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Real Time Power Quality Monitoring Using Discrete Wavelet Transform

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By

Mohammed Hekmat AlWawi

Supervisors

Dr. Fouad Zaro and Dr. Luay Shahin

Thesis submitted in partial fulfillment of requirements of the degree

Master of Science in Renewable Energy & Sustainability

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The undersigned hereby certify that they have read, examined and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University and the Faculty of Science at Al-Quds University the approval of a thesis entitled:

Real Time Power Quality Monitoring Using Discrete Wavelet Transform

Submitted by

Mohammed Hekmat AlWawi

In partial fulfillment of the requirements for the degree of Master in Renewable Energy & Sustainability.

Graduate Advisory Committee:

Prof./Dr. ………………………………,…………………………..
(Supervisor), University (typed)
Signature: ______________________ Date:_______________

Prof./ Dr. ……………………………, …………………………………..
(Co-supervisor), University (typed)
Signature: ______________________ Date:_______________

Prof./Dr……………………………………………,……………………..
(Internal committee member), University (typed).
Signature: ______________________ Date:_______________

Prof./Dr. ……………………………………………,……………………..
(External committee member), University (typed).
Signature: ______________________ Date:_______________

Thesis Approved by:

Name:	Name:
Dean of Graduate Studies & Scientific Research	Dean of Faculty of Graduate Studies
Palestine Polytechnic University	Al-Quds University
Signature:…………………………………	Signature:…………………………………
Date:……………………………………	Date:…………………………………

Real Time Power Quality Monitoring Using Discrete Wavelet Transform

By **Mohammed Hekmat AlWawi**

ABSTRACT

The revolution of renewable energy resources (RES) lead to a significant increase in using power electronics devices which have increased the power quality (PQ) issues. Poor PQ causes several problems such as; misoperation of the equipment, loss of important data, protection devices misoperation, and overheating. The mitigation of PQ disturbances can be easily done only if these disturbances are well detected and classified.

Traditional detection techniques have some shortages in case of power system signals which are non-stationary and have transients. Unlike Fourier transform (FT) a discrete wavelet transform (DWT) multi-resolution analysis (MRA) is used to deal with the PQ disturbances in order to accurately detect, localize, and classify these events.

In this research, an attempt will be made to design a real time system for monitoring the PQ, to detect and classify PQ disturbances using DWT; specifically voltage sag, swell, and interruption. The proposed system has been simulated and built using National Instruments compact RIO controller (NI-cRIO 9063) and the monitoring has been done using laboratory virtual instrument engineering workbench (LabVIEW). Utilizing the high speed acquisition of the cRIO based system using field-programmable gate array (FPGA) and real time, results in a significant accuracy in detection and classification of the PQ events in terms of magnitude and time (Sag/ Undervoltage, Swell/ Overvoltage, and Interruption/ Sustained Interruption). Connecting the proposed system with the grid shows very high speed and accuracy in grid monitoring.

مراقبة زمنية لحظية لجودة الطاقة باستخدام التحليل الرياضي (تحويلة المويجات المتقطعة)

إعداد: محمد حكمت الواوي

ملخص

إن الثورة في استخدام مصادر الطاقة المتجددة أدت إلى زيادة كبيرة في استخدام أجهزة إلكترونيات القدرة التي تؤدي إلى زيادة في مشاكل عدم استقرار جودة الطاقة. عدم استقرار جودة الطاقة تسبب مشاكل عديدة مثل: عمل الأجهزة بشكل غير صحيح, وفقدان في البيانات الهامة, وارتفاع حرارة الأجهزة, وتفعيل أجهزة الحماية بشكل خاطئ, وارتفاع درجة حرارة الأجهزة. و بالتالي فإن عملية معالجة هذه المشاكل يمكن أن تتم بسهولة بعد عملية التقاطها وتصنيفها بشكل جيد.

تقنيات التقاط مشاكل جودة الطاقة التقليدية تحتوي على بعض المشاكل في حالة إشارات أنظمة الطاقة التي تعتبر غير ثابتة وفيها تغيرات عابرة. على عكس تحويلة فورير الرياضية, فإن تحويلة المويجات المتقطعة متعددة الوضوع (MRA-DWT) تستخدم للتعامل مع مشاكل جودة الطاقة وذلك من أجل التقاطها وتصنيفها بشكل دقيق.

في هذا البحث سيتم تصميم نظام مراقبة زمنية لحظية لجودة الطاقة من أجل التقاط وتصنيف مشاكل جودة الطاقة باستخدام تحويلة المويجات المتقطة (MRA-DWT) على وجه التحديد هبوط الجهد, وارتفاعه, وانقطاعه. تم عمل محاكاة للنظام المقترح ومن ثم بناؤه بشكل عملي باستخدام متحكم (NI-cRIO 9063) وتم استخدام منصة البرمجة لإجراء عملية المحاكاة باستخدام (LabVIEW). إن استخدام متحكم (cRIO 9063) والاستفادة من سرعته ودقته العالية عن طريق استخدام مصفوفة البوابات القابلة للبرمجة (FPGA) و (Real Time) نتج عنه سرعة كبيرة ودقة عالية في التقاط وتصنيف مشاكل جودة الطاقة من ناحية مقدار ومدة المشكلة (Sag/ Undervoltage, Swell/ Overvoltage, and Interruption/ Sustained Interruption). كما أظهر التوصيل المباشر دقة عالية وسرعة كبيرة جداً في مراقبة الشبكة أولاً بأول.

DECLARATION

I declare that the Master Thesis entitled**" Real Time Power Quality Monitoring using Discrete Wavelet Transform"** is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: **Mohammed Hekmat AlWawi**

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DEDICATION

To the first teachers, my mother and father

To the soul mate, my wife

To my beloved children

To my brother and sisters

To my family

To my colleagues

To all my friends

To Palestine

This work is dedicated for everyone supports me

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LIST OF ABBREVIATIONS

RES	Renewable Energy Source
PQ	Power Quality
PE	Power Electronics
SMPS	Switch Mode Power Supply
UPS	Uninterruptable Power Supply
DSP	Digital Signal Processing
RMS	Root Mean Square
THD	Total Harmonic Distortion
NI	National Instruments
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
VI	Virtual Instrument
FPGA	Field Programmable Gate Array
RT	Real Time
WT	Wavelet Transform
ST	Stockwell Transform
FT	Fourier Transform
DWT	Discrete Wavelet Transform
CWT	Continuous Wavelet Transform
WPT	Wavelet Packet Transform
MRA	Multi Resolution Analysis
FDST	Fast Discrete Stockwell Transform
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
STFT	Short Time Fourier Transform
FDST	Fast Discrete Stockwell Transform
IEEE	Institute of Electrical and Electronics Engineers
DSTATCOM	Distribution Static Compensator
ANN	Artificial neural network
DAQ	Data Acquisition
ADC	Analog to Digital Converter

NEMA	National Electrical Manufacturers Association
TDMS	Technical Data Management Streaming
FIFO	First In First Out
GUI	Graphical User Interface
DC	Direct Current
LED	Light Emitting Diode

LIST OF SYMBOLS

ψ	Mother Wavelet
φ	Scaling Function

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CHAPTER 1

Introduction

1.1 Background

The new technologies in all life aspects have significantly increased the energy demand where this leads us to look for new Renewable Energy Sources (RES's) instead of fossil fuels to cover the increasing demand on energy. In order to penetrate the RES's along with the utility network, Power Electronics (PE) devices are needed. On the other hand, the complexities in life needs have increased the use of sensitive electronic devices, Switch Mode Power Supply SMPS (in TV's, Computers, fluorescent and energy saving lamps with dimmers), Uninterruptable Power Supply (UPS), and the Motor drives in the industrial applications [1, 2].

The wide use of above mentioned devices and systems raised the concern about Power Quality (PQ) among the main key players: utility companies, equipment manufacturers, and the consumers. In general PQ problem is any problem in voltage, current, and frequency that results in failure or malfunction of the equipment. Utility and consumers have two PQ definitions; for the utility it is the availability and reliability of the power supply that enable the loads to work correctly. For the consumers it is avoiding any problem in voltage, current, and frequency deviations that cause failure or operation loss of equipment [3, 4].

1.2 Motivation and Problem Statement

In residential and industrial applications several problems are directly related to the poor PQ; such as voltage sag, swell, interruption, total harmonic distortion, and poor power factor. In this research the voltage sag, swell, and interruption will be detected and classified, so as to make a good decision for mitigating these problems.

PQ disturbances in power system signals can be classified into two main categories: one is magnitude related problems; such as voltage sag, swell, and interruption, and the other is shape related problems; such as total harmonic distortion (THD) for voltage and current. In events of voltage sag, and/or swell, and/or interruption, the starting and ending time should be exactly determined. In case of shape related problems, the THD magnitude of voltage and/or current should be exactly determined. To determine these problems a good mathematical model should be used along with suitable data acquisition device fast enough to acquire data from targeted power system signals.

For achieving high quality monitoring system, a good algorithm using DWT with Daubechies (4 or 6) as mother Wavelet should be instructed and implemented on the acquired data. For power system signals, the most effective mathematical tool used for detection and classification is DWT with Daubechies (4 or 6) as mother Wavelet, because the shape of this mother wavelet is suitable to detect PQ disturbances [5]. Using traditional mathematical tool; such as Fourier transform FT is not suitable for this type of signals in real time monitoring, due to non-stationary and abrupt changes, using Stockwell transform (ST) will be a good choice but it has redundancy of data and this will slow the whole operation. Hence, the best choice to overcome these problems is DWT.

Data acquiring process needs DAQ devices; accurate, and fast enough to collect the signals data to be analyzed after converting these signals from analog to digital. A very fast and accurate controller acts as data collector for input signals and controller for output signals should be used; this controller is compact RIO (NI-cRIO 9063). Unlike the traditional DAQ devices used for this purpose; which are not fast enough, and based on windows which may have operation hang off. The solution will be using real time and FPGA in cRIO.

NI Compact RIO 9063 is a very accurate and fast controller with a processor (667MHz dual-core CPU), and user-programmable FPGA is connected with I/O modules, available in both rugged industrial and board level design. It's ideal for advanced control and monitoring applications [6].

1.3 Objectives of the Thesis

Building integrated system for detecting and classifying the PQ disturbances, by using suitable devices connected with the network along with the NI-cRIO 9063 controller and MRA-DWT as mathematical model. Whereas using a cRIO will support the parallelism and this is very important feature in real-time systems to perform more than one task at the same time and so minimizing the processing time of the proposed model. In addition to, the cRIO is very fast and accurate controller to be used in PQ disturbances detection, classification, and mitigation purposes, so the objectives are: design a real time PQ monitoring system for detection and classification of PQ disturbances (voltage sag, swell, and interruption), simulation of the proposed system, and implementation of the proposed system using cRIO-9063 controller.

1.4 Methodology

The proposed system will be built as a real time monitoring system (hardware connected) with mathematical model MRA-DWT to detect, localize, and classify PQ disturbances which are voltage sag, swell, and interruption. This will be done using suitable devices; I/O modules, and NI-cRIO 9063 as an accurate and fast independent real time controller connected with the network, as follows:

1- Building a mathematical model using MRA-DWT for feature extraction to determine the PQ issues in LabVIEW environment. In addition to, making use of parallelism that LabVIEW support to minimize processing time of the model.
2- Simulate the proposed system using LabVIEW.
3- Connecting voltages with the NI-cRIO 9063 I/O modules; NI-9225, 3-CH +/-300V Analog Input for input voltages. Internally the analog signals will be transferred into digital signals to deal with.
4- Real time PQ monitoring using LabVIEW environment and NI-cRIO 9063 as controller for accurate and fast detection, to detect and classify any voltage sag, undervoltage, swell, overvoltage, interruption, and sustained interruption.

Figure 1.1 shows the general flow chart of the monitoring system and PQ detection and classification process.

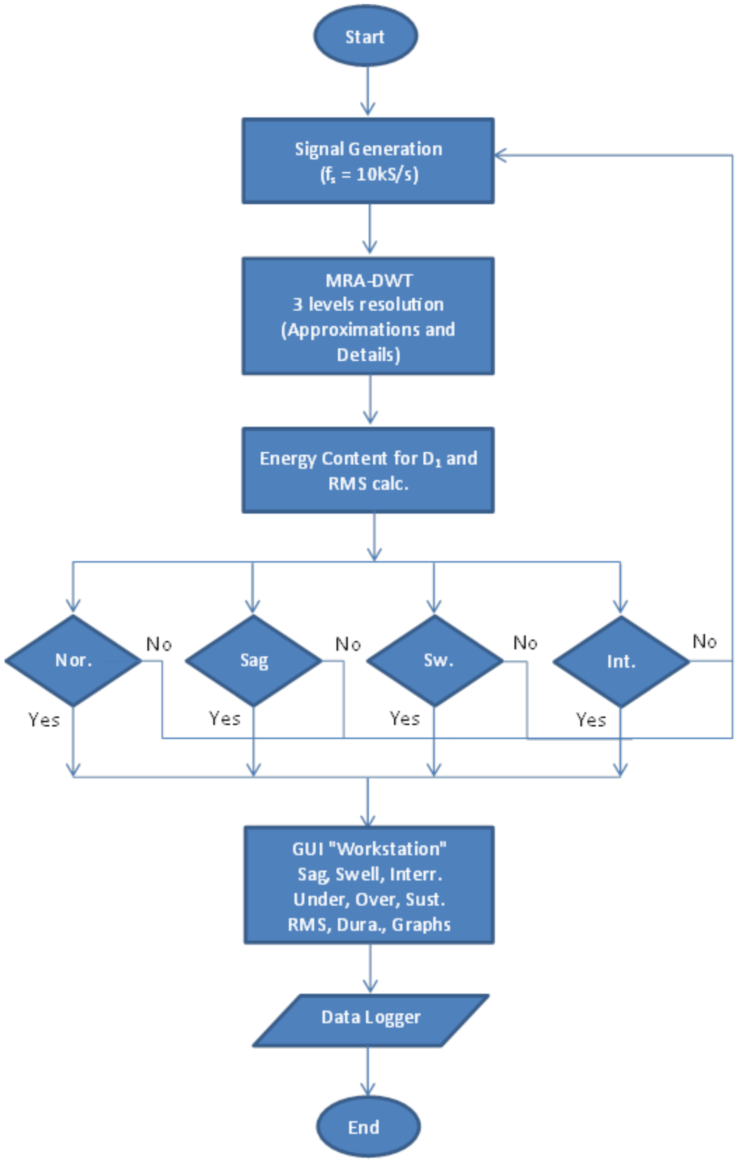


Figure 1.1: Flow chart of the proposed system.

