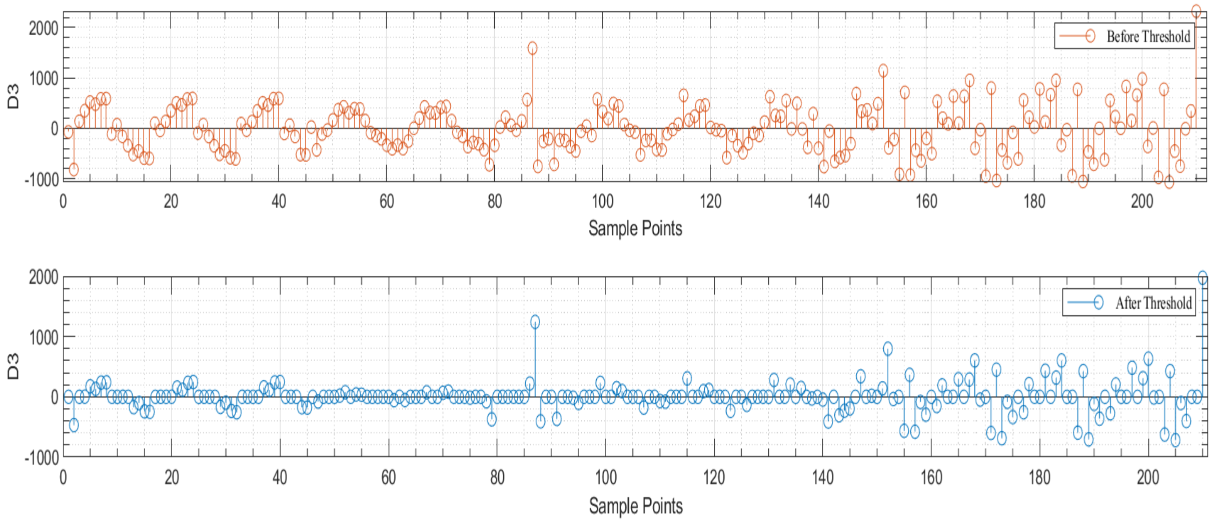
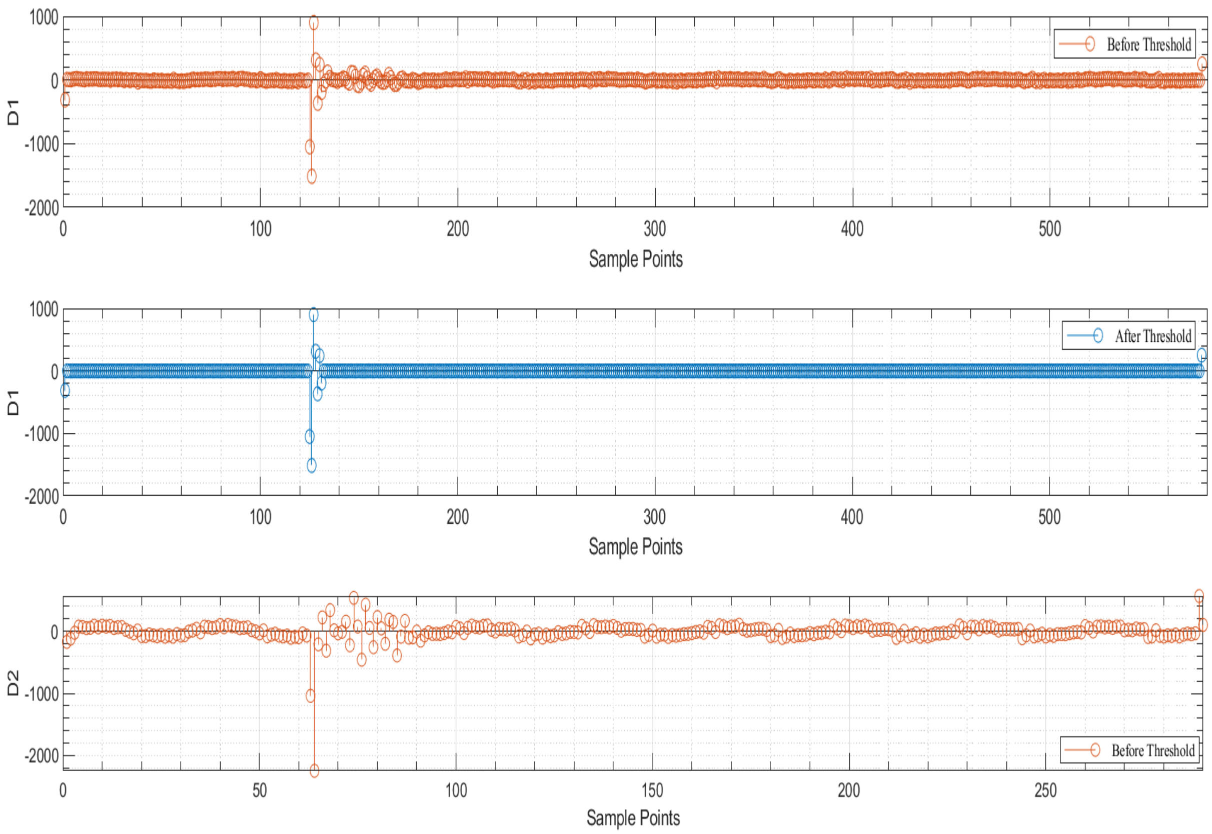


