

POWER QUALITY ANALYSIS USING RELAY RECORDED DATA

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by

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ABSTRACT

Demand for electrical power is increasing everyday. Along with the increase in power demand, the characteristics of the loads are also changing. From being high power consuming, simple, robust loads, today loads are more efficient, but at the same time more sensitive. The performance and life of these highly sensitive loads depend a lot on the quality of power supplied to them.

Power quality is any deviation of the voltage or current waveform from its normal sinusoidal waveshape. These disturbances include, but are not limited to, sag, undervoltage, interruption, swell, overvoltage, transients, harmonics, voltage flicker and any other distortions to the sinusoidal waveform. Occurrence of one or more of such disturbances is called a power quality event. Automatic classification of these disturbances is important for quick determination of the causes and to characterize possible impacts of the disturbances.

Modern microprocessor based protective relays have numerous integrated functions that allow them to provide information on power quality events. It is proposed to utilize the existing numerical relays to analyze the quality of power at any point in the power system. The numerical relays can be programmed to capture the oscillographic waveform or any disturbance on the analogue signal or change of state of the digital signals and store it in the form of Common Format For Transient Data Exchange (COMTRADE) format. These records are then transferred to a central monitoring workstation for off-line analysis.

This thesis describes a technique to automate the classification and analysis of the power quality events using relay recorded data. The technique uses voltage duration and magnitude (as specified in the IEEE Std. 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality) of three phases to detect and classify the events. The classified results are then presented in a user-friendly graphical form. Fast Fourier Transform (FFT) is used to estimate the fundamental frequency and harmonic components in power systems. The graphical user interface of the power quality analysis tool is developed using Microsoft Visual C++ IDE and the algorithms are programmed in C++.

The proposed technique was tested using data obtained by simulating different power system disturbances as well as on the data recorded by relays. The algorithms were able to classify the power quality events accurately. In the future, this facility will: enhance the real time monitoring of power quality and provide statistical analysis of available power quality data. From the utility viewpoint, it would allow them to monitor power quality in a cost effective manner and assist in preventive and predictive maintenance besides helping them to fix differential tariff based on the quality of the delivered power. It may

also turn out to be a smart tool for them to penalize the consumer polluting the power quality.

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Dedicated to my Family

Mrs. Ajaib Kaur Birdi (Grandmother)

Mrs. Balwinder Kaur Birdi (Mother)

Mr. Ajit Singh Birdi (Father)

Mr. Paramjit Singh Birdi (Brother)

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LIST OF SYMBOLS

A/D	Analog to Digital, 17
API	Application Programming Interface, 146
CBEMA	Computer Business Equipment Manufacturers, 12
COMTRADE	Common Format for Transient Data Exchange, 5
CT	Current Transformer, 14
DFT	Discrete Fourier Transform, 18
DLL	Dynamic Link Library, 148
DSP	Digital signal Processor, 16
EEPROM	Electrically-Erasable Programmable Read-Only Memory, 16
EMTDC	Electromagnetic Transients including DC, 84
EPRI	Electric Power Research Institute, 46
FFT	Fast Fourier Transform, 18
FFT	Fast Fourier Transform, 21
GUI	Graphical User Interface, 12
IDE	Integrated Development Environment, 54
IEEE	Institute of Electrical and Electronics Engineer, 25
ITE	Information Technology Equipment, 46
ITIC	Information Technology Industry Council, 12
MFC	Microsoft Foundation Class, 146
MTBF	Mean Time Between Failure, 44
PC	Personal Computer, 54
PQAT	Power Quality Analysis Tool, 52
PSCAD	Power Systems CAD, 84
RAM	Random Access Memory, 16
ROM	Read Only Memory, 16
RUP	Rational Unified Process, 52
TDD	Total Demand Distortion, 44
THD	Total Harmonic Distortion, 44
UML	Unified Modeling Language, 52
UPS	Uninterrupted Power Supply, 37
VC++	Visual C++, 54
VT	Voltage Transformer, 14
VT	Voltage Transformer, 85

CHAPTER 1

INTRODUCTION

1.1 Background

An electrical power system consists of three main divisions: generation, transmission and distribution. Generators convert mechanical power to electrical power that is transported over long distances over transmission lines and is distributed to a variety of customers via local networks.

In a power system, all equipment such as generators, transformers and transmission lines, must function together to attain the primary objective of distributing electrical power without unnecessary interruptions. Faults and disturbances, which disrupt the continuity of power supply, are experienced sometimes. The consequence of these events include serious damage to the equipment if the faulted equipment is not promptly isolated from the system.

Protective relays are designed to detect faults and abnormal conditions by continuously monitoring power system voltages and/or currents, and then initiating the opening of appropriate circuit breakers for isolating the faulted section. They are a vital component of the power system. Modern microprocessor based protection relays have numerous functions that allow them to monitor power system quality.

1.1.1 History

The electric power industry continues to shape and contribute to the welfare, progress, and technological advances of the human race. The growth of electric energy consumption has been phenomenal over the past century. Ever since the first station, inaugurated by Edison Electric Illuminating Company of New York, started generating electricity in 1881 at the Pearl Street in New York, the generation, distribution, and use of electricity have steadily evolved. The station had six engine-dynamo sets with four 250-hp boilers supplying steam to them. Edison's system used a 110 V dc underground distribution network with copper conductors insulated with jute wrapping. In 1882 the, first water wheel-driven generator was installed in Appleton, Wisconsin [1].

In the early days the electrical machines were crude but very utilitarian. They consumed large amounts of electricity and performed very well. The design of the machines was such that the cost concerns were only secondary to performance considerations. They

were probably susceptible to whatever power quality anomalies existed at that time. However the results were not readily detectable due to the robustness of the machines and partly due to the lack of effective ways to measure power quality parameters.

In the last 50 years, the industrial age has driven the need for the products to be economically competitive. This has led to the electrical machines becoming more efficient and smaller without performance margins. At the same increased demand for electricity has created extensive power generation and distribution grids. The electricity generation has been stretched to the limit because of the growing use of electricity in the residential sector as well as the huge demand by the industries. Modern day Electric Utilities are a part of large network of independently operated utilities tied together in the ever growing complex grid. The combination of these factors has created electrical systems requiring a certain standard of power quality [2].

Figure 1.1 shows the evolution of the Power Quality Instrumentation.

1.2 Power Quality

Electric power quality has emerged as a major area of electric power engineering. The predominant reason for this emergence is the increase in the sensitive end-use equipment. The term power quality is defined as *the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of the equipment* [3]. The term power “quality” is however a misnomer. It is actually the voltage quality that is being addressed. Power is the rate of energy delivery and is proportional to the product of voltage and current. It is difficult to define the quality of this quantity in a meaningful manner. The power supply system can control only the voltage quality. It has no control over the currents that particular loads might draw.

There is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage. e.g.

1. The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.
2. Currents from lightning strokes passing through the power system cause high - impulse voltages that frequently flash over insulation and lead to other phenomena.
3. Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Thus a distorted voltage is presented to other end users.

AC Power Systems operate at a frequency of 50 or 60 Hz. Any significant deviation in the waveform magnitude is a potential power quality problem [4].

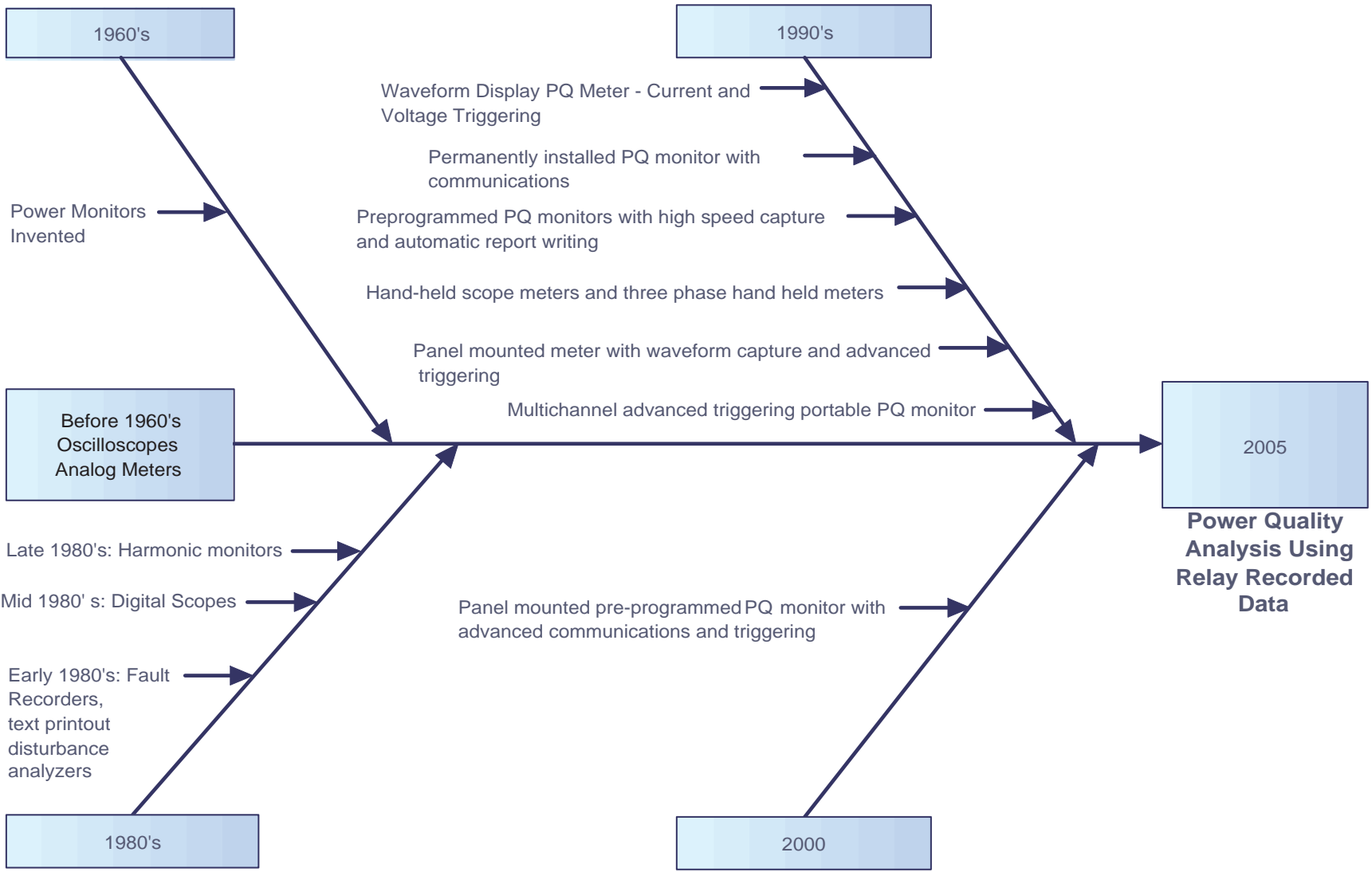


Figure 1.1: Evolution of the Power Quality Instrumentation

1.2.1 Concern about Power Quality

Over the past decade, the amount of electronic equipment such as personal computers, process control, variable speed drives has increased dramatically. As the electronic equipment became more powerful and versatile, the potential for power problems also increased. Two identical devices or pieces of equipment might react differently to the same power quality parameters due to difference in their manufacturing and component tolerance. Such an equipment can both cause and be affected by electromagnetic disturbances. On one hand these loads are highly sensitive to the quality of the source power and on the other hand they might be contributing factor to both voltage and current distortion on the power grid side. Power quality has an economic impact on utilities, customers and load equipment suppliers [2].

1.2.1.1 Impact on Utilities

End users have become more aware about the power quality issues. The customers of a utility have become better informed and have high expectations. Moreover the deregulation of the electric power industry has led to competition between various utilities. If the customer is unsatisfied with the quality of supply, the utility risks losing the customer to the competing power supplier. Meeting customer expectations and maintaining customer confidence have become strong motivators. As a result a large number of utilities have begun to apply extensive monitoring systems throughout their distribution systems to determine the typical level of service quality provided.

1.2.1.2 Impact on Industrial Customers

An increasingly large number of customers utilize electronically controlled and energy efficient devices that are more sensitive to the small deviations in the supply voltage. There is big money associated with minor disturbances in the power system. e.g. a single momentary utility breaker operation results in a \$ 10,000 loss to an average sized industrial concern by shutting down a production line that requires 4 hours to restart.

1.2.1.3 Impact on Load Equipment Suppliers

Customers tend to buy the various load equipment solely on the basis of lowest price. Due to this the equipment manufacturers find themselves in a highly competitive market. This acts as deterrent to add more features to the equipment to withstand common disturbances unless the customer specification includes those features. Many manufacturers are also unaware of the type of disturbance that can occur on power systems. It is for the end user to protect the sensitive loads from power quality disturbances by installing protection equipment.

1.3 Power Quality Monitoring in Protective Relays

As mentioned in previous sections, protective relays are a vital component of power systems. The microprocessor based relays record voltage, current and logical signals directly from the power system and store in the Common Format for Transient Data Exchange (COMTRADE) format [5]. This contains detailed information on the conditions of the power systems during various power quality events events such as sag, undervoltage, interruption, swell, overvoltage, transients, harmonics, voltage flicker etc. Some of the advantages of power quality monitoring in protective relays are:

1. It allows for much more economical monitoring of multiple points within the utility using the existing assets. There is no need to invest on additional power quality devices like power quality meter.
2. A relay is attached to the power system all the time, thus enabling continuous monitoring.
3. The relay, connected to the substation batteries, can monitor events during system disturbances and does not require a separate UPS battery.
4. Relay is attached to the communication networks and information access systems. It is able to utilize the existing networking and communication investments more fully.
5. It minimizes maintenance.
6. Higher speeds and lower costs for microprocessor technology will allow continued function integration into relay systems.

Thus power quality monitoring in a relay can be another tool for customer monitoring and response [6].

1.4 Locations for Monitoring Power Quality

The power quality monitoring is an important step to identify and resolve power related equipment or facility problems. It is an organized systematic approach to problem solving. If all the steps for a power quality monitoring are completed, information is obtained that either identifies a solution for a power related problem or reveals that the problem is not related to the electrical power system. Power quality monitoring involves the following steps:

1. Planning for the monitoring
2. Preparing for the monitoring

3. Inspecting the site
4. Monitoring the power
5. Analyzing, monitoring and inspecting data
6. Applying corrective solutions

The monitoring of a power quality at a particular location is determined by the objective [7], [8].

Monitoring power quality for network The power quality is monitored in power system network to identify and correct sources of interference in power system network.

Monitoring at service entrance A power quality survey of an entire facility usually starts as far upstream in the electrical distribution as possible. The initial location is typically the secondary side of the main service transformer. It may also be useful to monitor simultaneously at more than one location within a facility. The relay will record the quality of power supplied to the facility as well as the effect of major loads within the facility.

Monitoring at the point of use or at a branch circuit To diagnose an equipment performance problem the relay is placed as close to the load as possible. This applies to performance problems with both sensitive electronic loads such as computers and adjustable speed drives, and electrical distribution equipment such as circuit breakers and capacitors. After the voltage fluctuations are detected, the relay may be moved upstream on the circuit to determine the source of the disturbance.

1.5 Places where Power Quality is Being Monitored

In today's 7×24 uptime world, a power outage begins after four milliseconds of breaker operation and can cost millions of dollars a year in downtime. Minimizing the probability of that impact requires facility managers to fully understand their power system infrastructure so they can maximize power reliability and quality. Power monitoring is key to maximizing uptime and ensuring all power infrastructure is functioning properly [9]. Some of the places where power quality is being monitored on a continuous basis are listed below:

- **Data Centers**

Most data centers invest in power mitigation technologies such as UPS and backup generation technologies. A 24×7 operation needs continuous power information to ensure that these systems are delivering highly reliable, clean power.

- **Banking & Financial**

The cost of downtime for brokerage operations is more than \$6 million per hour and \$2.6 million per hour for credit card operations. The various transactions taking place each day by banks can be negatively impacted by even the slightest power quality disturbance, either delivered by the electric grid or caused within the facility. Monitoring and managing power quality is key to maximizing uptime and increasing profitability.

- **Hospital & Emergency**

With the rapid advance in medical technology, hospitals, medical clinics and laboratories increasingly rely on sophisticated electronic devices for diagnosis, treatment and monitoring. This reliance, in turn, demands a high degree of power quality and reliability to prevent disruption of mission-critical operations and procedures. Power quality disturbances can be caused by a range of internal and external phenomena and often re-occur because the location and nature of the event is not well understood or identified. Power monitoring can detect deterioration in power quality before power infrastructure or other equipment problems arise.

- **Telecommunications**

Just as the digital economy is redefining business operations, it is setting new standards for electric power reliability and quality. Downtime is catastrophic for telecommunications centers, where even the smallest interruption or power quality event can cause equipment failure, data loss and lost revenue. This is especially true for telecommunications centers, where communications and connectivity are essential elements of our daily lives. Using power monitoring instrumentation, telecommunications facilities can dramatically improve the performance of their power systems infrastructure.

- **Manufacturing**

Depending upon the industry and facility, energy is one of a manufacturing plants most significant budget items. Experience tells us that a typical manufacturing plant can save from 10 percent to as much as 40 percent annually on energy costs by implementing a comprehensive energy action plan. Plus, power quality disturbances, whether delivered by the utility or internally generated by equipment such as adjustable speed drives or motor starts, can result in downtime, scrapped product, and lost revenue. Power monitoring can detect deterioration in power quality before equipment problems arise, while simultaneously supporting an energy cost savings program.

- **Semiconductor**

Semiconductor manufacturing is one of the most complex manufacturing processes

in the world. The semiconductor manufacturing process is extremely susceptible to power quality events, especially sags, surges and overvoltage/undervoltage events. These events can impact product quality, resulting in scrapped product and sizeable revenue loss. The semiconductor industry was one of the first to recognize these impacts and employ power monitoring to minimize damage.

- **Process/Chemical/Petrol**

Minor fluctuations in power quality can cause interruption / disruption of continuous-process industries. This leads up to substantial start-up costs and time. If the product stream is disrupted, lost productivity and lost product can create a large financial burden e.g. a voltage sag in a paper mill can inflict a \$250,000 loss, while a 5-cycle interruption at a glass manufacturing facility can cost a minimum of \$200,000. Power monitoring can detect deterioration in power quality before problems arise.

- **Power Quality**

Power quality events can impact sensitive equipment such as servers, motors, process equipment and computers. This end-use equipment is often interconnected within networks, industrial processes and power infrastructure and can be negatively affected by events that arise both from the supplying power system and are generated within the facility. The cost of downtime can run into thousands, or even millions of dollars per hour. Power monitoring is key to maximizing uptime and ensuring all power infrastructure is functioning properly.

- **Distributed Generation**

With changes in the energy marketplace, concerns over grid reliability and security, and increased interest and cost advantages for some facilities in generating their own power, a diverse set of distributed generation and alternative energy solutions have emerged. Those solutions include new reciprocating engines, microturbines, fuel cells, photovoltaics and wind farms. These solutions are used for primary power, premium power, peak shaving, green power, cogeneration and backup power. Additionally, a new opportunity exists for the aggregation of multiple distributed generation devices to participate in today's energy markets

- **Customer Service**

Power quality is a key customer service issue for investor-owned utilities, municipal utilities and rural cooperatives. From supermarkets and retail operations, to manufacturing and high-tech facilities, customers expect a certain level of power quality and reliability delivered from their local utility. Education and power quality monitoring have been effective tools in developing trusted, cooperative relationships between the utility and their customers.

- **Substation Monitoring**

The restructuring of the electric utility industry has placed a premium on distribution system reliability and operational efficiency. Customers are increasingly sensitive to power system interruptions and transmission and distribution system constraints. Monitoring is a critical component in ensuring substation performance and uptime. Key objectives are to monitor changes in output to evaluate transformer loading, enabling you to plan transformer servicing and upgrades before problems occur; conduct performance monitoring for breaker operation, providing information on current and impedance during operation to determine how the system protection circuitry is performing; and measuring and analyzing fault condition to determine current characteristics.

- **Military / Government**

It is estimated that three percent of every sales dollar in the US is spent on power quality problems. 75% of all power quality problems occur inside customer facilities, requiring governmental power engineers and electricians to diagnose and solve these problems themselves. Unfortunately, these percentages will only increase as loads become more sensitive to power quality events and the power utilities become more decentralized. For military and government facility managers and engineers, understanding and managing power system infrastructure is essential to ensuring public safety and security, optimizing equipment performance, and controlling escalating energy costs.

- **Education**

For colleges and universities, power quality and reliability have increased in importance as these institutions host highly sensitive data processing equipment, computerized control infrastructures, and sophisticated research facilities. For primary through high schools, energy management and cost containment is a key issue in budget management. For both, power monitoring is essential to delivering success.

1.6 Importance of Monitoring Power Quality

Of the many important reasons to monitor power quality, the primary reason which stands over all others is economic. Effects on equipment and process operations can include misoperation(s), damage, process disruption and many other conditions. Such disruptions are costly since a profit-based operation is interrupted unexpectedly and must be restored to continue production. In addition, equipment damage and subsequent repair cost both money and time. Listed below are some of the reasons outlining the importance of monitoring power quality [7].

1. Power Quality Monitoring is necessary to detect and classify disturbance at a particular location on the power system. Because of the technology and software now

available, this monitoring is a highly-effective means to prevent problems on both utility and customer power systems. A monitoring system can provide information about system disturbances and their possible causes. It can also detect problem conditions throughout the system before they cause customer complaints, equipment malfunctions, and even equipment damage or failure.

2. PQ monitoring assists in preventive and predictive maintenance. Identifying pattern changes enables better planning of maintenance activities and avoid interruptions of critical business processes, while system data allows just-in-time maintenance procedures to be developed and implemented.
3. Problems can be detected before they cause widespread damage by sending automated alerts when conditions begin to deteriorate. It helps in the identification of the disturbance source location, frequency and timing of events. Based on power quality trends maintenance schedules can be developed.
4. PQ Monitoring can be used to determine the need for mitigation equipment by monitoring and trending conditions e.g by analyzing harmonics, voltage sag, power factor correction). The continuous capture of all events enables users to develop trend lines and algorithms to maintain real-time illustrations of system performance and improve reliability. This aids in determining future performance of load equipment and helps making decisions based on documented trends.
5. Monitoring aids in assessing sensitivity of process equipment to disturbances and evaluate performance against specifications.
6. PQ monitoring helps in benchmarking overall system performance, make multi-site and energy rate comparisons. Load profile can be generated to track daily, weekly and seasonal variations in energy consumption, while critical loads can be metered and sub-metered to evaluate consumption and reduce energy costs.

1.7 Kinds of Relay Recorded Data

The data generated by triggered specified parameters is available in the relay in the following formats.

1. Oscillography / Disturbance Record
2. Event File
3. Fault Record
4. Data Logger

1.7.1 Oscillography / Disturbance Record

Oscillography or disturbance records contain waveforms captured at the sampling rate as well as other relay data at the point of trigger. Oscillography records are triggered by a programmable operands. Multiple oscillography records may be captured simultaneously. The Number of Records is selectable, but the number of cycles captured in a single record varies considerably based on other factors such as sample rate and the number of operational CT/VT modules. There is a fixed amount of data storage for oscillography; the more data captured, the less the number of cycles captured per record. The relay can record multiple analog and binary signals. The oscillography is initiated by a tripping and/or reclosing signal. Pre-fault recording time and post-fault recording time is user selectable. The maximum number of stored records depends on the post-fault recording time. The format of the Comtrade record is explained in detail in Appendix D. All the relays being manufactured these days store the oscillography in the Comtrade format.

1.7.2 Event File

The Event Records shows the contextual data associated with up to the last fixed number of events, listed in chronological order from most recent to oldest. If all event records have been filled, the oldest record will be removed as a new record is added. Each event record shows the following.

- Event identifier/sequence number
- Cause and date/time stamp associated with the event trigger
- Alarms
- Change of binary input signal
- Change of relay setting
- Relay failure

1.7.3 Fault Record

A trip signal initiates fault recording. The fault report stores data, in non-volatile memory, pertinent to an event when triggered. The captured data contained in the Fault Record.txt file includes:

- Fault report number
- Name of the relay, programmed by the user
- Firmware revision of the relay

- Date and time of trigger
- Name of trigger (specific operand)
- Line/Feeder ID via the name of a configured signal source
- Active setting group at the time of trigger
- Pre-fault current and voltage phasors
- Fault current and voltage phasors
- Elements operated at the time of triggering

Each fault report is stored as a file. After a fixed number of files an additional trigger overwrites the oldest file.

1.7.4 Data Logger

The data logger samples and records analog parameters at a user-defined sampling rate. This recorded data may be downloaded and displayed with parameters on the vertical axis and time on the horizontal axis. For a fixed sampling rate, the data logger can be configured with a few channels over a long period or a larger number of channels for a shorter period. The relay automatically partitions the available memory between the channels in use.

1.8 Objective of the Research

The objective of this research was to develop and test algorithms for Power Quality Analysis in the form of Software Tool with Graphical User Interface (GUI) which should be able to detect and characterize the various Power Quality Disturbances from the data captured and stored by a relay.

1.9 Outline of the Thesis

The thesis is organized in seven chapters and three appendices. The current chapter presents the background on power quality, introduces the subject of the thesis and describes its organization.

An overview of numerical relays, the algorithms used in them and the disadvantages of these conventional algorithms are reviewed in Chapter 2.

The various power quality events are introduced in Chapter 3. The characterization, causes and effects of the various Electromagnetic Phenomena, is also examined. The information technology industry council (ITIC) curve formerly known as Computer Business Equipment Manufacturers (CBEMA) curve is briefly examined in this chapter, as well.

A brief description of the various features of the Power Quality Analysis Tool is given in Chapter 4. Algorithms for characterizing the various power quality events were developed. The procedural steps involved in implementing of the algorithms are illustrated using the flow charts. The proposed algorithms were tested using the Comtrade Files provided by General Electric Multilin.

Results obtained from the power quality characterization algorithms are presented and discussed in Chapter 5.

The future developments in the area of power quality are discussed in chapter 6. Some of the limitations in the detection of power quality events are also listed.

An introduction to the Microsoft Visual C++ programming software is given in Appendix A. The Quinn Curtis Graphics Library used for plotting is described in Appendix B. The list of power quality standards is given in Appendix C. Appendix D explains the Comtrade Format in brief. Appendix E explains the Power Systems Computer Aided Design software.

1.10 Summary

A brief introduction to the concept of power quality and power system protection has been presented in this chapter. The scope and purpose of power quality is discussed. The objective and outline of the thesis have been presented as well.

CHAPTER 2

NUMERICAL RELAYS

An introduction to the subject of numerical relays is presented in this chapter. The major functional blocks of a typical numerical relay are described. The features of numerical relays are outlined. Then, the conventional algorithms used in numerical relays are presented.

2.1 Numerical Relays

Numerical relays are microprocessor-based devices that use software to process quantized signals for implementing protection functions. The general purpose of a numerical relay is the same as the purpose of a conventional relay, in the sense that it should accept data representing voltage and current, process the data and execute a control action, like giving a trip signal to the breaker, when it is deemed to be necessary. Because the inputs from a power system are analog in nature, they are converted to digital form for the microprocessors. Numerical relays, therefore require appropriate hardware for analog to digital conversion. A block diagram of a typical numerical relay [10] is shown in Figure 2.1.

A numerical relay receives currents and voltages from a power system through Current Transformer (CT) and Voltage Transformer (VT) . The outputs of these transducers are applied to the relay. Each block of a typical relay is briefly explained in the following sections.

2.1.1 Analog Input Subsystem

The analog input subsystem consists of the isolation and scaling system and the data acquisition system. The isolation and scaling system comprises of auxiliary CTs and VTs. This system also includes surge arrestors to block surges from the power system. The data acquisition system consists of the anti-aliasing filters, sample and hold circuits and the analog to digital converters. The analog input subsystem performs the following functions.

- Isolates the relay from the power system using surge arrestors.
- Scales down the input voltage or current using auxiliary CTs and VTs.

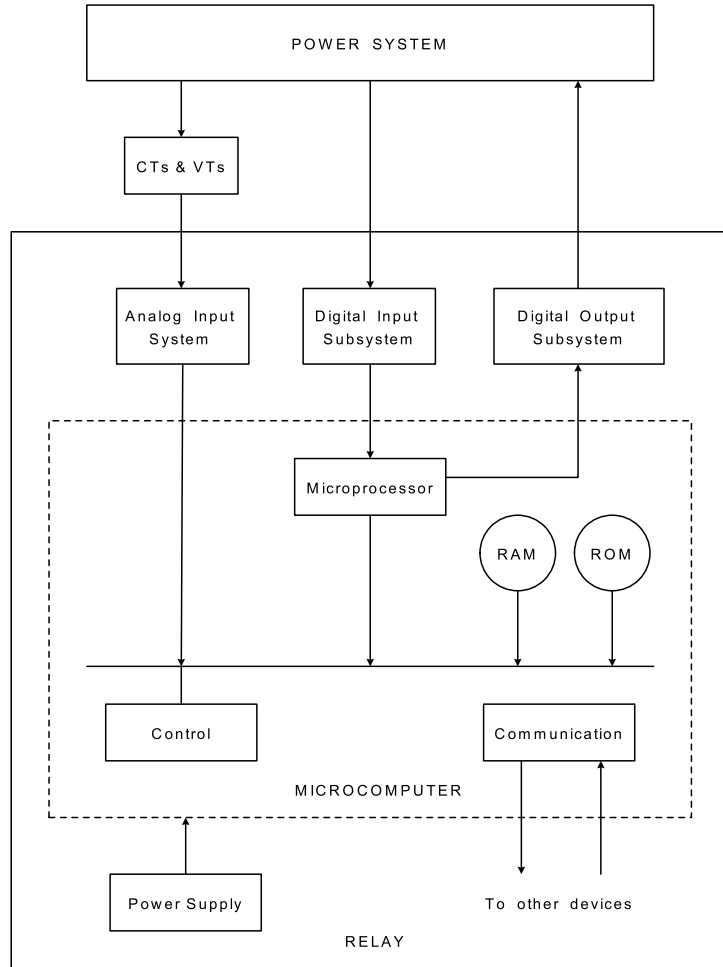


Figure 2.1: Block Diagram of a Typical Numerical Relay

- Filters the high frequency components and noise using anti-aliasing filters.
- Samples the scaled down filtered voltage using sample and hold circuits.
- Converts the analog input signal to digital signal using analog to digital converters.

2.1.2 Digital Input Subsystem

This subsystem receives information like status of breakers (ON/OFF), isolators and relay targets. The number of digital inputs can be twenty or more [1].

2.1.3 Central Processing Unit

The central processing unit processes data from the input subsystems and makes decisions based on the algorithms stored in the memory. It also controls the sample and hold circuits, the multiplexer and the A/D converters. This unit could be a general-purpose micropro-

cessor, a Digital Signal Processor (DSP) or a micro-controller. Sometimes two processors are used, one for performing calculations and the other for control and communication.

2.1.4 Memory

There are three types of memory.

- Read-Only Memory (ROM) is used for storing programs.
- Electronically-Erasable Programmable Read-Only Memory (EEPROM) is used for storing relay settings and other vital information.
- Random Access Memory (RAM) is used for temporarily storing intermediate numbers and fault data records.

The processor communicates with these memory elements through its data, address and control buses. Some times multiple-input RAMs are used. This is useful when more than one processor is to read from and write on the same memory.

2.1.5 Digital Output Subsystem

The output of a numerical relay is provided to the power system through its digital output subsystem. A maximum of five to ten outputs are sufficient for most relaying applications.

2.1.6 Other Components

Communication ports are provided to share information with other devices. Numerical relays are usually powered from the station battery, which is provided with a battery charger. This ensures that the relay continues to perform its intended function during outages of the station ac supply.

2.2 Features of a Numerical Relay

A numerical relay has many special features. Some of the features are listed here.

1. Its ability to perform self-diagnostic tests to detect component failures. This eliminates the need to remove the relay from operation for maintenance; this increases the reliability of the system.
2. Most manufacturers use a common hardware platform for several classes of relays. The function of such a relay can be changed by changing the software.
3. The relay settings can be changed by using communication interface, making adaptive relaying possible.

4. A numerical relay can be programmed to do multiple protection functions with a single unit, thus reducing the cost of protection systems.
5. A digital relay can store fault data, which can be used for diagnostic purposes and system improvements. Fault locations can be calculated from the stored data making it easier for the maintenance staff to carry out repairs.

2.2.1 Nature of Signals

A power system is a complex network of linear and non-linear components. The major part, of voltages and currents experienced in power systems are of the fundamental frequency. A voltage may, therefore, be expressed as

$$y(t) = V_p \cdot \sin(\omega_0 \cdot t + \theta) + e(t) \quad (2.1)$$

where ω_0 is the nominal power system frequency
 V_p is the peak value of the voltage
 θ is the phase angle of the voltage phasor
 $e(t)$ is the error signal

This error signal $e(t)$, includes the unpredictable contributions from

- transducer (CTs and VTs) errors,
- fault arc,
- exponentially decaying offsets,
- truncating and rounding by Analog to Digital (A/D) converters,
- transient outputs of anti-aliasing filters, and
- the power system

The nature of the signals experienced in power systems depends on fault location, fault resistance and the fault incidence angle. The nature of the signals experienced during a disturbance is, therefore, unpredictable. A current could be represented by an equation similar to 2.1.

2.2.2 Extracting Phasors

Consider that the signal $y(t)$ is sampled every ΔT seconds. From these samples, the parameters of the phasors, such as V_p and θ are to be estimated.

Algorithms differ in the ways they estimate the unknown parameters of the phasors from the quantized samples. They also differ in the number of samples they use to obtain

an estimate. The number of samples used to obtain an estimate is called the data-window size.

Because the voltages and currents contain components of the fundamental and other frequencies, it would be useful to include the components of other frequencies in formulating the model of a signal. This ensures that the phasor estimates are more accurate. It can be seen that the error $e(t)$ reduces as more components of the signals are included in the model. However, this may require the use of larger data-window for estimating the unknown parameters increasing the delay for obtaining the estimates.

2.3 Classification of Algorithms

The relaying algorithms can be broadly classified by the mathematical principles that are used for estimating phasors [11]. Some of the classifications are as follows.

1. Trigonometric Algorithms
 - Mann and Morrison Algorithm
 - Rockfeller and Udren Algorithm
 - Gilbert and Shovlin Algorithm
 - Miki and Makino Algorithm
2. Correlation Algorithms,
 - Discrete Fourier Transform (DFT) Algorithm
 - Fast Fourier Transform (FFT) Algorithm
 - Even and Odd Functions Algorithm
 - Walsh Functions Algorithms
3. Least Error Square Algorithms.

The algorithms, which use a window of less than half-cycle, are called short-window algorithms and the algorithms, which use a window of more than half-cycle, are called long-window algorithms. A phasor estimate is a complex number and, therefore, has a real part and an imaginary part.

$$V = V_p \angle \theta = V_{Re} + j \cdot V_{Im} \quad (2.2)$$

The algorithms generally estimate the real and imaginary parts of the phasors separately. The processes are basically digital filters. Depending on the frequency response of the filters some frequencies are passed without attenuation and the others are attenuated or

amplified. The peak value and angle of the phasor are calculated from the estimated real and imaginary parts using the following equations.

$$V_p = \sqrt{(V_{Re}^2 + V_{Im}^2)} \quad (2.3)$$

$$\theta = \tan^{-1} \left(\frac{V_{Im}}{V_{Re}} \right) \quad (2.4)$$

2.4 Correlation Algorithms

2.4.1 Discrete Fourier Transform

These algorithms use two orthogonal functions, which would effectively extract components of the frequency of interest from a given signal [12]. It can be shown that

$$V_p \cdot \cos(\theta) = \frac{1}{\pi} \int_0^{2\pi} V_p \cdot \sin(\omega t + \theta) \cdot \sin(\omega t) d(\omega t) \quad (2.5)$$

and

$$V_p \cdot \sin(\theta) = \frac{1}{\pi} \int_0^{2\pi} V_p \cdot \sin(\omega t + \theta) \cdot \cos(\omega t) d(\omega t) \quad (2.6)$$

Equations 2.5 and 2.6 give the real and imaginary parts of the phasor representing the waveform.