1.5 Organization of the Thesis

The thesis is organized into five chapters, as follows:

The first chapter includes the introduction that the background, motivation and problem statement, objectives, methodology, results, and software and equipment are discussed.

In chapter two the power quality problem is described; PQ problems definitions and their effect on the appliances through literature review. Also in this chapter the IEEE standards are discussed.

The third chapter discusses the simulation studies of the proposed system. In this chapter detection and classification of PQ disturbances simulated using virtual instrument (VI) in LabVIEW environment.

In chapter four the hardware implementation is discussed. In this chapter the hardware specifications, installations, and different scenarios are done.

The conclusions, recommendations, and future work from the work done in this research are presented in the fifth and final chapter.

CHAPTER 2

Power Quality Disturbances and Classifications

2.1 Introduction

The electric power network should be stable and reliable in order to meet the consumer needs by delivering the electric power in good quality. This means that the magnitude and shape of the signal should follow the international standards like IEEE standard 1195 that concern about voltage sag, swell, and interruption according to the voltage magnitude and duration.

Power quality is very important matter for both the utility and consumer; the utility has to deliver reliable power supply that enables the consumer equipment to work correctly, for the consumer avoiding any problem in voltage, current, and frequency.

2.2 Literature Review

Power quality problem in the power system has gained importance since the late 1980's. PQ problems can be classified according to the magnitude and duration; such as sag, swell, interruption, and one of the most well-known PQ problem related to the installation of renewable energy resources and load is Harmonic because of the power electronic devices, and non-linear loads. The harmonic effects on the appliances and distribution lines are equipment overheating, operation failure of equipment, protection equipment fail operation, and process disturbance [4, 7].

Due to the development of Digital Signal Processing (DSP), many mathematical tools are used in the field of analyzing and detecting the PQ problems and every tool has advantages and disadvantages; such as Fast Fourier Transform (FFT), Fast Discrete Stockwell Transform (FDST), and Discrete Wavelet Transform (DWT). First of all, feature extraction should be done in order to achieve efficiently detection, localization, and classification of the PQ problems. For this purpose DWT has proven to be a strong and efficient tool [8]. A critical review of PQ detection, classification, and effect of noise on PQ classifiers has been discussed in [9].

One of the most used mathematical tools for PQ detection is Short Time Fourier Transform (STFT), but the main disadvantage of this tool that it has a fixed window size for all frequencies, which is not suitable for real time power signals. However, this can be overcome by using wavelet transform (WT) through changing the window size according to the frequency; by choosing small window for high frequencies and vice versa. Hence, using WT with some computing tools can classify the disturbances after being detected. Using Stockwell transform (ST) which is a good choice to deal with real-time signals (non-stationary data) to make online training for unknown harmonics disturbances [1]. However ST is similar to Continuous Wavelet Transform (CWT) and this transforms have redundancy of data.

The Fourier transform (FT) is a powerful tool for data analysis; however it doesn't represent sudden changes efficiently, because it represents data as a sum of sine and cosine waves which are not localized in time and oscillate forever. To accurately analyze signals that have sudden and unexpected changes, we need to use a new class of functions that are well localize in time and frequency, such as the Wavelet Transform (WT); a wavelet is rapidly decaying wave like oscillation that has zero energy mean with limited durations [10].

There are two important wavelet transform concepts scaling and shifting; scaling means stretching or shrinking the mother wavelet in time $\Psi(\frac{t}{s})$ where s should be greater than zero and inversely proportional to frequency. Shifting means delaying or advancing the wavelet along the length of the signal $\Phi(t-\tau)$, shifting the wavelet used to align with the feature we are looking for in a signal [10, 11].

The most frequently used mathematical tool in analyzing power signals is WT especially DWT. It can be effectively used for real time monitoring. It can be used for disturbances detection with accurate transient time localization. Moreover, small hand-held digital signal processor DSP along with analog to digital converter (ADC) is implemented to minimize the overall cost. The most familiar mother wavelet is Daubechies 4 [5].

Usually real time power systems analysis are done using DWT since the signals are non-stationary, also operating conditions determine the fastest DWT algorithm [12]. In some cases fast and accurate classification can be done using a hybrid approach built from DWT and discrete Fourier transform (DFT) [13]. PQ disturbances detection has been made using M-band Wavelet packet transform which has been found within the IEEE standards, and also it can be classified using whether wavelet packet transform, or M-band transform [14, 15].

In [16] PQ and energy metering using fast discrete Stockwell Transform (FDST) implemented with automatic scaling for accurate detection of PQ disturbances performed in National Instruments (NI) laboratory virtual instrument engineering workbench (LabVIEW), using data Acquisition DAQ card. Whereas using DAQ cards need sensing instruments.

In [17] authors show that DWT Multi-Resolution Analysis can be used in decomposition and reconstruction the signal at various resolution levels for detecting the PQ disturbances, it reduces the sampling frequency without any loss in order to reduce the memory usage. It depends on scaling and orthogonal wavelet functions, from the engineers and signal processing perspective it deals with signal as low pass filter to extract the low frequency component of the signal (Approximation 'A') and high pass filter to extract the high frequency component (Detail 'D'), and this can be done for more than one level as shown in the figure 2.1.

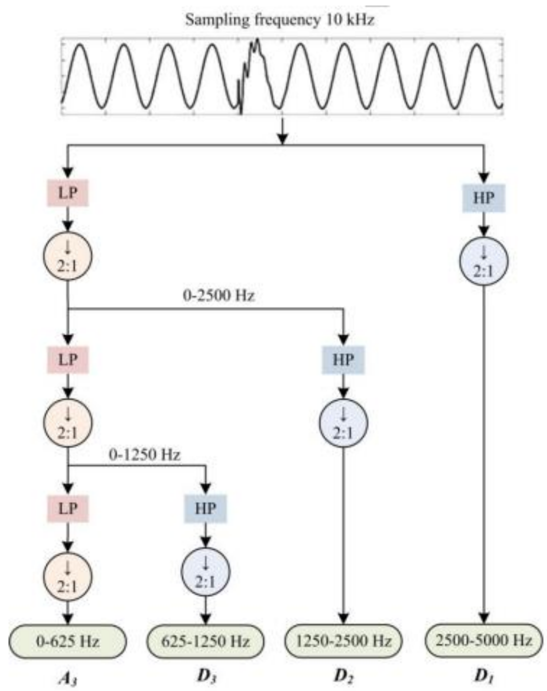


Figure 2.1: Multi-resolution analysis (MRA).

In order to achieve effective detection and time localization of PQ disturbances a good denoising technique should be done on the wavelet coefficients [18].

In [19] authors show that using DWT with db4 as mother wavelet can be considered as a powerful tool for PQ detection. However using db6 as mother wavelet in detection the sag, swell, and interruption disturbances will be more suitable than using db4 because the shape of db6 as mother wavelet will be closer to the sudden changes in the voltage waveforms.

To achieve better classification of PQ disturbances the mother wavelet basis should be carefully chosen, many wavelet families have been tested. The authors used wavelet packet transform (WPT) to show that the best family in performance is daubechies [20].

In [21] islanding events are detected using artificial neural network (ANN) algorithm, and the performance in hardware has been verified using the graphical programing language LabVIEW along with real time platform cRIO-9025/cRIO-9018, by analyzing the voltage waveforms using the analog module NI-9225. A smart energy meter with multi-tariff modes and power quality measurements is developed using NI Compact-DAQ along with analog modules. As well as connecting the consumer and utility via web [22].

In [23] authors developed a system to measure, report, and draw the voltage and current waveforms using DAQ card for real time monitoring. Not like cRIO the DAQ card is not fast enough to be used in PQ monitoring.

According to quadrature based RMS method, the real time PQ monitoring system has been implemented using LabVIEW FPGA Compact-Rio; this method depends on using only four samples to calculate the RMS of voltage waveform (quadrature method), and to determine the voltage disturbances (Sag, Swell, and interruption) [24]. In fact FPGA VI level used for high speed data acquisition. Moreover, using only 4 samples will make the process faster, while this method has some limitations with polluted signals.

PQ disturbances (Sag, Swell, and Interruption) can be effectively detected using wavelet packet transform (WPT) in LabVIEW platform and acquiring the required data by data acquisition (DAQ) card. WPT is very accurate and suitable method for the separation of PQ problems that overlap in time and frequency, while it can't determine the magnitude of PQ disturbance [25].

Finally, precise classification of the PQ disturbances means easily mitigation of these problems. For example to mitigate the harmonics there are three main mitigation techniques; passive, active, and hybrid [24]. For example Distribution Static Compensator (DSTATCOM) can be used to mitigate the harmonics related PQ problems. [27]

2.3 Power Quality Problems Classification

Power quality disturbances can be classified according to the shape of the waveform, magnitude, and duration. In this section the disturbances will be generally classified as follows [28, 29]: Waveform transients, interruptions, short duration and long duration voltage variations, waveform distortion, voltage fluctuations, voltage imbalance, and frequency variation. These disturbances will be clarified by IEEE standard 519-1992 and IEEE standard 1159-1995 as shown below in the next section.

2.3.1 Waveform Transients

The term transient is referred to any voltage or current variation that is randomly and momentary happen. It can be divided into:

1- Impulsive transient: it is sudden change in voltage and/or current waveform with positive polarity in the positive cycle half or negative polarity in the negative cycle half as shown in figure 2.2A, this transient can be determined by its amplitude, rise and decay time.
2- Oscillatory transient: it is sudden change in voltage and/or current waveform with both positive and negative polarity on one cycle half as shown in figure 2.2B, this transient can be determined by its amplitude, frequency of the oscillation, and duration [29].

A: Impulsive transient B: Oscillatory transient

Figure 2.2: Waveform transients.

2.3.2 Voltage Variation

Voltage variations divided into two main categories:

1- Short duration variation.
2- Long duration variation.

These two categories are summarized in table 2.1 as shown below. Voltage variation depends on two factors; the duration and the magnitude per unit (pu).

Table 2.1: Voltage variation categories

Voltage Variation					
Short Duration (duration < 1 minute)			Long Duration (duration ≥ 1 minute)		
Sag	Swell	Interruption	Undervoltage	Overvoltage	Sustained Interruption
Voltage Magnitude			Voltage Magnitude		
10% - 90% pu	≥ 110% pu	< 10% pu	10% - 90% pu	≥ 110% pu	< 10% pu

Now in order to understand each one of these events, IEEE standard 1195-1995 gives clear definitions as shown in figure 2.3.

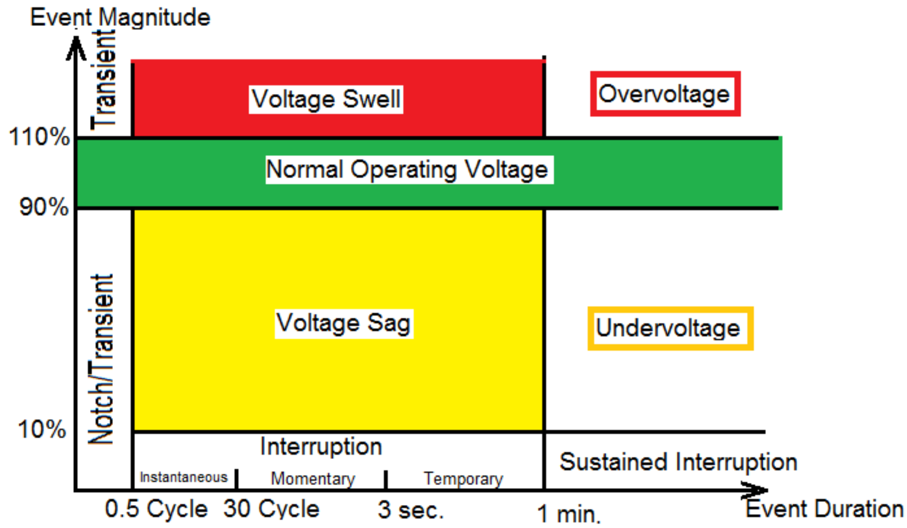


Figure 2.3: Voltage disturbances.

2.3.2.1 Short Duration Voltage Variation

This category describes RMS voltage variations from the standard values that stay for a period of less than 1 minute [29]. It includes:

1- Voltage sag (also called dip).
2- Voltage swell (also called rise).
3- Interruption.

1. Voltage Sag.

Voltage sag (Also called voltage dip) is a decrease in RMS voltage to 10% - 90% of rated voltage as shown in figure 2.4. According to IEEE standards this event may stay from 0.5 cycle to 1 minute. The frequently sources of sags are system faults, energizing large loads, and starting large motors. It can be mitigated using uninterruptable power supply (UPS) or power conditioners.