Figure 6.21: Sample Points Reduction Visuals for Event#2

6.6.3 Event#3



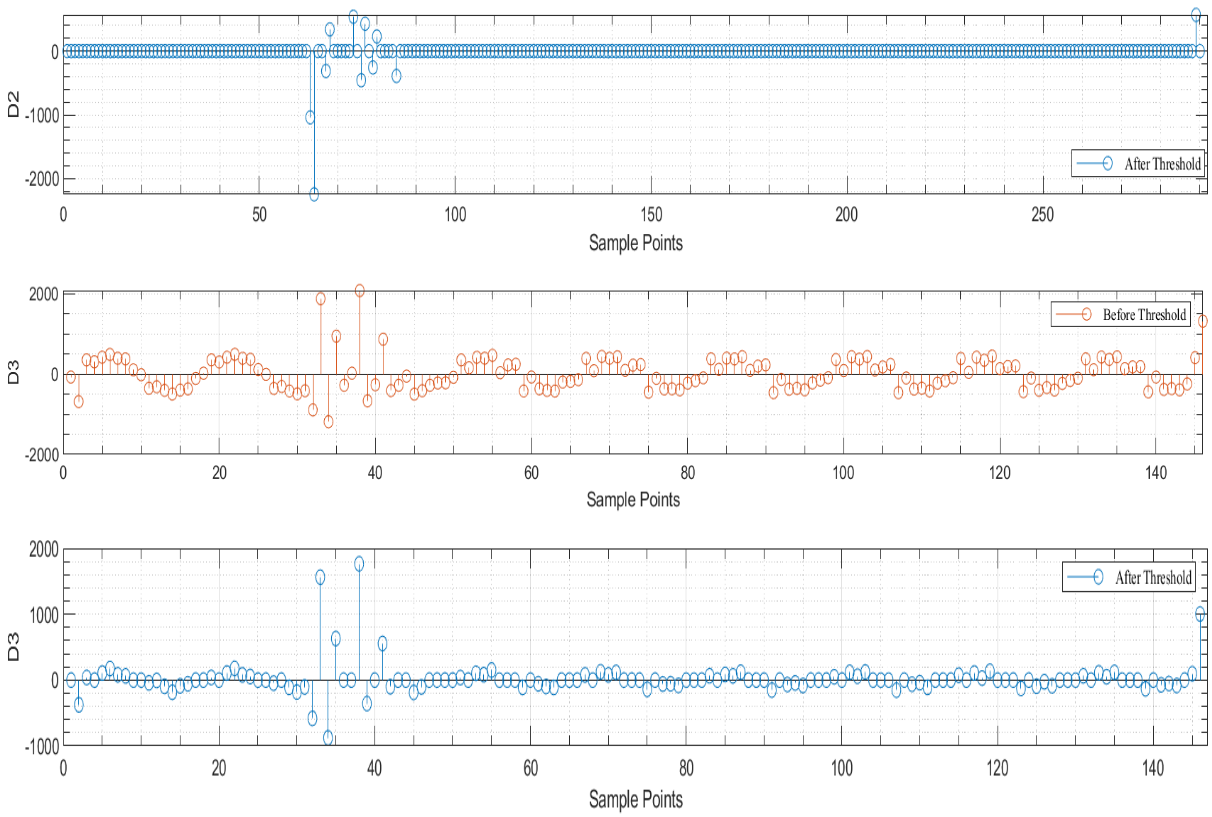
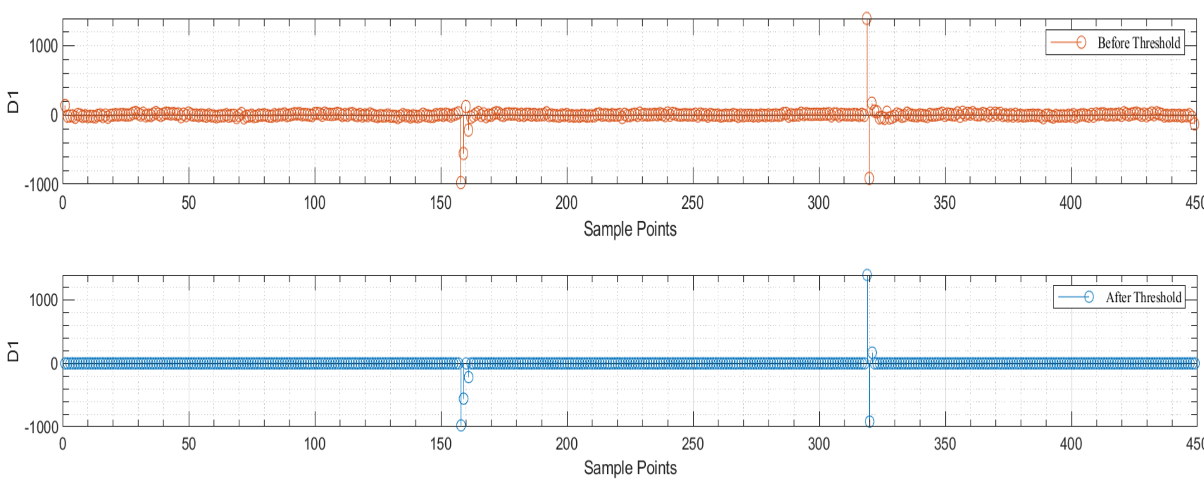