Replacing the integrations in Equations 2.5 and 2.6 by numerical processes provides

$$V_{Re}(k) = \frac{2}{m} \sum_{n=0}^{m-1} v_{k+n-m+1} \cdot \sin(2\pi \cdot \frac{n}{m}) \quad (2.7)$$

$$V_{Im}(k) = \frac{2}{m} \sum_{n=0}^{m-1} v_{k+n-m+1} \cdot \cos(2\pi \cdot \frac{n}{m}) \quad (2.8)$$

where,

k is the most recent sample, and

m is the number of samples taken in one cycle of the fundamental frequency

These equations show that correlating a signal with the cosine waveform provides the imaginary part of the phasor and correlating with the sine waveform provides the real part of the phasor. For a 60 Hz signal, sampled at 720 Hz, Equations 2.7 and 2.8 yield the following coefficients.

For calculating the real part of the phasor the filter is given by the coefficients

$$[0, 0.5, 0.866, 1.0, 0.866, 0.5, 0, -0.5, -0.866, -1.0, -0.866, -0.5].$$

For calculating the imaginary part of the phasor the filter is given by the coefficients

$$[1.0, 0.866, 0.5, 0, -0.5, -0.866, -1.0, -0.866, -0.5, 0, 0.5, 0.866].$$

The filter, which gives the real part of the phasor ($V_p \cos(\theta)$), is called the cosine filter and the filter, which gives the imaginary part of the phasor ($V_p \sin(\theta)$), is called the sine filter.

Figures 2.2 and 2.3 show the frequency responses of the sine and cosine filters respectively when a sampling frequency of 720 Hz is used to calculate phasors of 60 Hz frequency. These figures show that both the sine and cosine filters

- pass 60Hz component without any attenuation,
- completely remove the non-decaying dc component,
- and remove all harmonics.

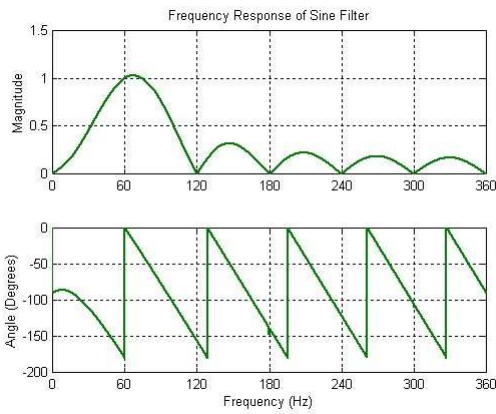


Figure 2.2: Frequency Response of a DFT Sine Filter

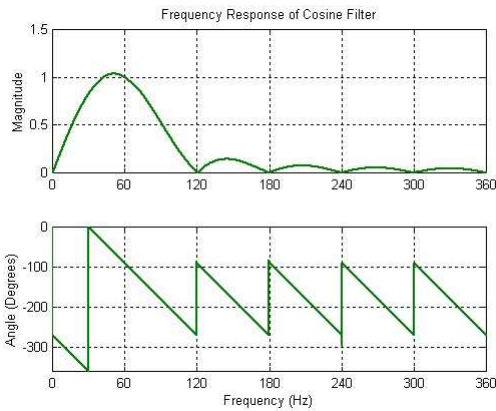


Figure 2.3: Frequency Response of a DFT Cosine Filter

The frequency response of the DFT algorithm, which is the most widely used algorithm in relays, is better than the frequency response of the trigonometric algorithms. The transient response of the DFT is slower than the transient response of the trigonometric algorithms because the DFT uses longer data window. The DFT algorithm, however, does not remove the decaying part of the DC component.

2.4.2 Fast Fourier Transform

A large number of numerical analysis tools involve the use of the Fourier analysis. Fourier transform is used in speech, image, radar, and general signal processing. The Fast Fourier Transform (FFT) is the computationally efficient algorithm for computing the DFT Discrete Fourier Transform. It takes advantage of the fact that many computations to estimate the amplitude and phase of the fundamental frequency as well as harmonics are repeated due to the periodic nature of the DFT. FFT transforms the signal from time domain to the frequency domain.

A complex summation of N complex multiplications is required for each of N samples. This adds up to N^2 complex multiplications and N^2 complex additions to compute an N point DFT. A 1024 point DFT would require 4 million floating point multiplications and 4 million floating point additions. In the early 1960's researchers (notably Cooley and Tukey) noticed patterns in the DFT calculation that, when exploited properly, could be used to reduce the number of complex multiplications to $N \cdot \log_2 N$. The number of floating point multiplications in a 1024 point DFT is reduced by 99% to 40,000.

2.5 Least Error Squares

In this approach, the samples are assumed to be of a current or voltage which has a known form with some unknown parameters [11]. A simple example of such a signal is

$$y(k) = Y_c \cdot \cos(\omega_0 \cdot t) + Y_s \cdot \sin(\omega_0 \cdot t) + e(t) \quad (2.9)$$

where,

ω_0 is the nominal power system frequency,

Y_c, Y_s are unknown parameters, and

$e(t)$ is an error signal (all the things are not the fundamental frequency signal in this simple model).

The signal $y(t)$ is either a voltage or current. The term $e(t)$ includes unpredictable contributions from the transducers (cts and vts), traveling wave effects, fault arc, the exponential offset in the current, A/D converters, the transient response on the anti-aliasing filters, and the power system itself.

The general expression can be written as

$$y_n = \sum_{k=1}^K S_k(nT)Y_k + e_n \quad (2.10)$$

If we let y represent a vector of N samples and Y a vector of K unknown coefficients then there are N equations in K unknowns in the form

$$[y] = [S][Y] + [e] \quad (2.11)$$

The matrix S is made up of samples of the signals s_k .

$$\mathbf{S} = \begin{pmatrix} s_1(T) & S_2(T) & S_k(T) \\ s_1(2T) & S_2(2T) & S_k(2T) \\ \vdots & \vdots & \vdots \\ s_1(NT) & S_2(NT) & S_k(NT) \end{pmatrix} \quad (2.12)$$

An estimate of $[Y]$, denoted by $[\hat{Y}]$, is necessary because the error $[e]$ is not known. If the samples used to form the equations are more than the number of unknown parameters, the number of equations will be more than the number of unknowns ($N > K$). One criterion for choosing the estimate $[\hat{Y}]$ is to minimize the scalar formed as the sum of the squares of the error terms in equation 2.11 viz.

$$\begin{aligned} [e]^T[e] &= [[y] - [S][Y]]^T [[y] - [S][Y]] \\ &= \sum_{n=1}^n (e_n)^2 \end{aligned} \quad (2.13)$$

It can be shown that the minimum least squared error is achieved by

$$\begin{aligned} [\hat{Y}] &= [[S]^T[S]]^{-1}[S]^T[y] \\ &= [B][y] \end{aligned} \quad (2.14)$$

where, $[B]$ is the left pseudo-inverse of $[S]$ and is defined by $[B] = [S]^T[S]^{-1}[S]^T$.

In this equation the, the elements of [S] and [Y] are

$$\begin{aligned}
 s_1(t) &= \cos(\omega_0 t) \\
 s_2(t) &= \sin(\omega_0 t) \\
 s_3(t) &= \cos(2\omega_0 t) \\
 s_4(t) &= \sin(2\omega_0 t) \\
 &\vdots \\
 s_{N-1}(t) &= \cos\left(\frac{N\omega_0 t}{2}\right) \\
 s_N(t) &= \sin\left(\frac{N\omega_0 t}{2}\right)
 \end{aligned} \tag{2.15}$$

$$\mathbf{Y} = \begin{pmatrix} Y_{1C} \\ Y_{1S} \\ Y_{2C} \\ Y_{2S} \\ \vdots \\ Y_{\frac{N}{2}C} \\ Y_{\frac{N}{2}S} \end{pmatrix} \tag{2.16}$$

The calculations involving the matrix [S] followed by the calculations of matrix [B] can be performed off-line to create an algorithm. An estimation of each of the K parameters is obtained by multiplying the N samples by a set of stored numbers which are the elements of [B]. The rows of equation 2.14 represent a number of different algorithms depending on the choice of the models of the signals and the interval over which the samples are taken.

2.6 Disadvantages of Conventional Algorithms

Filters are essential parts of a relay and whenever filtering is done delays are introduced. There are two stages of filtering in a numerical relay, the low-pass analog filters in the input and the digital filters used to estimate phasors. Low pass filters introduce a delay roughly proportional to the inverse of the cut-off frequency [10]. As the cut-off frequency approaches the power frequency, elimination of higher frequencies requires a longer delay. The sharpness of cut-off also affects the delay. The sharper the cut-off, longer is the delay required.

Reasonably accurate estimate of the phasors can be obtained only by using window

sizes of one-cycle of the nominal frequency. For a nominal frequency of 60 Hz it takes at least 16ms for an algorithm to respond to a fault. After the relay gives a trip command, the breaker takes time to operate. It, therefore, takes at least three cycles ($\approx 50ms$) to isolate a faulted circuit. If a fault is not cleared in reasonable time, some components are likely to be damaged resulting in financial losses including those due to interruption of power.

These days load demands are increasing and construction of new transmission lines are not cost effective solutions. Power systems are, therefore, operated close to their design limits. It is essential that faults be identified as early as possible, and that the faulted components be isolated quickly.

2.7 Summary

This chapter has provided an overview of numerical relays. Block diagram of a typical numerical relay has been described and advantages of numerical relays have been discussed. Algorithms used in these relays have been outlined and Discrete Fourier Transform has been described in detail. The disadvantages of the conventional algorithms have been outlined.

CHAPTER 3

POWER QUALITY EVENTS

3.1 Introduction

This chapter provides an introduction to the concept of power quality. Quite often it has been said that power quality means different things to different people. For most part it was true when there was no existing standard for the measurement of power quality events. The scenario has changed with the availability of the IEEE (Institute of Electrical and Electronics Engineer) Standard 1159 - 1995. The standard presents concise definitions of words that convey the basic philosophy of power quality monitoring. The more commonly used power quality terminology in the thesis is defined in this chapter and the impact of poor power quality on the semiconductor industry is examined in brief.

Power Quality refers to a wide variety of electromagnetic phenomenon that characterize the voltage and current at a given time and at a given location on the power system [7]. It is the combination of voltage quality and current quality. The three inherent characteristics which may be used to define the power quality qualitatively are:

1. The waveshape of the electric power supply at the point of use.
2. The magnitude of the voltage at the point of use.
3. The uninterrupted duration i.e. continuity with which the power is supplied.

3.2 Frequently Used Power Quality Terms

Some of the important terms which will be used are described below.

Fundamental: The component of an order 1 (50 or 60 Hz) of the Fourier series of a periodic quantity usually voltage or current.

Nominal Voltage: A value assigned to a circuit or system for the purpose of conveniently designating its voltage class, for example, 120/208 V.

Variation: The deviation from a nominal value is referred to as variation. The variation could be in the form of “voltage variation” or “current variation”. Variations are a continuous phenomena, for example, the variation of the voltage magnitude. The

voltage magnitude are almost equal to their nominal value but they are never exactly equal. Measuring voltage and current variations requires continuous recordings of their values.

Event: The deviation of the voltage magnitude from its normal rms magnitude with a rather well-defined starting and end time is called an event, for example, Sag, Swell, Interruption etc. Different events have different magnitudes and durations. Events are the phenomenon which happen every once in a while. The monitoring of the events takes place by recording the voltage and current whenever a threshold is exceeded.

Instantaneous: It refers to the range of time from 0.5 to 30 cycles at the power frequency.

Momentary: It refers to the range of time from 30 cycles to 3 s at the power frequency.

Temporary: It refers to the range of time from 3s to 1 min at the power frequency.

Harmonics: Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate usually 50 Hz or 60 Hz.

Voltage Tolerance: The immunity of a piece of equipment against voltage magnitude variations and short duration overvoltages.

Power Quality Disturbance The deviation of the voltage or the current waveform from its ideal waveform is called as power quality disturbance.

3.3 Types of Power Quality Events

The various types of power quality disturbances can be divided into the following categories. These are also shown in Figure 3.1.

3.3.1 Short Duration Variations

The variation of the rms voltage from nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to 60 seconds is called short duration variation. These variations are further classified using two modifiers:

- The first modifier indicates the magnitude of the voltage variation i.e. sag, swell or interruption and
- The second modifier indicates the duration of the voltage variation, for example, instantaneous, momentary or temporary.

The short duration variations are further classified into the following three categories:

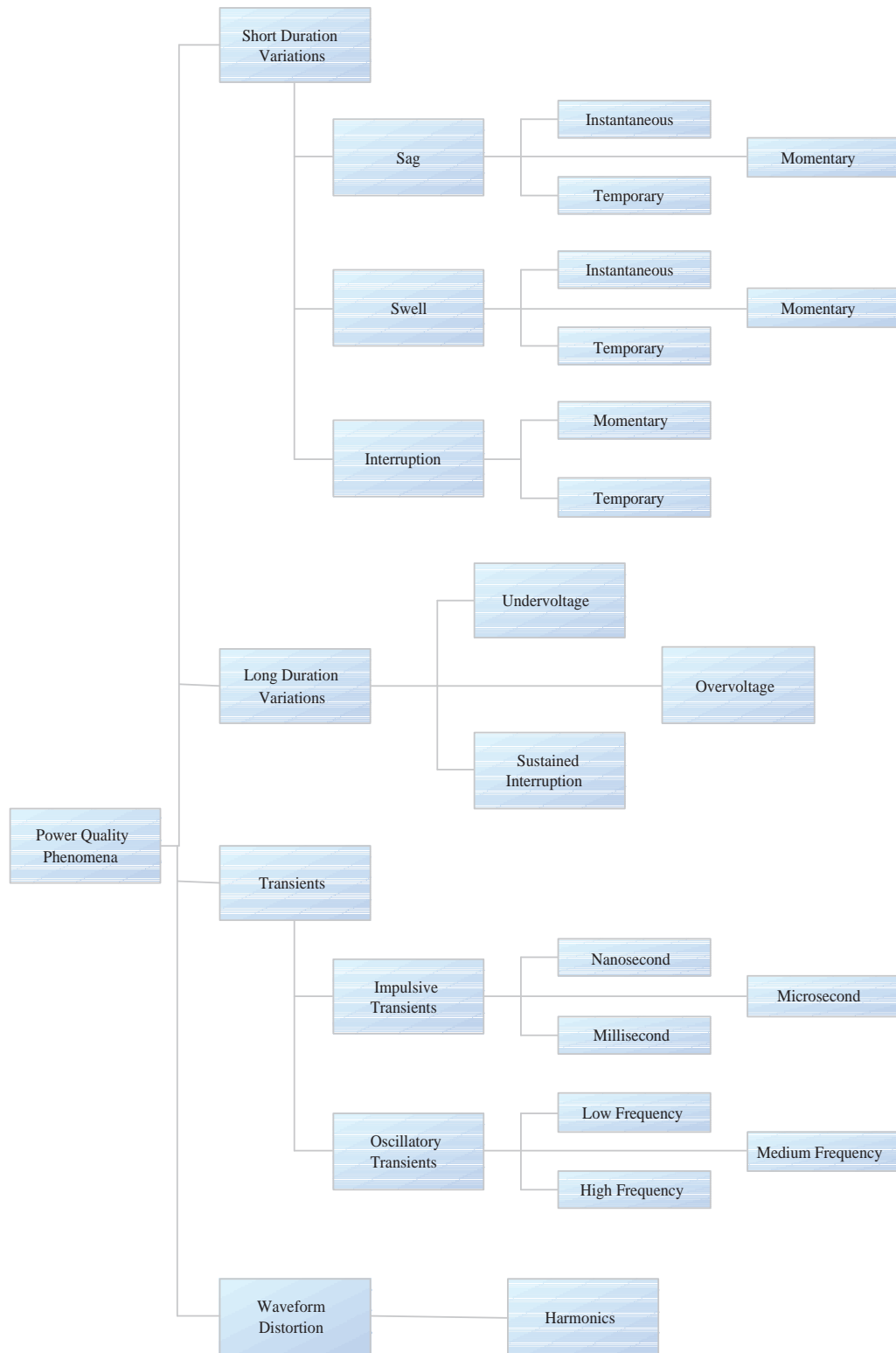


Figure 3.1: Various Types of Power Quality Phenomena

1. Sag
 - (a) Instantaneous
 - (b) Momentary
 - (c) Temporary
2. Swell
 - (a) Instantaneous
 - (b) Momentary
 - (c) Temporary
3. Interruption
 - (a) Momentary
 - (b) Temporary

3.3.2 Long Duration Variations

The variation of the rms value of the voltage from nominal voltage for a time greater than 60 seconds is called long duration variation. These variations are further described using a single modifier indicating the magnitude of a voltage variation i.e. undervoltage, overvoltage, or sustained interruption.

3.3.3 Transients

Transients are disturbances that occur for a very short duration. These may be of either polarity and can be additive or subtractive from the nominal waveform [4]. Transients can be further classified into:

1. Impulsive Transients
 - (a) Nanosecond Impulsive Transients
 - (b) Microsecond Impulsive Transients
 - (c) Millisecond Impulsive Transients
2. Oscillatory Transients
 - (a) Low Frequency Oscillatory Transients
 - (b) Medium Frequency Oscillatory Transients
 - (c) High Frequency Oscillatory Transients

3.3.4 Waveform Distortion

It is the deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation. Harmonics is one of the many types of waveform distortion.

3.4 Linear and Non - Linear Loads

The biggest reason for poor power quality is the proliferation of the electronics devices. At the forefront is the switched mode power supply. The switched power supply is found in information technology equipment like computer, fax machines, laser printers, office copiers, etc.

A linear electrical load draws a sinusoidal current proportional to the sinusoidal voltage as shown in Figure 3.2(a). The reason for such a behavior is that the linear loads do not depend on the voltage to determine their impedance at a given frequency. These loads do not cause any problem to the network to which they are connected or other consumers of a utility. They always follow the ohm's law.

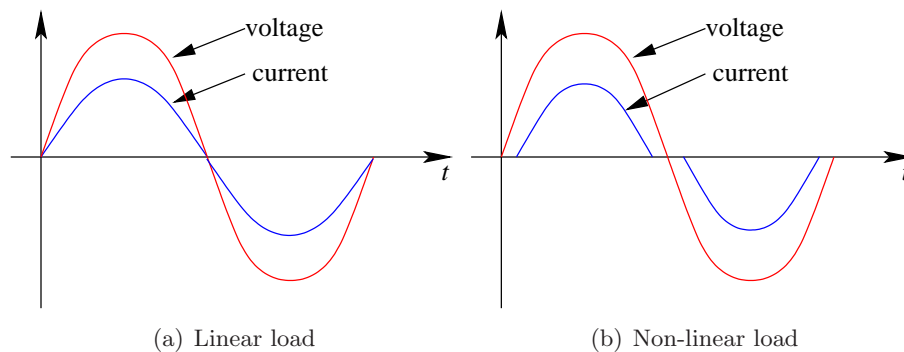


Figure 3.2: Voltage and Current Relationship for the Two Kinds of Loads.

Power electronics loads do not always follow the ohm's law. Unlike the linear loads they do not consume power continuously. When a sinusoidal voltage is applied to a non - linear electrical load, it does not draw a sinusoidal current. Also the current is not proportional to the applied voltage. The non - sinusoidal current is due to the device impedance changing over a complete voltage cycle. These loads have the potential of distorting the supply voltage waveform and might as well cause problems to other loads [13], for example, Figure 3.2(b) shows a sinusoidal voltage applied to a solid state power supply. The current drawn is approximately zero until a critical firing voltage is reached on the sinusoidal wave. At this firing voltage, the transistor gates allows current to be conducted. The current increases until the peak of the sinusoidal voltage waveform is reached and then decreases until the critical firing voltage is reached on the downward side of the sine wave. The

device shuts off and the current goes to zero. A second negative pulse of current is drawn in the negative half cycle of the sine wave. The current drawn is a series of positive and negative pulses and not the sine wave drawn by linear systems.

3.4.1 Impact on Industry

The quality of power has a direct economic impact on many industrial consumers and the industry that suffers the most from power quality problems is the semiconductor industry. Poor power quality can result in monetary loss to an industrial concern in terms of assembly start up costs after shutting down a production line, delay in production speed, loss in profits and overtime labor costs.

Frost and Sullivan, an independent consulting firm specializing in evaluating technology markets estimated that voltage disturbances alone cost US industry over \$ 20 billion every year. Table 3.1 shows the estimated losses in various industries in the United States of America per voltage sag event [13].

Table 3.1: Impact of Voltage Sags on Industry

Industry	Loss
Semiconductor Industry	\$ 2.5 million
Credit Card Processing	\$ 250,000
Equipment Manufacturing	\$100,000
Automobile Industry	\$75,000
Chemical Industry	\$ 30,000

3.5 Characteristics of Power Quality Events

3.5.1 Sag

The most common power frequency disturbance is voltage sag. Statistics show that 40 % to 60 % of the time a power quality event is a voltage sag event. Voltage Sag is an event in which the rms voltage decreases to between 0.1 and 0.9 per unit at the power frequency. It lasts for durations of 0.5 cycle to 1 min. Figure 3.3 shows the Sag classification.

3.5.1.1 Types of Sag

Based on the time duration and voltage magnitude, sag is further classified as

1. **Instantaneous Sag**

Instantaneous Sag is said to occur when the rms voltage decreases to between 0.1 and 0.9 per unit for a time duration of 0.008333 second to 0.5 second.

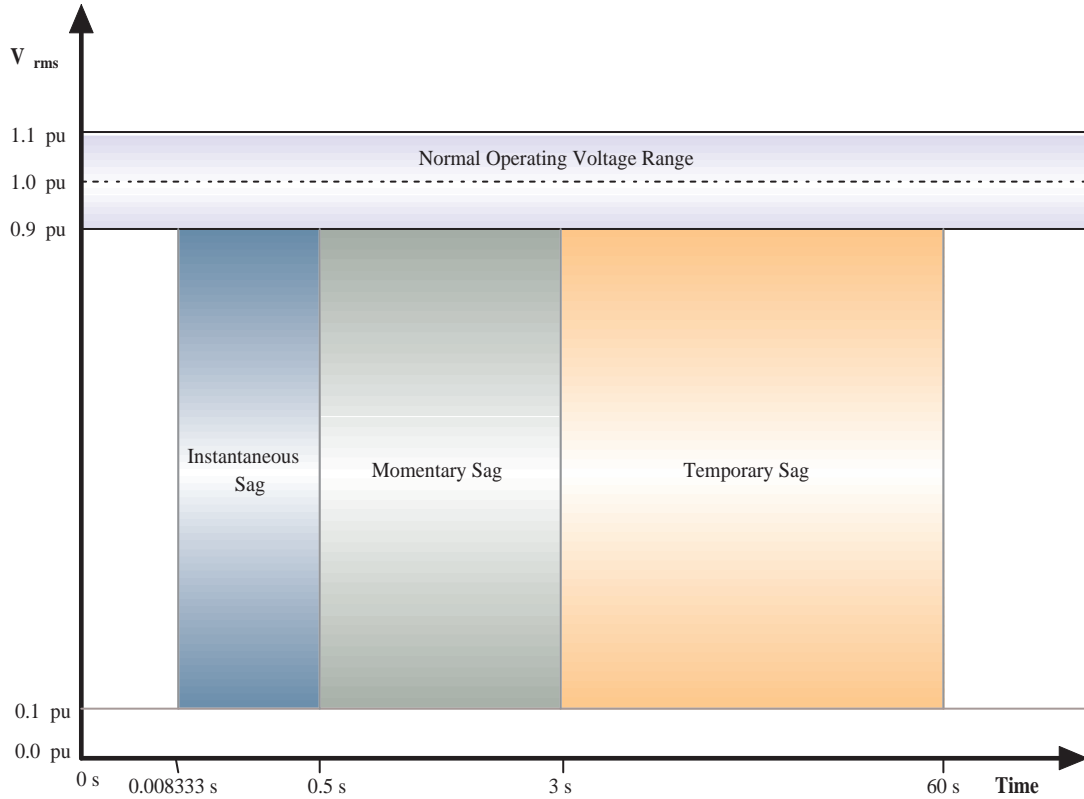


Figure 3.3: Sag Classification

2. Momentary Sag

Momentary Sag is said to occur when the rms voltage decreases to between 0.1 and 0.9 per unit for a time duration of 0.5 second to 3 seconds.

3. Temporary Sag

Temporary Sag is said to occur when the rms voltage decreases to between 0.1 and 0.9 per unit for a time duration of 3 to 60 seconds.

The Sag characteristics are shown in Table 3.2.

3.5.1.2 Causes

Voltage sags are usually associated with system faults but can also be caused by the switching of heavy loads. Voltage sags are caused by motor starting, for example, an induction motor will draw six to ten times its full load current. This lagging current causes a voltage drop across the impedance of the system. If the current magnitude is large relative to the system available fault current, the resulting voltage sag can be significant.

Table 3.2: Sag Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude</i> (in per unit)
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Sag				
Instantaneous	0.5 - 30	0.008333 - 0.500000	8.333 - 500	0.1 - 0.9
Momentary	30 - 180	0.500000 - 3.000000	500 - 300	0.1 - 0.9
Temporary	180 - 3600	3.000000 - 60.000000	300 - 60000	0.1 - 0.9

3.5.1.3 Equipment Impacts

Sags cause numerous process disruptions. Often, the sag is sensed by electronic process controllers equipped with fault-detection circuitry, which initiates shutdown of other, less-sensitive loads. A common solution to this problem is to serve the electronic controller with a constant-voltage transformer, or other mitigating device, to provide adequate voltage to the controller during a sag. The application challenge is to maintain the electronic controller during sags that will not damage process equipment protected by the fault circuitry, while simultaneously reducing nuisance shutdowns. Electronic devices with battery backup should be unaffected by short duration reductions in voltage. Equipment such as transformers, cable, bus, switchgear, CTs and PTs should not incur damage or malfunction due to short duration sags. The visible light output of some lighting devices may be reduced briefly during a sag.

3.5.1.4 Estimating the Costs of the Voltage Sag Events

The costs associated with sag events can vary significantly from nearly zero to several million dollars per event. The cost will vary not only among different industry types and individual facilities but also with market conditions. Higher costs are typically experienced if the end product is in short supply and there is limited ability to make for the lost production. Not all costs are easily quantified or truly reflect the urgency of avoiding the consequences of a voltage sag event. The cost of a power quality disturbances can be captured primarily through three major categories:

- Product related losses, such as loss of product and materials, lost production capacity, disposal charges, and increased inventory requirements.
- Labor - related losses, such as idled employees, overtime, cleanup, and repair.
- Ancillary costs such as damaged equipment, lost opportunity cost, and penalties due

to shipping delays.

Focussing on these three categories will facilitate the development of detailed list of all costs and savings associated with a power quality disturbance. Costs will typically vary with the severity (both magnitude and duration) of the power quality disturbance. The relationship can often be defined by a matrix of weighting factors. The weighting factors are developed using the cost of a momentary interruption as the base.

Usually, a momentary interruption will cause a disruption to any load or process that is not specifically protected with some type of energy storage technology. Voltage sags and other power quality variations will always have an impact that is some portion of this shutdown. If a voltage sag to 40 percent causes 80 percent of the economic impact that a momentary interruption causes, then the weighting factor for a 40 percent sag would be 0.8. Similarly if a sag to 75 percent only results in 10 percent of the costs that an interruption causes, then the weighting factor is 0.1. After the weighting factors are applied to an event, the costs of the event are expressed in per unit of the cost of a momentary interruption. The weighted events can then be summed and the total is the total cost of all events expressed in the number of equivalent momentary interruptions.

Table 3.3 provides an example of weighting factors that were used for one investigation. The weighting factors can be further expanded to differentiate between sags that affect all three phases and sags that only affect one or two phases. Table 3.4 combines the weighting factors with expected performance to determine a total annual cost associated with voltage sags and interruptions. The cost is 16.9 times the cost of an interruption. If an interruption costs \$ 40,000 the total costs associated with voltage sags and interruptions would be \$ 676,000 per year [4].

Table 3.3: Example of Weighting Factors for Different Voltage Sag Magnitude

<i>Category of Event</i>	<i>Weighting for economic analysis</i>
Interruption	1.0
Sag with minimum voltage below 50%	0.8
Sag with minimum voltage between 50 % and 70 %	0.4
Sag with minimum voltage between 70 % and 90 %	0.1

3.5.2 Swell

Swell is an event in which the rms voltage increases to between 1.1 and 1.8 per unit at the power frequency. It lasts for durations of 0.5 cycle to 1 min. Figure 3.4 shows the Swell classification.

Table 3.4: Example of Combining the Weighting Factors with Expected Voltage Sag Performance to Determine the Total Costs of Power Quality Variations.

<i>Category of Event</i>	<i>Weighting for economic analysis</i>	<i>Number of events per year</i>	<i>Total equivalent interruptions</i>
Interruption	1.0	5	5
Sag with minimum voltage below 50%	0.8	3	2.4
Sag with minimum voltage between 50 % and 70 %	0.4	15	6
Sag with minimum voltage between 70 % and 90 %	0.1	35	3.5
Total			16.9

3.5.2.1 Types of Swell

Based on the time duration and voltage magnitude, Swell is further classified as:

1. **Instantaneous Swell**

Instantaneous Swell is said to occur when the rms voltage decreases to between 1.1 and 1.8 per unit for a time duration of 0.008333 second to 0.5 second.

2. **Momentary Swell**

Momentary Swell is said to occur when the rms voltage decreases to between 1.1 and 1.4 per unit for a time duration of 0.5 second to 3 seconds.

3. **Temporary Swell**

Temporary Swell is said to occur when the rms voltage decreases to between 1.1 and 1.2 per unit for a time duration of 3 to 60 seconds.

The Swell characteristics are shown in Table 3.5.

3.5.2.2 Causes

Swells are also associated with system fault conditions, but they are much less common than voltage sags. For example, faults on one line cause voltage rise on other phases. Swells can be caused by switching off a large load and by switching on a large capacitor bank.

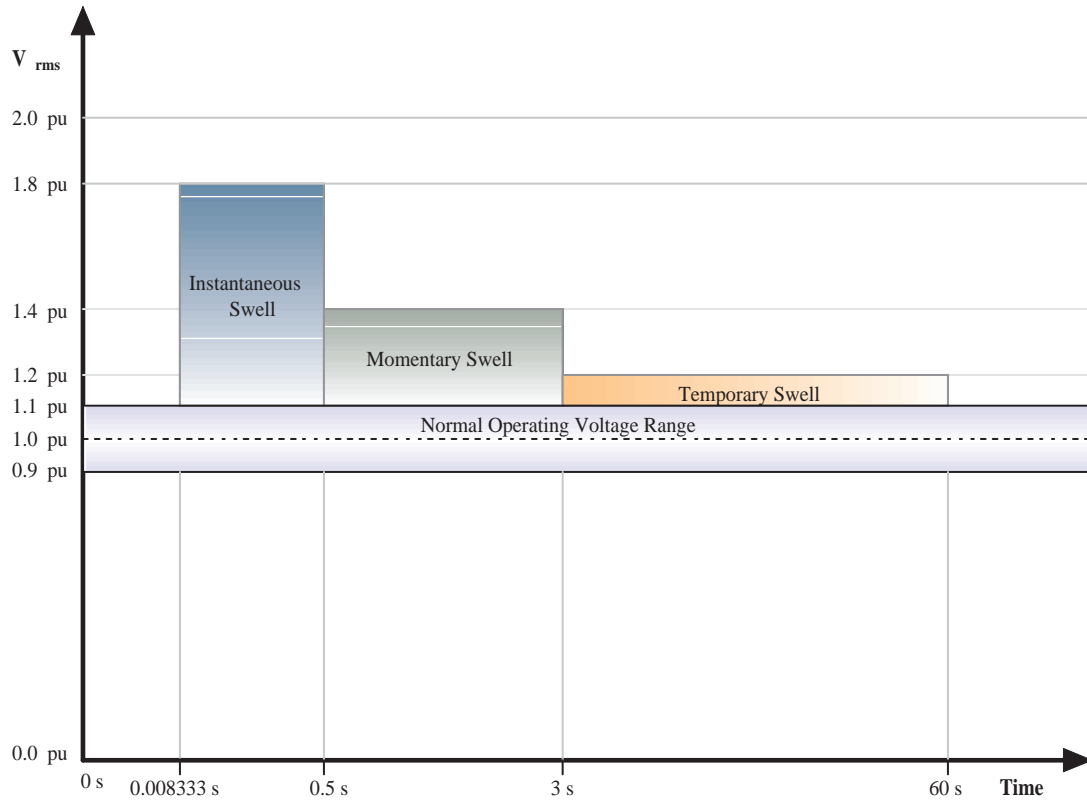


Figure 3.4: Swell Classification

Table 3.5: Swell Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude (in per unit)</i>
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Swell				
Instantaneous	0.5 - 30	0.008333 - 0.500000	8.333 - 500	1.1 - 1.8
Momentary	30 - 180	0.500000 - 3.000000	500 - 300	1.1 - 1.4
Temporary	180 - 3600	3.000000 - 60.000000	300 - 60000	1.1 - 1.2

3.5.2.3 Equipment Impacts

An increase in voltage applied to equipment above its nominal rating may cause failure of the components depending upon the frequency of occurrence. Electronic devices, including adjustable speed drives, computers, and electronic controllers, may show immediate failure modes during these conditions. However, transformers, cable, bus, switchgear, CTs, PTs, and rotating machinery may suffer reduced equipment life over time. A temporary increase

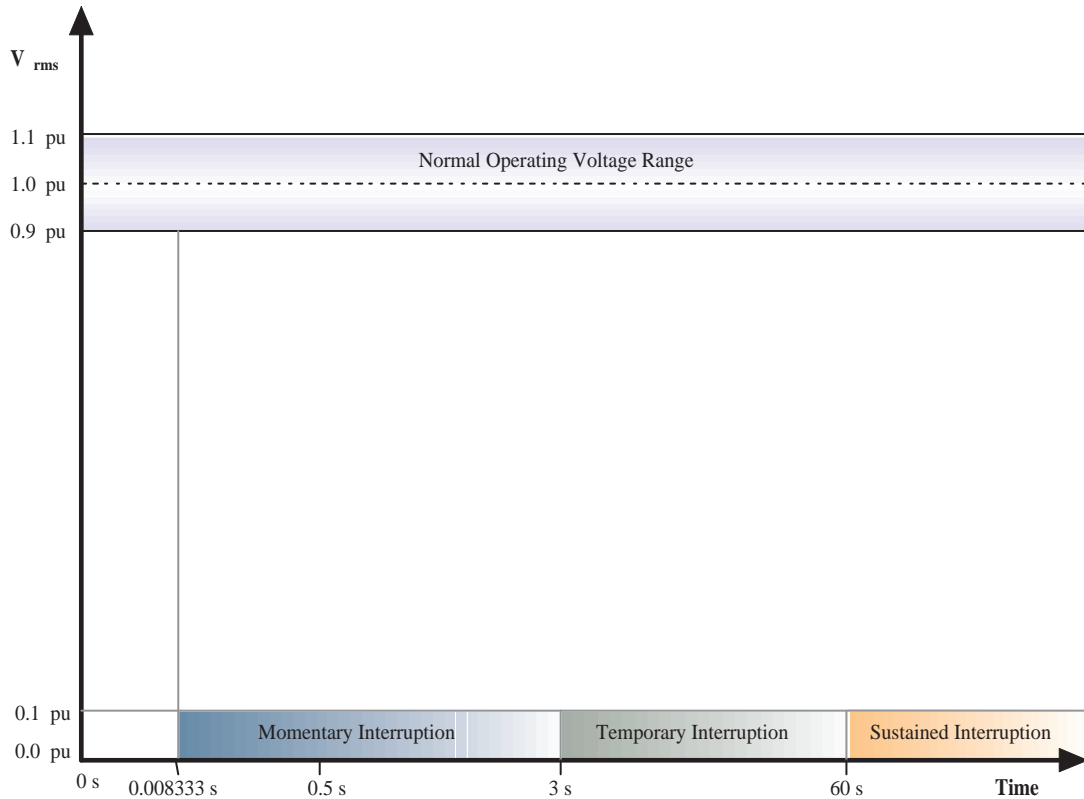


Figure 3.5: Interruption Classification

in voltage on some protective relays may result in unwanted operations while others will not be affected. Frequent voltage swells on a capacitor bank can cause the individual cans to bulge while output is increased from the bank. The visible light output from some lighting devices may be increased during a temporary swell.