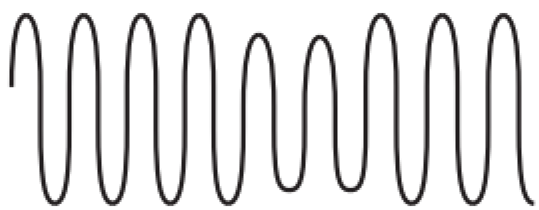


Figure 2.4: Voltage sag.

2. **Voltage Swell.**

Voltage swell is opposite to the sag. It's an increase in RMS voltage from 110% and up of rated voltage as shown in figure 2.5. This event may stay for duration of 0.5 cycle to 1 minute. The common sources of swells are system faults, switching on capacitor bank, switching off heavy loads, and wrong settings of transformer tap changer. It can be mitigated using uninterruptable power supply (UPS) or power conditioners.

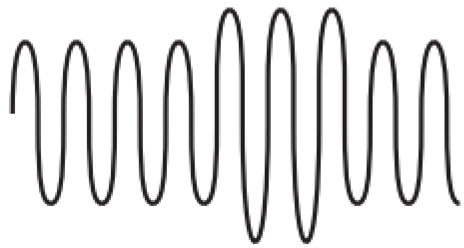


Figure 2.5: Voltage swell.

3. Interruption.

An interruption happens when the RMS voltage is less than 10% of rated voltage as shown in figure 2.6. Interruption may stay between 0.5 cycle up to 1 minute. The frequently sources of interruptions are system faults, and equipment or control failure.

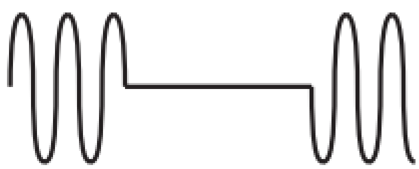


Figure 2.6: Interruption.

2.3.2.2 Long Duration Voltage Variation

This category describes RMS voltage deviations from the standard values that stay for a period of more than 1 minute [29], as shown in figure 2.7. It includes:

1- Undervoltage.
2- Overvoltage.
3- Sustained interruption.

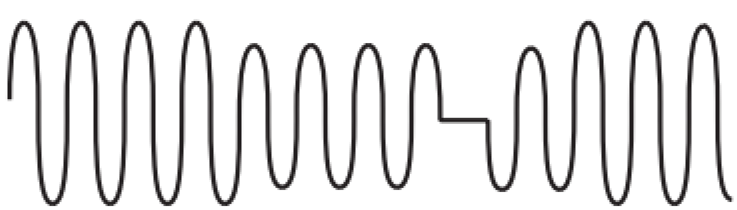


Figure 2.7: Long duration variations.

1. **Undervoltage.**

Undervoltage is a reduction in RMS voltage to between 10% - 90% of nominal voltage. According to IEEE standards this event will stay more than 1 minute.

2. **Overvoltage.**

Overvoltage is opposite to undervoltage. It means that there is an increase in RMS voltage from 110% and up of rated voltage. This event stays for duration more than 1 minute.

3. **Sustained Interruption.**

A sustained interruption happens when the RMS voltage is less than 10% of rated voltage. The sustained interruption last for more than 1 minute.

2.3.3 Waveform Distortion

Waveform distortion is any steady state deviation of the voltage waveform from the typical sine wave. The following is the 4 main types of waveform distortion and short brief about these types:

1- DC offset: is the dc voltage or current components that existing in the ac waveform, figure 2.8 shows the dc offset [30].

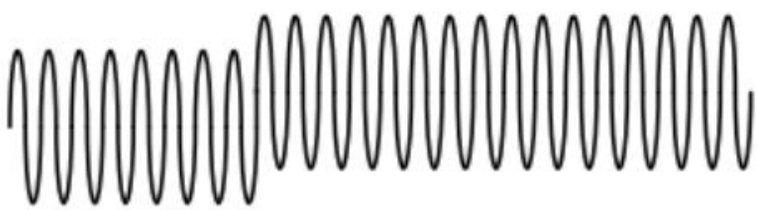


Figure 2.8: DC offset waveform.

2- Harmonics: a harmonic is a sinusoidal voltage or current component of the waveform which has frequency that is integer multiple of the fundamental frequency, figure 2.9 shows the harmonic distortion [29].

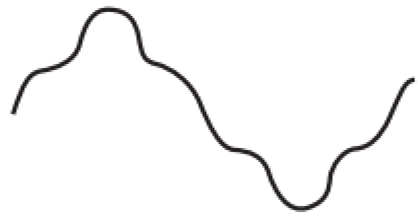


Figure 2.9: Harmonic distortion.

3- Notching: as shown in the figure 2.10 notching is a drop in voltage close to zero caused by a momentary short circuit between two phases, during current commutation in the power electronic devices [31].

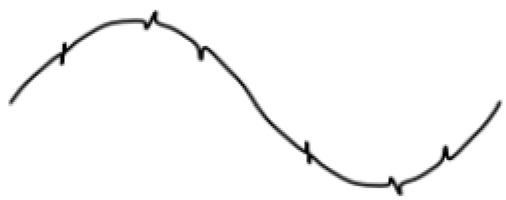


Figure 2.10: Notch waveform.

4- Noise: is undesirable electrical signal with broadband spectral content lower than 200 kHz existing on the power signal. Figure 2.11 shows the noise signal [29].

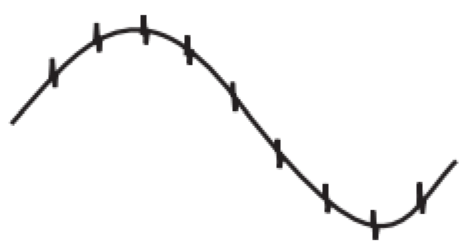


Figure 2.11: Noise waveform.

2.3.4 Voltage Fluctuations

Voltage fluctuations are small variations in RMS voltage that not exceed ± 5 percent of the nominal voltage value, it can be caused by any device that draw current not synchronized with line frequency and it can be noticed by the user in form of lighting intensity variations which known as "flicker". Figure 2.12 shows the voltage fluctuations [29].

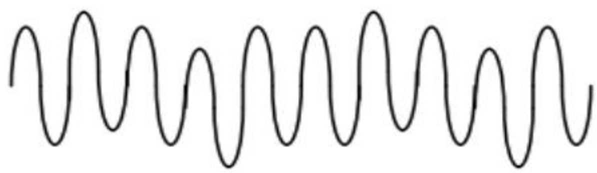


Figure 2.12: Voltage fluctuations.

2.3.5 Voltage Imbalance

Voltage imbalance also called "voltage unbalance" is a variation of the three phase voltages one to another, it is also mathematically defined by the National Electrical Manufacturers Association (NEMA) in the following relationship:

$$voltage\ imbalance = \frac{Vmax - Vav}{Vav} \qquad (2.1)$$

Where: V_{max}: maximum variation of the line voltages.

V_{av}: average voltage of the three phase system.

2.3.6 Frequency Variation

Frequency variation is defined as the deviation of the system frequency from the rated frequency, it caused by the presence of imbalance in supply and demand. Large variations are caused due to the failure of generator and its controller or sudden switching on/off of heavy loads. Frequency variations can be shown in figure 2.13 [31].

Figure 2.13: Frequency variations.

CHAPTER 3

Proposed Simulation Using Discrete Wavelet Transform

3.1 Introduction

This chapter will briefly introduce the Multi-Resolution Analysis Discrete Wavelet Transform (MRA-DWT) as powerful mathematical tool for detection and classification, LabVIEW as a simulation platform, and the simulation studies.

Wavelet is a waveform of limited duration with zero average value, starting from this point we can define the wavelet transform (WT) as mathematical tool that used to present the signal in form of shifted and scaled versions of the mother wavelet. WT can be effectively used for the analysis of PQ disturbances in a power system because most of these disturbances are non-stationary transients [17, 32].

There are two major wavelet transforms [32]:

- Continuous Wavelet Transform CWT

CWT for a continuous signal x(t) with respect to the wavelet function Ψ(t) is mathematically defined as:

$$\mathrm{CWT}(\tau,s) = \int_{-\infty}^{\infty} x(t)\Psi_{\tau,s}(t)dt\,; \qquad \tau > 0 \text{ and } -\infty < s < \infty \tag{3.1}$$

Where x(t) is the signal, $\Psi_{\tau,s}(t)$ is the mother wavelet shifted by a factor (τ) and scaled by a factor (s).

$$\Psi_{\tau,s}(t) = \frac{1}{\sqrt{s}}\Psi\left(\frac{t-\tau}{s}\right) \tag{3.2}$$

Now the CWT is given by:

$$\mathrm{CWT}(\tau,s) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} x(t)\Psi\left(\frac{t-\tau}{s}\right)dt\,; \qquad \tau > 0 \text{ and } -\infty < s < \infty \tag{3.3}$$

In equation 3.3 (a) and (b) are scaling and translation parameters, respectively. The scale parameter (s) represents the wavelet frequency (scale = 1/frequency) and the translation parameter (τ) represents its shifting across the original signal. Since the output will be a combination of wavelet coefficients then there will be redundancy in data and this is not suitable for real time PQ monitoring.

- Discrete Wavelet Transform DWT

DWT is mathematically defined as:

$$\mathrm{DWT(m,n)} = \frac{1}{\sqrt{S_0^m}} \sum_k x(k)\, \Psi\left(\frac{\mathrm{n-k}\tau_0 S_0^m}{S_0^m}\right); \quad \mathrm{m, n\ are\ integers} \tag{3.4}$$

In DWT the scaling and translation parameters are replaced by integers m and n, where S= S_0^m and $\tau=\mathrm{k}\tau_0 S_0^m$, while x(k) is the discrete points of the x(t) time signal. As mentioned before choosing mother wavelet is very important process for feature extraction of the PQ disturbances, in the simulation the mother wavelet will be daubechies 6 (db6).

Multi-resolution analysis (MRA) its algorithm using for decomposing and reconstruction of the signal at multiple resolution levels, MRA significantly used in decomposing the PQ disturbances; because it is reducing the memory usage. In this algorithm two functions are used, the first one is scaling function $\varphi_{m,n}(t)$ and the second one is wavelet function $\Psi_{m,n}(t)$. The time signal x(t) is passed across two filters in each level; one is low pass filter (LPF) for low frequency components of the x(t) signal which is known as approximation coefficient (A), and the second is high pass filter (HPF) for high frequency component of the x(t) signal which is known as detail coefficient (D).

Frequency band of both LPF and HPF is same and the sampling frequency divided by two after each level of decomposition. The following relationships are mathematically describing the scaling function which is related to LPF and wavelet function which is related to HPF of the original signal x(t).

$$\varphi_{m,n}(t) = 2^{-\frac{m}{2}} \varphi(2^{-m}t - n) \tag{3.5}$$

$$\Psi_{m,n}(t) = 2^{-\frac{m}{2}} \Psi(2^{-m}t - n) \tag{3.6}$$

The decomposition of the discrete signal x(k) with MRA-DWT produce A and D coefficients and mathematically expressed as follows:

$$x(k) = \sum_{j=1}^{l} D_j\,(k) + A_j(k) \tag{3.7}$$

$$x(k) = [D1, D2, ..., Dl, Al] \tag{3.8}$$

Figure 3.1 shows an example of 3-levels MRA-DWT of a signal, the decomposition of the PQ signal produces three details (D_1, D_2, and D_3), and one approximation A_1 [32].

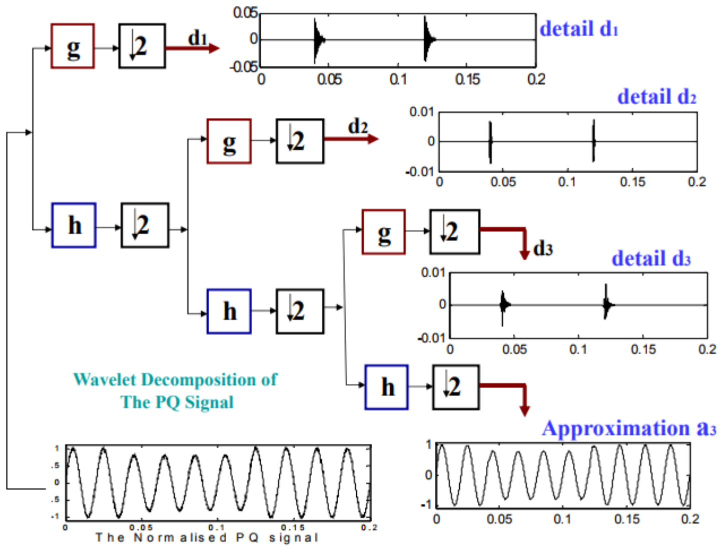


Figure 3.1: MRA-DWT.

LabVIEW and the controllers from National Instruments is a very powerful tool for testing and monitoring purposes, so it can be used in detection and classification of the PQ disturbances. Also the robust, accurate, and very fast controllers from the NI-company can be used to acquire the data and perform fast response in case of taking decisions while using in mitigation of the PQ disturbances. Writing the codes will be done in the Virtual Instruments VI's, and they called so because they are imitating the process of real instruments.

Here the simulation study will focus on short duration disturbance which is voltage sag, swell, and interruption, in addition to long duration disturbance such as undervoltage, overvoltage, and sustained interruption.

3.2 DWT Simulation

In this section the proposed method will be highlighted using LabVIEW environment and the PQ disturbances will be simulated to test the detection and classification performance.

3.2.1 The Proposed Method

In order to detect the PQ disturbances and then classify them a well code should take place in the LabVIEW environment using a MRA-DWT as a mathematical tool.