Figure 6.22: Sample Points Reduction Visuals for Event#3

6.6.4 Event#4



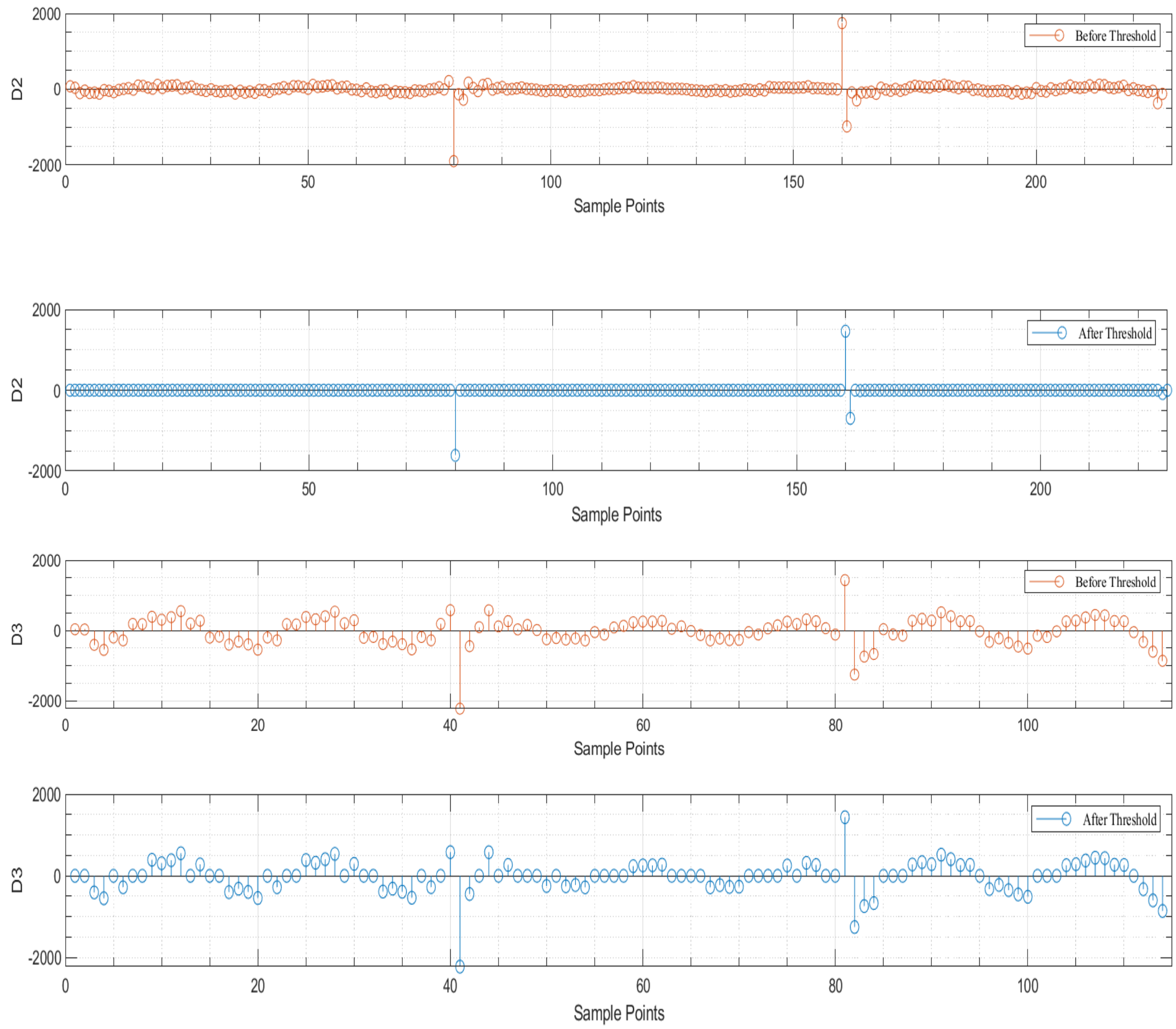


Figure 6.23: Sample Points Reduction Visuals for Event#4

6.7. Real Time RT-Lab Simulation Results

The main objective of this simulation is to send the disturbance signals to OPAL-RT mother board which acts as an IED modeled on the super micro mother board and receive the published GOOSE messages. The Opfrom block is used to transfer the signal from RT-Lab to OPAL-RT. This block ensures the signal is transferred properly to the mother board over ethernet (IEC61850). Another property of this block is it can easily transfer MATLAB disturbance signals. As shown in Fig.6.14, the SM (Master subsystem) and SC (console subsystem) are used in this simulation and they are considered the major subsystems that each simulation must have in RT-LAB. Additionally, all the computational elements and the calculations occur in the SM block, whereas the