3.5.3 Interruption

An interruption is said to have occurred when the supply voltage decreases to less than 0.1 per unit. Figure 3.5 shows the Interruption classification.

3.5.3.1 Types of Interruption

Based on the time duration and voltage magnitude, Interruption is further classified as:

1. **Momentary Interruption**

Momentary Interruption is said to occur when the rms voltage decreases to less than 0.1 per unit for a time duration of 0.008333 second to 3 second.

2. **Temporary Interruption**

Temporary Interruption is said to occur when the rms voltage decreases to less than

0.1 per unit for a time duration of 3 second to 60 seconds.

3. Sustained Interruption

Sustained Interruption is said to occur when the rms voltage decreases to 0.0 per unit for a time duration greater than 60 seconds. Voltage interruptions longer than 60 seconds are often permanent in nature and require manual intervention for restoration.

The Interruption characteristics are shown in Table 3.6.

Table 3.6: Interruption Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude (in per unit)</i>
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Interruption				
Momentary	0.5 - 180	0.008333 - 3.000000	8.333 - 500	< 0.1
Temporary	180 - 3600	3.000000 - 60.000000	500 - 300	< 0.1
Sustained	> 3600	> 60.000000	300 - 60000	= 0.0

3.5.3.2 Causes

Voltage Interruptions are caused by the operation of protective devices such as breakers and fuses. Voltage interruptions longer than 1 minute are often permanent in nature and require manual intervention and restoration. Sometimes system maintenance can require voltage interruption in certain sections of power systems.

3.5.3.3 Equipment Impacts

Instantaneous interruptions may affect electronic and lighting equipment causing misoperation or shutdown. Electronic equipment includes power and electronic controllers, computers, and the electronic controls for rotating machinery. Momentary and temporary interruptions will almost always cause equipment to stop operating, and may cause drop-out of induction motor contactors. In some cases, interruptions may damage electronic soft-start equipment. The effect of a sustained interruption is equipment shutdown, except for those loads protected by Uninterrupted Power Supply (UPS) systems, or other forms of energy storage devices.

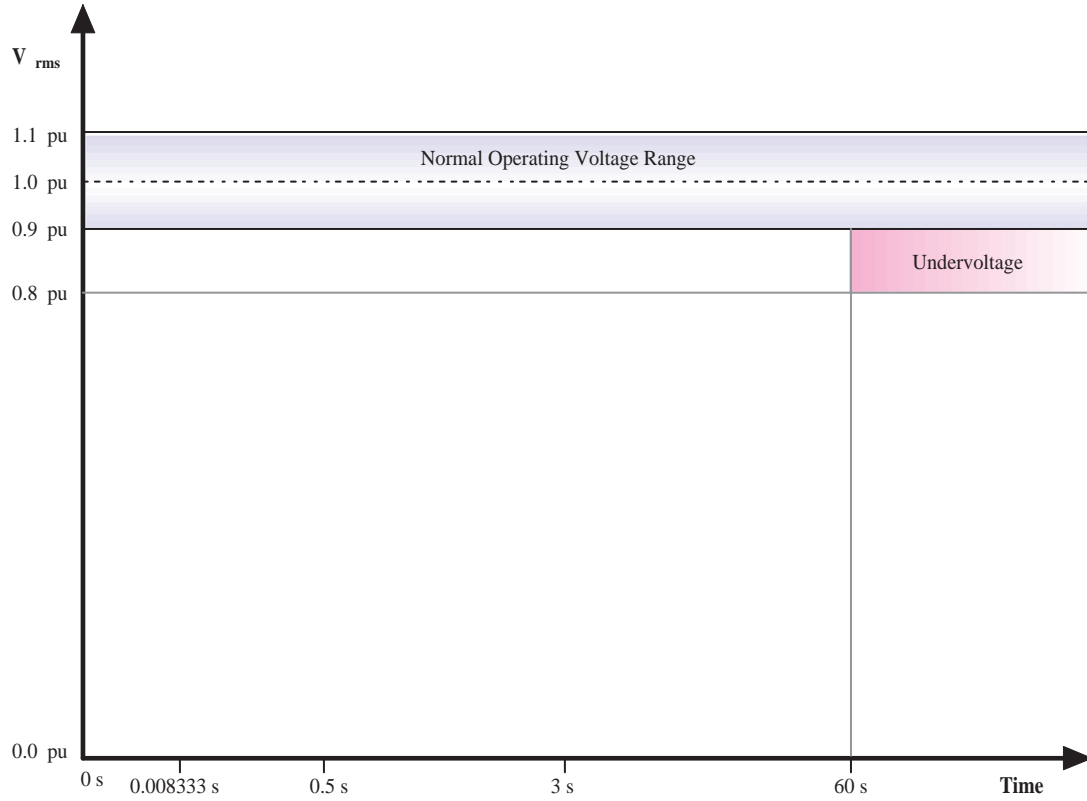


Figure 3.6: Undervoltage Classification

3.5.4 Undervoltage

Undervoltage is an event in which the rms voltage decreases to between 0.8 and 0.9 per unit at the power frequency for a period of time greater than 1 min. Figure 3.6 shows the Undervoltage classification.

The Undervoltage characteristics are shown in Table 3.7.

Table 3.7: Undervoltage Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude (in per unit)</i>
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Undervoltage	> 3600	> 60	> 60000	0.8 - 0.9

3.5.4.1 Causes

Undervoltages can be the result of load switching, for example, switching on a large load and system switching operations like switching on a large inductor. These last until voltage regulation equipment on the system can bring the voltage back to normal. Overloaded circuits can also lead to undervoltages. Sometimes faulty connections or wiring and Loose or corroded connections can also cause undervoltages.

3.5.4.2 Equipment Impacts

Undervoltages can cause equipment to malfunction. Motor controllers can drop out during undervoltage conditions. The dropout voltage of motor controllers is typically 70 - 80 % of nominal voltage. Long duration undervoltages cause an increased heating loss in induction motors due to increased motor current. Speed changes are possible for induction machinery during undervoltage conditions. Electronic devices such as computers and electronic controllers may stop operating during this condition. Undervoltage conditions on capacitor banks result in a reduction of output of the bank, since VAR output is proportional to the square of the applied voltage. Generally, undervoltage conditions on transformers, cable, bus, switchgear, CTs, PTs, metering devices, and transducers do not cause problems for the equipment. The visible light output from some lighting devices may be reduced during undervoltage conditions.

3.5.5 Overvoltage

Overvoltage is an event in which the rms voltage increases to between 1.1 and 1.2 pu at the power frequency for a period of time greater than 1 min. Figure 3.7 shows the Overvoltage classification.

The Overvoltage characteristics are shown in Table 3.8.

Table 3.8: Overvoltage Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude (in per unit)</i>
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Undervoltage	> 3600	> 60	> 60000	1.1 - 1.2

3.5.5.1 Causes

Overvoltages can be the result of load switching, for example, switching off a large load and system switching operations like Switching on a large capacitor bank. Poor system

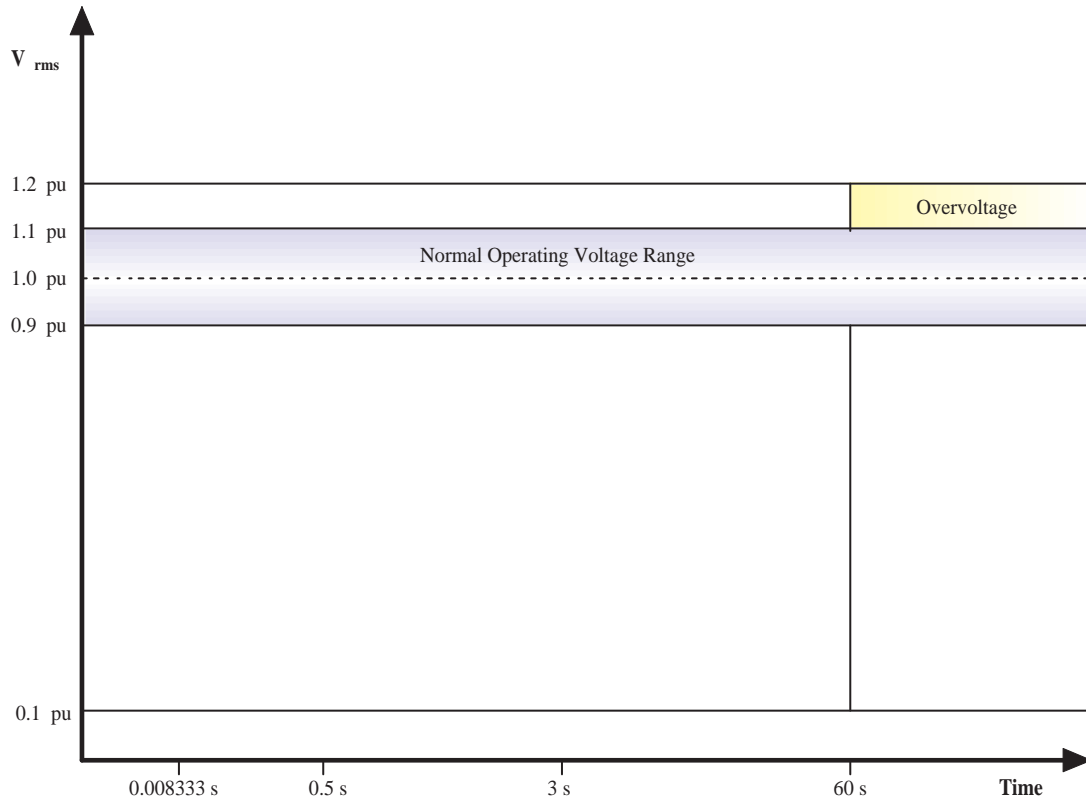


Figure 3.7: Overvoltage Classification

voltage regulation capabilities or controls result in overvoltages. Incorrect tap settings on transformers can also result in system overvoltages.

3.5.5.2 Equipment Impacts

Overvoltages may cause equipment failure. Electronic devices may experience immediate failure during the overvoltage conditions; however, transformers, cable, bus, switchgear, CTs, PTs, and rotating machinery do not generally show immediate failure. Sustained overvoltage on transformers, cable, bus, switchgear, CTs, PTs and rotating machinery can result in loss of equipment life. An overvoltage condition on some protective relays may result in unwanted operations while others will not be affected. A sign of frequent overvoltage conditions on a capacitor bank is the bulge of individual cans. The VAR output of a capacitor will increase with the square of the voltage during an overvoltage condition. The visible light output from some lighting devices may be increased during overvoltage conditions.

3.5.6 Transients

Transients are disturbances that occur for a very short duration. This may be of either polarity and can be additive or subtractive from the nominal waveform. The main reason for the occurrence of the transients is a sudden change in the voltage or current in power system. The primary characteristics that define a transient are the peak amplitude, the rise time, the fall time and the frequency of oscillation. Subcycle (lasting less than one cycle) transients are the most difficult to detect [2], [14]. Transients can be further classified into:

- Impulsive Transients
- Oscillatory Transients

3.5.7 Impulsive Transients

An impulsive transient is a non-power frequency event in which the steady state condition of the voltage, current or both changes suddenly. The change is unidirectional in polarity predominantly either positive or negative. The impulsive transients are characterized by the rise and fall time, for example, a 1.2/50 μ s 2000 V impulsive transient rises to its peak value of 2000 V in 1.2 μ s and then decays to half its peak value in 50 μ s.

3.5.7.1 Types of Impulsive Transients

Based on the rise time and duration, impulsive transients are further classified as:

1. **Nanosecond Impulsive Transient**

A transient with a rise time of 5 nanosecond and a duration less than 50 nanosecond is considered a Nanosecond Impulsive Transient.

2. **Microsecond Impulsive Transient**

A transient with a rise time of 1 microsecond and a duration that lasts between 50 nanosecond and 1 millisecond is considered a Microsecond Impulsive Transient.

3. **Millisecond Impulsive Transient**

A transient with a rise time of 0.1 millisecond and a duration greater than 1 millisecond is considered a Millisecond Impulsive Transient.

The Impulsive Transients characteristics are shown in Table 3.9.

3.5.7.2 Causes

The most common cause of impulsive transients is lightning. Due to the high frequencies involved, impulsive transients are damped quickly by resistive circuit components and are not conducted far from their source. There can be significant differences in the transient

Table 3.9: Impulsive Transient Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Voltage Rise Time</i> (in per unit)
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Impulsive Transients				
Nanosecond	< 0.0000003	< 0.000000005	< 0.000050	5 ns rise
Microsecond	0.0000003 - 0.06	0.000000005 - 0.001	0.000050 - 1	1 μ s rise
Millisecond	0.06	> 0.001	> 1	0.1 ms rise

characteristic from one location within a building to another. Impulsive transients can excite power system resonance circuits and produce oscillatory transients.

3.5.8 Oscillatory Transients

An oscillatory transient is a non-power frequency event in which the steady state condition of the voltage, current or both changes polarity rapidly. The change in polarity is bidirectional. Figure 3.8 shows the Swell classification.

3.5.8.1 Types of Oscillatory Transients

Based on the frequency content, time duration and voltage magnitude, oscillatory transients are further classified as:

- 1. Low Frequency Oscillatory Transient**

A transient with a primary frequency component less than 5 kHz and a duration from 0.3 to 50 ms, is considered a low frequency transient. This category of transients is encountered on utility sub-transmission and distribution systems. The most frequent cause is capacitor bank energization, which results in an oscillatory voltage transient with primary frequency between 300 and 900 Hz.

- 2. Medium Frequency Oscillatory Transient**

A transient with a primary frequency component between 5 and 500 kHz and a duration of 20 μ s is termed a medium frequency transient. They can be the result of system response to an impulsive transient or back to back capacitor energization.

- 3. High Frequency Oscillatory Transient**

A transient with a primary frequency component greater than 500 kHz and a duration of 5 μ s is termed as a high frequency transient. These transients are often the result of a local system response to an impulsive transient.

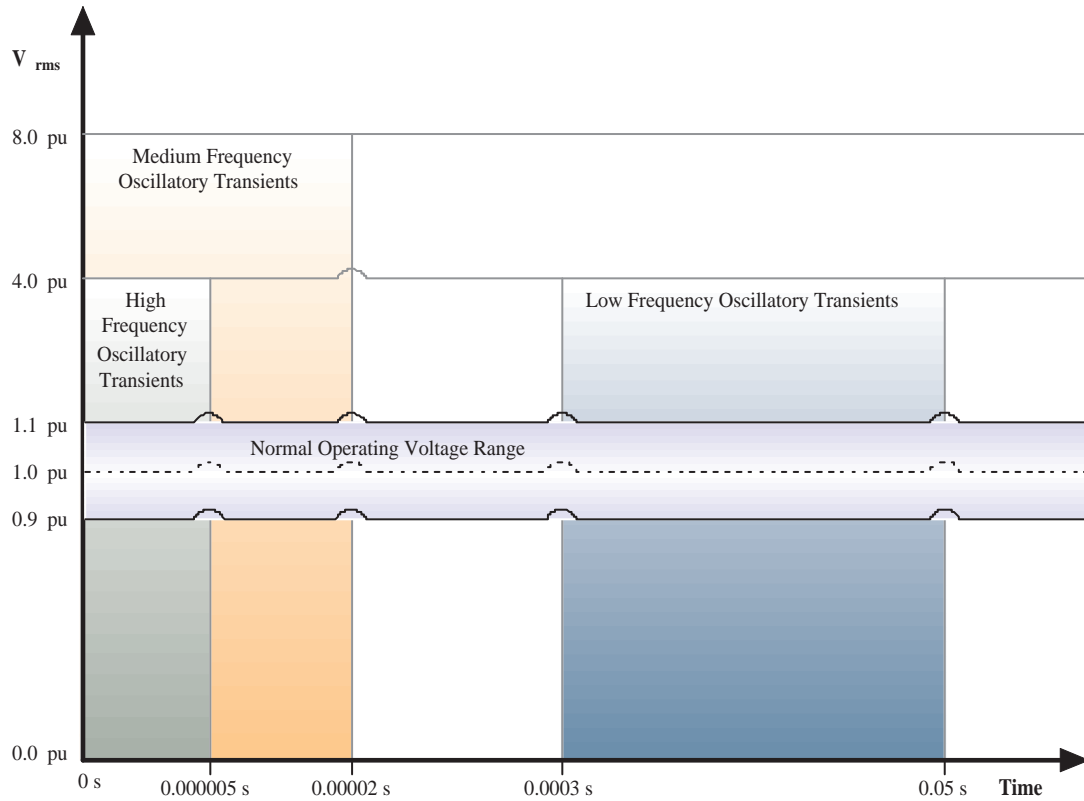


Figure 3.8: Oscillatory Transients Classification

The Oscillatory Transients characteristics are shown in Table 3.10.

Table 3.10: Oscillatory Transient Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude (in per unit)</i>
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Oscillatory Transients				
Low Frequency	0.018 - 3	0.000300 - 0.050000	0.3 - 50	0 - 4
Medium Frequency	0.0012	0.000020	0.020	0 - 8
High Frequency	0.0003	0.000005	0.005	0 - 4

3.5.9 Equipment Impacts Due to Transients

Transient voltages caused by lightning or switching operations can result in degradation or immediate dielectric failure in all classes of equipment. High magnitude and fast rise time contribute to insulation breakdown in electrical equipment like rotating machinery,

transformers, capacitors, cables, CTs, PTs, and switchgear. Repeated lower magnitude application of transients to these equipment type cause slow degradation and eventual insulation failure, decreasing equipment mean time between failure (MTBF) . In electronic equipment, power supply component failures can result from a single transient of relatively modest magnitude.

3.5.10 Harmonics

3.5.10.1 Characterization

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency at which the supply system is designed to operate usually 50 Hz or 60 Hz. Harmonics produce distortion in the waveform of the fundamental voltage or current.

Harmonics distortion exists due to the nonlinear characteristics of the devices and loads on the power system. These devices are modelled as current sources that inject harmonic currents into the power system. Voltage distortion results as these currents cause non linear voltages across the system impedance. Harmonic distortion is of growing concern for many customers and for the overall power system due to increasing application of power electronics equipment.

Harmonics distortion levels are characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion (THD) and total demand distortion (TDD) .

Total Harmonic Distortion: The total harmonic distortion is defined as the square root of the sum of the squares of the rms value of the voltages or currents from *2nd* to the *hth* harmonic divided by the fundamental value of the voltage or current and is expressed as a percent.

$$THD \% \text{ of fundamental} = \left(\frac{Q_{rms \text{ distorted}}}{Q_{fundamental}} \right) \times 100 \quad (3.1)$$

$$= \frac{\sqrt{\sum_{h=2}^{25} Q_h^2}}{Q_1} \times 100 \quad (3.2)$$

where, $Q_{rms \text{ distorted}}$ is the rms value of the distorted waveform with the fundamental left out of the summation, and

$Q_{fundamental}$ is the value of the voltage or current at the fundamental frequency.

Total Demand Distortion: The total demand distortion is defined as the square root of the sum of the squares of the rms value of the currents from *2nd* to the *hth* harmonic divided by the peak demand load current and is expressed as a percent.

The TDD index is most often used to describe current harmonic distortion.

$$TDD \text{ \% of peak demand} = \left(\frac{I_{rms \text{ distorted}}}{I_{maximum \text{ demand}}} \right) \times 100 \quad (3.3)$$

$$= \frac{\sqrt{\sum_{h=2}^{25} I_h^2}}{I_d} \times 100 \quad (3.4)$$

where, $I_{rms \text{ distorted}}$ is the rms value of the distorted waveform with the fundamental left out of the summation, and

I_d is the peak or maximum, demand load current at the fundamental frequency component measured at the point of common coupling. There are two ways to measure I_d

- With a load already present in the system, it is calculated as the average of the maximum demand current readings for the preceding 12 months.
- For a new facility where load is to be connected in the system, I_d has to be estimated based on the predicted load profiles.

The Harmonics characteristics are shown in Table 3.11.

Table 3.11: Harmonics Characteristics

<i>Category</i>	<i>Harmonic Content</i>	<i>Duration</i>	<i>Voltage Magnitude</i>
Harmonics	0 - 25th	steady state	0 - 20 %

3.5.10.2 Causes

The main cause of harmonics in the electric power system is the presence of non - linear loads (See section 3.4 on page 29).

3.5.10.3 Equipment Impacts

Harmonic current injection from customer loads into the utility supply system can cause harmonic voltage distortion to appear on the utility system supply voltage. This harmonic current and voltage distortion can cause overheating of rotating equipment, increase in transformer winding temperature which reduces the efficiency and the life span, and current-carrying conductors. Harmonics can influence the operation of protective devices such as electromechanical relays, fuses etc. They may trip too soon or too late. Harmonic voltage distortion on a utility system can cause the same problems to a customer's equipment and can cause overheating of utility transformers, power-carrying conductors, and other power equipment.

3.6 Information Technology Industry Council Curve

The ITIC Curve (See Figure 3.9) is published by Technical Committee 3 (TC3) of the Information Technology Industry Council. ITIC was formerly known as the Computer & Business Equipment Manufacturers Association. It was developed in collaboration with Electric Power Research Institute's (EPRI) Power Electronics Application Center. The curve defines the magnitude and duration of input AC voltage that can be tolerated by computers, their peripherals and other information technology equipment (ITE) like copiers, fax machines, and point-of-sales terminals. While most of the modern information technology equipment has a higher tolerance, the ITIC curve has become a design guideline for the equipment manufacturers. The curve is designed for computer equipment designed to operate at nominal voltage of 120 V rms in a 60 Hz system.

The *horizontal axis* represents the duration for which an event lasts and the *vertical axis* represents the voltage magnitude of the event as a percent of the nominal voltage for the duration of event. Disturbances that fall within the envelope defined by the upper and the lower curve are not harmful to electrical equipment; disturbances that fall outside the envelope may disrupt or damage the equipment [15]. Seven types of events are described in this composite envelope.

Steady-State Tolerances The steady-state range describes a slowly varying or constant rms voltage. It varies + or - 10 % from the nominal voltage. Any voltages in this range may be present for an indefinite period, and are a function of normal loadings and losses in the distribution system.

Line Voltage Swell This region describes a voltage swell having an rms amplitude of up to 120% of the rms nominal voltage, with a duration of up to 0.5 seconds. This may occur when large loads are removed from the system or when voltage is supplied from sources other than the electric utility.

Low-Frequency Decaying Transient Ringwave This region describes a decaying ring-wave transient (non-repetitive damped oscillatory transient) which typically results from the connection of power factor correction capacitors to an AC distribution system. The frequency of this transient may range from 200Hz to 5KHz, depending upon the resonant frequency of the AC distribution system. The magnitude of the transient is expressed as a percentage of the peak 60Hz nominal voltage (not the RMS value). The transient is assumed to be completely decayed by the end of the half-cycle in which it occurs. The transient is assumed to occur near the peak of the nominal voltage waveform. The amplitude of the transient varies from 140% for 200Hz ringwave to 200% for 5KHz ringwaves.

High-Frequency Impulse and Ringwave This region describes the transients which typically occur as a result of lightning strikes. This region of the curve deals with

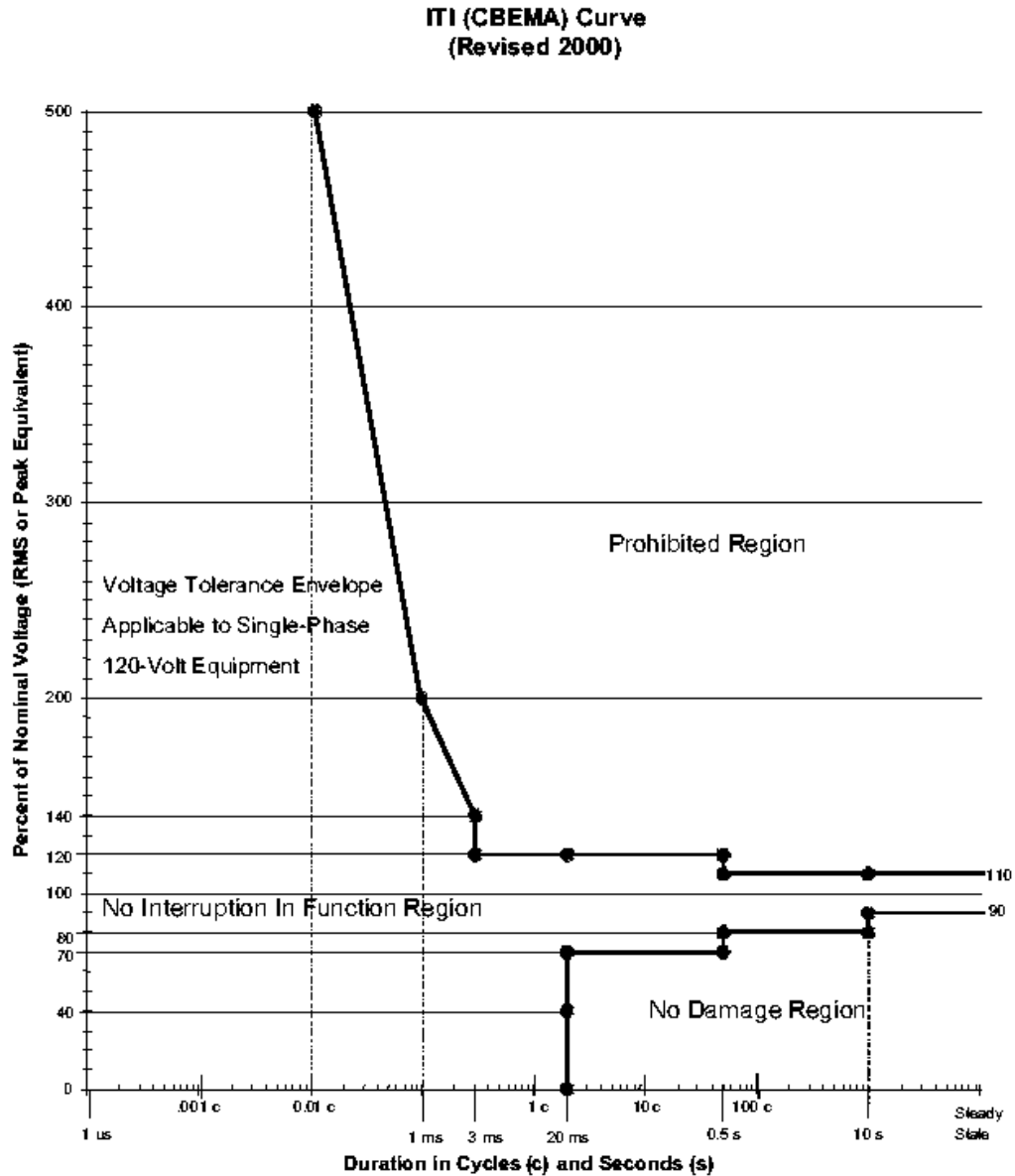


Figure 3.9: Information Technology Industry Council Curve

both amplitude and duration (energy), rather than rms amplitude. The intent is to provide an 80 Joule minimum transient immunity.

Voltage Sags Two different rms voltage sags are described. Generally, these result from application of heavy loads, as well as fault conditions, at various points in the AC distribution system. Sags to 80% of nominal are assumed to have a typical duration of up to 10 seconds, and sags to 70% of nominal are assumed to have a duration of up to 0.5 seconds.

Dropout A voltage dropout includes both severe rms voltage sags and complete inter-

ruptions of the applied voltage, followed by immediate re-application of the nominal voltage. The interruption may last up to 20 milliseconds. This transient typically results from the occurrence and subsequent clearing of faults in the AC distribution system.

No Damage Region The region on the *bottom right side* of the curve includes events such as sags and dropouts which are more severe than those specified before and continuously applied voltages which are less than the lower limit of the steady-state tolerance range. The ITE does not function normally during these conditions, but no damage to the ITE is expected either.

Prohibited Region The region on the *top right side* of the curve includes any surge or swell which exceeds the upper limit of the envelope. If ITE is subjected to such excessive voltage conditions, damage to the ITE may result.

The ITIC curve is meant to be used only as a guideline. Certain processes may be more sensitive to voltage variation, so a modified curve could be needed for the safe operation of such equipment.

3.7 Implementation

All the procedures described in this chapter were implemented in the algorithms for classifying the power quality events.

3.8 Summary

The characteristics of the various power quality events have been described in this chapter and their causes and effects have been outlined. The Information Technology Industry Council Curve used by the sensitive equipment manufacturers as a measure of tolerance to voltage variations has also been explained.

CHAPTER 4

POWER QUALITY ANALYSIS TOOL

4.1 Introduction

The data record collected by the relay must be analyzed in an offline mode to look for power quality events in it. A PC running a Power Quality Analysis Software is used to perform this function. The Power Quality Analysis Software is discussed in this chapter. Its main features are examined. The algorithms for detecting the various power quality events are shown in the form of flowchart.

4.2 Software Lifecycle Models

The process of object-oriented analysis and design is much more complex and important than the modeling language. The three types of software lifecycle models are explained below [16].

1. Waterfall

The waterfall method, shown in Figure 4.1, is the most commonly used lifecycle approach, because it is the closest to common sense - it comes more naturally to people than the other two approaches. In waterfall development, the output from one stage becomes the input to the next and there is no going back. In a waterfall development process, the requirements are detailed and the clients sign off. The requirements are then passed on to the designer, set in stone. The designer creates the design and passes it off to the programmer who implements the design. The programmer in turn hands the code to a person who tests the code and then releases it to the customer. The iterative software lifecycle model is a little different in that it involves repeating the waterfall method over and over until the product is done.

2. Iterative

The iterative process, shown in Figure 4.2, starts with analysis, continues with design, follows up with implementation and then repeats itself by returning to the analysis phase. This method allows the development team to progressively complete a project. Perhaps the first phase only provides must - have functionality, the second adds some nice to have features, and the final pass includes far - out never

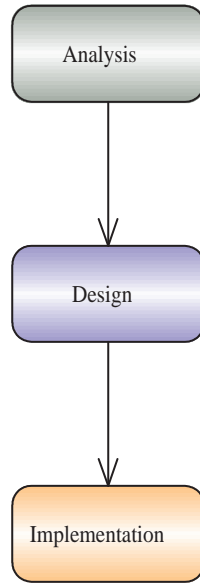


Figure 4.1: The Waterfall Software Lifecycle Model

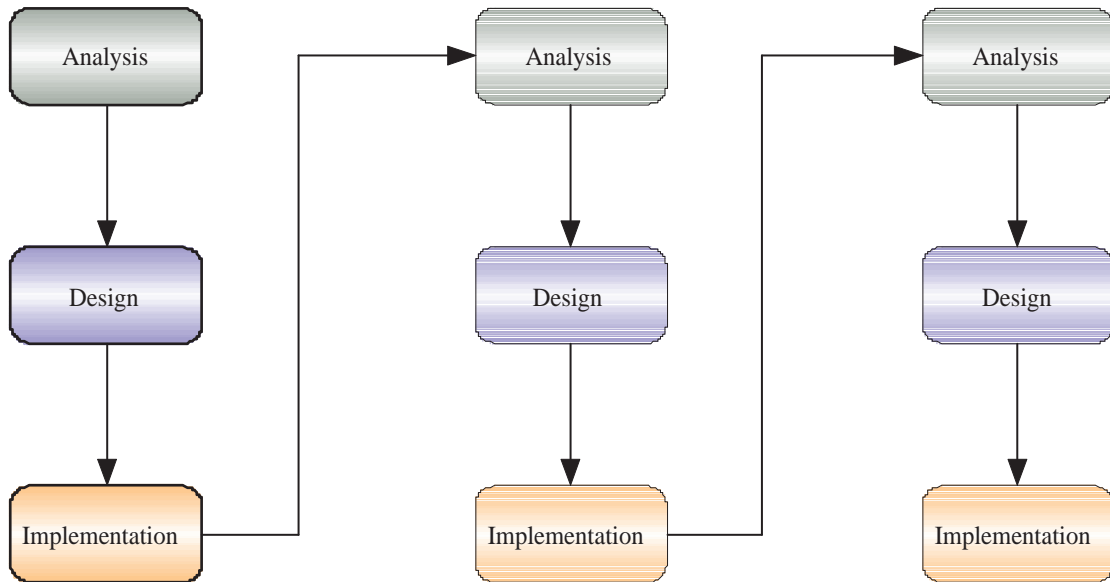


Figure 4.2: The Iterative Software Lifecycle Model

used functionality. On the other hand it could take several passes through analysis, design and implementation phases before anything remotely meaningful to the end user is obtained.

3. Incremental Iterative

The third software lifecycle model, shown in Figure 4.3, that is very popular is the iterative - incremental method. Basically, this approach divides a project into

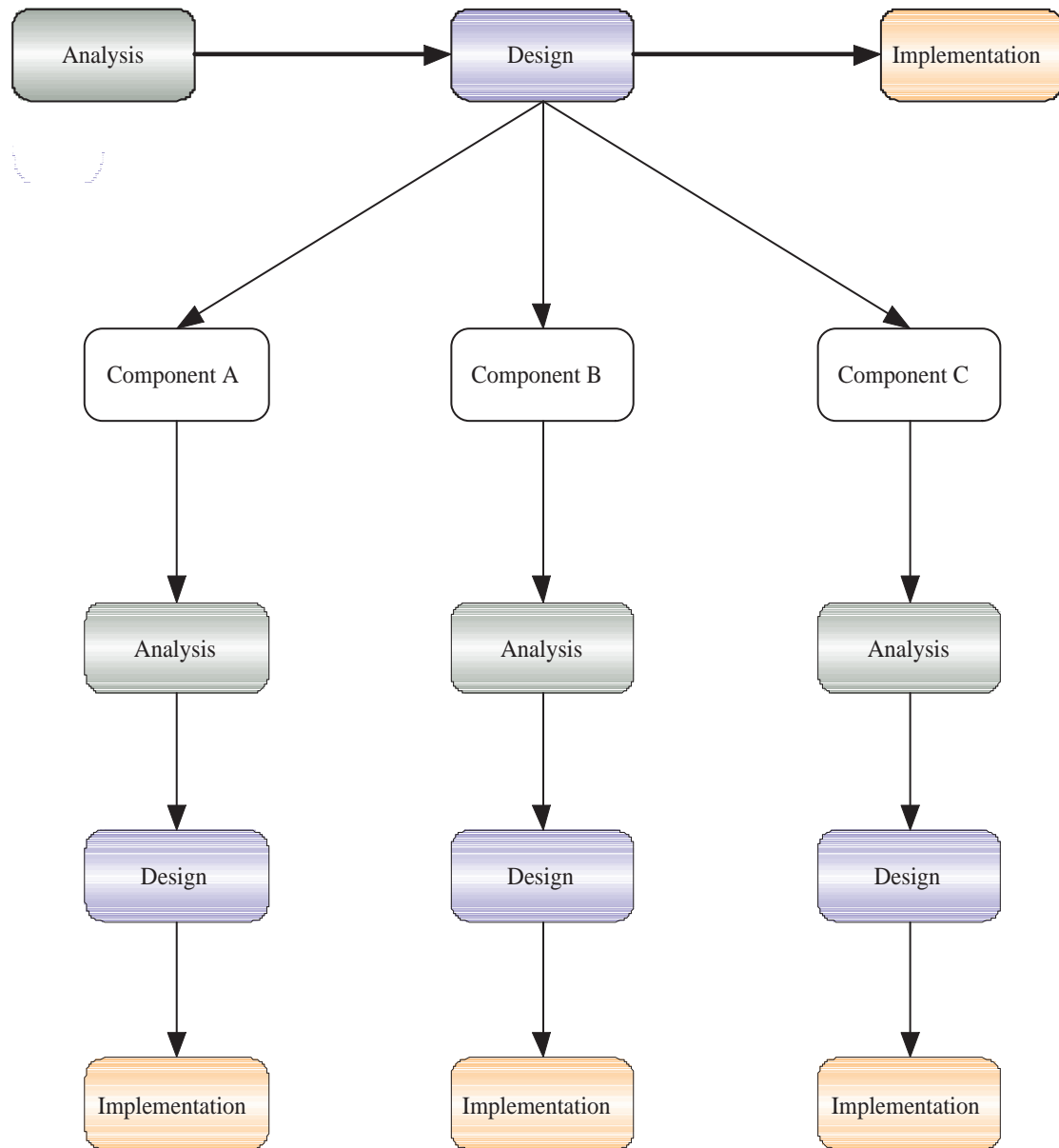


Figure 4.3: The Incremental Iterative Software Lifecycle model

subprojects, and allows you to perform the waterfall method on each. Instead of completing functionality in the entire application with each pass as with the iterative method. With the iterative - incremental process approach, each completed component does not necessarily become a deliverable that is usable by a client. At milestones, however, the components can be joined to create a usable product. This method is preferred because of reusable code. By separating your functionality into different components, such as data access, business logic and GUI controls

4.3 The Design Process

The software development process for the Power Quality Analysis Tool (PQAT) was modeled using the Unified Modeling Language (UML) and Rational Unified Process Method (RUP) was applied to it. The software development process was broadly divided into the following four phases that were followed to bring the PQAT from conception to delivery.