LabVIEW has two main parts; front panel as user interface and block diagram for writing the code. First of all the code should be written in a while loop for continuous execution until a specific condition occurs, this condition maybe an error occurred or using a stop push button. Inside the LabVIEW program the sinusoidal waveform generated using a Simulate Signal express VI. Inside this express VI you can modify the configuration like the signal type, frequency, amplitude, sampling, and other parameters as shown in the figure 3.3, the frequency set on 50 Hz, and sampling frequency on 10 KHz.

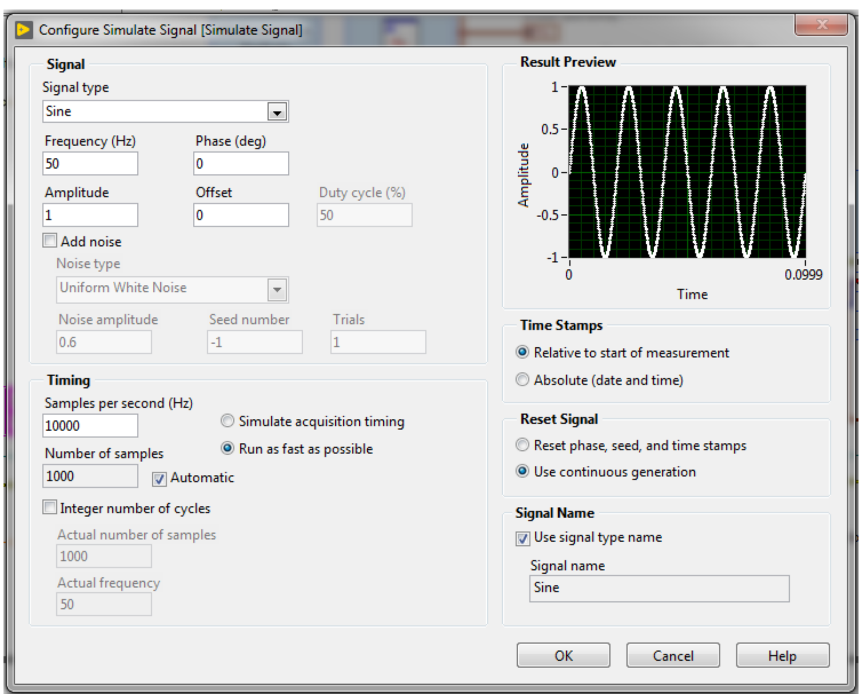


Figure 3.2: Simulate signal configuration.

The simulated sinusoidal signal will be analyzed to extract the approximations and details using the three levels MRA-DWT with db6 as mother wavelet, and so getting 3 Approximations "A" A_1, A_2, A_3 and 3 Details "D" D_1, D_2, D_3; where D1 is the highest frequency component and A3 is the lowest frequency component of the signal.

The express VI (Multiresolution Analysis) can be configured as shown in the following figure 3.5, using this page you can see the original and reconstructed signal, choosing the mother wavelet, determine the level of reconstruction, and determine whether it's approximation or detail. Moreover you can take a general look on the scaling and the shape of used wavelet.

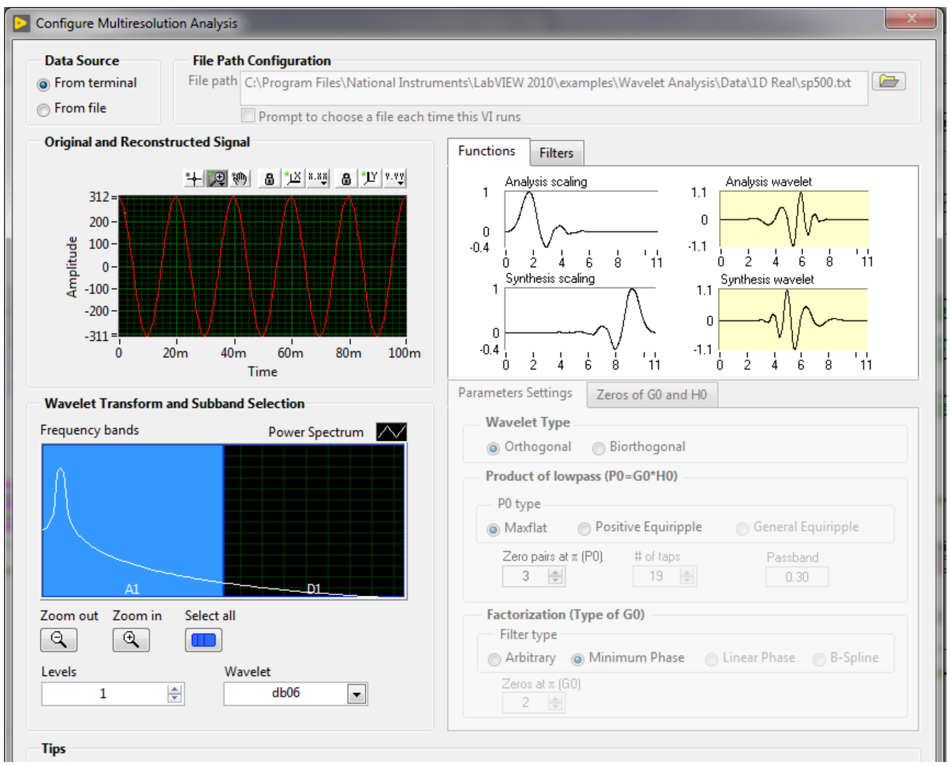


Figure 3.3: Configure multi-resolution express VI.

In order to detect the event and then classify it. First, the RMS value of the input voltage will be monitored according to IEEE standards; when the RMS value within normal limits (0.9pu – 1.1pu) then there is no event and the condition description is "normal", if the RMS value is greater than 1.1pu it will be detected as "swell", if the RMS value lies between 0.1pu and less than 0.9pu it will be detected as "sag", but if the RMS value is less than 0.1 pu it will be detected as "interruption". Second, to classify these events the details will be monitored along with the time to determine whether these events are short or long duration disturbances; if the disturbance time is less than 1 minute so this disturbance will be regarded as short duration disturbance (sag, swell, and interruption), but if the disturbance time is equal or greater than 1 minute then this disturbance will be classified as long duration disturbance (undervoltage, overvoltage, and sustained interruption).

All classified and detected events will be displayed immediately in the front panel and saved in TDMS file. A TDMS file is Technical Data Management Streaming format developed by NI Company which is suitable for storing large amounts of data in case of simulation, measurements, and different engineering testing purposes. Also TDMS file is supported by MathWorks MATLAB and Microsoft Excel.

Finally, in case of any detected event there is an output signal to mitigate that event in the best possible way; in the simple way if there was a sag or swell event activates Uninterruptable Power Supply UPS or voltage conditioner, and if it was an interruption event activates UPS or generator.

3.2.2 The User Interface

VI in LabVIEW software has two windows one of them for block diagram that used to write the code and the other for front panel that used as user interface for data entry or monitoring purposes, figure 3.13 shows that the front panel in this thesis includes the following:

1- Numeric control as input for testing the events.
2- Four indicators; two numeric indicators (one for calculated RMS, one for event duration), one string indicator for events description, and one time stamp.
3- Ten square LED's as Boolean function to show the events and mitigation techniques.
4- Seven waveform graphs to display the signal and reconstructed signal at once.
5- One waveform chart that display the signal waveform in addition to RMS value.
6- Stop button to stop the VI.

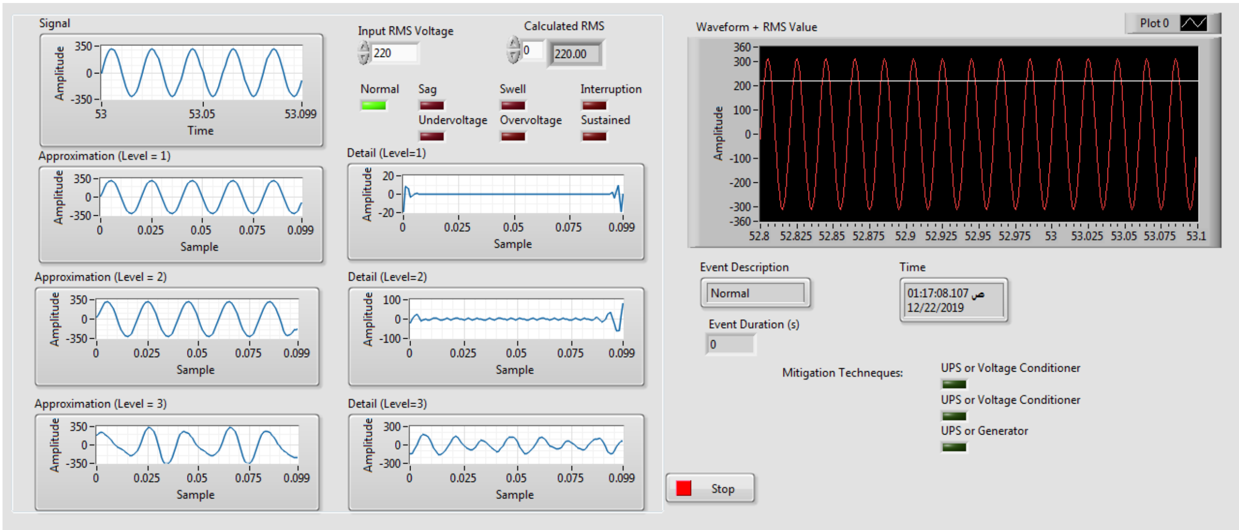


Figure 3.4: User interface.

3.2.3 Events Simulation

In this section short duration disturbances or so-called short duration voltage variation, and long duration disturbances or so-called long duration voltage variations will be simulated in order to test the system efficiency in detection and classification process of these events.

3.2.3.1 Short Duration Disturbances

Short duration disturbance is any variation in RMS voltage from the standard values for less than one minute, such as voltage sag, swell, and interruption.

The above mentioned events can be tested through changing the RMS value of the input voltage in the user interface, in order to verify the system efficiency in detection and classification of these events. First of all, if the RMS value of the input voltage within its standard (90% - 110%) pu then there is no event detected and the system display normal status as shown above in the figure 3.13. Second, if the RMS value is greater than 110% pu then the system will detect swell event as shown in the figure 3.14. Third, if the RMS value is less than 90% pu to 10% pu then the system will detect sag event as shown in the figure 3.15. Finally, if the RMS value is less than 10% pu then the system will detect interruption as shown in the figure 3.16.

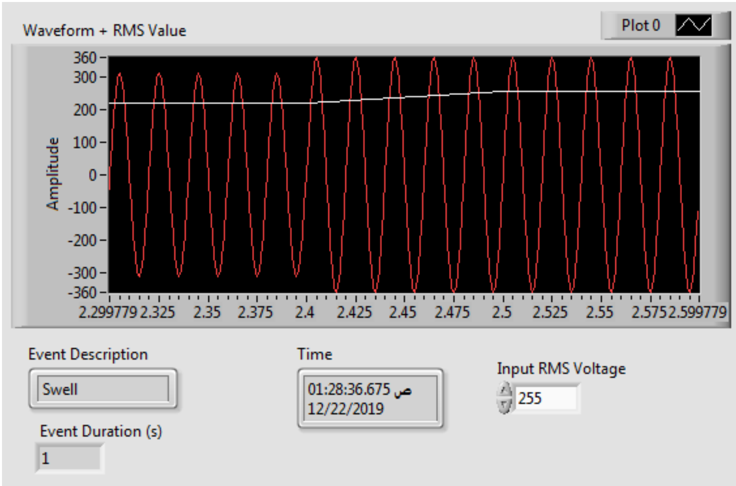


Figure 3.5: Swell event detection.

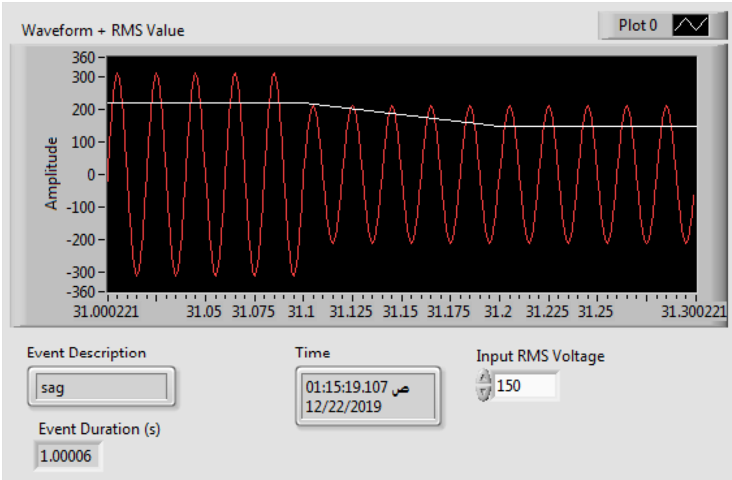


Figure 3.6: Sag event detection.

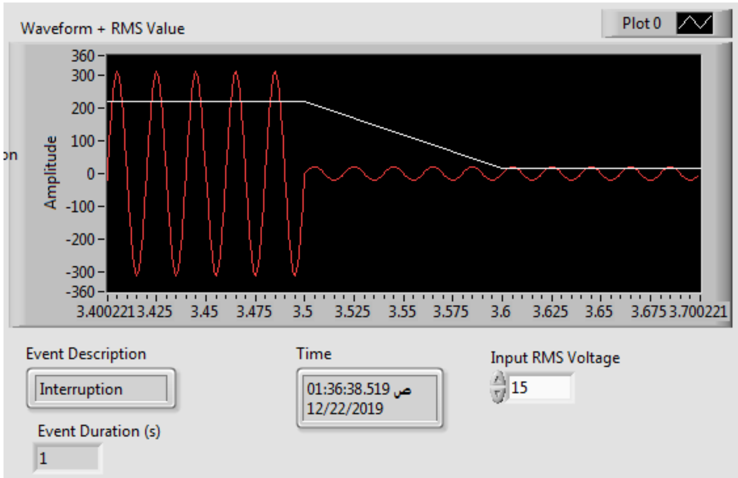


Figure 3.7: Interruption event detection.