SC block is available to the user during the execution of the simulation. Four test signals are used in this work to test the proposed approach for which the simulation setup for Opfrom block and disturbance signal transfer is shown in Fig. 6.15

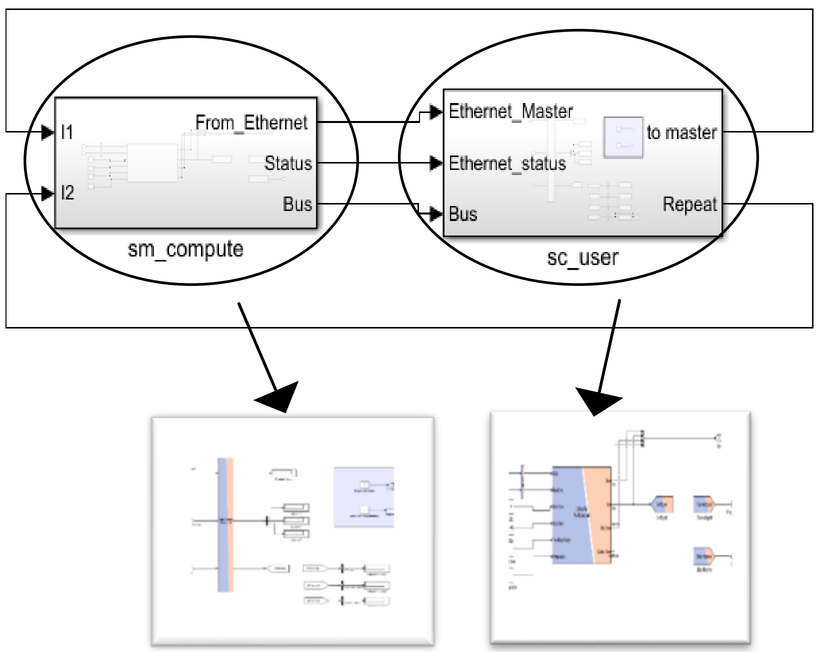


Figure 6.24: SM and SC Subsystem

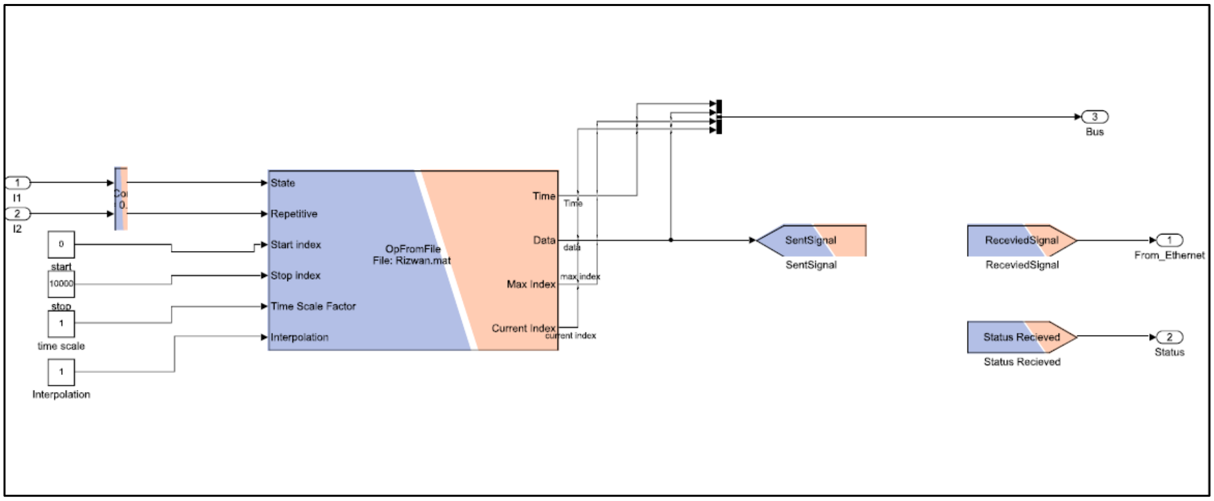


Figure 6. 25: Sending Disturbance Signal from PC (RT-LAB) to OPAL-RT

6.7.1 Troubleshooting of the Send-Receive of the signals

It is very important to have an indication that the subscriber has received all the signals that are sent by the PC, which acts as the publisher. In this research, the publisher and subscriber configuration set-up is done using the standard configuration setting in IEC61850 protocol and OPAL-RT. This configuration allows the publisher and subscribers to connect to each other virtually so that the GOOSE can transfer. More about configuration setup is discussed in [19].