1. Inception Phase

In the inception phase of the RUP, the initial analysis was done. In this phase the Power Quality Analysis Tool was designed in term of what it would be doing. The requirements were identified and modeled in Use Case Diagrams. These are the starting point of the analysis phase and show the main flow of events in the software system.

2. Elaboration Phase

The design was developed in the elaboration phase of the RUP. From the use cases a unified image of how the PQAT should be constructed was obtained. The design continued to iteratively pare down the PQAT into subsystems. The Power Quality Algorithms (Sag, Undervoltage, Interruption, Swell, Overvoltage, Oscillatory and Impulsive Transients), were modeled separately.

During the elaboration phase, the use cases evolved from the inception phase into a design of the domain, its subsystems and the business objects related to it. This domain model was turned into a software design using more detailed diagrams.

3. Construction Phase

The construction phase of the Unified Process was the actual building of the PQAT from the design of the system. In the RUP, the development portion was an incremental iterative process as explained in Section 3. Code was developed in portions that were manageable. Each portion went through minicycles similar to the entire Unified Process. The construction phase called for changes to the design and questions for the analysis, consistently going back to previous phases, particularly the elaboration phase, to design new components that were not realized earlier in the modeling process.

4. Transition Phase

In this phase the product was delivered to General Electric Multilin. This was not the real end of the software lifecycle. Constant maintenance, upgrades and bugfixes followed the successful completion of the PQAT. This phase was known as rolling out the system.

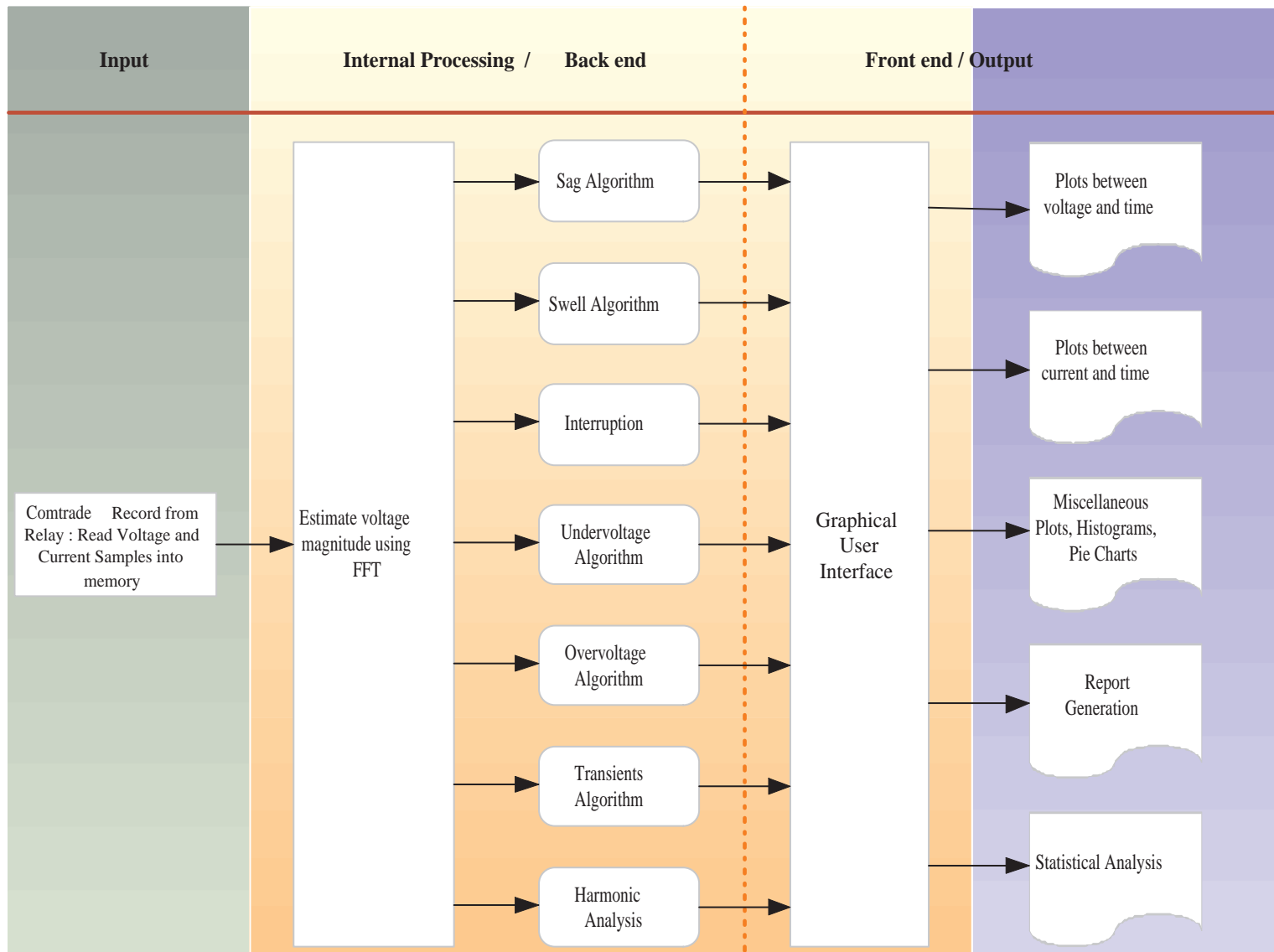


Figure 4.4: Philosophy Behind the Power Quality Analysis Tool

4.4 Working of the Power Quality Analysis Tool

Figure 4.4 shows the working of the PQAT. It is divided into three steps.

Input The input to the PQAT is the Comtrade record from the relay. The PQAT reads the current and voltage samples from the Comtrade record into memory for further action.

Internal Processing / Back End During this step the voltage and current magnitude is estimated using Fast Fourier Transform. The estimated voltage magnitude is then checked against the set limits in the software by the various algorithms. The algorithms are coded using the C++ programming language [17], [18], [19], [20], [20], [21].

Front End / Output The front end of the software consists of the Graphical User Interface. Microsoft Visual C++ (VC++) Integrated Development Environment (IDE) comprising of editor, compiler, debugger is used for development of the graphical user interface for the Tool [22], [23], [24]. The output of the algorithms is then presented to the user in the form of

- Plots between voltage and time
- Plots between current and time
- Histograms and Pie Charts
- Reports

4.5 Features of the Power Quality Analysis Tool

The main window of PQAT is shown in Figure 4.5.

Figure 4.7 shows the overview of the process in which the relay is triggered on the occurrence of a disturbance and the data is written to a COMTRADE record. The COMTRADE record is acquired from the relay to perform offline Power Quality Analysis on a Personal Computer (PC) . The Power Quality Analysis software application is used for the automatic detection and classification of the power quality events.

4.5.1 File Menu Options

The **File** menu allows the user to open a COMTRADE file, to save the plots and to exit the Power Quality Analysis application. After Choosing **File** from the menu bar, a dropdown menu is displayed. The different features contained within each **File** menu option, shown in 4.8, are described below.

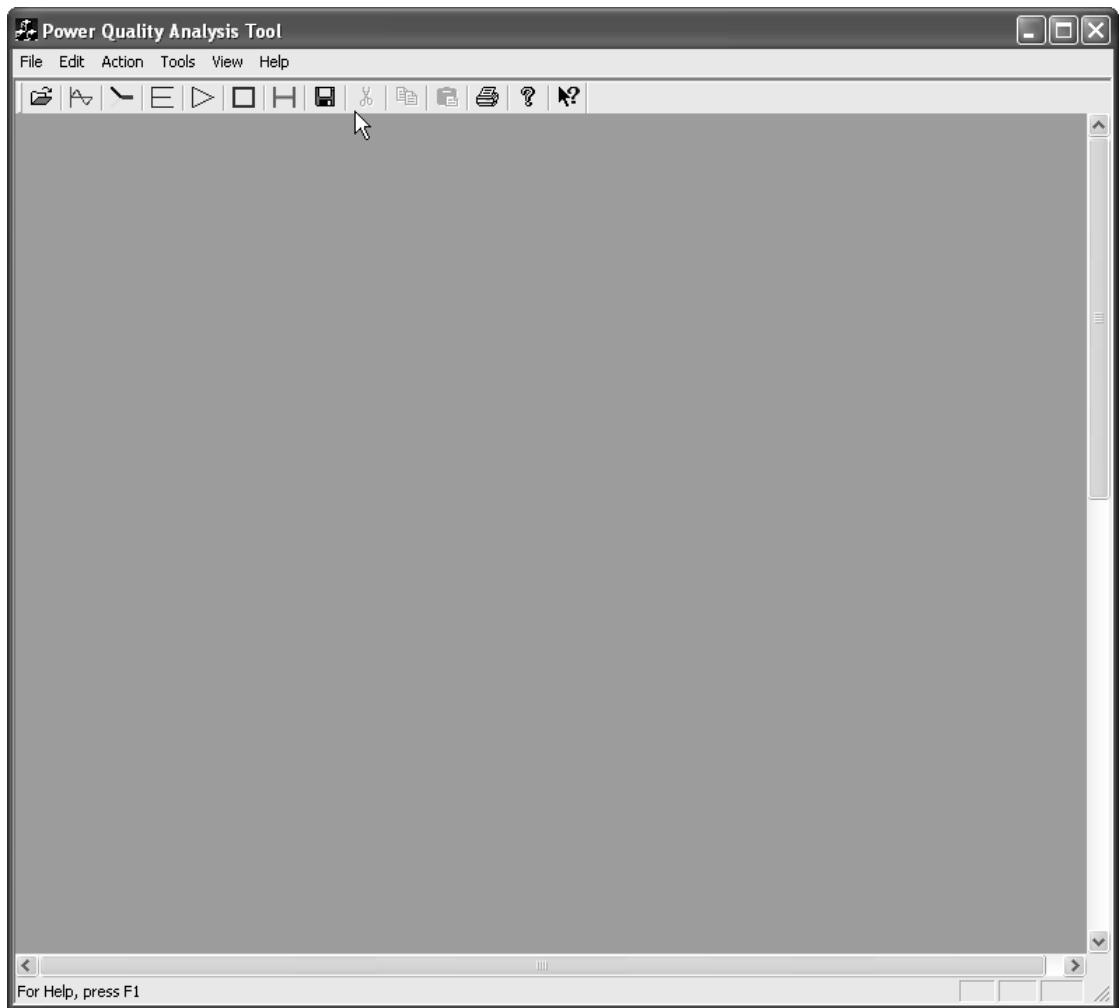


Figure 4.5: Main Window of Power Quality Analysis Tool



- | | |
|-------------------------------|-----------------|
| 1. Open Comtrade File | 8. Save |
| 2. Display Waveforms | 9. Cut |
| 3. Display Phasors | 10. Copy |
| 4. Event Settings | 11. Paste |
| 5. Run Power Quality Analysis | 12. Print |
| 6. Generate Report | 13. About |
| 7. Run Harmonic Analysis | 14. Help Topics |

Figure 4.6: List of Toolbar Items

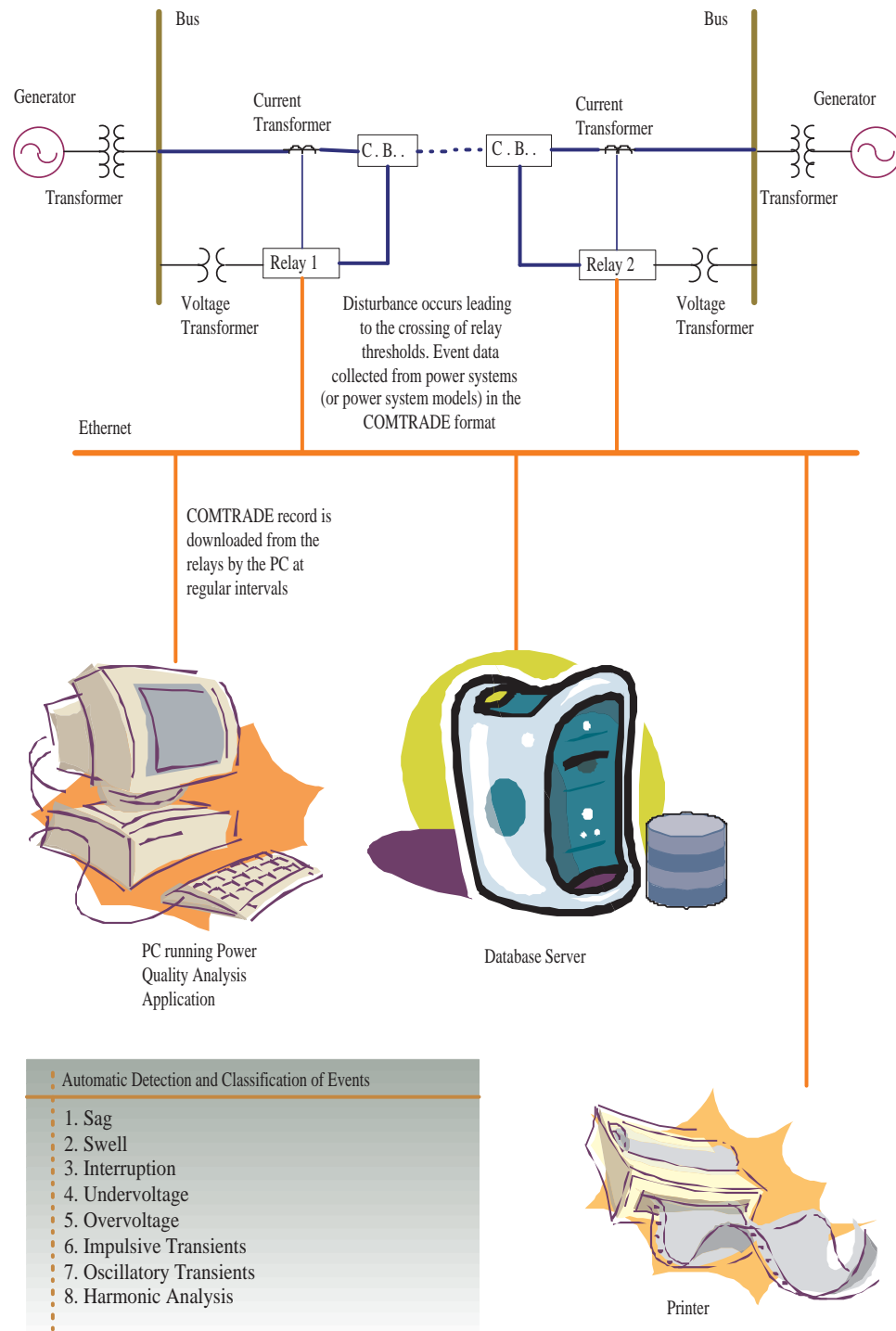


Figure 4.7: Obtaining Comtrade Record from Relay to Perform Offline Power Quality Analysis

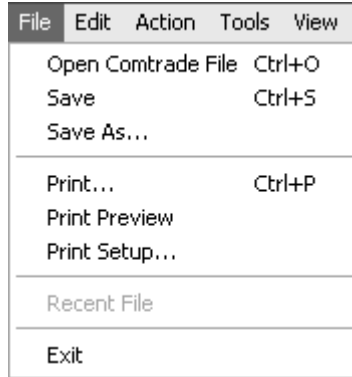


Figure 4.8: Dropdown Menu Item - File

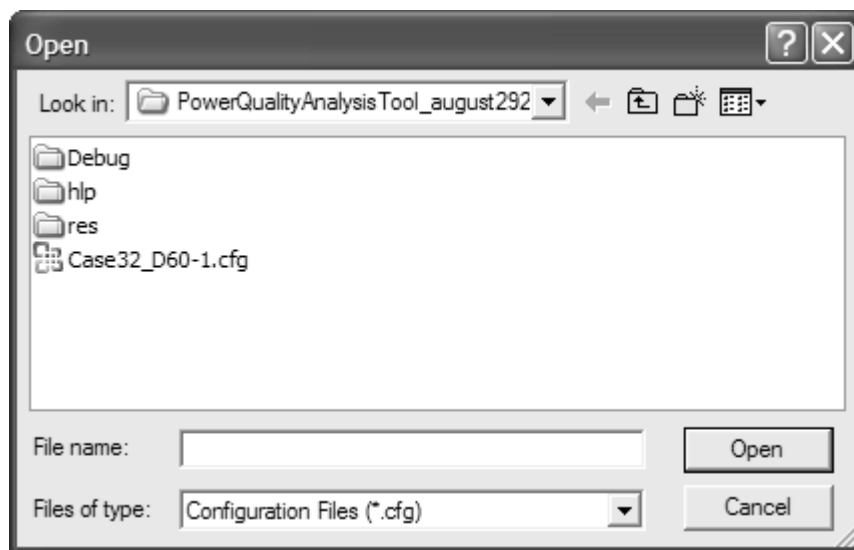


Figure 4.9: Opening the Comtrade File

4.5.1.1 Open Comtrade File

This option allows the user to open a Comtrade File as shown in Figure 4.9 in the Power Quality Analysis Application. The COMTRADE file is opened and the records for the three phase voltage and current from the configuration (a file with .cfg extension) file and data (a file with .dat file) file are read by the Power Quality Analysis Tool and stored in memory for further operation. The Comtrade files can also be opened from the toolbar shown in 4.6.

4.5.1.2 Save

This option is used to save a copy of the active document with a different name or in a different location.

Edit	Action	Tools
Undo	Ctrl+Z	
Cut	Ctrl+X	
Copy	Ctrl+C	
Paste	Ctrl+V	

Figure 4.10: Dropdown Menu Item - Edit

4.5.1.3 Save As

This option is used to save a copy of the active document with a different name or in a different location.

4.5.1.4 Print

This option prints all or part of the currently open single document.

4.5.1.5 Print Preview

This option is used for previewing a page before printing.

4.5.1.6 Page Setup

This option is used to setup the page margins (top, bottom, left and right) and the orientation (portrait or landscape) for printing purposes.

4.5.1.7 Recent File

This option allows the user to open the last four of the most recently opened Comtrade files with one click without any need to browse the disc looking for the files.

4.5.1.8 Exit

This option is used to Exit the Power Quality Analysis application.

4.5.2 Edit Menu Options

The different features contained within each **Edit** menu option, shown in 4.10, are described below.

4.5.2.1 Undo

This option is used to undo the very last action taken.

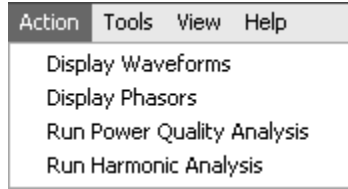


Figure 4.11: Dropdown Menu Item - Action

4.5.2.2 Cut

This option is used to cut the items to another document. This action is similar to the copy action but the original item is deleted from the document.

4.5.2.3 Copy

This option is used to copy or move the items to another document.

4.5.2.4 Paste

This option allows to paste items individually, or all at once. It pastes only the last item copied.

4.5.3 Action Menu Options

The different features contained within each **Action** menu option, shown in 4.11, are described below.

4.5.3.1 Display Waveforms

This option brings up a channel data dialog box on clicking. The user has the choice of selecting one or more of the three phase current and voltage phases for viewing the waveform plots. By default all the current and voltage phases are selected for viewing. The “Channel Data” dialog box is shown in 4.12.

The currents and voltage waveforms are displayed in the form of plots. The time is plotted along the abscissa and the voltage and current values are plotted along the ordinate. The following eight plots are displayed in the opened document of the application.

- Phase A Current (I_a) vs time
- Phase B Current (I_b) vs time
- Phase C Current (I_c) vs time
- Ground Current (I_g) vs time
- Phase A Voltage (V_a) vs time

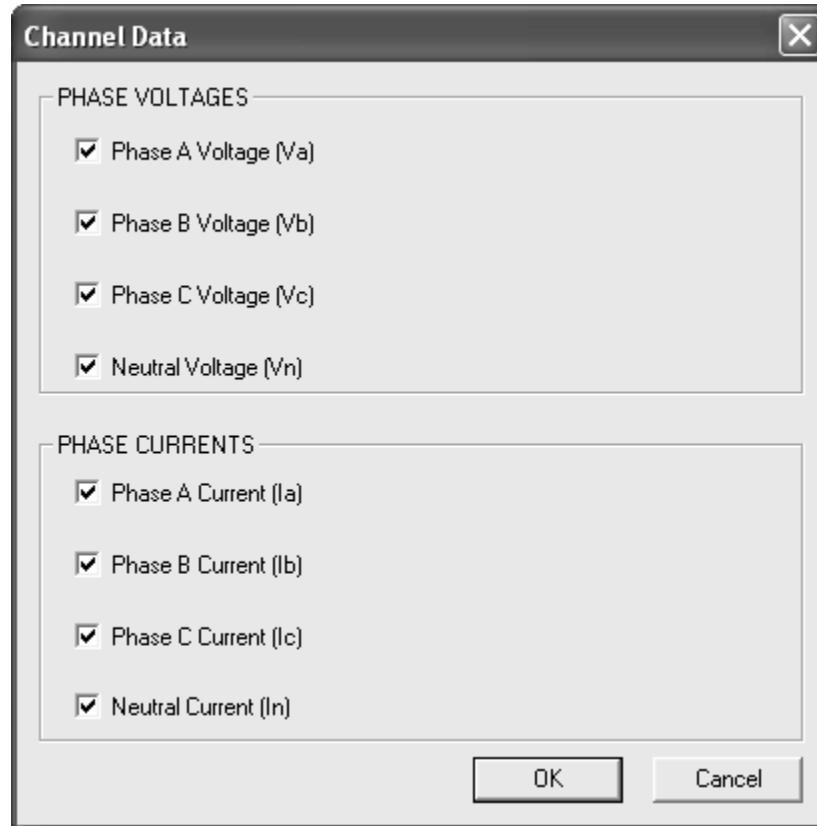


Figure 4.12: Channel Data Dialog Box

- Phase B Voltage (V_b) vs time
- Phase C Voltage (V_c) vs time
- Neutral Voltage (V_n) vs time

These plots can also be displayed from the toolbar by clicking the button shown in Figure 4.6.

4.5.3.2 Display Phasors

FFT is used to estimate the fundamental frequency and the harmonic components in each voltage and current signal up to the 25th harmonic. The estimated phase angle of three phase voltages and currents is displayed in the form of phase angle plots against time. Initially, this option brings up a channel data dialog box on clicking. The user has the choice of selecting one or more of the three phase current and voltage phases for viewing the phasor plots. By default all the current and voltage phases are selected for viewing.

The time is plotted along the abscissa and the voltage magnitude is plotted along the ordinate. The following eight plots are displayed in the opened document of the application.

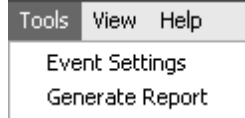


Figure 4.13: Dropdown Menu Item - Tool

- Phase A Current (I_a) vs time
- Phase B Current (I_b) vs time
- Phase C Current (I_c) vs time
- Ground Current (I_g) vs time
- Phase A Voltage (V_a) vs time
- Phase B Voltage (V_b) vs time
- Phase C Voltage (V_c) vs time
- Neutral Voltage (V_n) vs time

These plots can also be displayed from the toolbar by clicking the button shown in Figure 4.6.

4.5.3.3 Run Power Quality Analysis

This option leads the algorithms to act on the estimated voltage magnitude and time duration settings of the three phases to detect and then classify the type of event that occurred. The algorithms can classify single as well as multiple events occurring in the same phase. The plot shows the voltage magnitude (from the start of the event to the end of the event) displayed along abscissa and the time duration displayed along ordinate. These plots can also be displayed from the toolbar by clicking the button shown in Figure 4.6.

4.5.3.4 Run Harmonic Analysis

This option displays the Total Harmonic Distortion (along the abscissa) versus time (along the ordinate) plots. These plots can also be displayed from the toolbar by clicking the button shown in Figure 4.6.

4.5.4 Tools Menu Options

The different features contained within each **Tool** menu option, shown in 4.13, are described below.

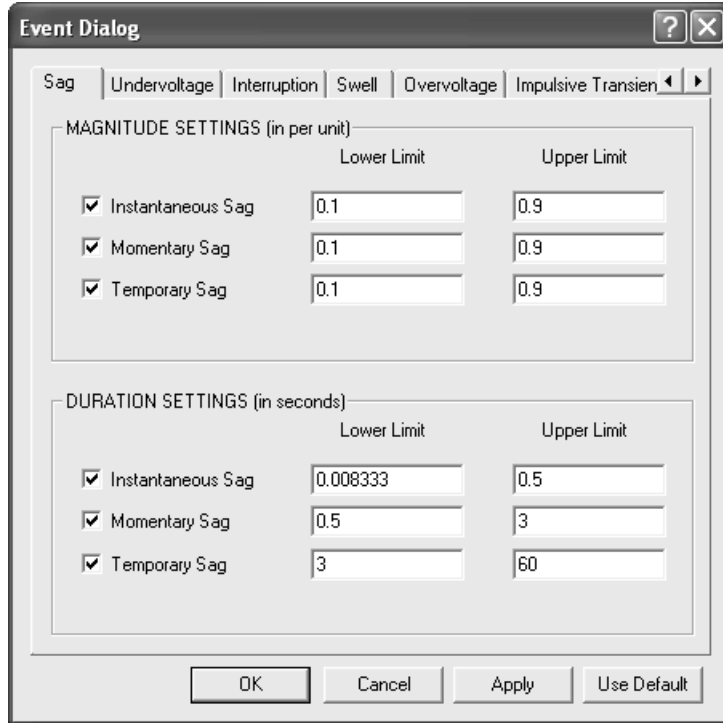


Figure 4.14: Event Settings for Sag

4.5.4.1 Event Settings

The technique uses voltage duration and magnitude, as specified in the IEEE Standard 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality, of three phases to detect and classify the events. The settings for sag, swell, interruption, undervoltage, overvoltage, impulsive transients and oscillatory transients are entered in the event settings dialog box shown in 4.14, 4.15, 4.16, 4.17, 4.18, 4.19 and 4.20 respectively in per unit and in seconds.

These plots can also be displayed from the toolbar by clicking the button shown in Figure 4.6. Table 4.1 lists the various types of Power Quality Events along with the method to characterize them.

4.5.4.2 Generate Report

The classified events are then presented in a user friendly tabular form. At present the following four items are shown in the report.

1. Event Type,
2. Start Time,
3. End Time and

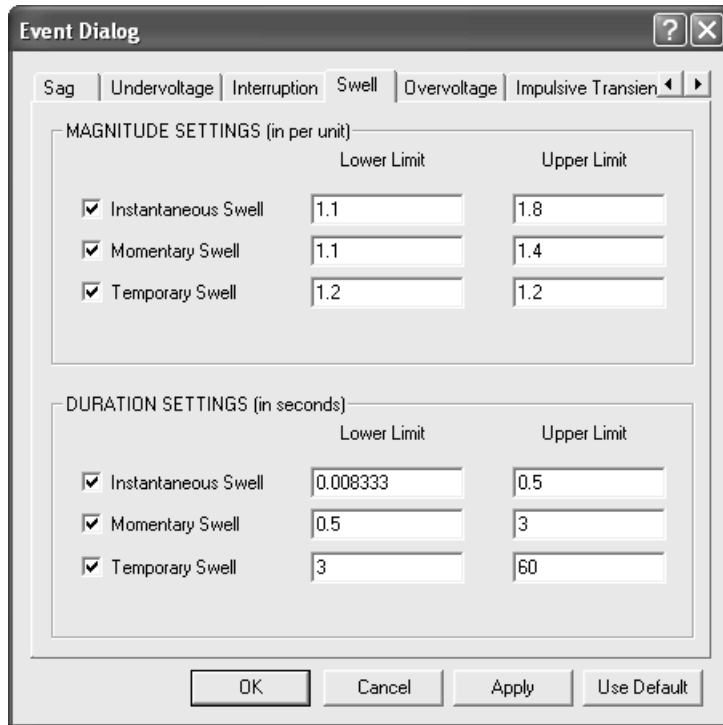


Figure 4.15: Event Settings for Swell

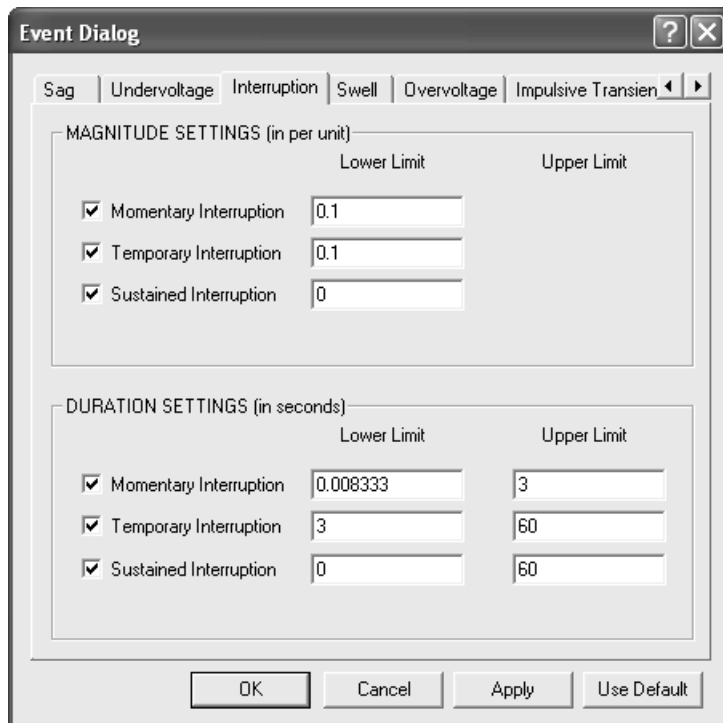


Figure 4.16: Event Settings for Interruption

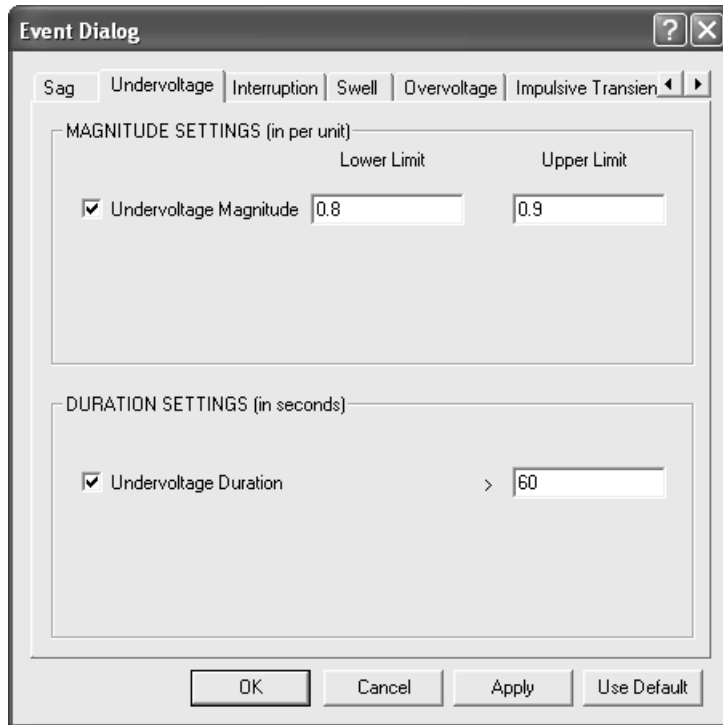


Figure 4.17: Event Settings for Undervoltage

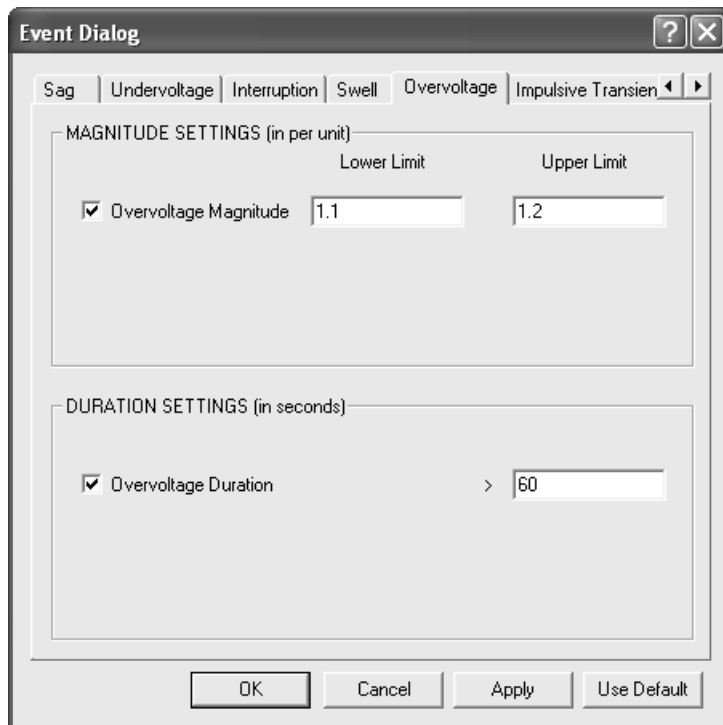


Figure 4.18: Event Settings for Overvoltage

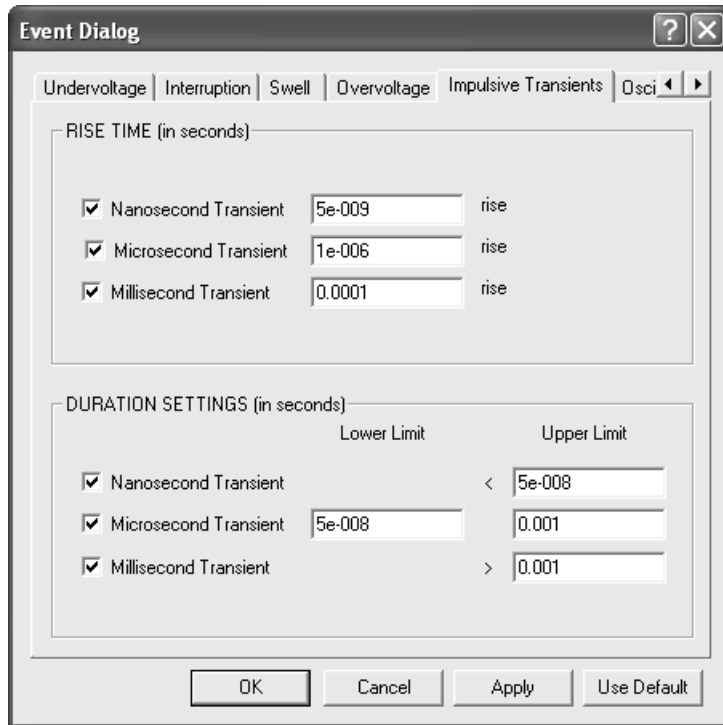


Figure 4.19: Event Settings for Impulsive Transients

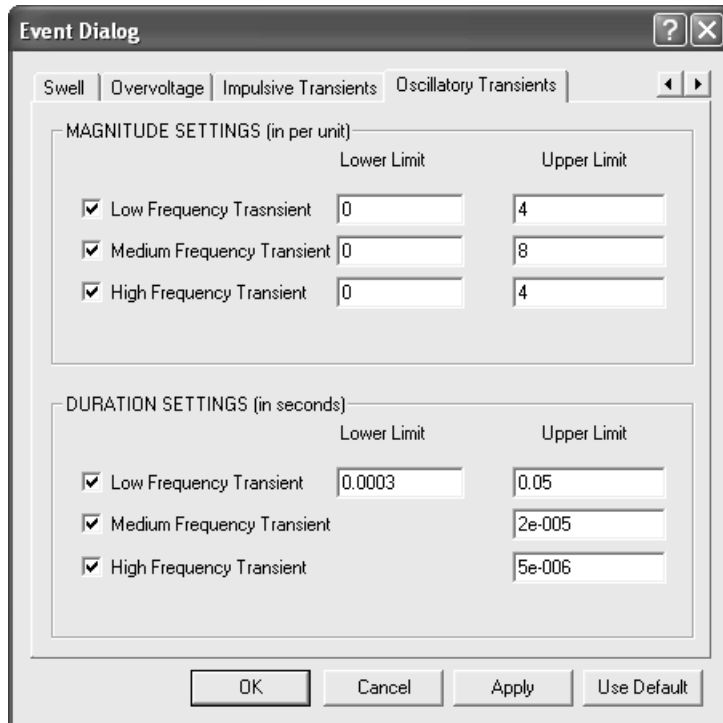


Figure 4.20: Event Settings for Oscillatory Transients

Table 4.1: Methods of Characterizing the Power Quality Events

<i>Event Type</i>	<i>Characterizing Parameter</i>
Sag	
Instantaneous	Voltage rms Magnitude, Duration
Momentary	Voltage rms Magnitude, Duration
Temporary	Voltage rms Magnitude, Duration
Undervoltage	Voltage rms Magnitude, Duration
Interruption	
Momentary	Voltage rms Magnitude, Duration
Temporary	Voltage rms Magnitude, Duration
Sustained	Voltage rms Magnitude, Duration
Swell	
Instantaneous	Voltage rms Magnitude, Duration
Momentary	Voltage rms Magnitude, Duration
Temporary	Voltage rms Magnitude, Duration
Overvoltage	Voltage rms Magnitude, Duration
Impulsive Transients	
Nanosecond	Voltage rms Magnitude, Duration
Microsecond	Voltage rms Magnitude, Duration
Millisecond	Voltage rms Magnitude, Duration
Oscillatory Transients	
Low Frequency	Voltage rms Magnitude, Duration
Medium Frequency	Voltage rms Magnitude, Duration
High Frequency	Voltage rms Magnitude, Duration
Harmonics	Total Harmonic Distortion

4. Duration

In case of non identification of events in any phase, a No Events Identified message is displayed. The unidentified event(s) is stored in a Undefined Events category for the purpose of record keeping of all the events that have occurred even though if they have not been identified.