3.2.3.2 Long Duration Disturbances

Long duration disturbance is any variation in RMS voltage from the standard values for more than one minute, such as undervoltage (long time sag), overvoltage (long time swell), and sustained interruption (long time interruption) as shown respectively in figures 3.17, 3.18, and 3.19.

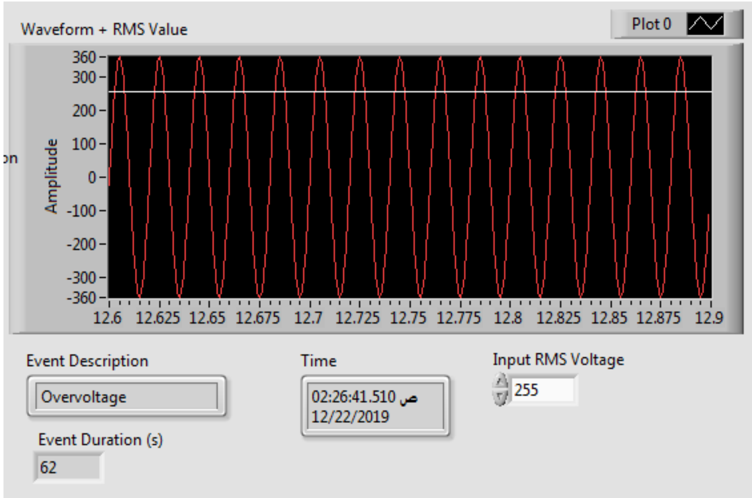


Figure 3.8: Overvoltage event detection.

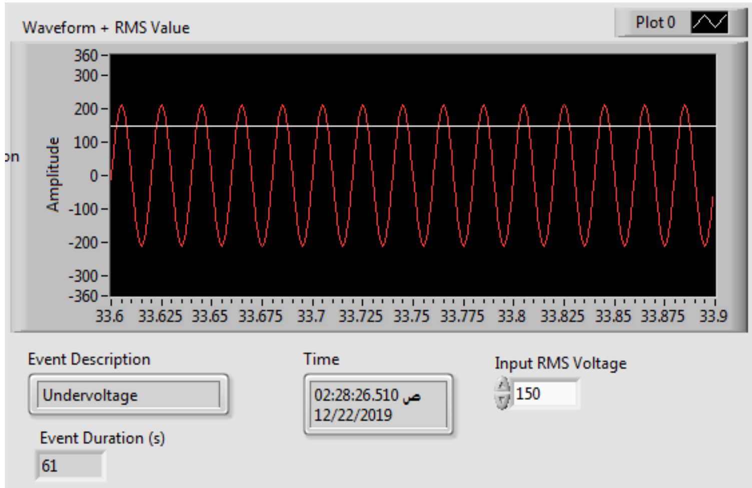


Figure 3.9: Undervoltage event detection.

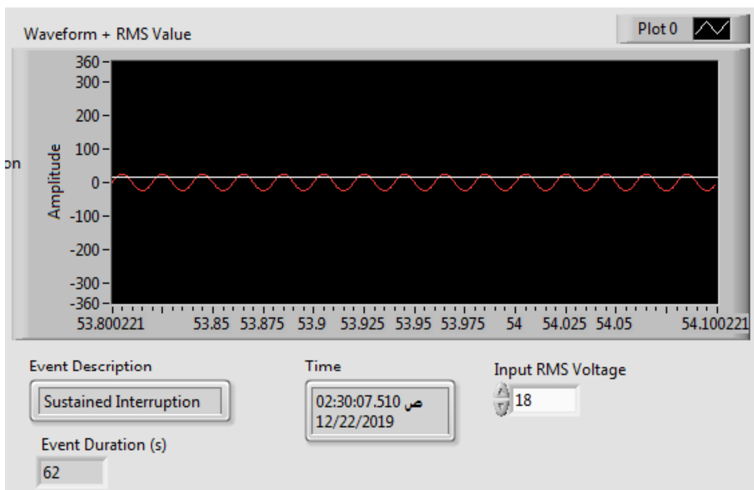


Figure 3.10: Sustained interruption event detection.

3.3 Data Logger

The simulated system not only used for detection and classification but also for data logging, so it can be used as data logger for recording and saving the detected events in special TDMS data file to be analyzed and make use of these data in research studies for the future planning of electrical grids, besides the accurate and precise data recordings.

Once you start the simulation all data and events will be recorded in a TDMS file, this .tdms file can be opened using Microsoft Excel and this file contains of 3 pages. Figure 3.20 shows the first and main page that includes general information, figure 3.21 shows the second page which consist of measured data along the time, and figure 3.22 shows the last and most important page which consist of events description and the time of detected events.

H	G	F	E	D	C	B	A	
		Description	**Groups**	**Date/Time**	**Author**	**Title**	**Root Name**	1
			2				Example Events Data	2
								3
					Description	**Channels**	**Group**	4
						1	Measured Data	5
						2	Event	6
								7
							Measured Data	8
NI_ChannelName	**Description**	**Maximum**	**Minimum**	**Length**	**Unit**	**Datatype**	**Channel**	9
Sine				3000		DT_DOUBLE	**Amplitude**	10
				Length	**Interval**	**Start**	**Implicit**	11
				3000	0.001	0	Amplitude _Time	12
								13
							Event	14
Start Index	**Description**	**Maximum**	**Minimum**	**Length**	**Unit**	**Datatype**	**Channel**	15
				30		DT_DATE	**Time**	16
				30		DT_STRING	**Description**	17
								18
								19
								20
								21
								22
								23
								24
								25
								26

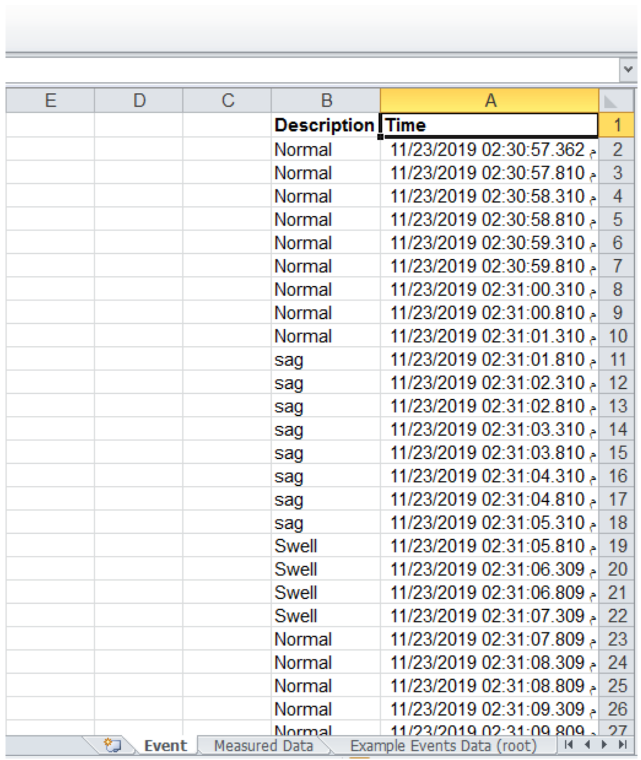
Event | Measured Data | **Example Events Data (root)**

Figure 3.11: Data logger first page.

E	D	C	B	A	
			Amplitude	**Amplitude _Time***	1
			0	0	2
			96.14352538	0.001	3
			182.8758526	0.002	4
			251.7070172	0.003	5
			295.8993453	0.004	6
			311.1269837	0.005	7
			295.8993453	0.006	8
			251.7070172	0.007	9
			182.8758526	0.008	10
			96.14352538	0.009	11
			1.13687E-13	0.01	12
			-96.14352538	0.011	13
			-182.8758526	0.012	14
			-251.7070172	0.013	15
			-295.8993453	0.014	16
			-311.1269837	0.015	17
			-295.8993453	0.016	18
			-251.7070172	0.017	19
			-182.8758526	0.018	20
			-96.14352538	0.019	21
			-2.55795E-13	0.02	22
			96.14352538	0.021	23
			182.8758526	0.022	24
			251.7070172	0.023	25
			295.8993453	0.024	26
			311.1269837	0.025	27

Event | **Measured Data** | Example Events Data (root)

Figure 3.12: Data logger second page.



B	A	
Description	Time	1
Normal	11/23/2019 02:30:57.362 م	2
Normal	11/23/2019 02:30:57.810 م	3
Normal	11/23/2019 02:30:58.310 م	4
Normal	11/23/2019 02:30:58.810 م	5
Normal	11/23/2019 02:30:59.310 م	6
Normal	11/23/2019 02:30:59.810 م	7
Normal	11/23/2019 02:31:00.310 م	8
Normal	11/23/2019 02:31:00.810 م	9
Normal	11/23/2019 02:31:01.310 م	10
sag	11/23/2019 02:31:01.810 م	11
sag	11/23/2019 02:31:02.310 م	12
sag	11/23/2019 02:31:02.810 م	13
sag	11/23/2019 02:31:03.310 م	14
sag	11/23/2019 02:31:03.810 م	15
sag	11/23/2019 02:31:04.310 م	16
sag	11/23/2019 02:31:04.810 م	17
sag	11/23/2019 02:31:05.310 م	18
Swell	11/23/2019 02:31:05.810 م	19
Swell	11/23/2019 02:31:06.309 م	20
Swell	11/23/2019 02:31:06.809 م	21
Swell	11/23/2019 02:31:07.309 م	22
Normal	11/23/2019 02:31:07.809 م	23
Normal	11/23/2019 02:31:08.309 م	24
Normal	11/23/2019 02:31:08.809 م	25
Normal	11/23/2019 02:31:09.309 م	26
Normal	11/23/2019 02:31:09.809	27

Figure 3.13: Data logger third page.

For example if a predetermined event simulated, with input values as follows: 220V for 3 seconds, 150V for 3 seconds, and 220V again for 3 seconds, then the simulation result will be as follows in the figure 3.23, and the data will be logged in TDMS file as shown in the figure 3.24.

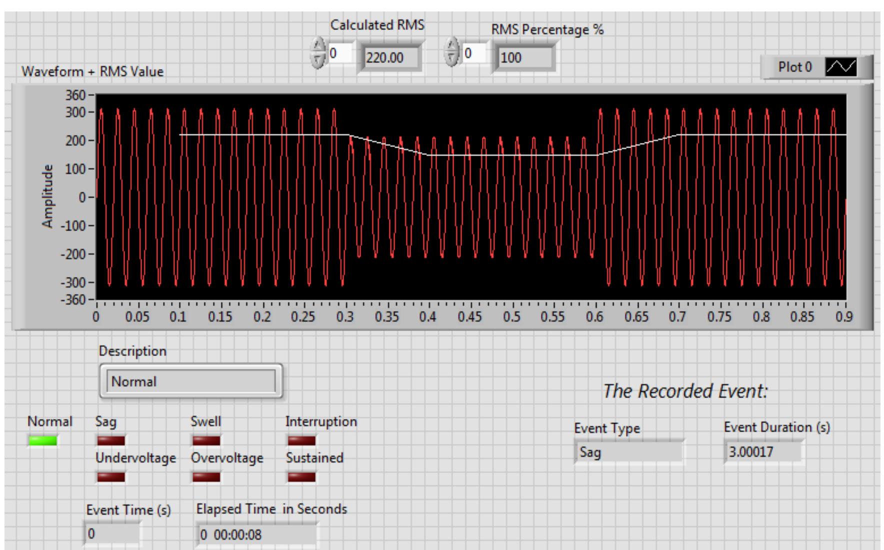


Figure 3.14: Predetermined event detection in seconds.

B	A
Description	**Time**
Normal	12/22/2019 03:03:18.476
Normal	12/22/2019 03:03:19.467
Normal	12/22/2019 03:03:20.467
sag	12/22/2019 03:03:21.467
sag	12/22/2019 03:03:22.467
sag	12/22/2019 03:03:23.467
Normal	12/22/2019 03:03:24.467
Normal	12/22/2019 03:03:25.467
Normal	12/22/2019 03:03:26.467

Figure 3.15: Predetermined event logging in seconds.

The proposed system has ability to deal with events in milliseconds, for example if a predetermined event simulated; 220V for 60 ms, 150V for 60 ms, and 220V again for 60 ms, then the simulation result will be as follows in the figure 3.25, and the data will be logged in TDMS file every 20ms as shown in the figure 3.26. As shown in the figures 3.25 and 3.26 the proposed system shows high efficiency in detection and classification of the disturbances.