While the signal is being transferred from the PC to the OPAL-RT using the Opfrom specialized block, the status property in OPAL-RT is being utilized as the confirmation of signal being received on the subscriber side. As soon as the signal is received by the IED (motherboard) the pre-defined indication section indicates the signal is being received by displaying “1” on the display as shown in fig. 6.26, which is a confirmation of the signal being transferred from the PC to the OPAL-RT mother board. In order to verify the signal is being received on IEC61850 communication protocol use a status confirmation section on the publisher side which keep the publishers updated. Not only this status section gives notification of signal received but also it keeps checking if there is any kind of transmission problem in sending the GOOSE messages to the other devices. Status are built-in features in the IEC61850 protocol and consist of StNum, Sqnum and different states. More about this is discussed in Chapter 5.6.2 Statuses section.

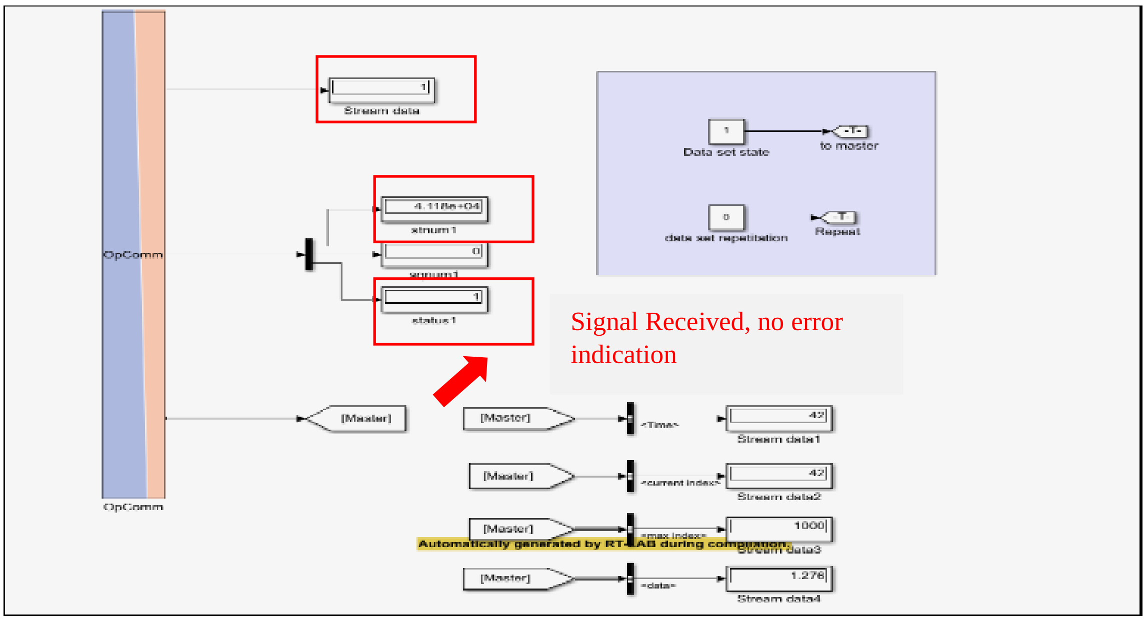


Figure 6.26: Statues Section

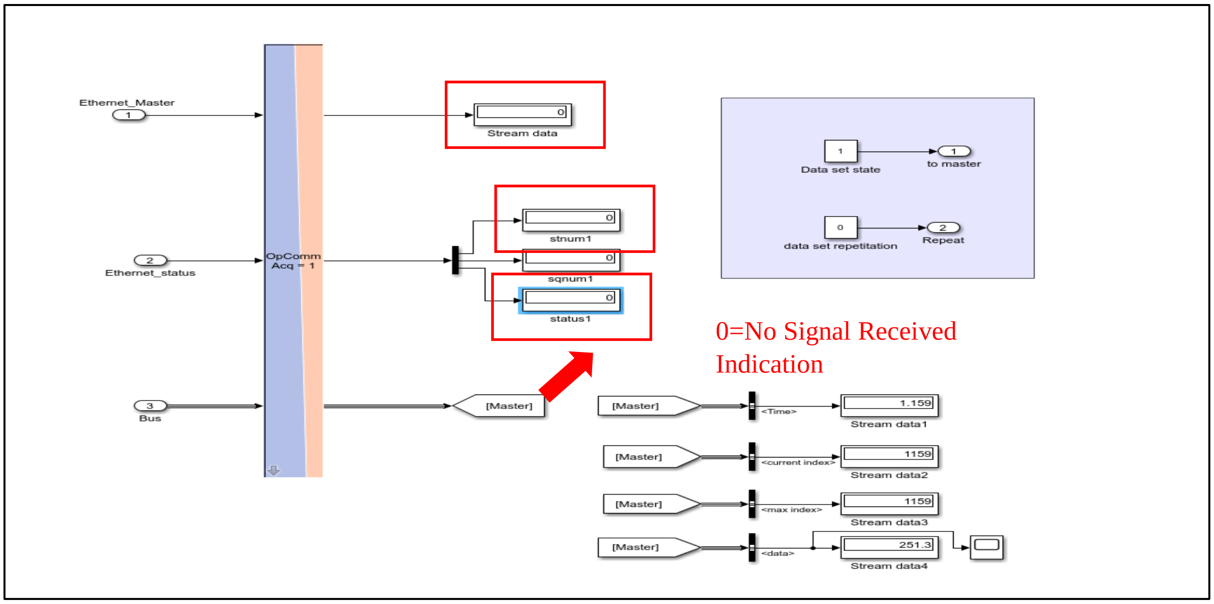


Figure 6.27: Status Error OPAL-RT Screen

As shown in Figure.6.26 and 6.27, the status of the signals is displaying ‘1’ when the signal is received and the transfer of GOOSE messages is operational with no error. On the other hand, when the status is displaying ‘0’, this indicates the GOOSE message was not received or the message reception stopped working. If the display is showing ‘-14’ then this means there was an error in the IEC-61850 communication protocol or in Ethernet.

6.8. Real-time Experimental Testing: System Description

To test the performance of the proposed data compression approach in terms of the number and sizes of the GOOSE messages exchanged, an experimental set up was developed where the uncompressed and compressed signal using both approaches were sent to OPAL-RT in real time. This was done using a loop back system as shown in Fig.6.1. The figure depicts the OPAL-RT OP4520 mother board, which is used as the publisher IED, whereas the PC is used as the subscriber IED with Wireshark receiving the Published messages in a loop-back manner. Furthermore, a Cisco Ethernet router is used to transmit the flow of messages using IEC61850 protocol in real-time. A schematic and a picture of actual experimental set-up are shown in Fig.6.2 and Fig. 6.3 respectively.

6.9. Results of the Experimental testing

Figure. 6.1,6.2 and 6.3 shows the experimental set-up used for testing the performance of the proposed approach. The number of GOOSE messages published were examined and counted using the Wireshark software[63]. Table 6.5 shows the comparison of GOOSE messages received for all the test signals used in this work.