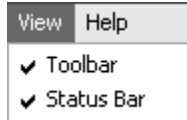


Figure 4.21: Dropdown Menu Item - View

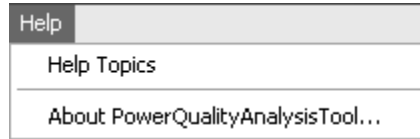


Figure 4.22: Dropdown Menu Item - Help

The report can also be displayed from the toolbar by clicking the button shown in Figure 4.6.

4.5.5 View Menu Options

The **View** menu lets you define how Power Quality Analysis Tool looks on the desktop. To access the **View** menu options, choose **View** from the menu bar. A dropdown menu will be displayed. The different features contained within each **View** menu option, shown in 4.21, are described below.

4.5.5.1 Toolbar

This option hides or displays the toolbar.

4.5.5.2 Status Bar

This option hides or displays the statusbar.

4.5.6 Help Menu Options

Power Quality Analysis Tool has a Help system that gives online access to the reference guide. To access the online help, choose **Help** and then **Help Topics**. The different features contained within each Help menu option, shown in 4.22, are described below.

4.5.6.1 Help Topics

Power Quality Analysis Tool has a Help system that gives online access to the reference guide. To access the online help, choose **Help** and then **Help Topics**. A Help Topics dialog box shown in Figure 4.23 is displayed.

The different ways of accessing information are listed on the tabs in the left panel in the help browser.

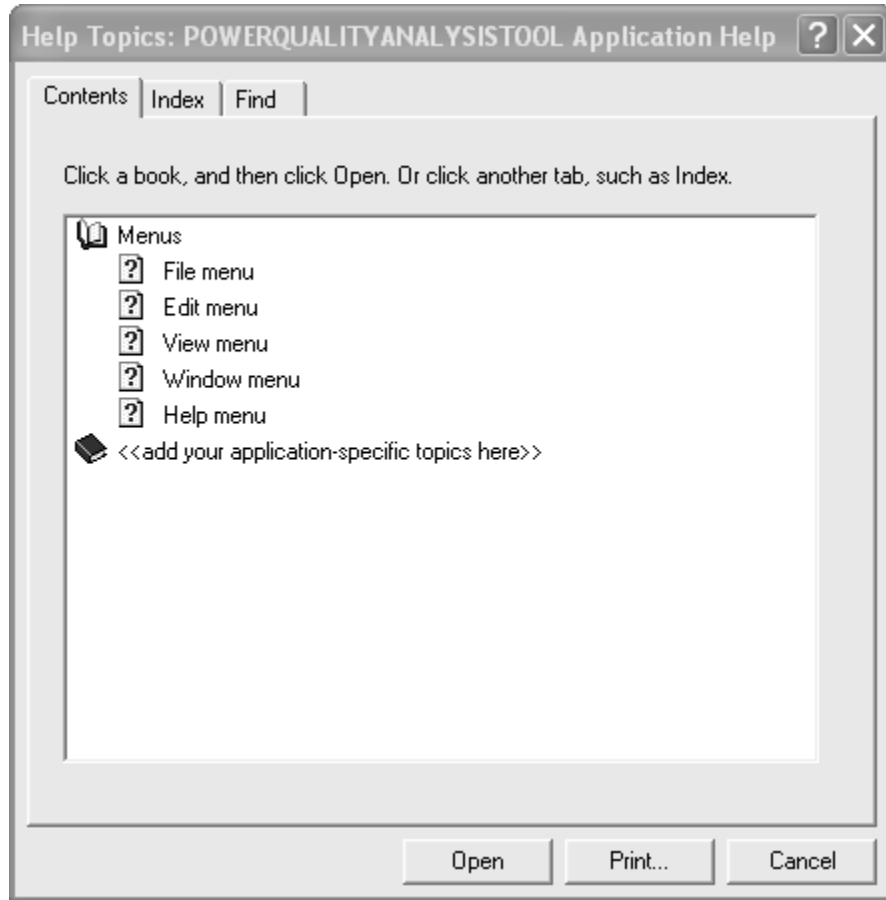


Figure 4.23: Help Topics - Dialog Box

Contents It displays high-level topic areas. The closed-book icon can be clicked to see a list of more topics.

Index It shows all topics in alphabetical order. The user can look through the topics by typing the first words, if it is known to them.

Search If topic name is not known, the Search tab can be used to search for Help topics. This finds topics containing the terms typed in by user. Then the related topics can be selected by referring to the Search dialog instructions on screen.

4.5.6.2 About Power Quality Analysis Tool

This option opens a dialog box shown in Figure 4.24 that lists the version number for Power Quality Analysis Tool. It also contains the copyright information.

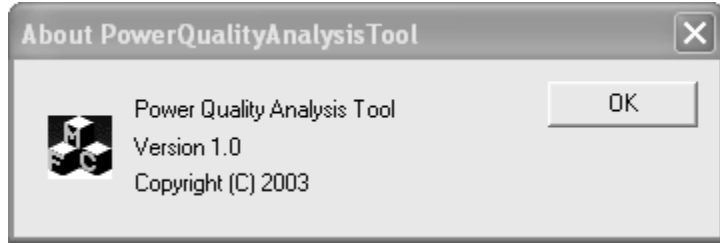


Figure 4.24: Dialog Box Showing the Version Number of the Power Quality Analysis Tool

4.6 Algorithms

4.6.1 Sag Algorithm

The Sag algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes below the Normal Operating Range.
3. Check to see if the voltage magnitude falls between 0.1 per unit and 0.9 per unit.
4. Record the start time and end time of the event for which it stays between 0.1 per unit and 0.9 per unit.
5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.008333 second and 0.5 second.
6. If yes, Instantaneous Sag is detected. Else, check for other events.
7. Again check to see if the voltage magnitude falls between 0.1 per unit and 0.9 per unit.
8. Record the start time and end time of the event for which it stays between 0.1 per unit and 0.9 per unit.
9. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.5 second and 3 second.
10. If yes, Momentary Sag is detected. Else, Check for other events.
11. Again check to see if the voltage magnitude falls between 0.1 per unit and 0.9 per unit.
12. Record the start time and end time of the event for which it stays between 0.1 per unit and 0.9 per unit.

13. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 3 second and 60 second.
14. If yes, Temporary Sag is detected. Else, check for other events
15. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Sag algorithm is illustrated in the flowchart given in Figure 4.25.

4.6.2 Undervoltage Algorithm

The Undervoltage algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes below the Normal Operating Range.
3. Check to see if the voltage magnitude falls between 0.8 per unit and 0.9 per unit.
4. Record the start time and end time of the event for which it stays between 0.8 per unit and 0.9 per unit.
5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, is greater than 60 seconds.
6. If yes, Undervoltage is detected. Else, check for other events
7. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Undervoltage algorithm is illustrated in the flowchart given in Figure 4.26

4.6.3 Interruption Algorithm

The Interruption algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes below the Normal Operating Range.
3. Check to see if the voltage magnitude is less than 0.1 per unit.
4. Record the start time and end time of the event for which it stays less than 0.1 per unit.

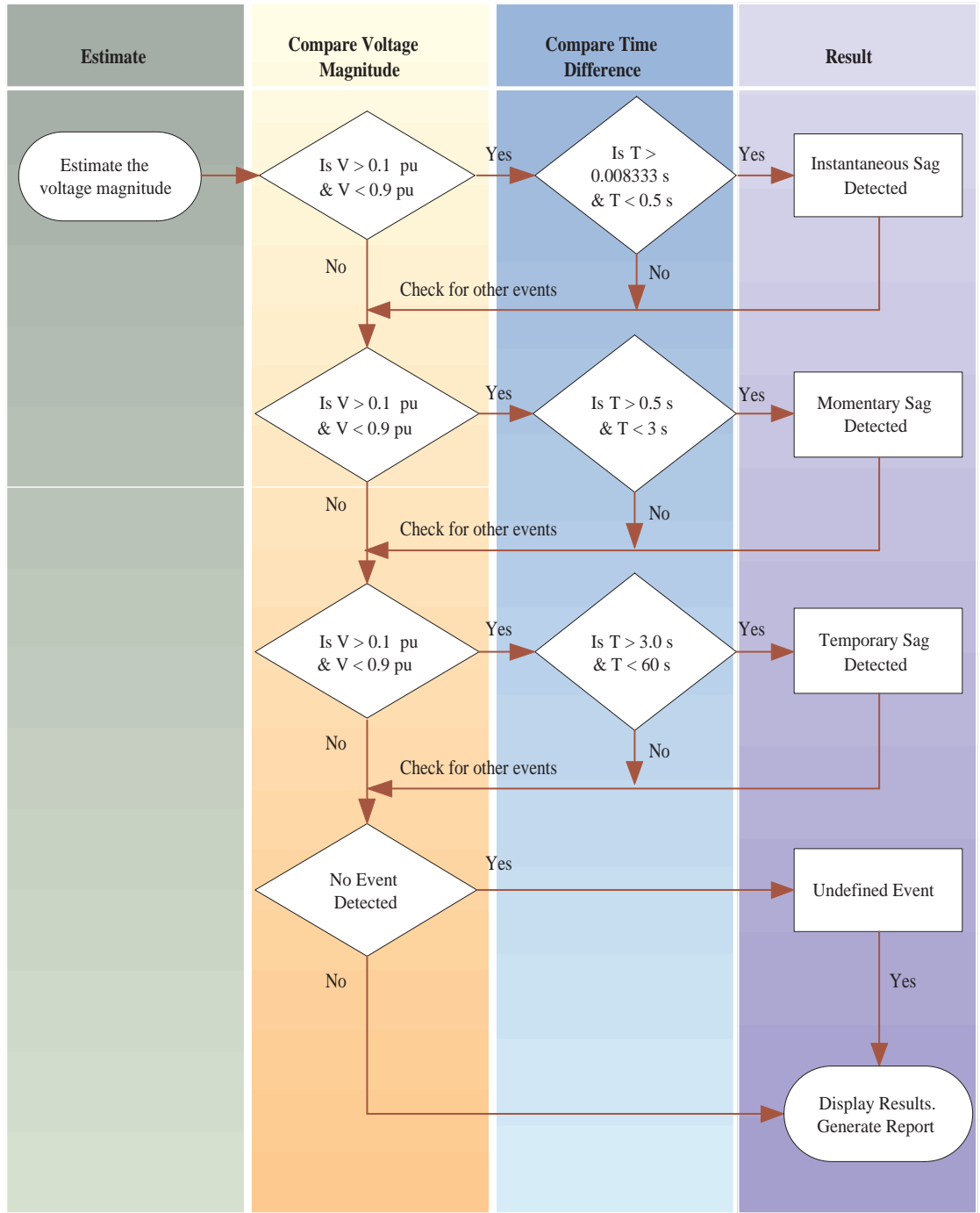


Figure 4.25: Overview of the Sag Algorithm

5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.008333 second and 0.5 second.
6. If yes, Momentary Interruption is detected. Else, Check for other events.
7. Check to see if the voltage magnitude is less than 0.1 per unit.

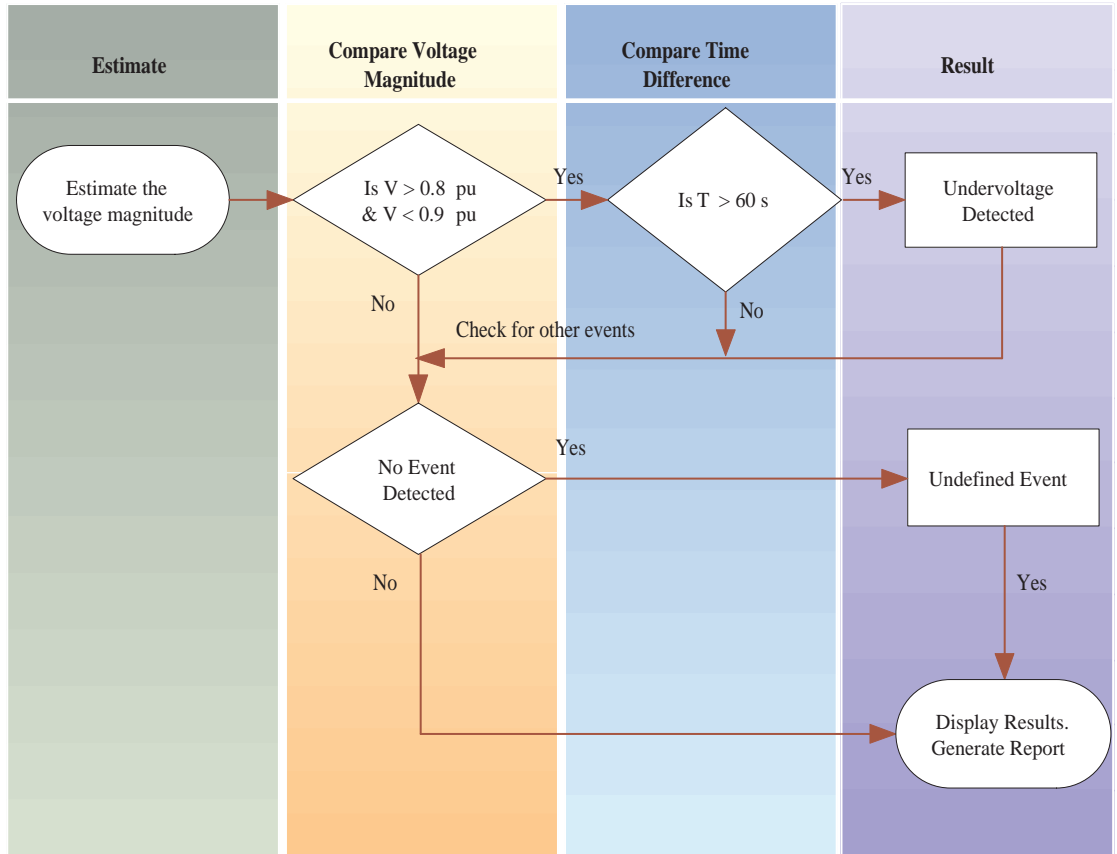


Figure 4.26: Overview of the Undervoltage Algorithm

8. Record the start time and end time of the event for which it stays less than 0.1 per unit.
9. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 3 second and 60 second.
10. If yes, Temporary Interruption is detected. Else, Check for other events.
11. Check to see if the voltage magnitude stays 0.0 per unit for a Time, T , greater than 60 second.
12. If yes, Sustained Interruption is detected. Else, Check for other events.
13. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Interruption algorithm is illustrated in the flowchart given in Figure 4.27.

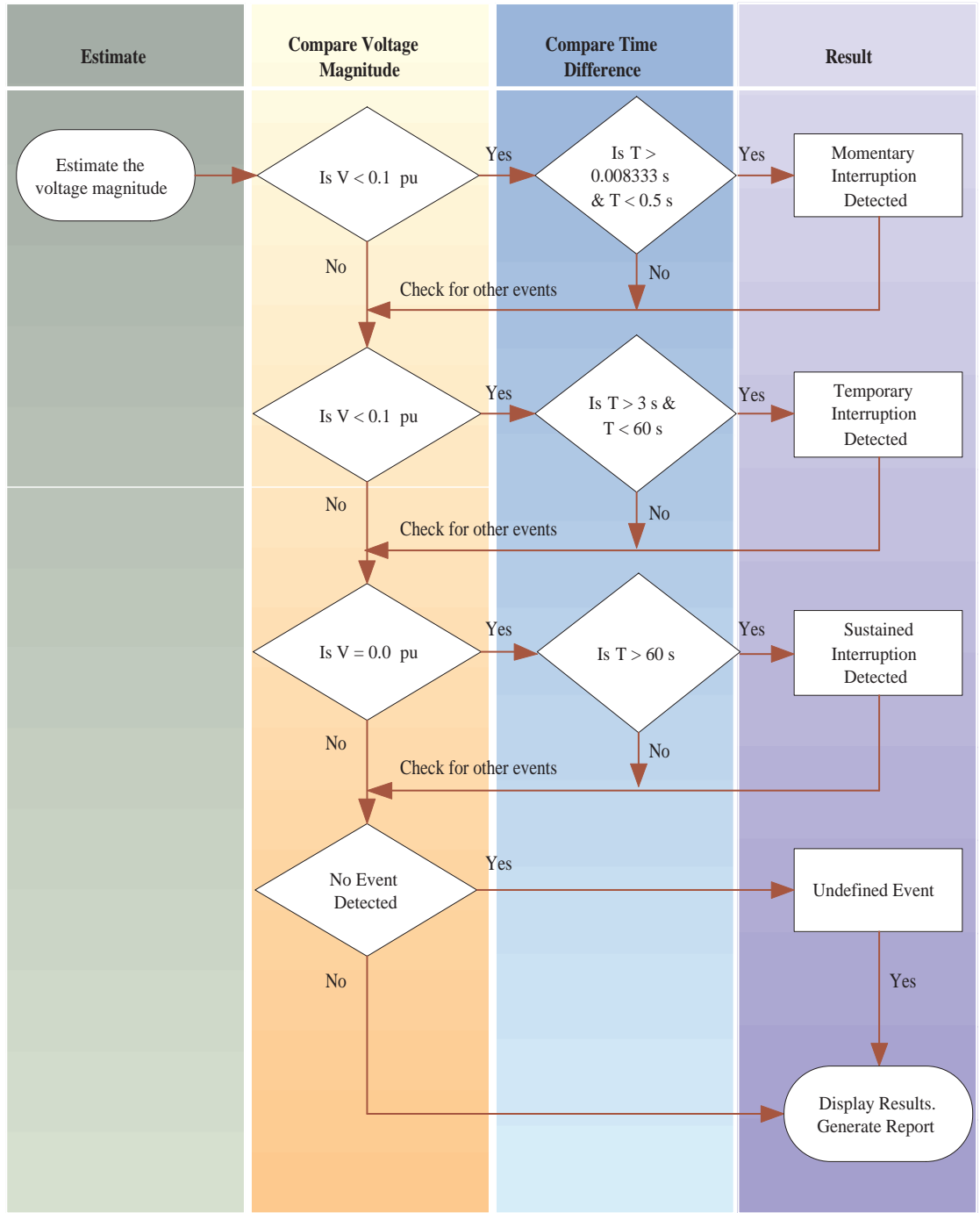


Figure 4.27: Overview of the Interruption Algorithm

4.6.4 Swell Algorithm

The Swell algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.

2. Detect when the voltage magnitude goes above the Normal Operating Range.
3. Check to see if the voltage magnitude falls between 1.1 per unit and 1.8 per unit.
4. Record the start time and end time of the event for which it stays between 1.1 per unit and 1.8 per unit.
5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.008333 second and 0.5 second.
6. If yes, Instantaneous Swell is detected. Else, Check for other events.
7. Check to see if the voltage magnitude falls between 1.1 per unit and 1.4 per unit.
8. Record the start time and end time of the event for which it stays between 1.1 per unit and 1.4 per unit.
9. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.5 second and 3 second.
10. If yes, Momentary Swell is detected. Else, Check for other events.
11. Check to see if the voltage magnitude falls between 1.1 per unit and 1.2 per unit.
12. Record the start time and end time of the event for which it stays between 1.1 per unit and 1.2 per unit.
13. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 3 second and 60 second.
14. If yes, Temporary Swell is detected. Else, Check for other events.
15. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Swell algorithm is illustrated in the flowchart given in Figure 4.28.

4.6.5 Overvoltage Algorithm

The Overvoltage algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes above the Normal Operating Range.
3. Check to see if the voltage magnitude falls between 1.1 per unit and 1.2 per unit.

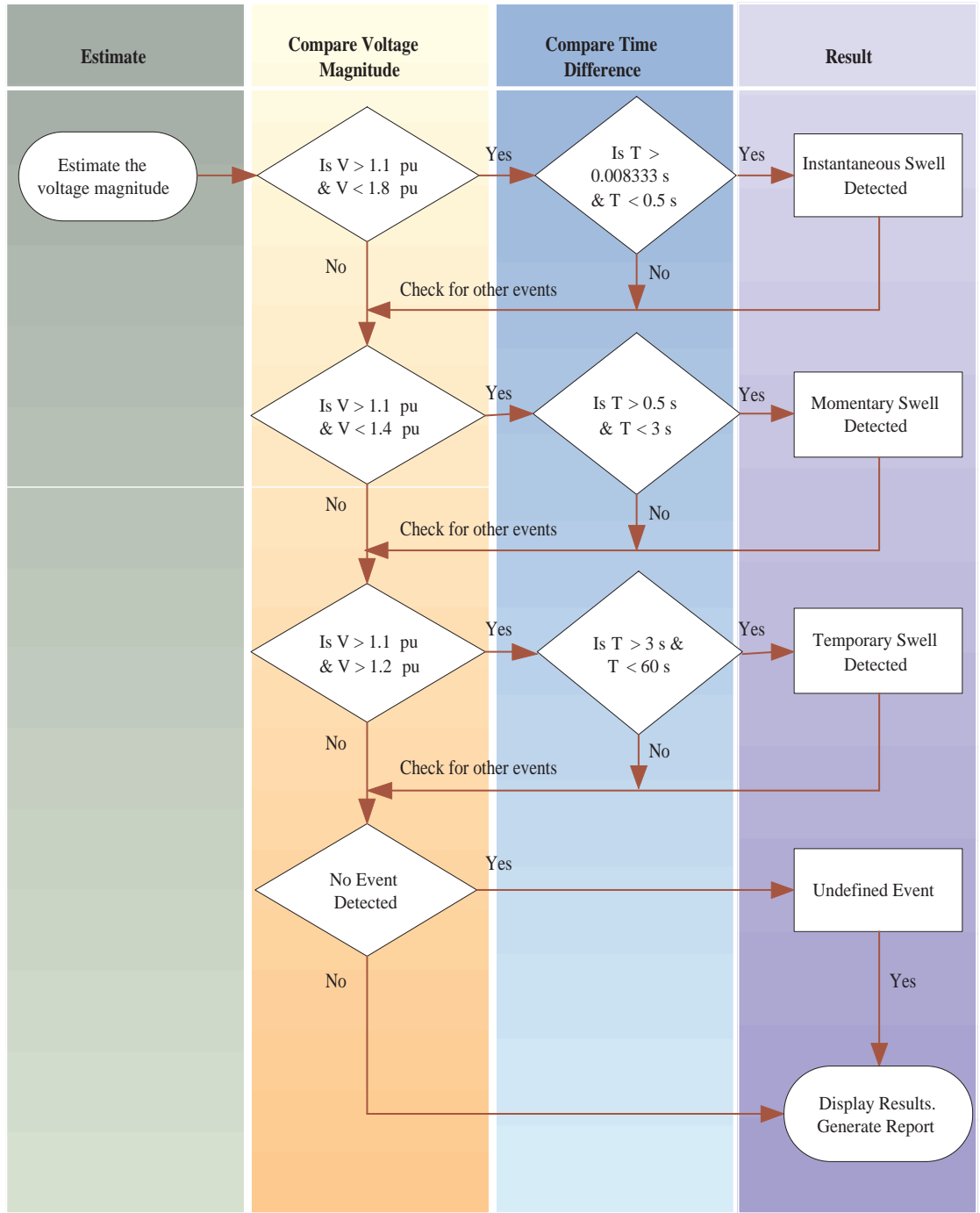


Figure 4.28: Overview of the Swell Algorithm

4. Record the start time and end time of the event for which it stays between 1.1 per unit and 1.2 per unit.
5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, is greater than 60 seconds.

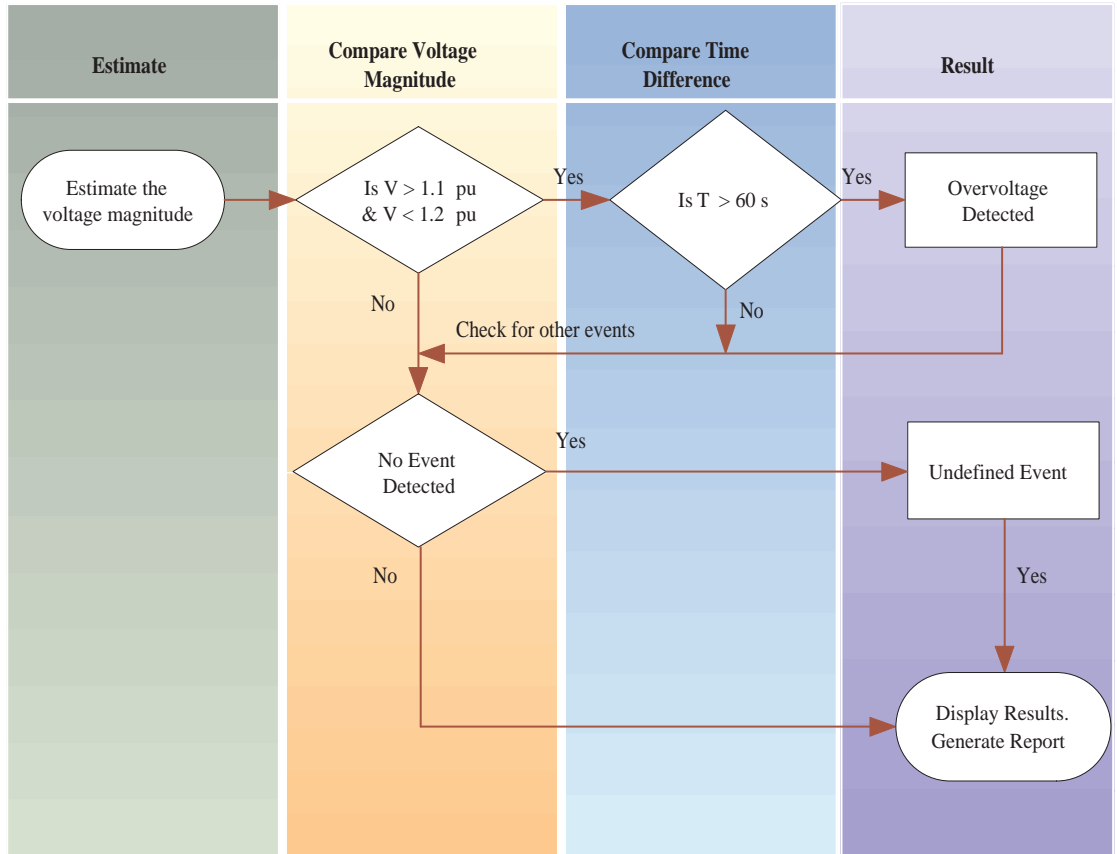


Figure 4.29: Overview of the Overvoltage Algorithm

6. If yes, Overvoltage is detected. Else, check for other events.
7. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Overvoltage algorithm is illustrated in the flowchart given in Figure 4.29.

4.6.6 Oscillatory Transient Algorithm

The Oscillatory Transients algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes below the Normal Operating Range.
3. Check to see if the voltage magnitude falls between 0 per unit and 4 per unit.
4. Record the start time and end time of the event for which it stays between 0 per unit and 4 per unit.

5. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, falls between 0.3 millisecond and 50 millisecond.
6. If yes, Low Frequency Oscillatory Transients are detected. Else, check for other events.
7. Check to see if the voltage magnitude falls between 0 per unit and 8 per unit.
8. Record the start time and end time of the event for which it stays between 0 per unit and 8 per unit.
9. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, is equal to 0.020 millisecond.
10. If yes, Medium Frequency Oscillatory Transients are detected. Else, check for other events.
11. Check to see if the voltage magnitude falls between 0 per unit and 4 per unit.
12. Record the start time and end time of the event for which it stays between 0 per unit and 4 per unit.
13. Find the difference of the two time stamps. Check to see if Time difference, $T = \text{End time of event} - \text{Start time of event}$, is equal to 0.005 millisecond.
14. If yes, High Frequency Oscillatory Transients are detected. Else, check for other events.
15. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Oscillatory Transients algorithm is illustrated in the flowchart given in Figure 4.30.

4.6.7 Impulsive Transients

The Impulsive Transients algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude using Fast Fourier Transform.
2. Detect when the voltage magnitude goes below the Normal Operating Range.
3. Check to see if the rise time is 5 nanoseconds.
4. Check to see if the event last for duration of 0.000050 millisecond.
5. If yes, Nanosecond Impulsive Transients are detected. Else, check for other events.

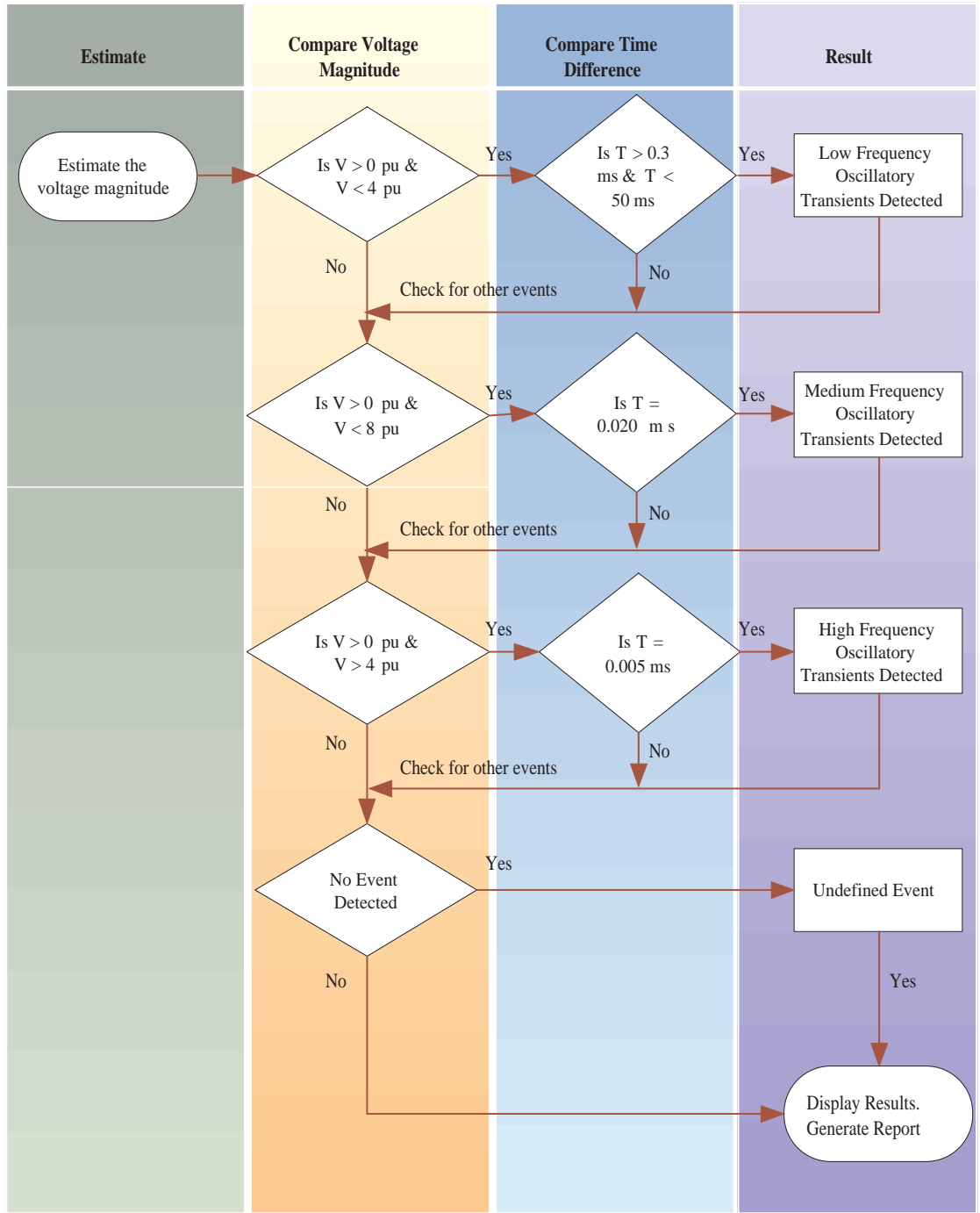


Figure 4.30: Overview of the Oscillatory Transients Algorithm

6. Check to see if the rise time is 1 microsecond.
7. Check to see if the event has duration between 0.000050 milliseconds and 1 millisecond.
8. If yes, Microsecond Impulsive Transients are detected. Else, check for other events.