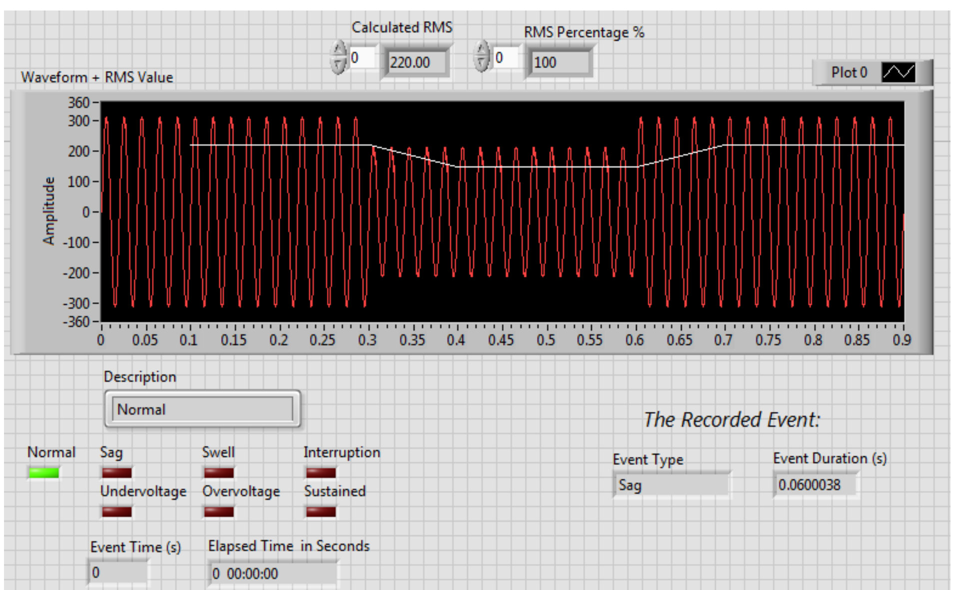


Figure 3.16: Predetermined event detection in milliseconds.

B	A
Description	**Time**
Normal	12/22/2019 03:41:51.792
Normal	12/22/2019 03:41:51.805
Normal	12/22/2019 03:41:51.825
sag	12/22/2019 03:41:51.845
sag	12/22/2019 03:41:51.865
sag	12/22/2019 03:41:51.885
Normal	12/22/2019 03:41:51.905
Normal	12/22/2019 03:41:51.925
Normal	12/22/2019 03:41:51.946

Figure 3.17: Predetermined event logging in milliseconds.

If a predetermined long duration event simulated; 220V for 3 seconds, 150V for 61 seconds then the simulation result will be as shown in the figure 3.27, and the data will be logged in TDMS file.

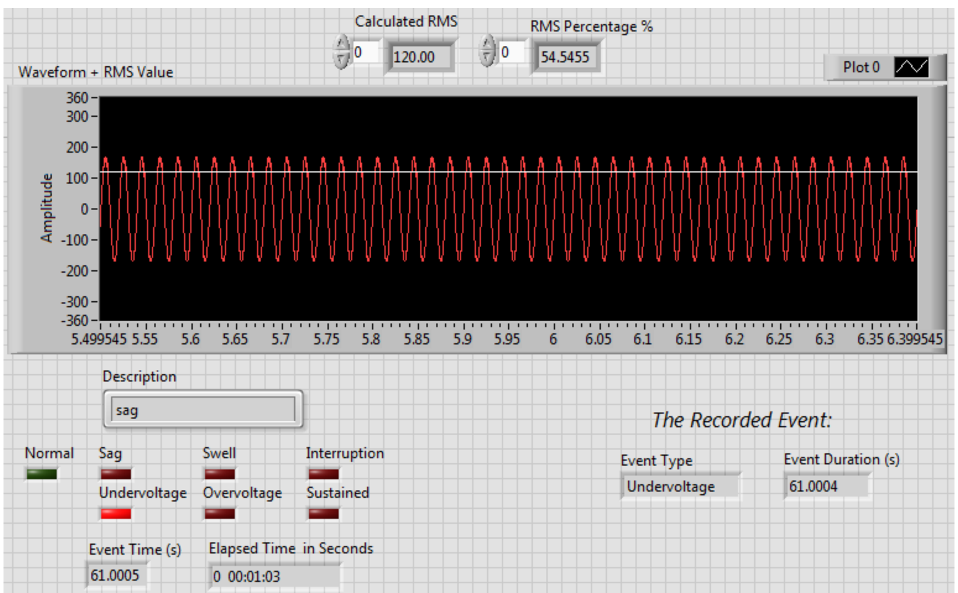


Figure 3.18: Predetermined long duration event detection.

Finally, the proposed system has ability to detect multi-events; for example if a predetermined event simulated as follows: 220V for 2 seconds, 150V for 2 seconds, 250V for 2 seconds, 15V for 2 seconds, 220V for 1 second , then the simulation result will be as shown in the figure 3.28, and the data will be logged in TDMS file.

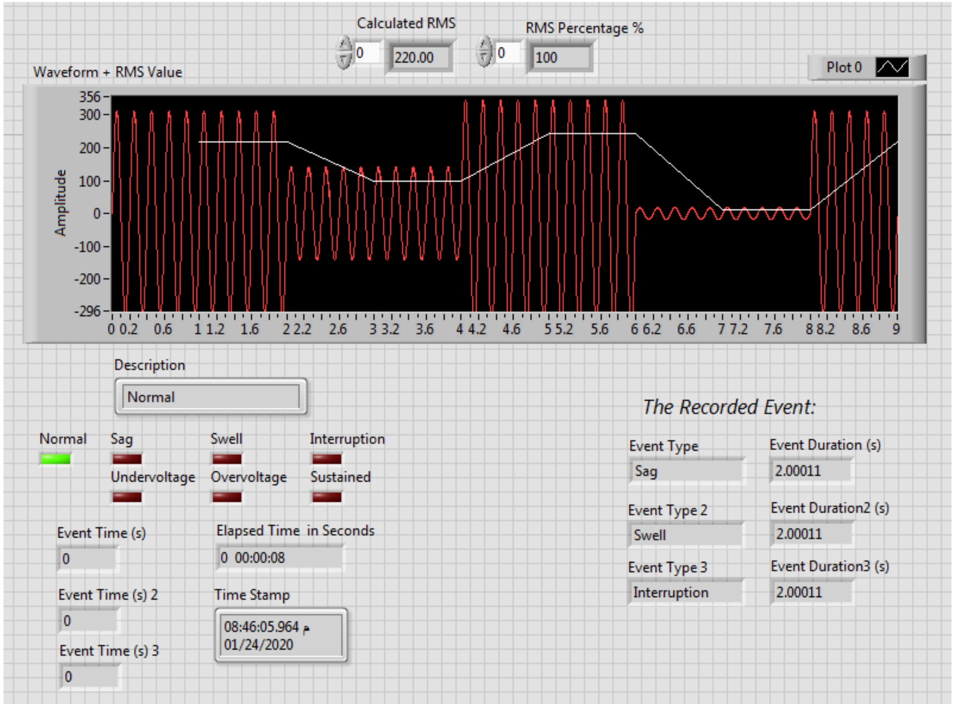


Figure 3.19: Predetermined multi-events detection.

CHAPTER 4

System Hardware

4.1 Introduction

In this study the proposed system not only simulated, but also hardware connected to verify the simulation results in chapter three. This chapter details a modeling of real time PQ monitor and data logger at the same time, and this will done using the c-RIO controller and LabVIEW platform that developed from NI Company.

LabVIEW is a platform offers a graphical programing approach that helps engineers and researchers in many aspects to design and simulate their systems, also to guarantee the maximum compatibility between the software and hardware NI Company produced very fast and accurate controllers that can be connected along with LabVIEW to form a complete system.

4.2 Hardware Specifications

In order to model the system that mentioned in the previous section we need a suitable controller, and so the chosen controller was CompactRIO controller cRIO-9063 because this controller is very suitable and fit for monitoring purposes besides high accuracy and speed of response which needed in such advanced monitoring applications, also cRIO-9063 has four of connection ports, including Ethernet, USB host, USB device, and serial port. Moreover this controller supports filed-programmable gate array FPGA for hardware programming to guarantee the best and fastest response.

The cRIO-9063 has four slots for input or output modules or so-called I/O modules, these modules can be chosen according to the application, hence for the voltage profile monitoring the suitable module should be voltage analog input and this module will be NI-9225. For more details refer to Appendix A.

4.3 Hardware Installation

The hardware devices mentioned in the 4.2 section are NI-9225 that represent the input module for the voltage input signal and cRIO-9063 that represents the controller, figure 4.1 shows the block diagram for the whole process in general.

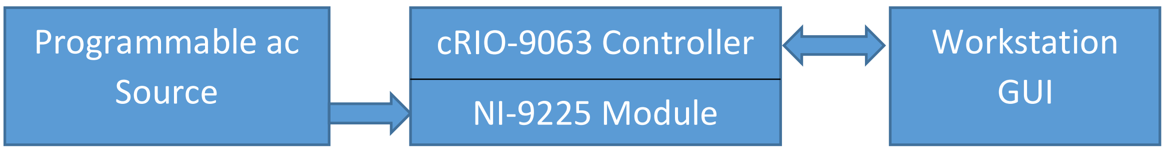


Figure 4.1: Block diagram of the proposed system.

First of all, NI cRIO-9063 should be powered using 24V DC NI power supply, and the NI-9225 input module will be connected to the cRIO-9063 controller through the slot number one. Then, the input voltage will be connected to NI-9225 analog input directly using the wires. After that, the cRIO-9063 will be connected to the computer using a network cable through the Ethernet connection ports.

Secondly, the programmable ac source will be used as input voltage source for the signal to be analyzed; the programmable source has been designed by connecting the auto-transformer with relay module of Arduino UNO as shown in the schematic diagram in figure 4.5. And so, by using this source the proposed system can be tested and verified. Moreover, the predetermined events that used for testing the system can be easily generated using this source by changing the programing of the Arduino. The transformer supply the relay module by four voltage input levels (normal, sag, swell, and interruption) and the period also can be controlled programmatically. Figure 4.6 shows the programmable ac source.

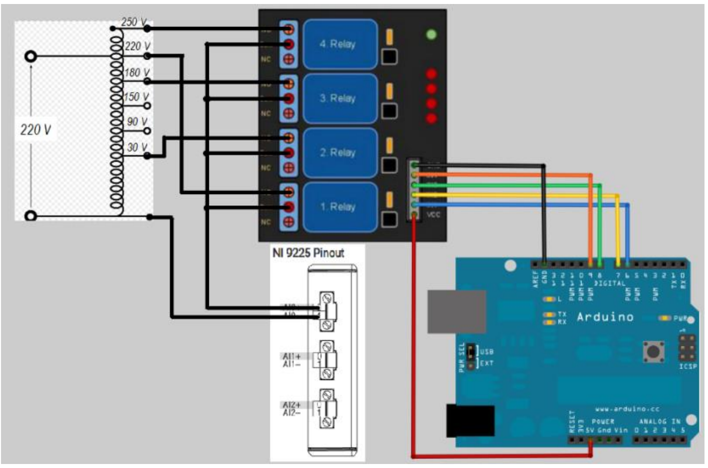


Figure 4.2: Schematic diagram of Programmable ac source.

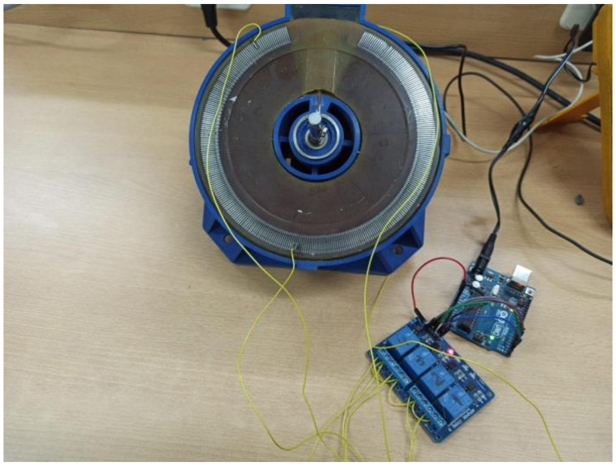


Figure 4.3: Programmable ac source.

Finally, connecting the programmable ac source with analog voltage input 9225 on cRIO-9063, and connecting the cRIO with the laptop through Ethernet cable. The monitoring and data logging of PQ will be done using LabVIEW environment on the laptop. Figure 4.7 shows the whole system hardware connection.

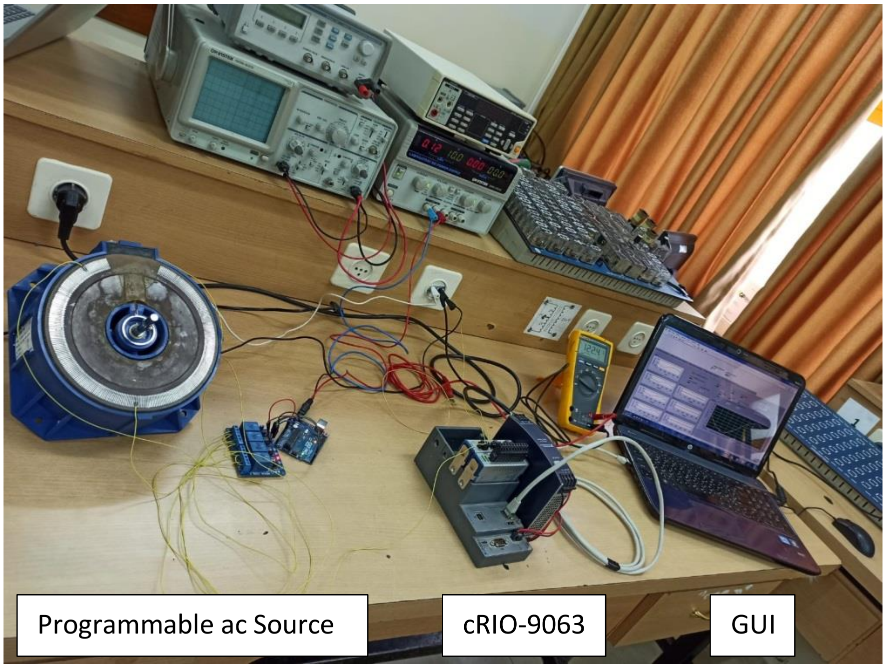


Figure 4.4: System hardware connections.