Table 6.5: Comparison GOOSE Messages received in Term of Traditional approach and Proposed approach

Uncompressed Signal	Compressed Using Traditional approach	Compressed using Proposed approach
Event#1		
GOOSE received:2832	GOOSE received:650	GOOSE received:625
Total length of all GOOSE received:467280	Total length of all GOOSE received:107250	Total length of all GOOSE received:103125
Event#2		
GOOSE received:1681	GOOSE received:437	GOOSE received:420
Total length of all GOOSE received:277365	Total length of all GOOSE received:72105	Total length of all GOOSE received:69300
Event#3		
GOOSE received:1169	GOOSE received:323	GOOSE received:305
Total length of all GOOSE received:192885	Total length of all GOOSE received:53295	Total length of all GOOSE received:50325
Event#4		
GOOSE received:919	GOOSE received:240	GOOSE received:224
Total length of all GOOSE received:151635	Total length of all GOOSE received:39600	Total length of all GOOSE received:369690

In this thesis, each disturbance signal is transferred through the Ethernet using IEC61850 communication protocol. For each disturbance signal (i.e., Event#1, Event#2, Event#3, Event#4) the number and the length of the GOOSE messages are compared in case of the traditional approach [12] and the proposed approach presented in this study. Table 6.5 lists the results obtained when both approaches are implemented in real-time using OPAL-RT and IEC61850 when considering the original (uncompressed) and the reconstructed (compressed) signals. With reference to Table 6.5, the percentage reduction in the number of the received GOOSE messages is computed in case of the compressed signal using the traditional and the proposed approaches.

$$\mu_R = \frac{\tilde{\gamma}}{\gamma} \times 100 \qquad (6.1)$$

Where, μ_R is the percentage reduction in the number of received GOOSE messages, $\tilde{\gamma}$ is the number of GOOSE messages received in case of the compressed signal while γ is the number of GOOSE message received in case of the uncompressed signal. Also, the compression ratio (*CR*) defined in (4.9) is used to assess the effect of compression on the total length of GOOSE messages received in case of both the traditional and the proposed compression approaches.

6.9.1 Event#1

In this case, the implementation of the proposed approach resulted in reduction in the number of GOOSE messages received compared to the traditional approach. The μ_R values are 22.06% and 22.95% in case of the proposed approach and the traditional approach respectively. The effect of the hybrid thresholding used in the proposed approach leads to higher compression ratio (*CR*) reaching 4.53 compared to 4.35 in case of the traditional approach.