9. Check to see if the rise time is 0.1 millisecond.
10. Check to see if the event has duration greater than 1 milliseconds.
11. In case the algorithm does not detect any event for any reason an “Undefined Events” message is displayed.

The implementation of the Impulsive Transients algorithm is illustrated in the flowchart given in Figure 4.31.

4.7 Harmonic Analysis

The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion and total demand distortion (Refer to section 3.5.10 on page 44).

4.7.1 Total Harmonic Distortion

The THD algorithm consists of the following steps.

1. Estimate the r.m.s voltage magnitude of the fundamental frequency up to the 25th harmonic using Fast Fourier Transform.
2. Calculate the square of the r.m.s voltage magnitude from 2nd to the 25th harmonic.
3. Sum the r.m.s voltage magnitude calculated in Step 2.
4. Calculate the square root of the r.m.s voltage magnitude calculated in Step 3.
5. Divide the r.m.s voltage magnitude calculated in Step 4 by fundamental r.m.s voltage magnitude.
6. Multiple by 100 to obtain THD in percent.

The implementation of the THD algorithm is illustrated in the flowchart given in Figure 4.32.

4.7.2 Total Demand Distortion

The TDD algorithm consists of the following steps.

1. Estimate the r.m.s current magnitude of the fundamental up to the 25th Harmonic using Fast Fourier Transform.
2. Calculate the square of the r.m.s current magnitude from 2nd to the 25th harmonic.

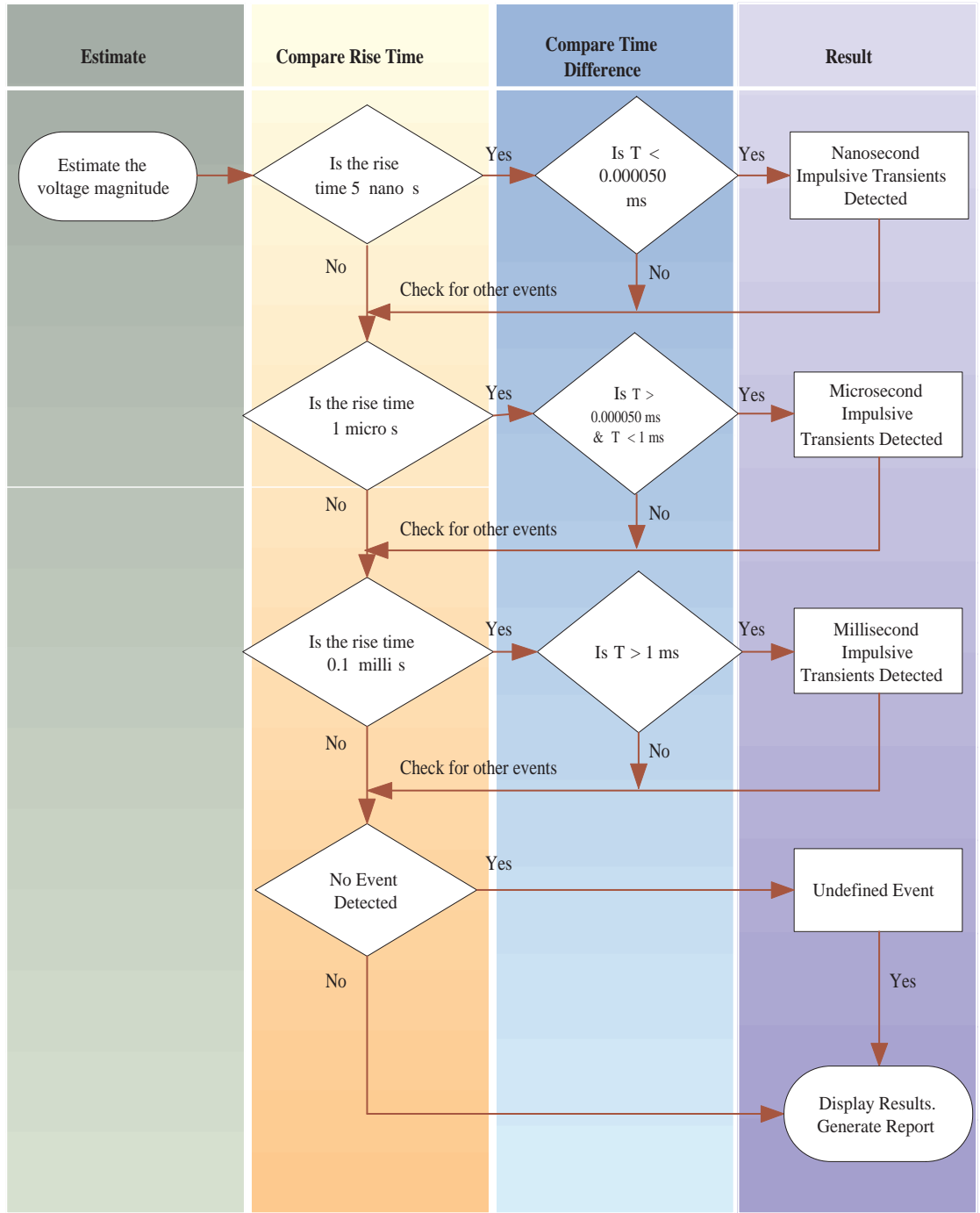


Figure 4.31: Overview of the Impulsive Transients Algorithm

3. Sum the r.m.s current magnitude calculated in Step 2.
4. Calculate the square root of the r.m.s current magnitude calculated in Step 3.
5. Divide the r.m.s current magnitude calculated in Step 4 by peak or maximum demand load current.

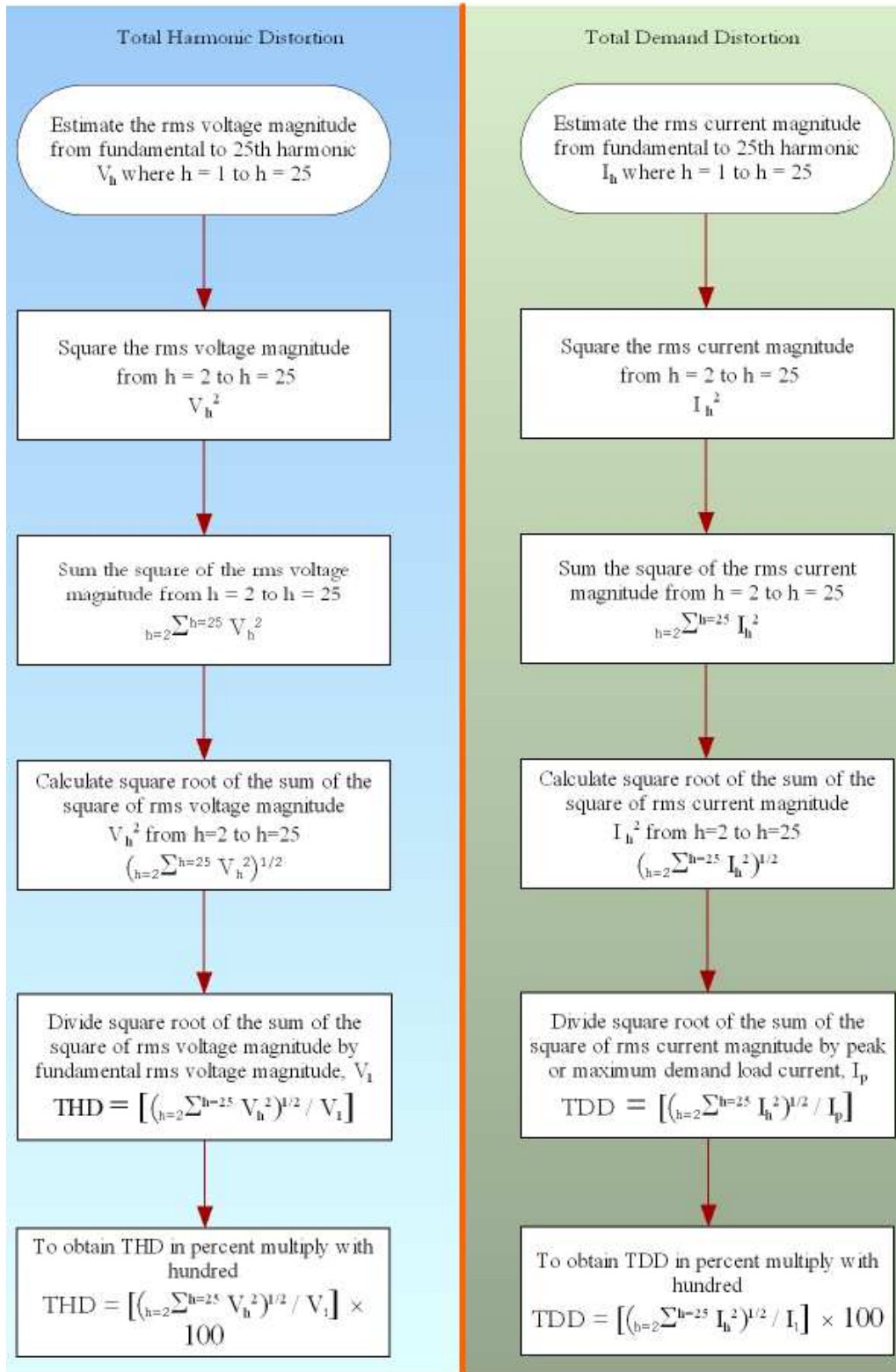


Figure 4.32: Overview of the THD and TDD Algorithm

6. Multiple by 100 to obtain TDD in percent.

The implementation of the TDD algorithm is illustrated in the flowchart given in Figure 4.32.

4.8 Offline vs Online Analysis

At present the Comtrade record with the voltage and current samples is retrieved from the relay to a PC to perform offline power quality analysis. PQAT starts its work by importing Comtrade record into a software application. In order to detect and classify the disturbance and obtain results, the data needs to be acted upon by algorithms and analyzed for disturbances.

Unfortunately, combining analysis with data acquisition and data presentation is not always a straightforward process in real time mode in the relay. Application software packages typically address one component of the application, but seldom address all aspects and needs to get to a complete solution. Online power quality analysis implies that the sampled voltage and current is analyzed within the relay where it is acquired. Online monitoring of power quality requires a comprehensive monitoring and data capturing system that is used to characterize disturbances and power quality variations in real time. These are computationally intensive and have an adverse effect on the performance of the relay. Also the sampling rate needs to be adapted to the characteristics of the measured voltage signal. For example high sampling rate is not required under normal operating circumstances whereas if a transient occurs the the application would have to quickly recognize the need for a higher sampling rate, and reduce it when the transient is over. By measuring and analyzing certain aspects of the signals the application can adapt to the circumstances and enable the appropriate execution parameters.

The following are the main requisites of for online power quality analysis:

1. Most of the present day relays have a sampling rate of upto 128 samples per cycle. A very high sampling rate is required for the detection of transients as transients having duration less than one sampling interval cannot be detected. High speed sampling rate can be achieved by using high speed digital signal processors and compatible hardware.
2. The relays must have data acquisition, data analysis, and data presentation all in one platform. During the acquisition process, every acquired data sample is shown on the front panel. This requires an extensive graphical plotting capabilities, including polar plots, time waveform plots, and statistics within the relay.
3. The relay must have higher onboard memory to store the larger number of samples and the associated rms data while still performing power quality measurements, in-

cluding sag, swell, interruption, undervoltage, overvoltage, transients and harmonic distortion

4. An automated retrieval system requires a high speed Ethernet connectivity with client/server architectures for comparison, analysis, and reporting. Multiple databases collected over long periods of time provide engineers with a comprehensive power history of the plant power system or utility infrastructure.
5. The relays should have alarming, reports, and data management and storing capabilities built within.
6. The relays should be modular in design with open and flexible approach, scalable to future systems.
7. The relays should be built on integrated platform based on commercial off-the-shelf components and tools.

4.9 Summary

The working of the power quality analysis tool have been detailed in this chapter. The algorithms for the detection and classification of the various power quality events have also been explained.

CHAPTER 5

TESTING

5.1 Introduction

The algorithms for the detection and classification of the Power Quality Events have been described in Chapter 4. The basis of event detection was presented in Chapter 3.

The algorithms were tested using the data generated by simulating a 3 bus power system using PSCAD. PSCAD is a powerful and flexible graphical user interface to the world-renowned, EMTDC solution engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment. Data representing different types of faults, at different locations, were obtained from the simulations. The data was then used to test the performance of the techniques during system disturbances. Some details of the simulations and results from the performance - tests are presented in this chapter.

5.2 Occurrence of Events

The power quality events may occur as a single event occurrence or multiple event occurrences in the power systems. The handling of the events by these algorithms is detailed below.

5.2.1 Occurrence of Single Event

In this type of occurrence of a power quality event, only one type of event occurs in one or more of the three phases of the power systems.

5.2.1.1 Treatment of Single Event Occurrence

This is easily identified by the algorithm based on the magnitude and duration of the event.

5.2.2 Occurrence of Multiple Event

In this type of happening of a power quality event, more than one type of event occurs in one or more of the three phases of the power systems.

5.2.2.1 Treatment of Multiple Event Occurrence

Consider the occurrence of a power quality event followed by the return of the voltage to the normal operating range. Immediately after the return to the normal operating range if the next voltage sample goes beyond the range, the event is treated as if more than one event occurred. The algorithm will characterize it as a multiple event.

5.3 System Modeling and Data Processing

Data were generated on a PC using PSCAD; an overview of the PSCAD is given in Appendix E. The three - bus power system, shown in Figure 5.7 was modeled for generating the fault data.

5.4 Three - Bus Power System

This system consists of three buses connected by three 230 kV transmission lines. Generator G1 is connected to Bus 1. The transmission line, T_{r1} and T_{r2} are 100 km long and connect Bus 1 to Bus 2. The transmission line, T_{r3} , is 100 km long and connects Bus 2 to Bus 3. Bus 3 is connected to another generator G2. The load L1 and L2 are connected to Bus 2. The parameters of all the components are given in Appendix F. The models of different parts of the system developed in the EMTDC are shown in Figures 5.1, 5.2, 5.3, 5.5, 5.6 and 5.4. Models of VTs of ratio 230 kV : 0.110 kV reduced the levels of the three phase currents. Models of CTs of ratio 400 : 1 A reduced the levels of the three phase currents. The outputs of the VTs and CTs were used by the relay models.

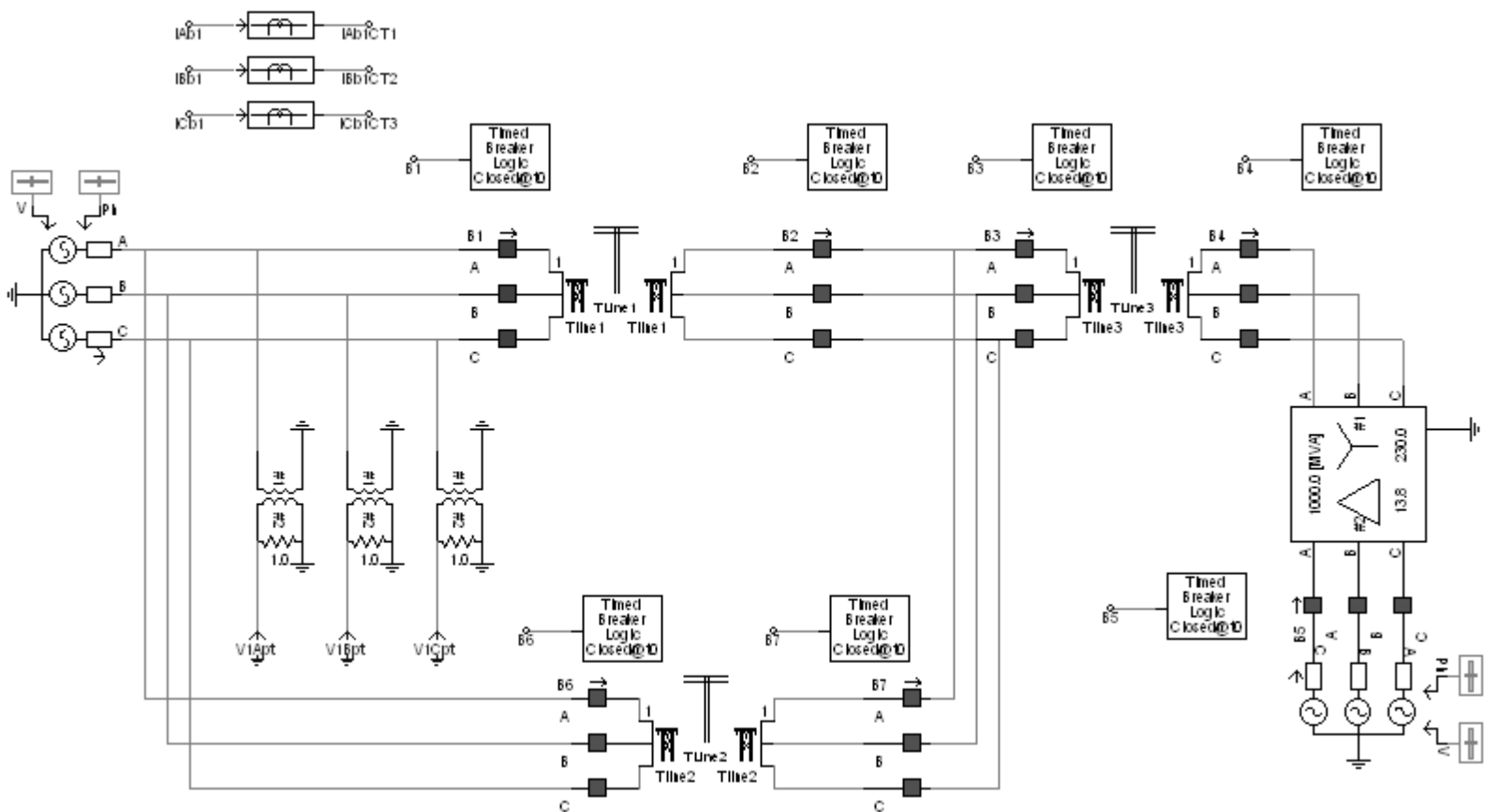


Figure 5.1: System Model in PSCAD

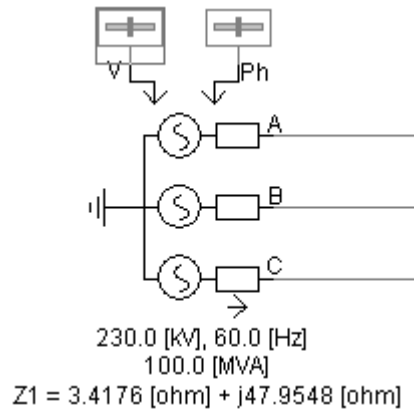


Figure 5.2: Source 1 Model in PSCAD

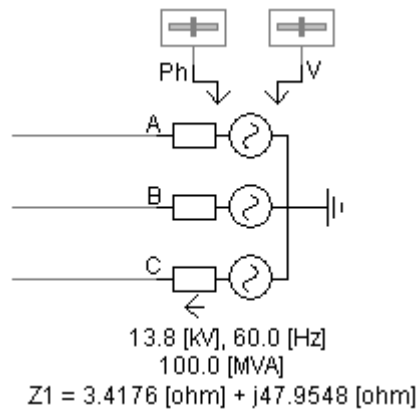


Figure 5.3: Source 2 Model in PSCAD

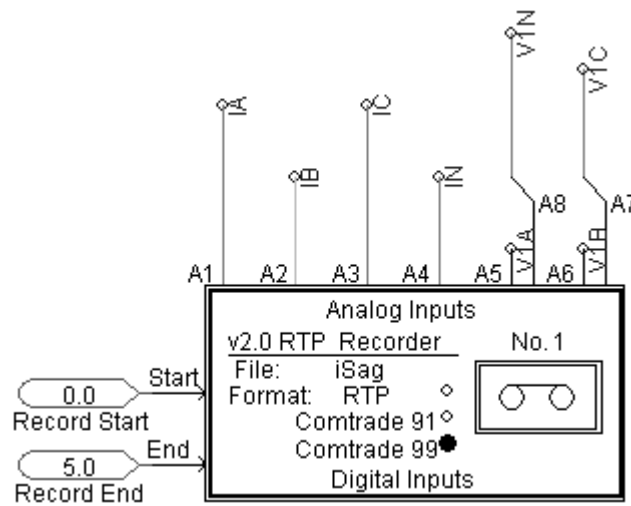


Figure 5.4: Comtrade Recorder Model in PSCAD

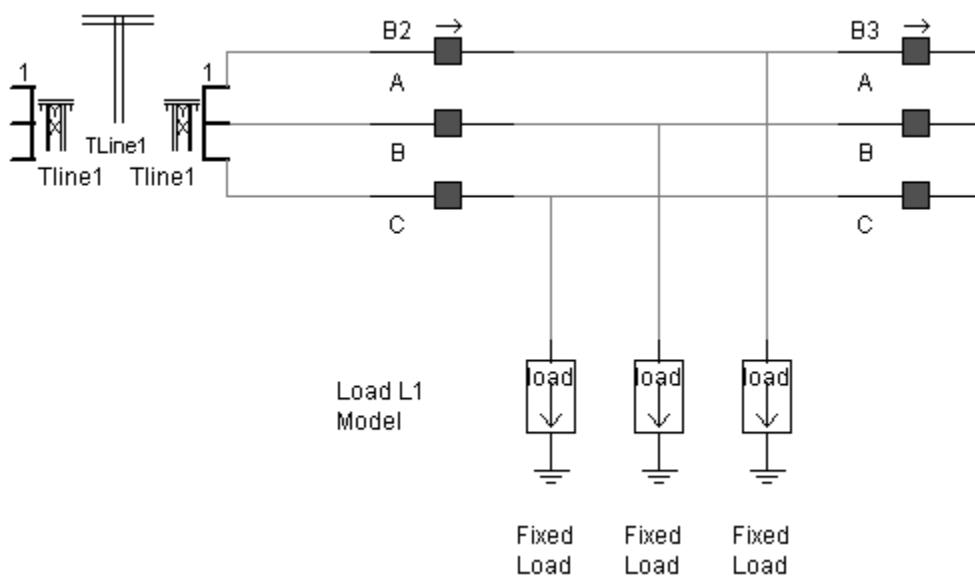


Figure 5.5: Load 1 Model in PSCAD

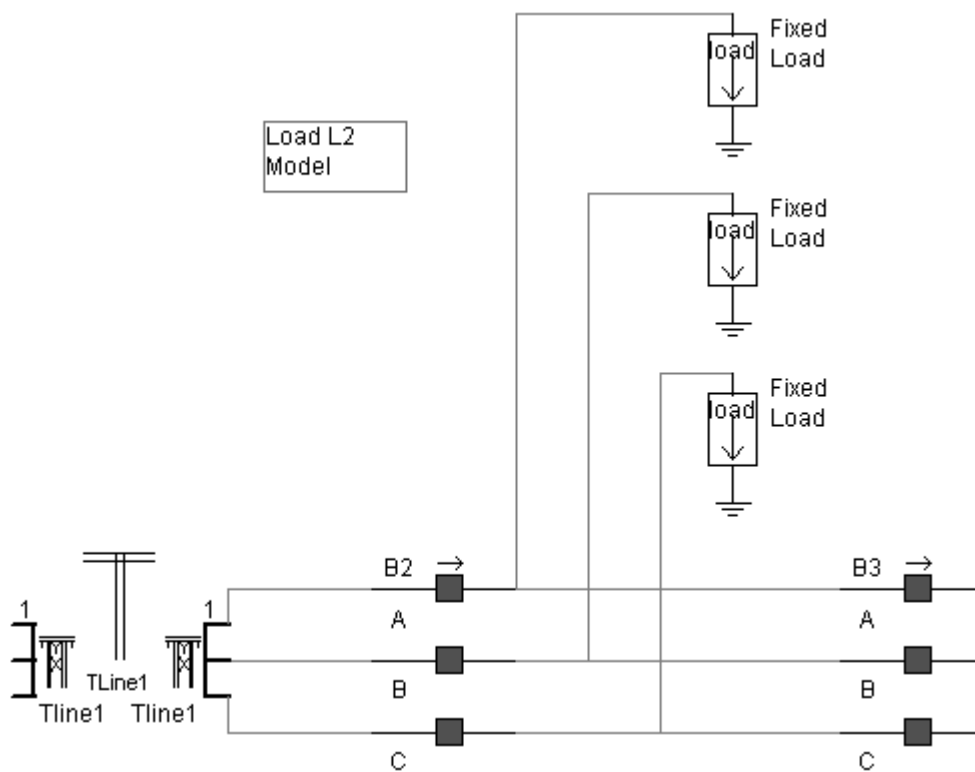


Figure 5.6: Load 2 Model in PSCAD

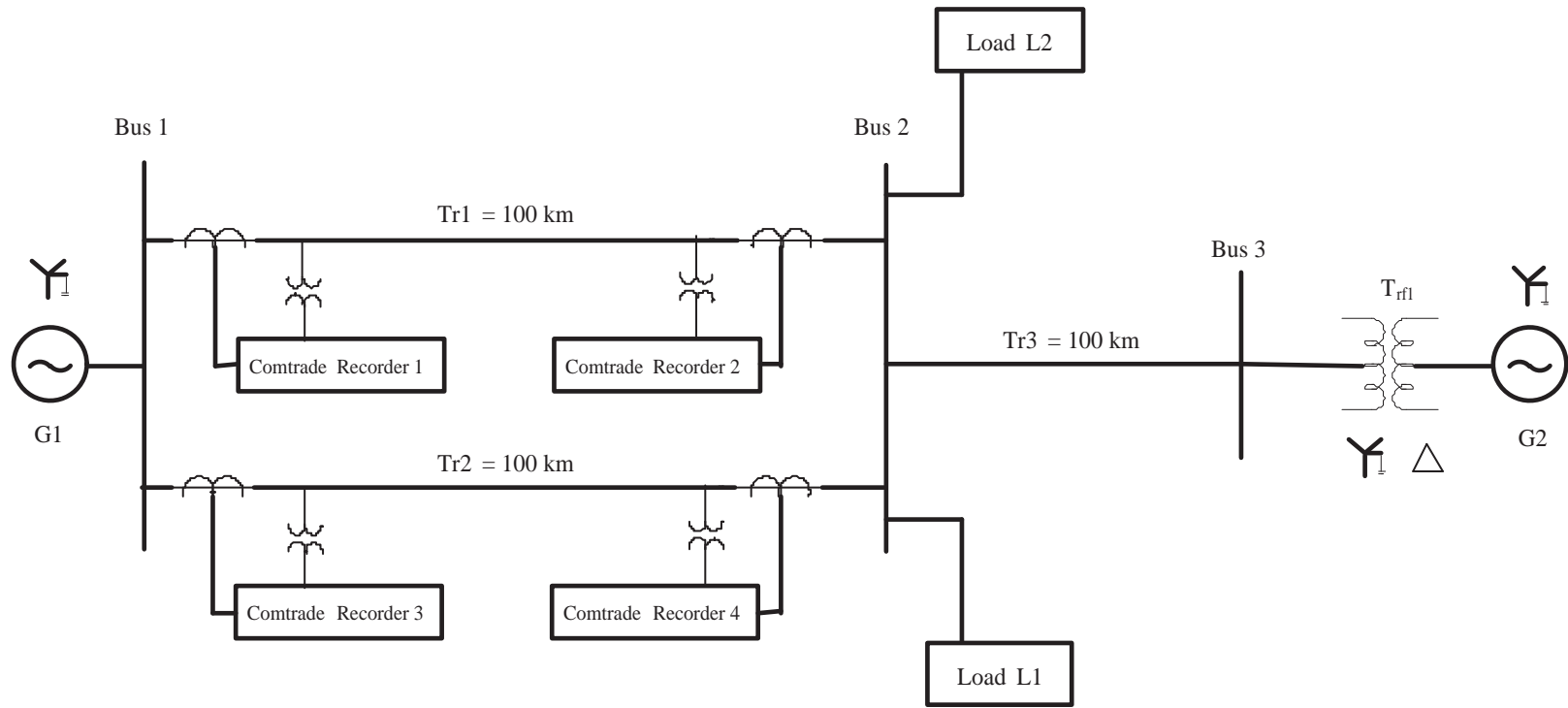


Figure 5.7: Single Line Diagram of the System - Model used for Generating Data

5.5 Test Cases using Simulated Data

Faults were simulated on all the three transmission lines of the system shown in Figure 5.7. One hundred fifty studies, listed in Tables 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6, were conducted. The parameters that were varied are fault type, fault location, and fault resistance. The impact of these changes on both the techniques were evaluated.

The cases listed in Tables 5.1, 5.2 and 5.3, were simulated using the calculation step of $50 \mu\text{s}$. The fault resistance was 0.001Ω . Fault types and fault locations were varied in these cases.

Single phase to ground faults listed in Tables 5.4, 5.5 and 5.6, were also simulated. The fault locations and fault resistance, were varied in these cases.

The length of the transmission line was varied in some cases.

5.6 Case Studies

The following cases are discussed in this section.

1. Three phase to ground fault at 25 km on the line T_{r1}
2. Three phase to ground fault at 25 km on the line T_{r1}
3. Three phase to ground fault at 25 km on the line T_{r1}
4. Three phase to ground fault at 25 km for a line length 520 km on the line T_{r2}
5. Three phase to ground fault at 25 km for a line length 520 km on the line T_{r1}
6. Three phase to ground fault at 25 km for a line length 100 km on the line T_{r1}
7. Three phase to ground fault at 25 km for a line length 600 km on the line T_{r2}
8. Three phase to ground fault at 25 km for a line length 600 km on the line T_{r2}
9. Three phase to ground fault at 25 km for a line length 400 km on the line T_{r2}
10. Three phase to ground fault at 25 km for a line length 520 km on the line T_{r2}

5.6.1 Sag

5.6.1.1 Instantaneous Sag

A three phase to ground fault was simulated on the line T_{r1} of length 100 km at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu\text{s}$
2. Fault ON resistance of 0.001Ω

Table 5.1: List of Studies for Different Fault Types at Different Locations

Case No.	Fault Type	Fault Location
1	Single Phase to ground fault	T_{r1} - 0 km
2	Single Phase to ground fault	T_{r1} - 25 km
3	Single Phase to ground fault	T_{r1} - 50 km
4	Single Phase to ground fault	T_{r1} - 75 km
5	Single Phase to ground fault	T_{r1} - 100 km
6	Two phase fault	T_{r1} - 0 km
7	Two phase fault	T_{r1} - 25 km
8	Two phase fault	T_{r1} - 50 km
9	Two phase fault	T_{r1} - 75 km
10	Two phase fault	T_{r1} - 100 km
11	Two phase to ground fault	T_{r1} - 0 km
12	Two phase to ground fault	T_{r1} - 25 km
13	Two phase to ground fault	T_{r1} - 50 km
14	Two phase to ground fault	T_{r1} - 75 km
15	Two phase to ground fault	T_{r1} - 100 km
16	Three phase fault	T_{r1} - 0 km
17	Three phase fault	T_{r1} - 25 km
18	Three phase fault	T_{r1} - 50 km
19	Three phase fault	T_{r1} - 75 km
20	Three phase fault	T_{r1} - 100 km
21	Three phase to ground fault	T_{r1} - 0 km
22	Three phase to ground fault	T_{r1} - 25 km
23	Three phase to ground fault	T_{r1} - 50 km
24	Three phase to ground fault	T_{r1} - 75 km
25	Three phase to ground fault	T_{r1} - 100 km
26	Single Phase to ground fault	T_{r2} - 0 km
27	Single Phase to ground fault	T_{r2} - 25 km
28	Single Phase to ground fault	T_{r2} - 50 km
29	Single Phase to ground fault	T_{r2} - 75 km
30	Single Phase to ground fault	T_{r2} - 100 km
31	Two phase fault	T_{r2} - 0 km
32	Two phase fault	T_{r2} - 25 km
33	Two phase fault	T_{r2} - 50 km
34	Two phase fault	T_{r2} - 75 km
35	Two phase fault	T_{r2} - 100 km

Table 5.2: List of Studies for Different Fault Types at Different Locations

Case No.	Fault Type	Fault Location
36	Two phase to ground fault	T_{r2} - 0 km
37	Two phase to ground fault	T_{r2} - 25 km
38	Two phase to ground fault	T_{r2} - 50 km
39	Two phase to ground fault	T_{r2} - 75 km
40	Two phase to ground fault	T_{r2} - 100 km
41	Three phase fault	T_{r2} - 0 km
42	Three phase fault	T_{r2} - 25 km
43	Three phase fault	T_{r2} - 50 km
44	Three phase fault	T_{r2} - 75 km
45	Three phase fault	T_{r2} - 100 km
46	Three phase to ground fault	T_{r2} - 0 km
47	Three phase to ground fault	T_{r2} - 25 km
48	Three phase to ground fault	T_{r2} - 50 km
49	Three phase to ground fault	T_{r2} - 75 km
50	Three phase to ground fault	T_{r2} - 100 km
51	Single Phase to ground fault	T_{r3} - 0 km
52	Single Phase to ground fault	T_{r3} - 25 km
53	Single Phase to ground fault	T_{r3} - 50 km
54	Single Phase to ground fault	T_{r3} - 75 km
55	Single Phase to ground fault	T_{r3} - 100 km
56	Two phase fault	T_{r3} - 0 km
57	Two phase fault	T_{r3} - 25 km
58	Two phase fault	T_{r3} - 50 km
59	Two phase fault	T_{r3} - 75 km
60	Two phase fault	T_{r3} - 100 km
61	Two phase to ground fault	T_{r3} - 0 km
62	Two phase to ground fault	T_{r3} - 25 km
63	Two phase to ground fault	T_{r3} - 50 km
64	Two phase to ground fault	T_{r3} - 75 km
65	Two phase to ground fault	T_{r3} - 100 km
66	Three phase fault	T_{r3} - 0 km
67	Three phase fault	T_{r3} - 25 km
68	Three phase fault	T_{r3} - 50 km
69	Three phase fault	T_{r3} - 75 km
70	Three phase fault	T_{r3} - 100 km

Table 5.3: List of Studies for Different Fault Types at Different Locations

Case No.	Fault Type	Fault Location
71	Three phase to ground fault	T_{r3} - 0 km
72	Three phase to ground fault	T_{r3} - 25 km
73	Three phase to ground fault	T_{r3} - 50 km
74	Three phase to ground fault	T_{r3} - 75 km
75	Three phase to ground fault	T_{r3} - 100 km

Table 5.4: List of Studies for Different Fault Resistances at Different Locations

Case No.	Fault Location	Parameter Changed	Value of the parameter
1	T_{r1} - 0 km	Fault Resistance	0.01 Ω
2	T_{r1} - 25 km	Fault Resistance	0.01 Ω
3	T_{r1} - 50 km	Fault Resistance	0.01 Ω
4	T_{r1} - 75 km	Fault Resistance	0.01 Ω
5	T_{r1} - 100 km	Fault Resistance	0.01 Ω
6	T_{r1} - 0 km	Fault Resistance	10 Ω
7	T_{r1} - 25 km	Fault Resistance	10 Ω
8	T_{r1} - 50 km	Fault Resistance	10 Ω
9	T_{r1} - 75 km	Fault Resistance	10 Ω
10	T_{r1} - 100 km	Fault Resistance	10 Ω
11	T_{r1} - 0 km	Fault Resistance	50 Ω
12	T_{r1} - 25 km	Fault Resistance	50 Ω
13	T_{r1} - 50 km	Fault Resistance	50 Ω
14	T_{r1} - 75 km	Fault Resistance	50 Ω
15	T_{r1} - 100 km	Fault Resistance	50 Ω
16	T_{r1} - 0 km	Fault Resistance	70 Ω
17	T_{r1} - 25 km	Fault Resistance	70 Ω
18	T_{r1} - 50 km	Fault Resistance	70 Ω
19	T_{r1} - 75 km	Fault Resistance	70 Ω
20	T_{r1} - 100 km	Fault Resistance	70 Ω
21	T_{r1} - 0 km	Fault Resistance	100 Ω
22	T_{r1} - 25 km	Fault Resistance	100 Ω
23	T_{r1} - 50 km	Fault Resistance	100 Ω
24	T_{r1} - 75 km	Fault Resistance	100 Ω
25	T_{r1} - 100 km	Fault Resistance	100 Ω

Table 5.5: List of Studies for Different Fault Resistances at Different Locations

Case No.	Fault Location	Parameter Changed	Value of the parameter
26	T_{r2} - 0 km	Fault Resistance	0.01 Ω
27	T_{r2} - 25 km	Fault Resistance	0.01 Ω
28	T_{r2} - 50 km	Fault Resistance	0.01 Ω
29	T_{r2} - 75 km	Fault Resistance	0.01 Ω
30	T_{r2} - 100 km	Fault Resistance	0.01 Ω
31	T_{r2} - 0 km	Fault Resistance	10 Ω
32	T_{r2} - 25 km	Fault Resistance	10 Ω
33	T_{r2} - 50 km	Fault Resistance	10 Ω
34	T_{r2} - 75 km	Fault Resistance	10 Ω
35	T_{r2} - 100 km	Fault Resistance	10 Ω
36	T_{r2} - 0 km	Fault Resistance	50 Ω
37	T_{r2} - 25 km	Fault Resistance	50 Ω
38	T_{r2} - 50 km	Fault Resistance	50 Ω
39	T_{r2} - 75 km	Fault Resistance	50 Ω
40	T_{r2} - 100 km	Fault Resistance	50 Ω
41	T_{r2} - 0 km	Fault Resistance	70 Ω
42	T_{r2} - 25 km	Fault Resistance	70 Ω
43	T_{r2} - 50 km	Fault Resistance	70 Ω
44	T_{r2} - 75 km	Fault Resistance	70 Ω
45	T_{r2} - 100 km	Fault Resistance	70 Ω
46	T_{r2} - 0 km	Fault Resistance	100 Ω
47	T_{r2} - 25 km	Fault Resistance	100 Ω
48	T_{r2} - 50 km	Fault Resistance	100 Ω
49	T_{r2} - 75 km	Fault Resistance	100 Ω
50	T_{r2} - 100 km	Fault Resistance	100 Ω
51	T_{r3} - 0 km	Fault Resistance	0.01 Ω
52	T_{r3} - 25 km	Fault Resistance	0.01 Ω
53	T_{r3} - 50 km	Fault Resistance	0.01 Ω
54	T_{r3} - 75 km	Fault Resistance	0.01 Ω
55	T_{r3} - 100 km	Fault Resistance	0.01 Ω
56	T_{r3} - 0 km	Fault Resistance	10 Ω
57	T_{r3} - 25 km	Fault Resistance	10 Ω
58	T_{r3} - 50 km	Fault Resistance	10 Ω
59	T_{r3} - 75 km	Fault Resistance	10 Ω
60	T_{r3} - 100 km	Fault Resistance	10 Ω

Table 5.6: List of Studies for Different Fault Resistances at Different Locations

Case No.	Fault Location	Parameter Changed	Value of the parameter
61	T_{r3} - 0 km	Fault Resistance	50 Ω
62	T_{r3} - 25 km	Fault Resistance	50 Ω
63	T_{r3} - 50 km	Fault Resistance	50 Ω
64	T_{r3} - 75 km	Fault Resistance	50 Ω
65	T_{r3} - 100 km	Fault Resistance	50 Ω
66	T_{r3} - 0 km	Fault Resistance	70 Ω
67	T_{r3} - 25 km	Fault Resistance	70 Ω
68	T_{r3} - 50 km	Fault Resistance	70 Ω
69	T_{r3} - 75 km	Fault Resistance	70 Ω
70	T_{r3} - 100 km	Fault Resistance	70 Ω
71	T_{r3} - 0 km	Fault Resistance	100 Ω
72	T_{r3} - 25 km	Fault Resistance	100 Ω
73	T_{r3} - 50 km	Fault Resistance	100 Ω
74	T_{r3} - 75 km	Fault Resistance	100 Ω
75	T_{r3} - 100 km	Fault Resistance	100 Ω

3. Fault OFF resistance 1000000 Ω
4. Transmission line T_{r1} of length 100 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figure 5.8. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.9(a).