4.4 Modeling of PQ Detection and Classification System

This section shows the attempt of modeling a detection and classification system for power quality disturbances using MRA-DWT as mathematical tool. This model detects the PQ disturbances in the grid by using cRIO-9063 as controller alongside LabVIEW as programming environment. Figure 4.8 shows the flow chart of RT monitoring system.

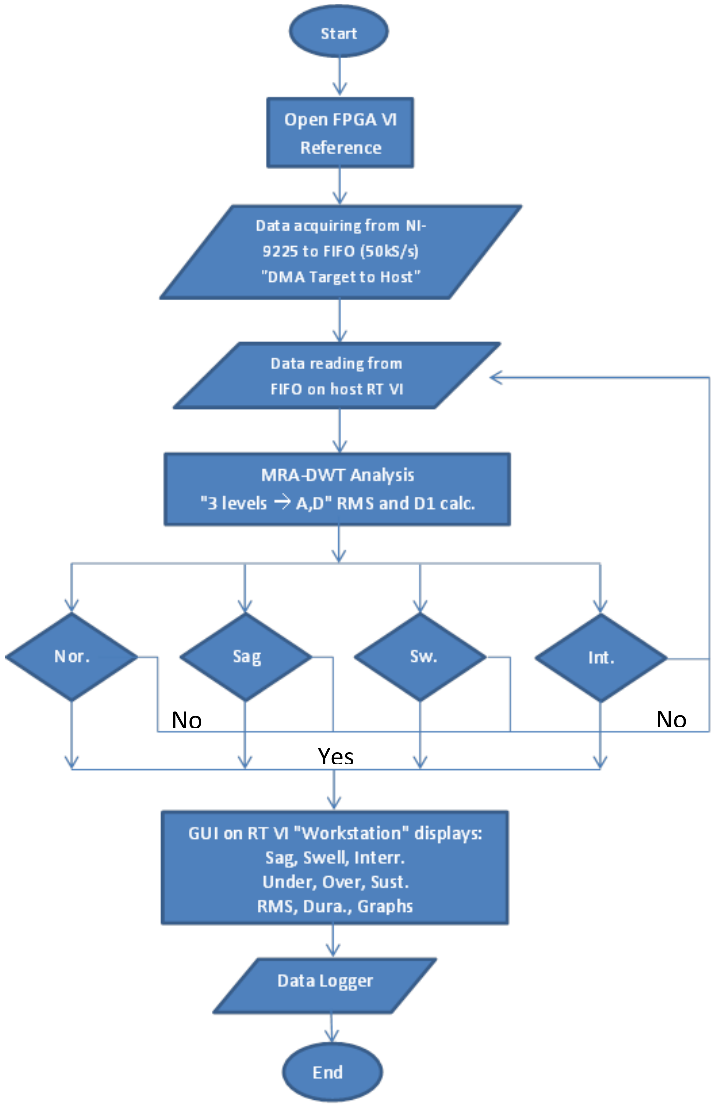


Figure 4.5: Flow chart of RT monitoring.

By using LabVIEW the code of detection and classification will be as mentioned before in chapter three, but this code should be written as LabVIEW project not VI because this code will take the data from the network through the NI-9225 module in cRIO9063 controller to be analyzed using the mathematical model. Figure 4.6 shows the main page of the project.

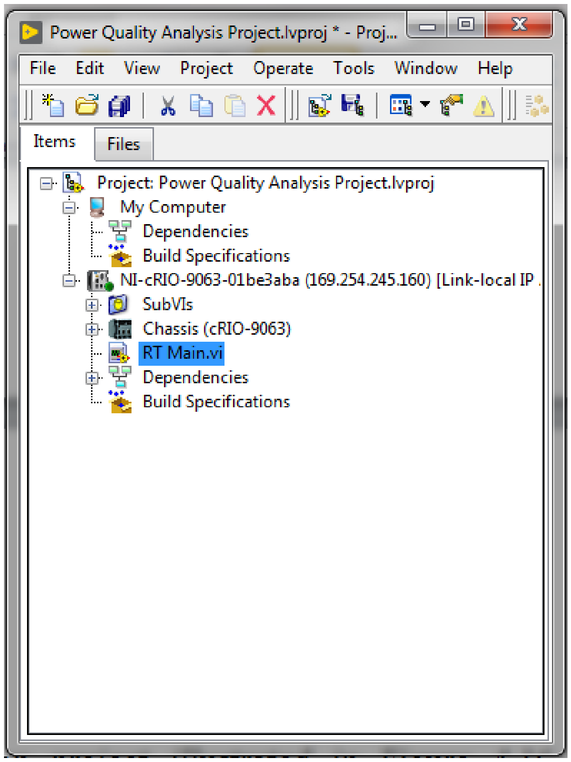


Figure 4.6: Power quality analysis project explorer.

The project will have an FPGA component, which collects data from NI-9225 and passes it to FIFOs. A FIFO is a data structure used as data holder and provides access to those data using a first in, first out access policy. And a real time RT component which displays and processes the data from FIFOs.

Graphical user interface GUI for monitoring purposes will be as shown in the figure 4.7, it contains tabs and shows the waveforms (network, RMS, details, and approximations), and status of the system (normal, sag, swell, interruption, undervoltage, overvoltage, and sustained interruption), alongside data logging from the starting of monitoring till stopping. In addition to, activation specific digital output in case of mitigation.

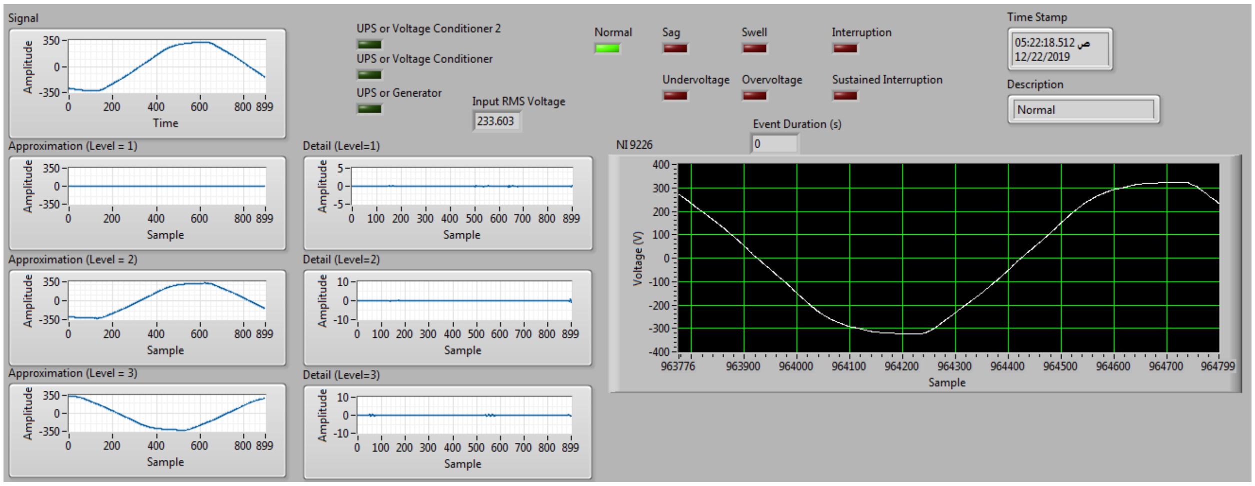


Figure 4.7: GUI of LabVIEW project.

4.5 Results and Discussions

In order to detect and classify PQ events which are voltage profile dependent there are two factors to be monitored, RMS value of the voltage and time elapsed of the event. Table 4.2 shows status of the system under different cases. Moreover, these events will be recorded in the cRIO-9063 controller using data logger.

Table 4.1: System status according to RMS value and time

RMS Value	Time Elapsed	System Status
(0 – 43) Volt	Less than 1 minute	Interruption
	Greater than or equal 1 minute	Sustained interruption
(44 – 197) Volt	Less than 1 minute	Sag
	Greater than or equal 1 minute	Undervoltage
(198 – 242) Volt	Less than 1 minute	Normal
	Greater than or equal 1 minute	
Greater than 242 Volt	Less than 1 minute	Swell
	Greater than or equal 1 minute	Overvoltage

When the network voltage is within nominal RMS value (233.603V) the green LED will be activated as indication of the system's normal status as shown in the figure 4.8. On the other hand, if the network voltage is less than 0.1pu (15.21V)for 25 seconds the red LED will light to show the interruption event as shown in the figure 4.9, and if this event last for more than 1 minute (89.29 seconds) the sustained interruption LED will be activated as shown below in the figure 4.10. Figure 4.11 shows the interruption event of zero input voltage.

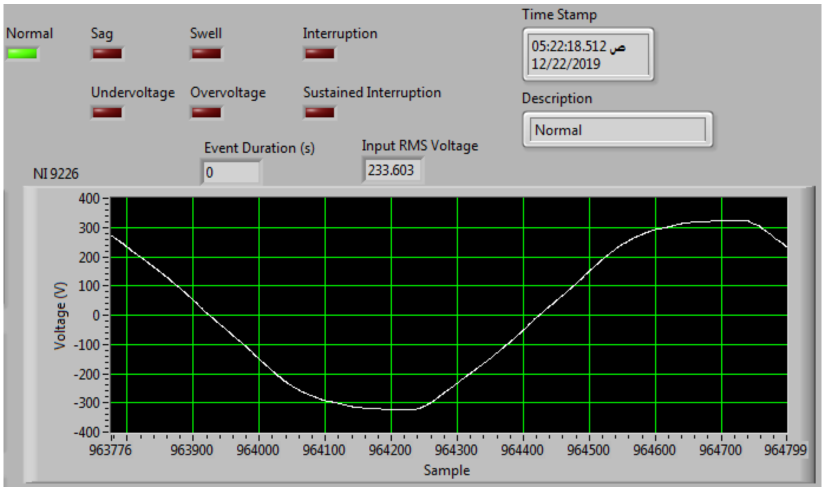


Figure 4.8: Normal status of the system.

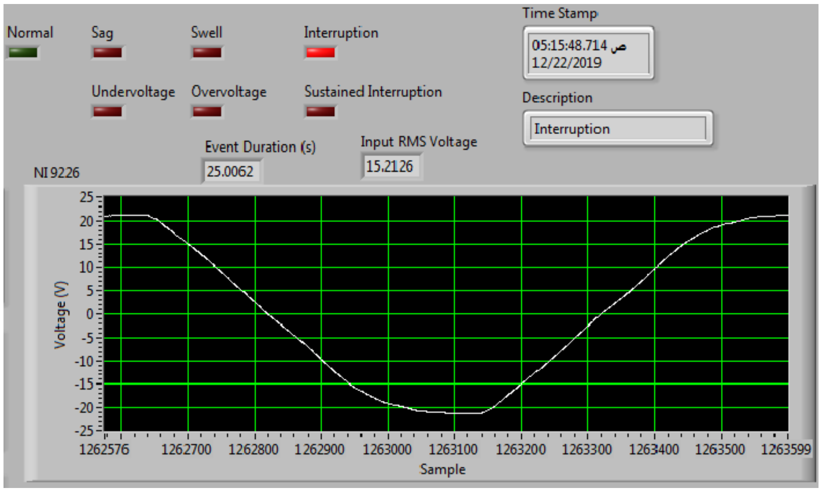


Figure 4.9: Interruption of the system.

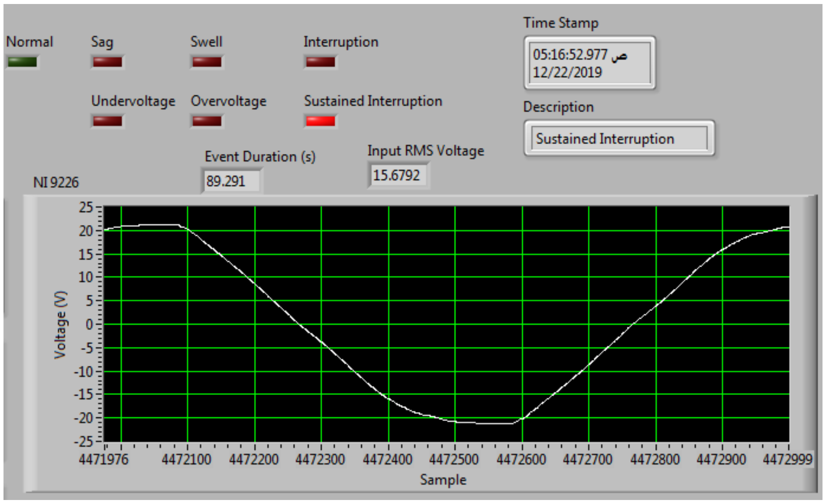


Figure 4.10: Sustained interruption of the system.

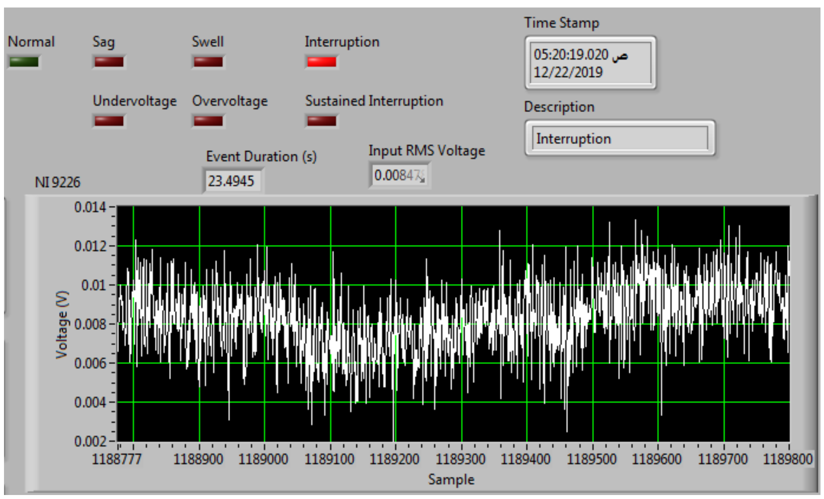


Figure 4.11: Zero input voltage interruption event.