6.9.2 Event#2

The proposed compression approach for this signal leads to lower μ_R values compared to the traditional approach. In case of the proposed approach, the μ_R value was 24.98% while in case of the traditional approach the μ_R value was 26.00%. Also, the total length of the GOOSE messages received was reduced leading to a *CR* values of 4.00 in case of the proposed approach and only 3.84 in case of the traditional approach.

6.9.3 Event#3

Visual inspection of Table 6.5 reveals that the number of GOOSE messages received in case of the uncompressed signal is 1,169 messages while in case of the compressed signal using the traditional approach it was found to be 305 messages. This demonstrates the effectiveness of the proposed approach in reducing the μ_R values to be 26.09% compared to 27.63% in case of the traditional approach. Also, the total length of the GOOSE messages was found to be significantly reduced from 192,885 in case of the uncompressed signal to only 50,325 in case of the compressed signal using the proposed approach. This is also seen from the *CR* values, which was found to be 3.83 and 3.61 in case of the proposed and the traditional approaches respectively.

6.9.4 Event#4

The number of GOOSE messages received in case of the uncompressed signal was 919 while in case of the proposed approach, this number was reduced to only 224. The implementation of the proposed approach leads to a significant reduction in the μ_R values to be 24.37%, which is lower compared to that of the traditional approach, which was found to be 26.11%. Also, with regard to the length of the GOOSE messages received, the proposed approach resulted into a significant reduction leading to a higher compression ratio of 4.10 while the *CR* value was only 3.82 in case of the traditional approach.

6.10. Result Discussion

The presented results demonstrate the effectiveness of implementing the proposed approach using the proposed combined wavelet-surrogate regression using hybrid thresholding in signal compression and hence a reduction in the number and length of the GOOSE messages received. The reduction in the number and length of the GOOSE messages in case of the compressed signals using the proposed approach are due to the reduction in the bytes of the messages that are directly related to the application of the predictor importance and the hybrid thresholding when applying compression.

Furthermore, after carefully inspecting the GOOSE messages properties in IEC61850 protocol, it became clear that the reduction in the number of GOOSE messages and the length of the messages was due to the fact that when the hybrid thresholding is applied, a large number of samples are set to zeros. Since GOOSE messages are only published when there is a change in the sample values, the effect of applying the hybrid thresholding increases the number of zeros, which results not only in reducing the number of GOOSE messages but also reducing the size of the published GOOSE messages.

Wireshark software is used to analyze packet transmission and count the GOOSE messages published on ethernet (IEC61850). A Wireshark screenshot with GOOSE messages published is shown Figure.6.28