The Instantaneous Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit on phase A at 0.60398 second as shown in 5.9(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The voltage magnitude reached 1.0 per unit at 0.9126 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 0.30862 seconds, it falls within the Instantaneous Sag limits of 0.008333 second to 0.5 seconds.

On phase B the Instantaneous Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.60138 second. The starting time of the event was noted and a counter was incremented for the number of events on phase B. The voltage magnitude reached 1.0 per unit at 0.91806 second. The

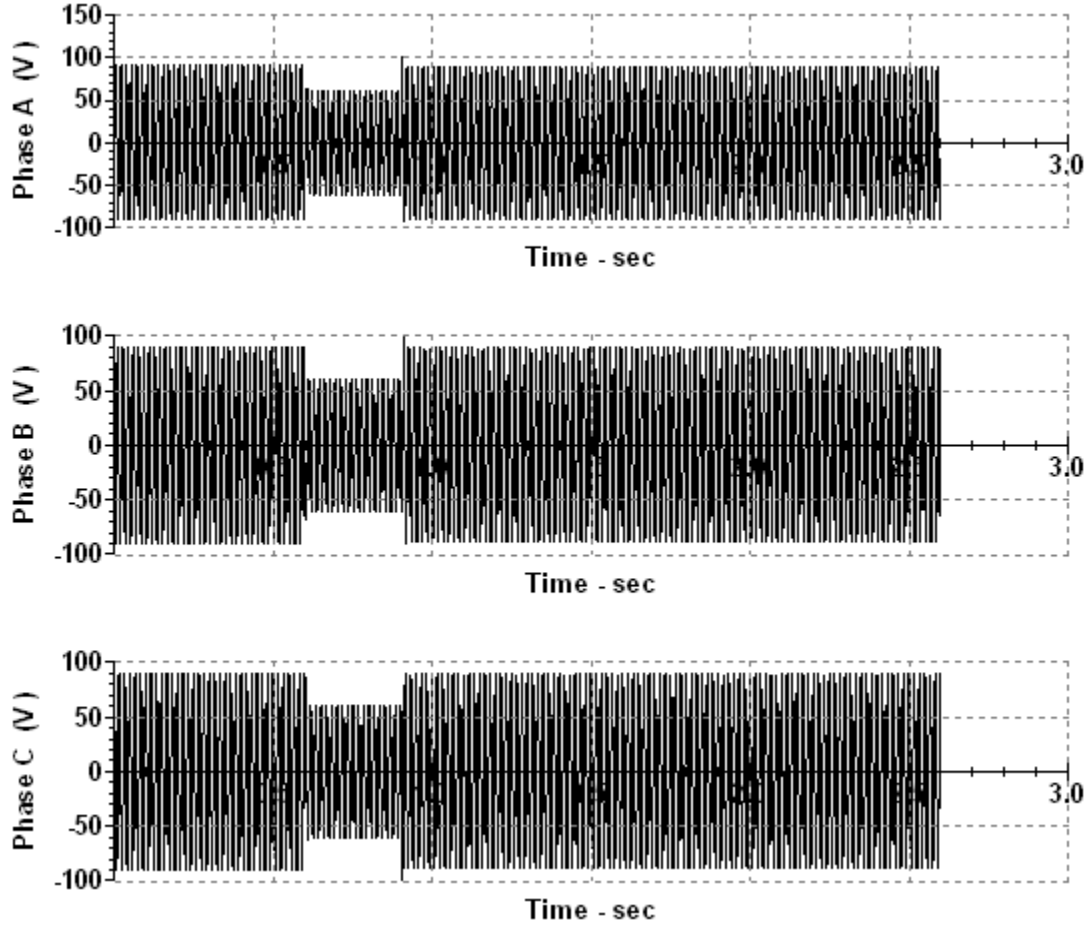
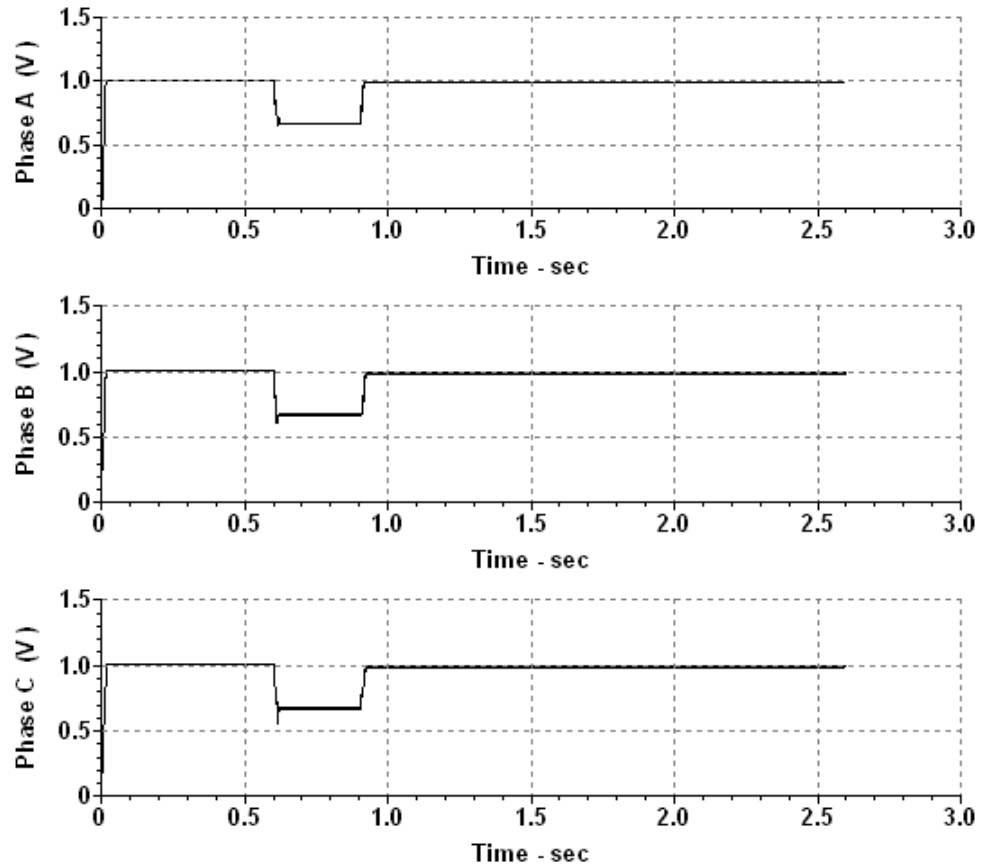


Figure 5.8: Instantaneous Sag Waveform

stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The duration of event on phase B is 0.31668. This falls within the Instantaneous Sag limits of 0.008333 second to 0.5 seconds.

Similarly, on phase C the Instantaneous Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.60476 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The voltage magnitude reached 1.0 per unit at 0.9152 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The duration of event on phase C is 0.31044. This falls within the Instantaneous Sag limits of 0.008333 second to 0.5 seconds.

Figure 5.9(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.



(a) Instantaneous Sag occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	0.60398	0.9126	0.30862

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	0.60138	0.91806	0.31668

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	0.60476	0.9152	0.31044

(b) Instantaneous Sag detected on three phases

Figure 5.9: Instantaneous Sag on Three Phases

5.6.1.2 Momentary Sag

A three phase to ground fault was simulated on the line T_{r1} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu s$
2. Fault ON resistance of 50Ω
3. Fault OFF resistance 1000000Ω
4. Transmission line T_{r1} of length 100 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figure 5.10. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.11(a).

The Momentary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit on phase A at 0.60398 second as shown in 5.11(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The voltage magnitude reached at 1.0 per unit at 3.11246 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 2.50848 seconds, it falls within the Momentary Sag limits of 0.5 second to 3 seconds.

On phase B the Momentary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.60138 second. The starting time of the event was noted and a counter was incremented for the number of events on phase B. The voltage magnitude reached 1.0 per unit at 3.11792 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The duration of event on phase B is 2.51654. This falls within the Momentary Sag limits of 0.5 second to 3 seconds.

Similarly, on phase C the Momentary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.60476 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The voltage magnitude reached 1.0 per unit at 3.11532 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The duration of event on phase C is 2.51056. This falls within the Momentary Sag limits of 0.5 second to 3 seconds.

Figure 5.11(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

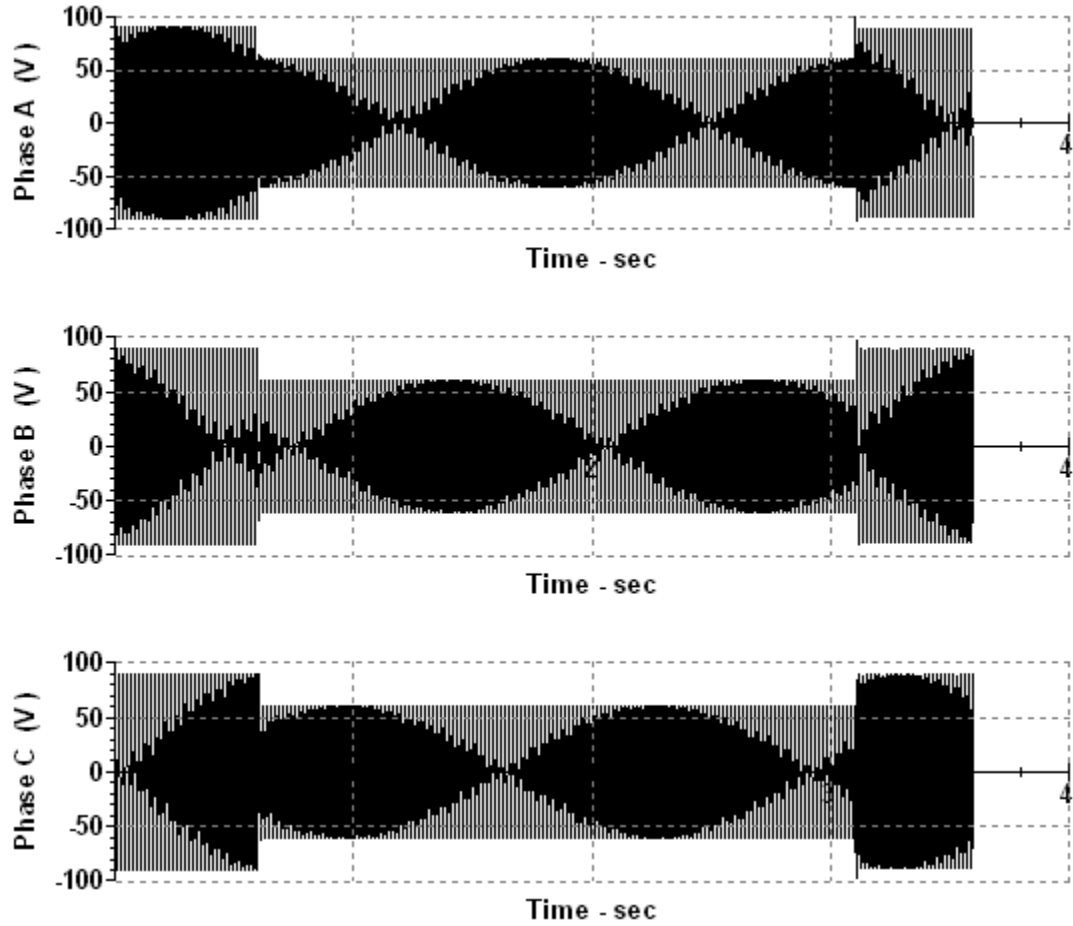


Figure 5.10: Momentary Sag Waveform

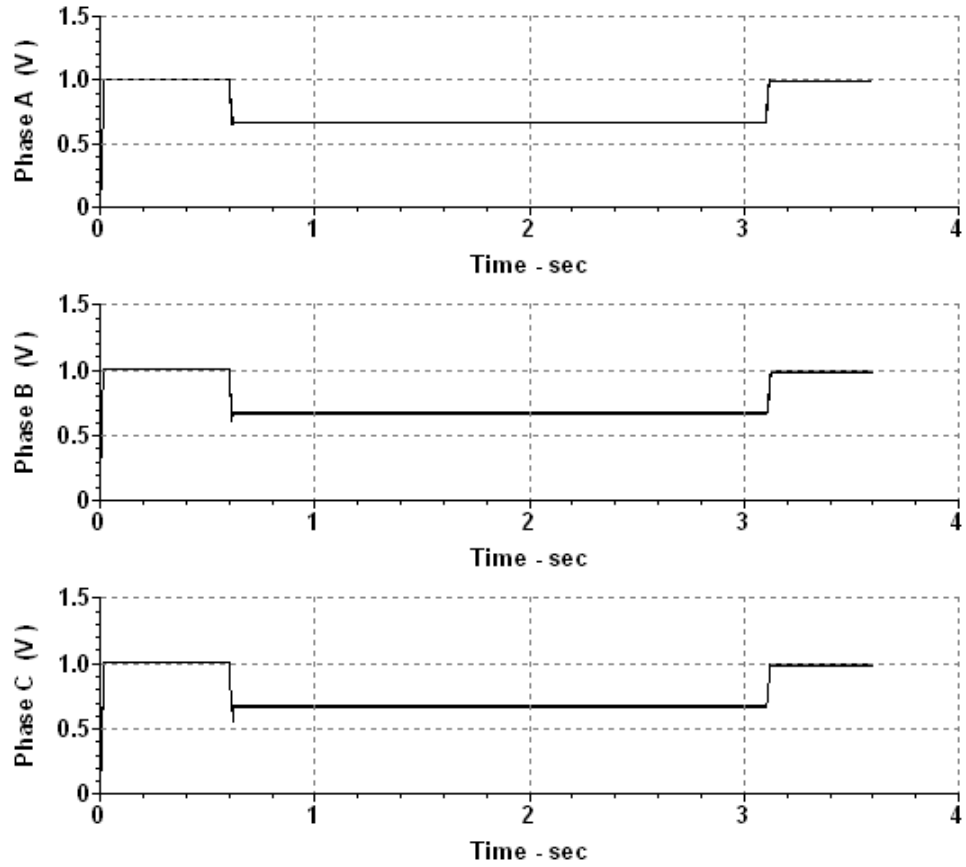
5.6.1.3 Temporary Sag

A three phase to ground fault was simulated on the line T_{r1} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu s$
2. Fault ON resistance of 20Ω
3. Fault OFF resistance 1000000Ω
4. Transmission line T_{r1} of length 100 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figures 5.12, 5.13 and 5.14 respectively. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.15(a).

The Temporary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit on phase A at 0.40274 second as shown in 5.15(a). The starting time of the event was noted and a counter was incremented



(a) Momentary Sag occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Sag	0.60398	3.11246	2.50848

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Sag	0.60138	3.11792	2.51654

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Sag	0.60476	3.11532	2.51056

(b) Momentary Sag detected on three phases

Figure 5.11: Momentary Sag on Three Phases

for the number of events on phase A. The voltage magnitude reached at 1.0 per unit at 6.41914 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 6.0164 seconds, it falls within the Temporary Sag limits of 3 seconds to 60 seconds.

On phase B the Temporary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.4004 second. The starting time of the event was noted and a counter was incremented for the number of events on phase B. The voltage magnitude reached 1.0 per unit at 6.41654 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The duration of event on phase B is 6.01614. This falls within the Temporary Sag limits of 3 seconds to 60 seconds.

Similarly, on phase C the Temporary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit at 0.4004 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The voltage magnitude reached 1.0 per unit at 6.422 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The duration of event on phase C is 6.0216. This falls within the Temporary Sag limits of 3 seconds to 60 seconds.

Figure 5.15(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

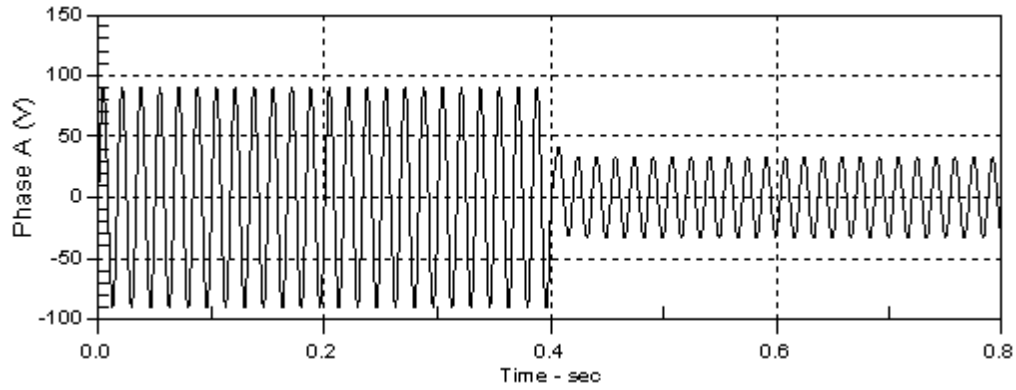
5.6.2 Undervoltage

A three phase to ground fault was simulated on the line T_{r2} at a location of 25 km from Bus 1. The following parameters were used.

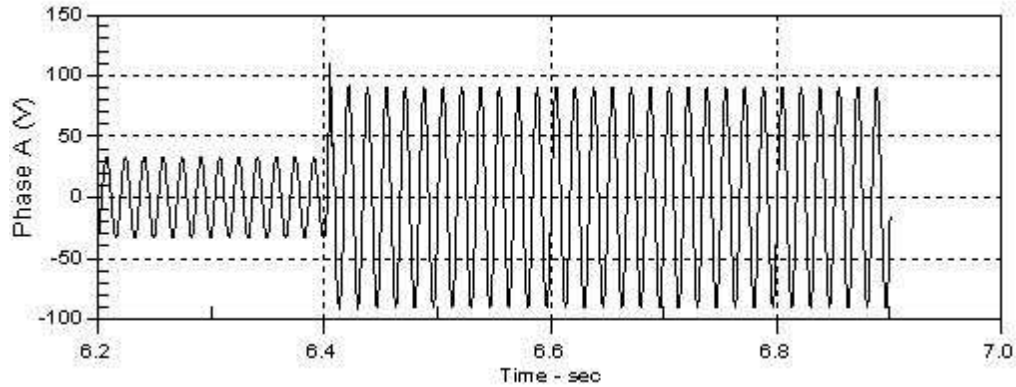
1. Calculation step of $50 \mu\text{s}$
2. Fault ON resistance of 50Ω
3. Fault OFF resistance of 1000000Ω
4. Transmission line T_{r2} of length 520 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figures 5.16, 5.17 and 5.18 respectively. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.19(a).

The Undervoltage algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.8 per unit on phase A at 1.515 second as



(a) Waveform Showing the Beginning of Temporary Sag in Phase A

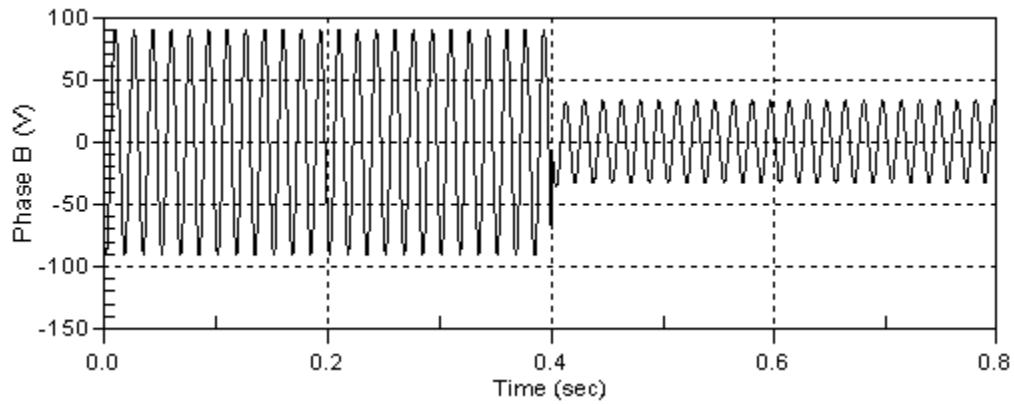


(b) Waveform Showing the End of Temporary Sag in Phase A

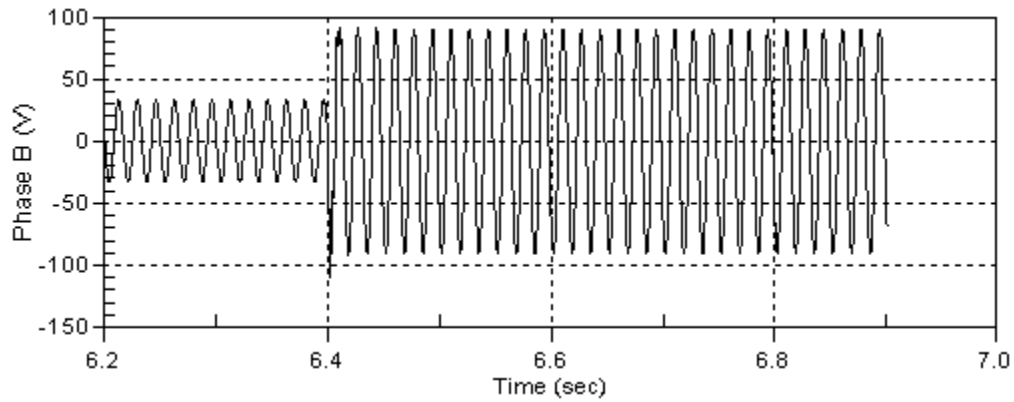
Figure 5.12: Temporary Sag on Phase A

shown in 5.19(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The event lasted till 62.495 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 60.95 seconds which is greater than 60 seconds, it is flagged as an Undervoltage.

On phase B the Undervoltage algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.8 per unit at 1.53 second. The starting time of the event was noted and a counter was incremented for the number of events on phase B. The event lasted till 62.495 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 60.965 seconds which is greater than 60 seconds, it is flagged as an Undervoltage.



(a) Waveform Showing the Beginning of Temporary Sag in Phase B

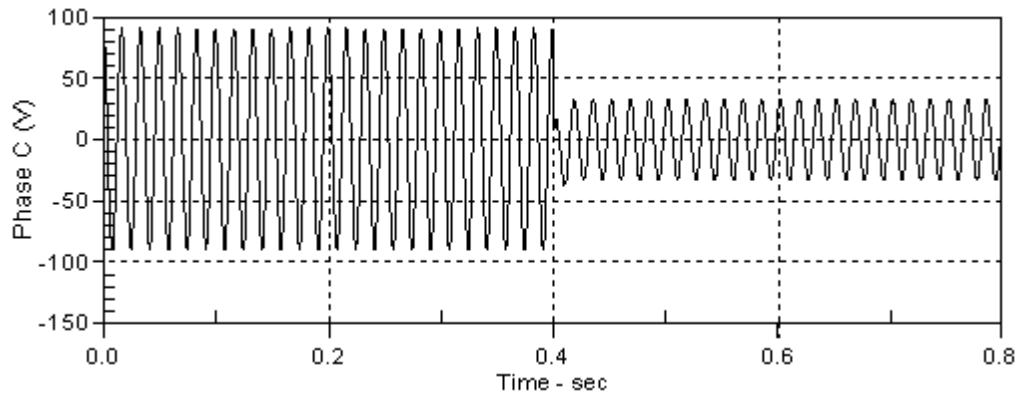


(b) Waveform Showing the End of Temporary Sag in Phase B

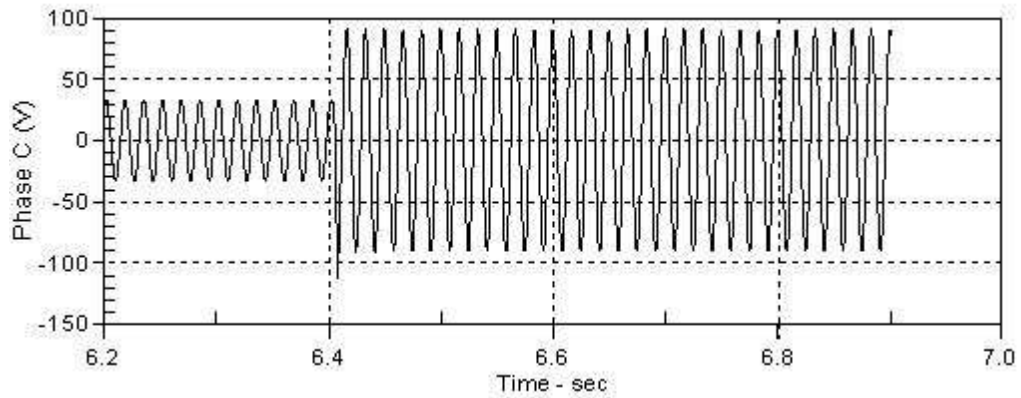
Figure 5.13: Temporary Sag on Phase B

Similarly, on phase C the Undervoltage algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.8 per unit at 1.53 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The event lasted till 62.495 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 60.965 seconds which is greater than 60 seconds, it is flagged as an Undervoltage.

Figure 5.19(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.



(a) Waveform Showing the Beginning of Temporary Sag in Phase C



(b) Waveform Showing the End of Temporary Sag in Phase C

Figure 5.14: Temporary Sag on Phase C

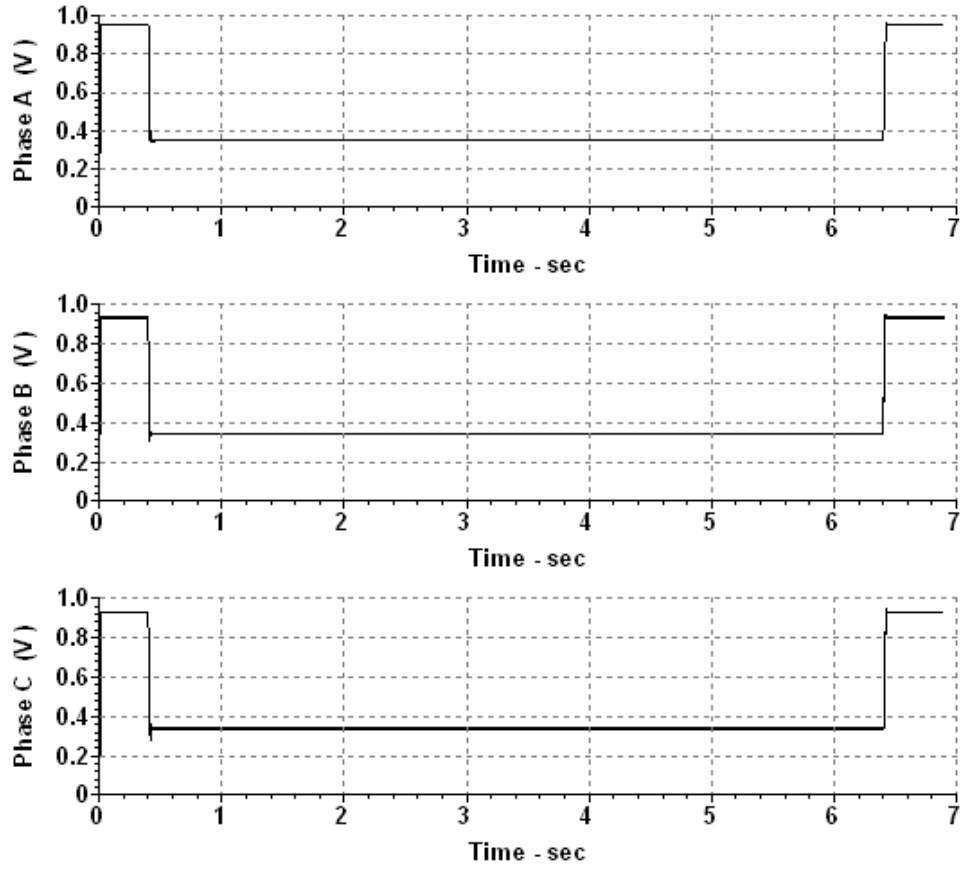
5.6.3 Interruption

5.6.3.1 Momentary Interruption

A three phase to ground fault was simulated on the line T_{r1} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu s$
2. Fault ON resistance of 50Ω
3. Fault OFF resistance 1000000Ω
4. Transmission line T_{r1} of length 520 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figure 5.20. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.21.