4.6 Summary

This chapter presents the system modeling using cRIO-9063 as controller and LabVIEW as software for monitoring the grid. This chapter also details the most important specifications of the hardware. On the other hand, the results show that using this system can be efficient technique for real time power quality monitoring, and the recorded data of the detected events can be helpful for the researchers.

CHAPTER 5

Conclusions, Recommendations, and Future Work

5.1 Introduction

The detection and classification of PQ disturbances is very important issue to effectively mitigate these disturbances, in this study the system simulated and practically installed to detect and classify the PQ disturbances on the grid. Based on the results the following conclusions are listed, in addition to, recommendations and some areas of future work are suggested.

5.2 Conclusions

According to this study the following conclusions are listed.

- Using MRA-DWT with db6 as mathematical tool is quite efficient in detection and classification of PQ disturbances especially short and long duration voltage disturbances, such as sag, swell, interruption, undervoltage, overvoltage, and sustained interruption.
- The detection and classification of PQ disturbances is the first step of effective mitigation.
- Data logger can be useful for power planning and researchers too.
- Reduce the processing time, since there is a parallelism in the model. In addition to the high sampling rate owing to the NI-cRIO 9063 controller.
- Detection of the events can be done in less than one cycle (20ms) in real time, and less than 5ms in the simulation.
- Accurate detection and classification of the PQ problems, because of the mathematical DWT used in the algorithm.
- Accurate waveforms display, since there is a mathematical model accurately analyze the acquired data. In addition to, high features of the NI-cRIO.
- PQ problems mitigation can be easily done according to high speed controller.

5.3 Recommendations

The suggested recommendations are listed below.

- Make use of the output modules that can be connected to NI-cRIO controller, in order to mitigate PQ problems.
- Using the modeled system for three phase power supply to monitor the three phase simultaneously.
- Monitoring the grid in case of connecting and disconnecting of RE sources.

5.4 Future Work

The suggestions of future work as follows.

- In short duration disturbances; such as sag, swell, and interruption, these disturbances can be classified according to elapsed time into three types: instantaneous, momentary, and temporary.
- In detection of the PQ events, the nature of disturbances can be determined for example sag inside sag or swell inside swell.
- The modeled system can be installed in smart grid.
- The modeled system can be used as a part of controller in real time for islanding detection.

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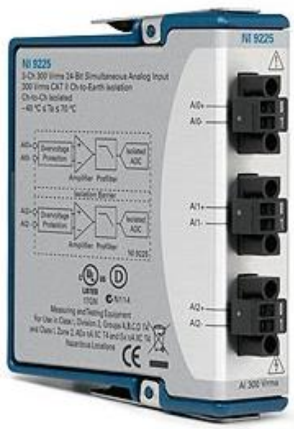
Appendices

Appendix A**:** Hardware specifications of cRIO-9063 and NI-9225.

Hardware	Specifications and Features
	- 667 MHz Dual-Core CPU - 256 MB DRAM - 512 MB Storage - Zynq-7020 FPGA - 4-Slot CompactRIO Controller - Ideal for advanced control and monitoring applications. - Rugged, fanless controller - Fast independent real time controller
	- 300 Vrms - 50kS/s/ch - 24-Bit - Simultaneous Input - 3-Channel C Series Voltage Input Module - 600 Vrms channel-to-channel isolation between the three NI-9225 channels - Well suited for high-voltage measurement applications such as power metering, power quality monitoring

Appendix B**:**

Since the LabVIEW is a graphical programming language it is hard to show the full code, instead we provide main sections of the code and refer to those sections in the main flow chart shown in figure B.1

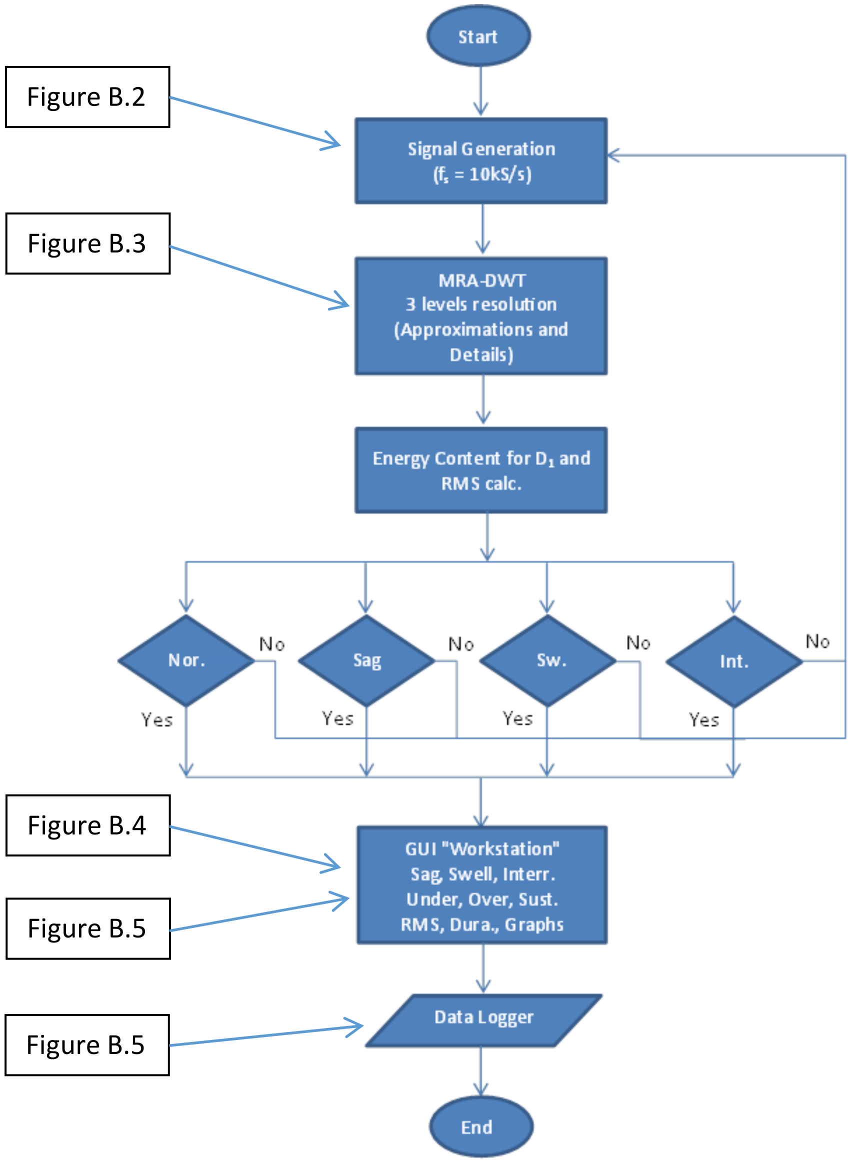


Figure B.1: Flow chart of the proposed system.

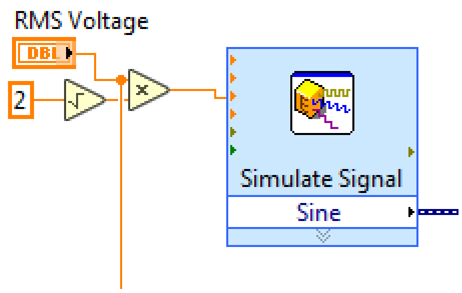


Figure B.2: Simulate signal VI.

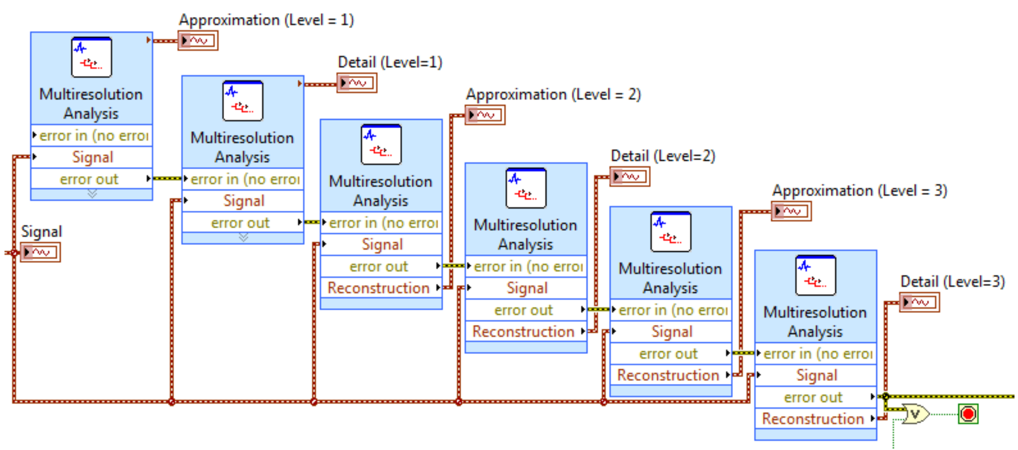


Figure B.3: Three levels MRA-DWT.

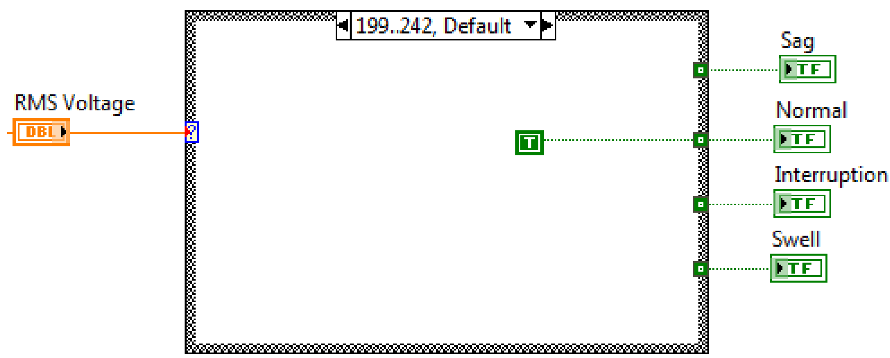


Figure B.4: Case structure for event detection.

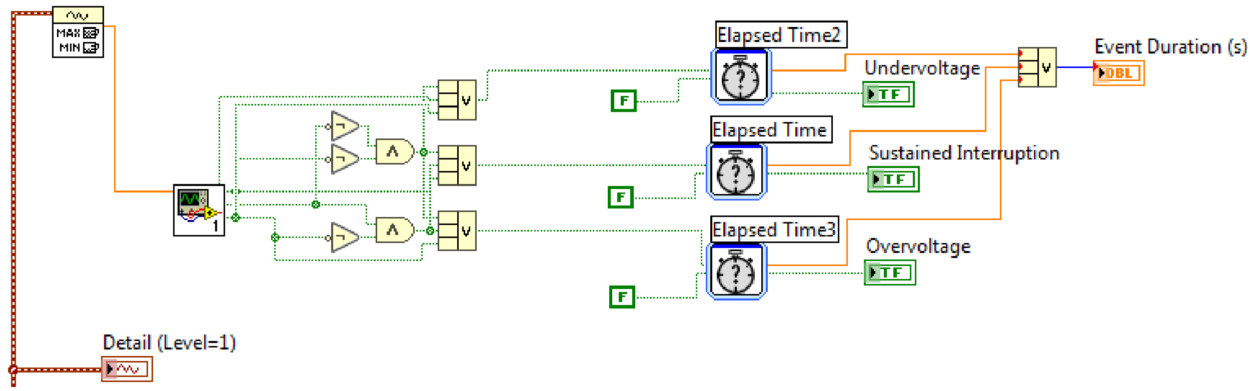


Figure B.5: Event classification code.

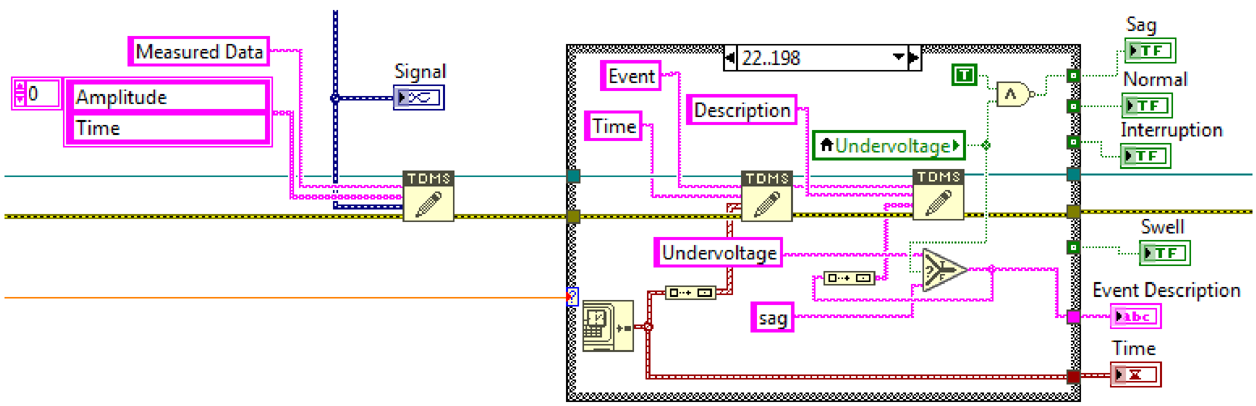


Figure B.6: Data logging code.