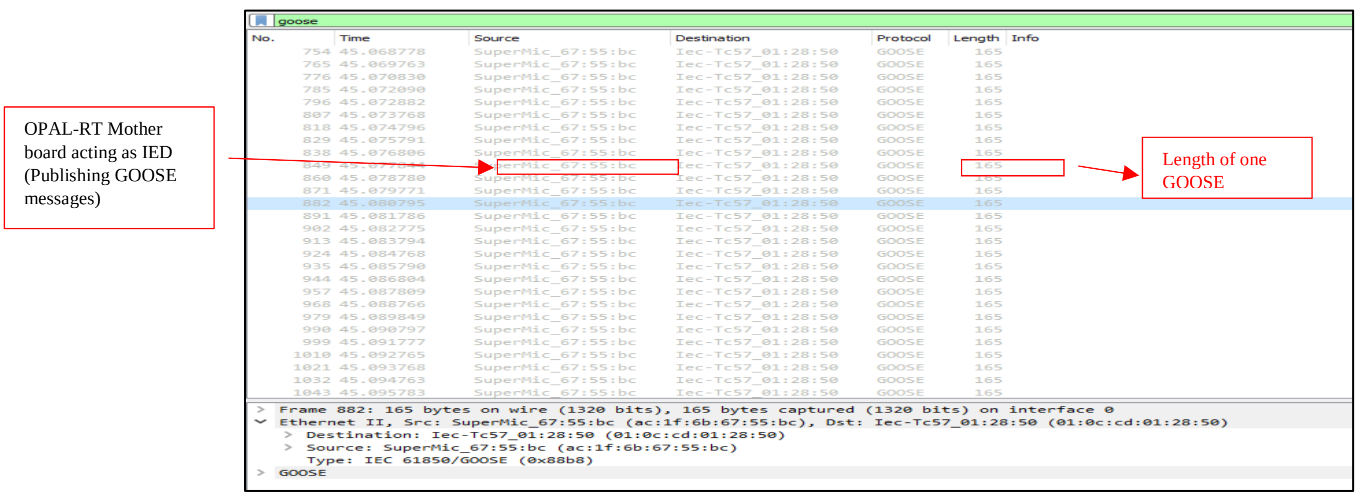


Figure 6.28: Wireshark Counting and Analyzing GOOSE Messages

6.11. Summary

In this chapter, two wavelet-based data compression approaches are implemented to compress the signals; namely the traditional approach and the proposed approach. Both of these approaches use the wavelet transform. In MATLAB these two approaches were implemented and decomposed using three decomposition level and using the Daubechies of order 2 (db2). Furthermore, these decomposed levels for every disturbance signal were passed through a threshold, which only keeps the important abrupt changes of the signal and discard rest. Moreover, the performance of these approaches was assessed based on the compression ratio, the file size measured in bytes and the Normalized mean square error (NMSE). The results have shown that the proposed approach was not only effective in increasing the compression ratio but also it was successful in reducing the file sizes in term of bytes compared to the traditional approach. Furthermore, the normalized Mean square error in case of the traditional approach was found to be within the acceptable range as defined in Literatures. The results of the real-time implementation of the proposed compression approach using OPAL-RT and IEC61850 were also presented after providing a detailed description of the experimental set-up used for testing the performance of the proposed data compression approach in terms of the number and sizes of the GOOSE messages exchanged. That was utilized while thoroughly describing each hardware devices. The OPAL-RT is used as the real-time simulator and the IEC61850 is used as the communication protocol to send and receive the GOOSE message via Ethernet. Experimental Results proves that for uncompressed signal amount of GOOSE messages published were higher whereas for Compressed signal using traditional approach messages decreased but for the proposed approach GOOSE messages published were even less then both of the cases. Which proves the effectiveness of proposed approach as compare to traditional approach. The inspection of the GOOSE messages properties in the IEC61850 have demonstrated a strong connection between the application of the hybrid thresholding and the reduction in the number and the sizes of the GOOSE messages, which was found to be due to mainly the large number of samples that are set to zeros. This has led to not only reduction in the number of GOOSE messages being published but also a significant reduction in the size of the GOOSE messages. Results for these cases was compared in this chapter as well.

7. Conclusion and Recommendations

7.1. Conclusion

The work presented in this thesis aims to study the compression of power disturbance signals in the context of IEC61850 communication protocol for smart grid applications. After reviewing the state-of-the-art literature, it became evident that most of the data compression methods use either hard thresholding or soft thresholding. Since each thresholding method has its own advantages and disadvantages this thesis proposed a hybrid thresholding to benefit from the advantages of both thresholding methods. Furthermore, in order to ensure that the most salient features in the analyzed disturbance signal is kept, the thesis proposed the use of the predictor importance and a surrogate binary regression tree to identify the wavelet detail level that holds the most important features. This will eliminate the need for the trade-off that must be made in traditional approaches between the compression ratios and the measured distortions and hence the salient features of the disturbances are kept in the reconstructed signal. The results of the simulation have shown that the proposed approach not only reduces bytes to more than half as compare to other approach but also increases Compression ratio by keeping the Normalized mean square error in acceptable range. Result shows that proposed approach perform more effective compression as compare to traditional approach by retaining the same features as of original signal in almost more than half the size in term of bytes and length .Same features i.e. Shape, abrupt changes of the signal are preserved using this approach.

On the other hand, in experimental work, the proposed approach has been experimentally tested in real-time using OPAL-RT in the context of IEC61850 by monitoring the number and the sizes of the GOOSE messages exchanged between the publisher and the subscriber IEDs after modeling them in RT-LAB. The results have demonstrated the effectiveness of the proposed approach in data compression as the hybrid thresholding was found to be very effective in leading to significant reduction in the number and the sizes of the GOOSE messages exchanged. This has been reflected from the results obtained when applying the proposed approach to the tested disturbance signals from which it was seen on average the percentage reduction in the number of GOOSE messages reaching 24% and the increase in the compression ratio reaching 4.11.

The inspection of the GOOSE messages properties in the IEC61850 have demonstrated a strong connection between the application of the hybrid thresholding and the reduction in the number and the sizes of the GOOSE messages, which was found to be due to mainly the large number of samples that are set to zeros. This has led to not only reduction in the number of GOOSE messages being published but also a significant reduction in the size of the GOOSE messages.

The results have also shown that the use of the predictor importance, which helps preserving the salient features of the disturbances leading to a high-quality signal reconstruction following the compression process, which has been demonstrated through the NMSE values obtained that remain within the acceptable range.

7.2. Recommendations

Based on the work presented in this thesis, following represents the recommendations on future work. Firstly, the preservation of important features of details at different scale is an important part. Researchers should not lose important features of signal during decomposition at different levels as well as during applying the threshold which might leads to error while performing reconstruction. Secondly, it is very important to select a proper wavelet family and level used while performing the decomposition of the signal otherwise it is impossible to achieve the original shape and features of signal at reconstruction stage. Lastly, during Real time experiment it is very important to choose an appropriate communication protocol that have modern and advance features that can handle different complicated scenario and operate as in real life Smart grid.

7.3. Future Work

Some next steps that can be taken to build the work presented in thesis are: Researchers can implement this data compression techniques in field of Electric vehicles as well as in renewable energy integration purposes and power utilities field. Moreover, this approach can also be applicable for Image compression as well to enhance image compression process.

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