(a) Temporary Sag occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Temporary Sag	0.40274	6.41914	6.0164

Events Detected - Phase B

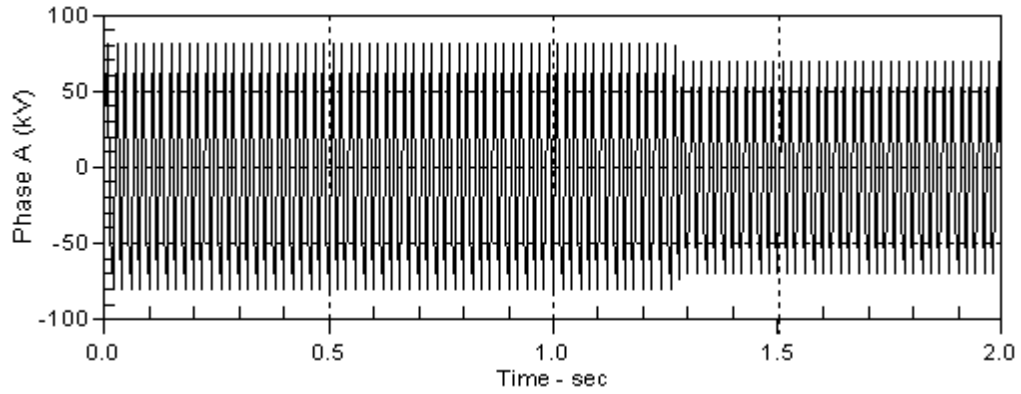
S.No	Event Type	Start Time	End Time	Duration
1	Temporary Sag	0.4004	6.41654	6.01614

Events Detected - Phase C

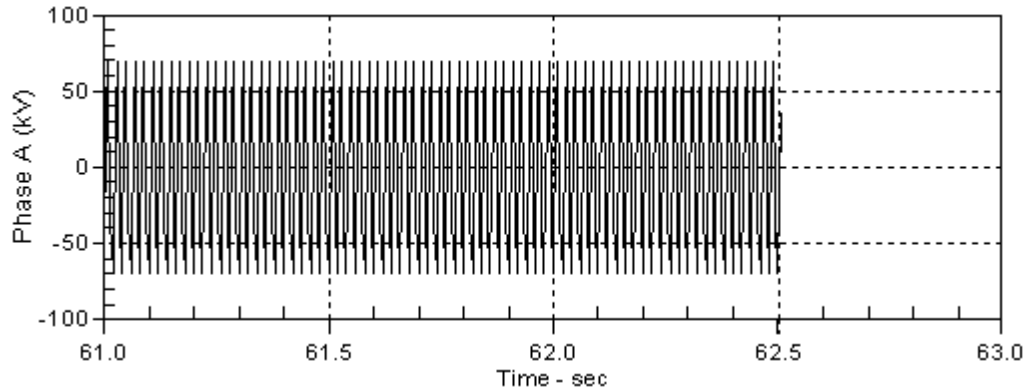
S.No	Event Type	Start Time	End Time	Duration
1	Temporary Sag	0.4004	6.422	6.0216

(b) Temporary Sag detected on three phases

Figure 5.15: Temporary Sag on Three Phases



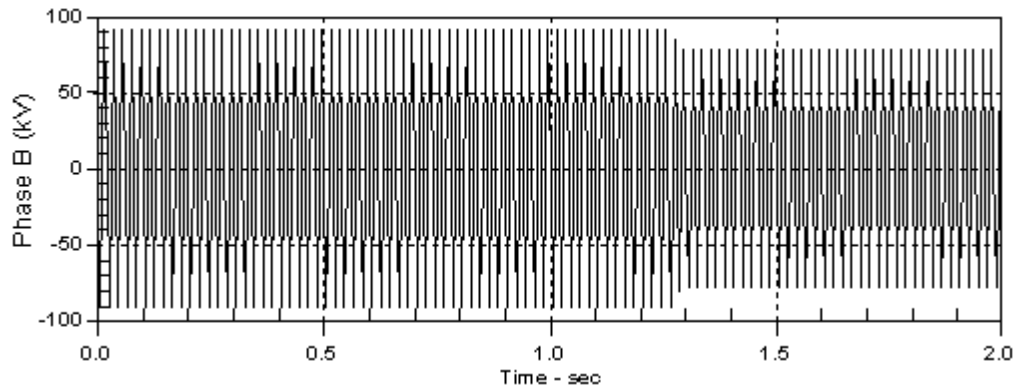
(a) Waveform Showing the Beginning of Undervoltage in Phase A



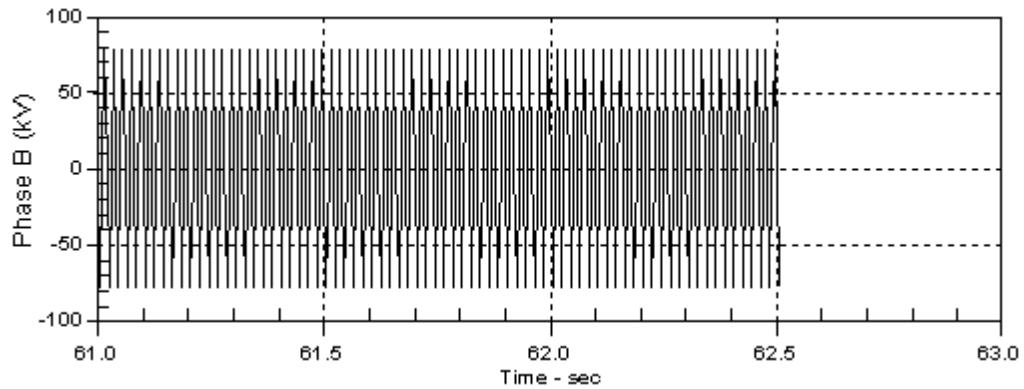
(b) Waveform Showing the End of Undervoltage in Phase A

Figure 5.16: Undervoltage on Phase A

An Instantaneous Sag of 0.001222 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase A. The Momentary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase A at 1.6159 second as shown in 5.21. The starting time of the Momentary Interruption event was noted and the counter was incremented by one for the number of events on phase A. The counter had a value of 2 as two events had occurred. The voltage magnitude became more than 0.1 per unit at 3.6023 second. The stopping time of the event was noted. The time duration of the Momentary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 1.9864 seconds, it falls within the Momentary Interruption limits of 0.008333 second to 3 seconds. An Instantaneous Sag of 0.001144 seconds is detected after the end of Momentary Interruption. The counter had now a value of three. The counter was stopped at this instant. In this case three types of event occurs on phase A. The Instantaneous Sag before the beginning and at the end of Momentary Interruption is due to the fact that



(a) Waveform Showing the Beginning of Undervoltage in Phase B

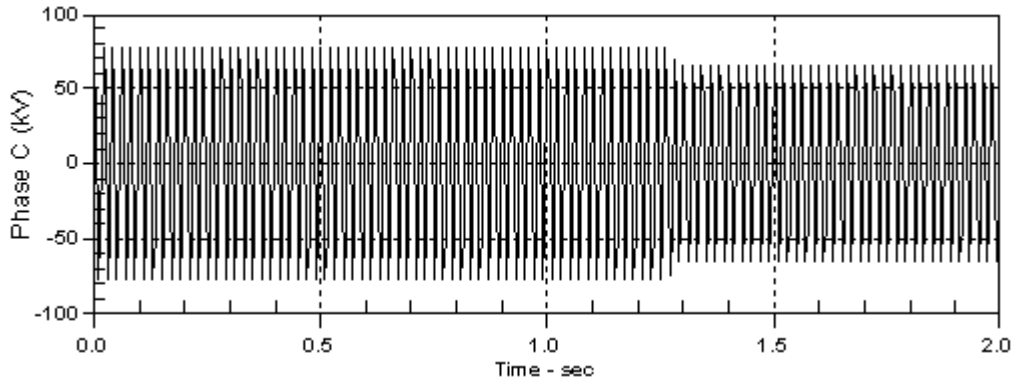


(b) Waveform Showing the End of Undervoltage in Phase B

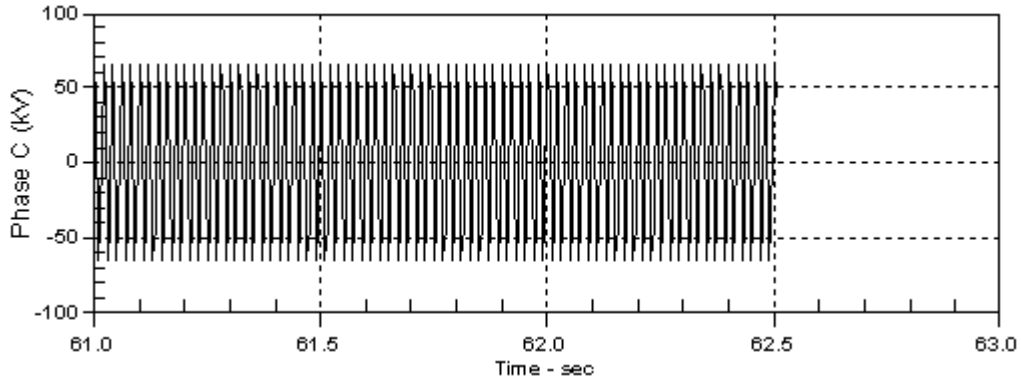
Figure 5.17: Undervoltage on Phase B

the voltage does not drop immediately to less than 0.1 per unit.

An Instantaneous Sag of 0.001196 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase B. The Momentary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase B at 1.6211 second as shown in 5.21. The starting time of the Momentary Interruption event was noted and the counter was incremented by one for the number of events on phase B. The counter had a value of 2 as two events had occurred. The voltage magnitude became more than 0.1 per unit at 3.6023 second. The stopping time of the event was noted. The time duration of the Momentary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 1.9799 seconds, it falls within the Momentary Interruption limits of 0.008333 second to 3 seconds. An Instantaneous Sag of 0.001196 seconds is detected after the end of Momentary Interruption. The counter had now a value of three. The counter was stopped at this instant. In this case three types of event occurs on phase B. The Instantaneous



(a) Waveform Showing the Beginning of Undervoltage in Phase C

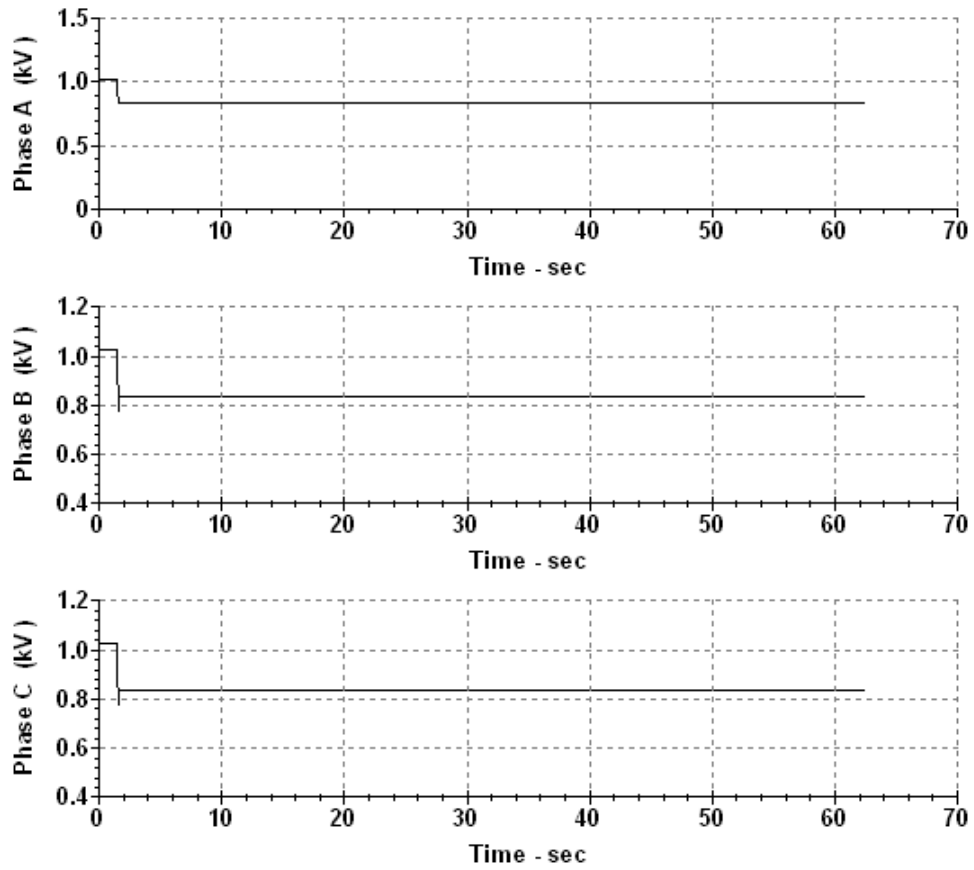


(b) Waveform Showing the End of Undervoltage in Phase C

Figure 5.18: Undervoltage on Phase C

Sag before the beginning and at the end of Momentary Interruption is due to the fact that the voltage does not drop immediately to less than 0.1 per unit.

An Instantaneous Sag of 0.001196 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase C. The Momentary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase C at 1.61824 second as shown in 5.21. The starting time of the Momentary Interruption event was noted and the counter was incremented by one for the number of events on phase C. The counter had a value of 2 as two events had occurred. The voltage magnitude became more than 0.1 per unit at 3.60126 second. The stopping time of the event was noted. The time duration of the Momentary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 1.98302 seconds, it falls within the Momentary Interruption limits of 0.008333 second to 3 seconds. An Instantaneous Sag of 0.001143 seconds is detected after the end of Momentary Interruption. The counter had now a value of three. The counter was stopped



(a) Undervoltage occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Under Voltage	1.515	62.495	60.98

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Under Voltage	1.53	62.495	60.965

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Under Voltage	1.53	62.495	60.965

(b) Undervoltage detected on three phases

Figure 5.19: Undervoltage on Three Phases

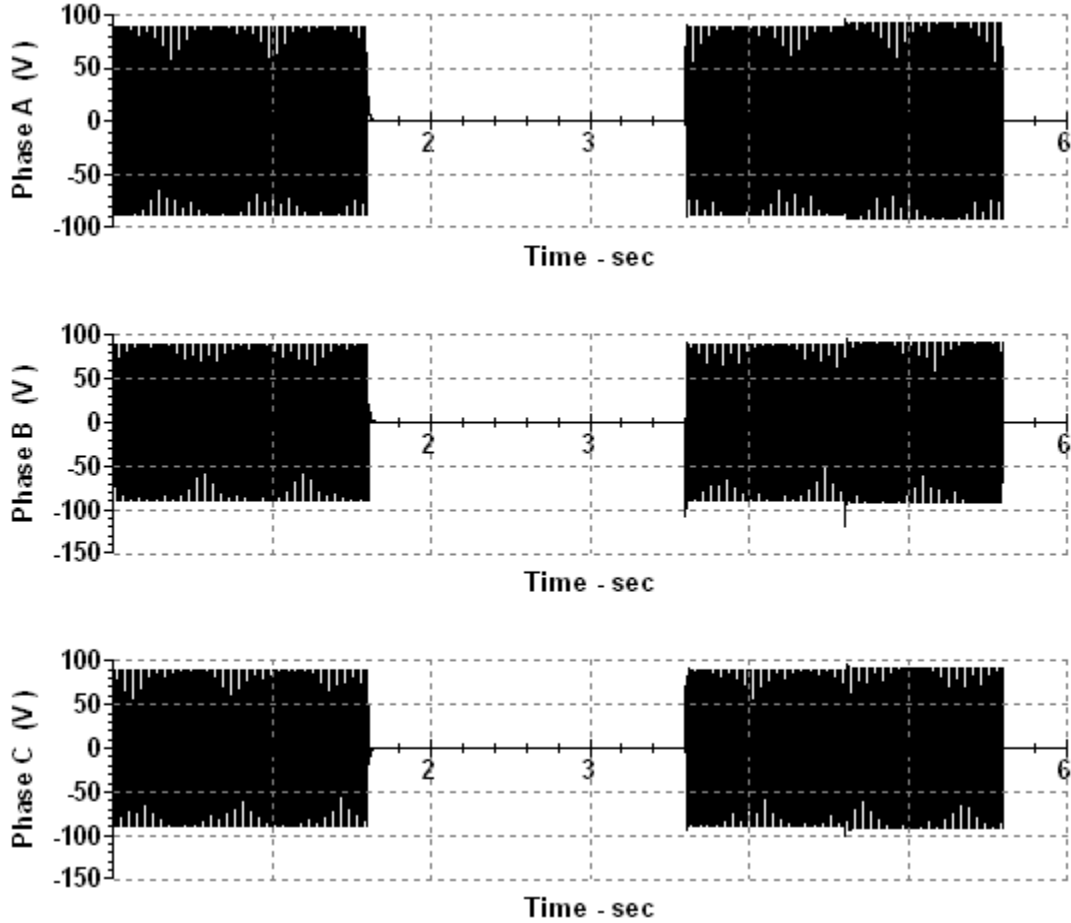


Figure 5.20: Momentary Interruption Waveform

at this instant. In this case three types of event occurs on phase C. The Instantaneous Sag before the beginning and at the end of Momentary Interruption is due to the fact that the voltage does not drop immediately to less than 0.1 per unit.

Figure 5.22 shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.3.2 Temporary Interruption

A three phase to ground fault was simulated on the line T_{r1} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu s$
2. Fault ON resistance of 50Ω
3. Fault OFF resistance 1000000Ω
4. Transmission line T_{r1} of length 100 km

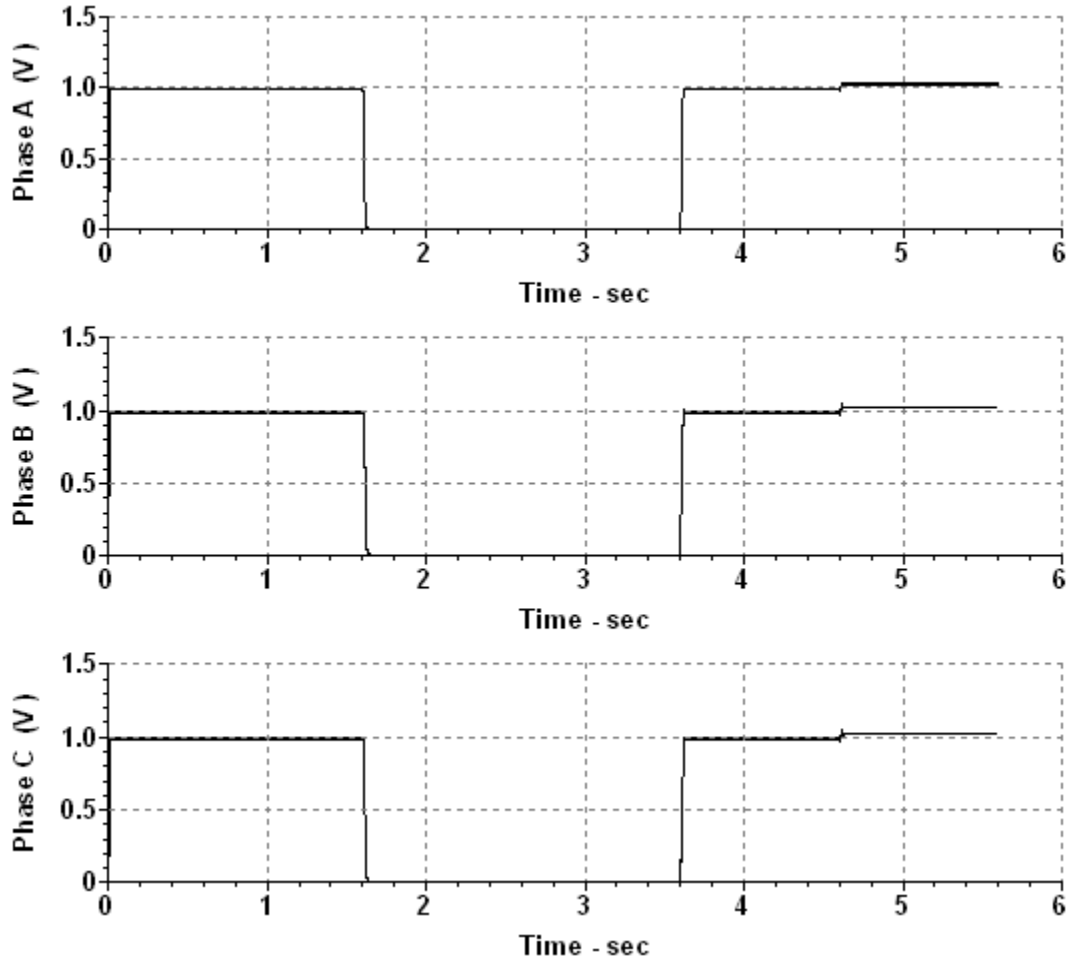


Figure 5.21: Momentary Interruption Occurred on Three Phases

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 1 are shown in Figure 5.23. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.24.

An Instantaneous Sag of 0.001222 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase A. The Temporary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase A at 1.6159 second as shown in 5.24. The starting time of the Temporary Interruption event was noted and the counter was incremented by one for the number of events on phase A. The counter had a value of 2 as two events had occurred. The voltage magnitude became greater than 0.1 per unit at 5.1025 second. The stopping time of the event was noted. The time duration of the Temporary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 3.4866 seconds, it falls within the Temporary Interruption limits of 3 second to 60 seconds. An Instantaneous Sag of 0.001092 seconds is detected after the end of Temporary Interruption. The counter had now a value of 3. The counter was stopped at this instant.

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.60342	1.61564	1.222e-002
2	Momentary Interruption	1.6159	3.6023	1.9864
3	Instantaneous Sag	3.60256	3.614	1.144e-002

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.60888	1.62084	1.196e-002
2	Momentary Interruption	1.6211	3.601	1.9799
3	Instantaneous Sag	3.60126	3.61322	1.196e-002

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.60602	1.61798	1.196e-002
2	Momentary Interruption	1.61824	3.60126	1.98302
3	Instantaneous Sag	3.60152	3.61582	1.43e-002

Figure 5.22: Momentary Interruption Detected on Three Phases

In this case three types of event occurs on phase A. The Instantaneous Sag before the beginning and at the end of Temporary Interruption is due to the fact that the voltage does not drop immediately to less than 0.1 per unit.

An Instantaneous Sag of 0.001170 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase B. The Temporary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase B at 1.6211 second as shown in 5.24. The starting time of the Temporary Interruption event was noted and the counter was incremented by one for the number of events on phase B. The counter had a value of 2 as two events had occurred. The voltage magnitude became more that 0.1 per unit at 5.1012 second. The stopping time of the event was noted. The time duration of the Temporary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 3.4801 seconds, it falls within the Temporary Interruption limits of 3 second to 60 seconds. An Instantaneous Sag of 0.001066 seconds is detected after the end of Temporary

Interruption. The counter had now a value of 3. The counter was stopped at this instant. In this case three types of event occurs on phase B. The Instantaneous Sag before the beginning and at the end of Momentary Interruption is due to the fact that the voltage does not drop immediately to less than 0.1 per unit.

An Instantaneous Sag of 0.001144 seconds is detected in the beginning and the counter was incremented by one for the number of events on phase C. The Temporary Interruption algorithm implemented in the software detected the first voltage magnitude below 0.1 per unit on phase C at 1.6185 second as shown in 5.24. The starting time of the Temporary Interruption event was noted and the counter was incremented by one for the number of events on phase C. The counter had a value of 2 as two events had occurred. The voltage magnitude became more that 0.1 per unit at 5.10146 second. The stopping time of the event was noted. The time duration of the Momentary Interruption was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 3.48296 seconds, it falls within the Temporary Interruption limits of 3 second to 60 seconds. An Instantaneous Sag of 0.001326 seconds is detected after the end of Temporary Interruption. The counter had now a value of three. The counter was stopped at this instant. In this case three types of event occurs on phase C. The Instantaneous Sag before the beginning and at the end of Temporary Interruption is due to the fact that the voltage does not drop immediately to less than 0.1 per unit.

Figure 5.25 shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.4 Swell

5.6.4.1 Instantaneous Swell

A three phase to ground fault was simulated on the line T_{r2} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of 50 μ s
2. Fault ON resistance of 0.001 Ω
3. Fault OFF resistance 1000000 Ω
4. Transmission line T_{r2} of length 600 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 4 are shown in Figure 5.26. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.27(a).

The Instantaneous Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.8 per unit on phase A at 0.30498 second as shown in 5.27(a). The starting time of the event was noted and a

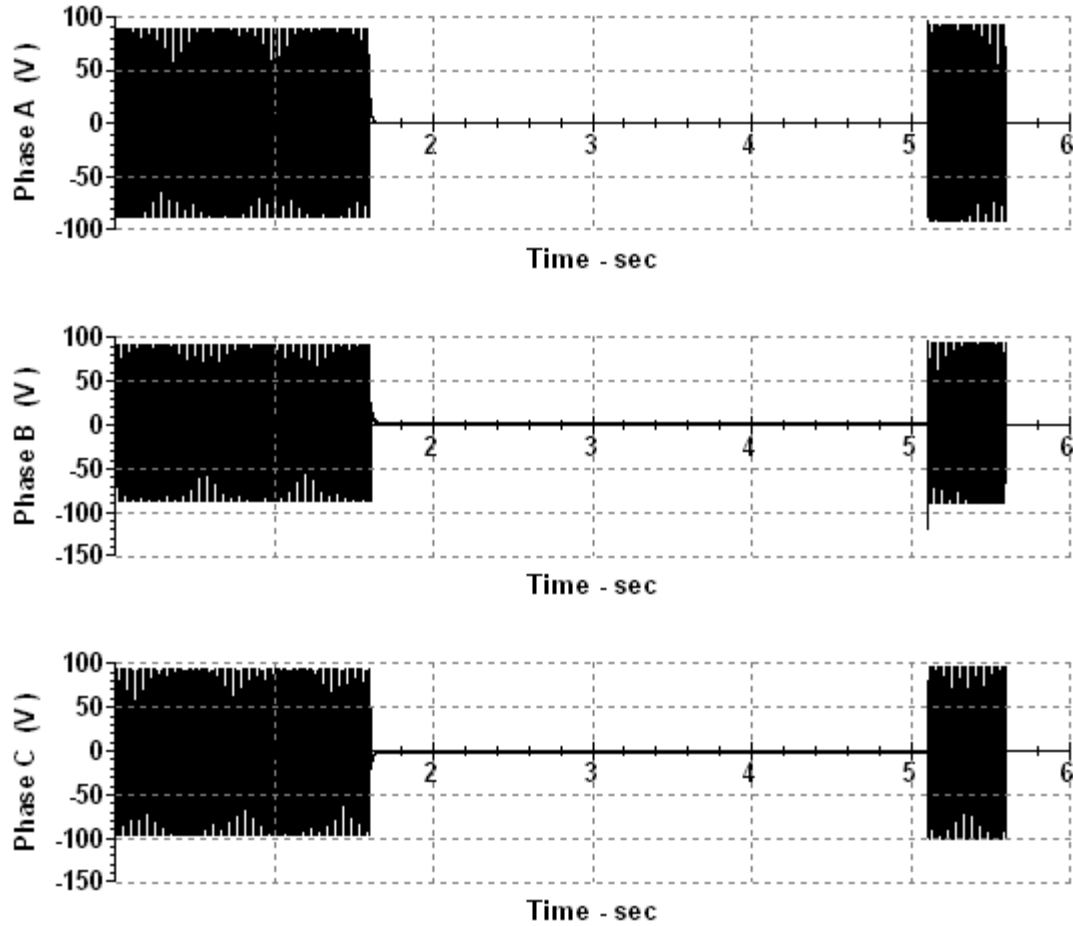


Figure 5.23: Temporary Interruption Waveform

counter was incremented for the number of events on phase A. The voltage magnitude reached 1.0 per unit at 0.71084 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 0.40586 seconds, it falls within the Instantaneous Swell limits of 0.008333 second to 0.5 seconds.

On phase B the Instantaneous Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.8 per unit at 0.31096 second. The starting time of the event was noted and a counter was incremented for the number of events on phase B. The voltage magnitude reached 1.0 per unit at 0.70772 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The duration of event on phase B is 0.39676. This falls within the Instantaneous Swell limits of 0.008333 second to 0.5 seconds.

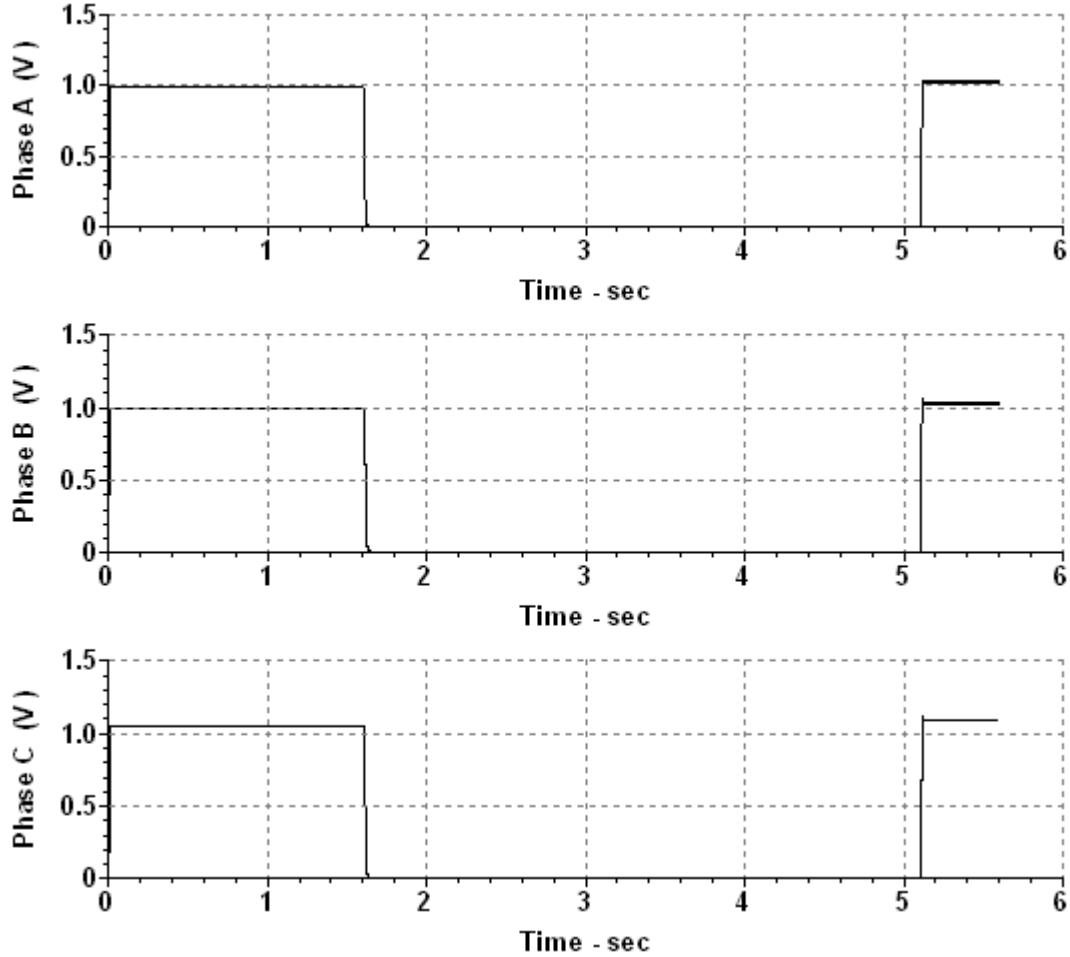


Figure 5.24: Temporary Interruption Occurred on Three Phases

Similarly, on phase C the Instantaneous Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.8 per unit at 0.30862 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The voltage magnitude reached 1.0 per unit at 0.70694 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The duration of event on phase C is 0.39832. This falls within the Instantaneous Swell limits of 0.008333 second to 0.5 seconds.

Figure 5.27(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.4.2 Momentary Swell

A three phase to ground fault was simulated on the line $T_{r,2}$ at a location of 25 km from Bus 1. The following parameters were used.

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.60342	1.61564	1.222e-002
2	Temporary Interruption	1.6159	5.1025	3.4866
3	Instantaneous Sag	5.10276	5.11368	1.092e-002

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.60914	1.62084	1.17e-002
2	Temporary Interruption	1.6211	5.1012	3.4801
3	Instantaneous Sag	5.10146	5.11212	1.066e-002

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Sag	1.6068	1.61824	1.144e-002
2	Temporary Interruption	1.6185	5.10146	3.48296
3	Instantaneous Sag	5.10172	5.11498	1.326e-002

Figure 5.25: Temporary Interruption Detected on Three Phases

1. Calculation step of $50 \mu s$
2. Fault ON resistance of 0.001Ω
3. Fault OFF resistance 1000000Ω
4. Transmission line T_{r2} of length 100 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 4 are shown in Figure 5.28. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.29(a).

The Momentary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.4 per unit on phase A at 0.273 second as shown in 5.29(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The event lasted till 2.79994 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The

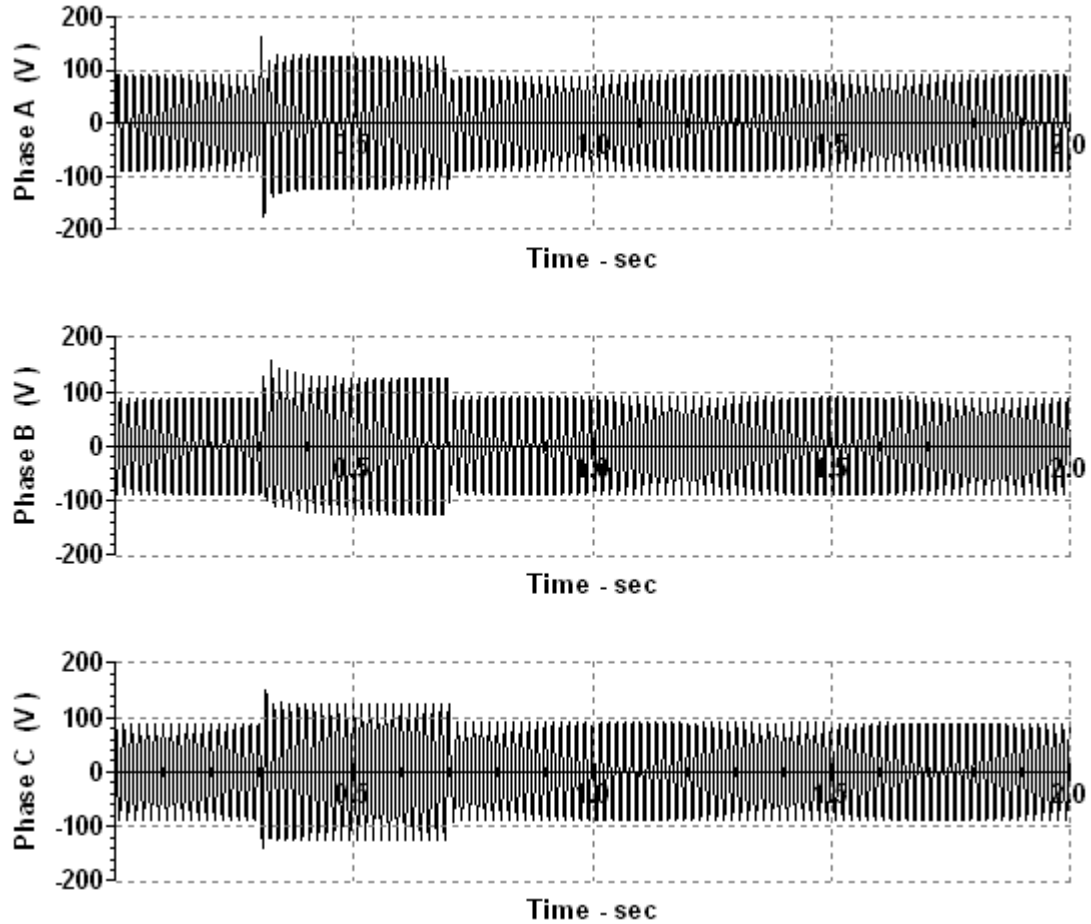
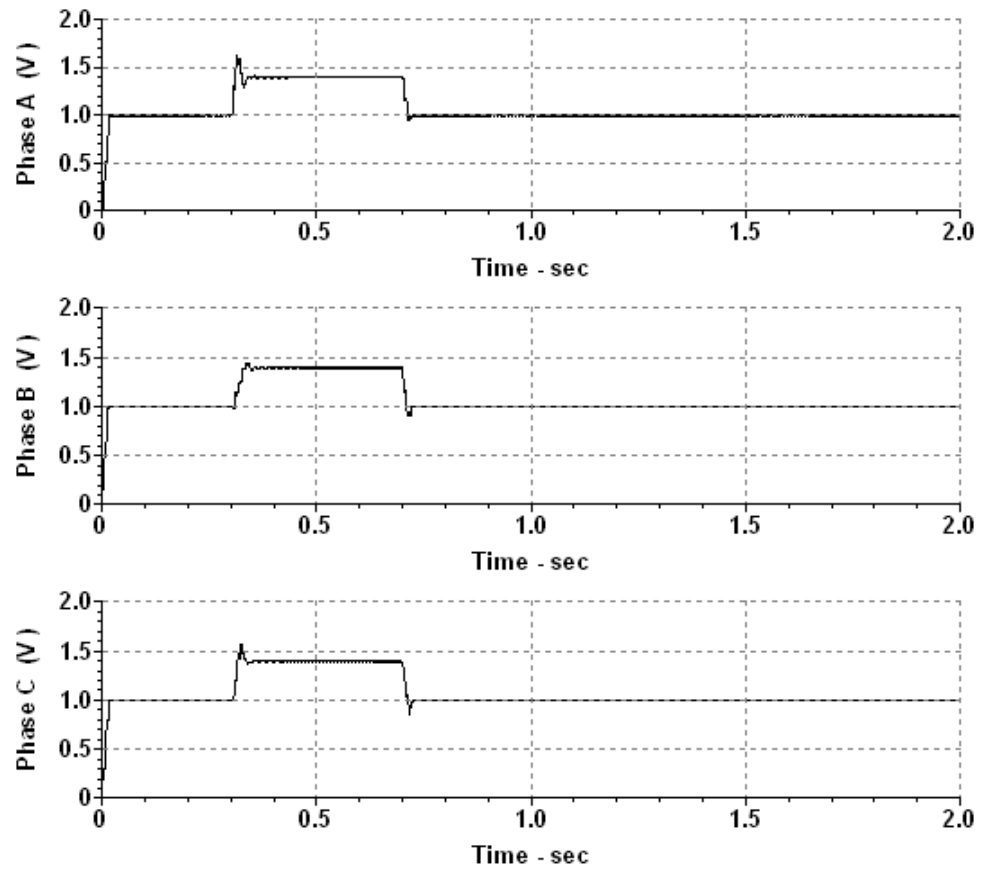


Figure 5.26: Instantaneous Swell Waveform

time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 2.52694 seconds which falls within the limits of 0.5 second to 3 seconds, it is flagged as Momentary Swell.

On phase B the Momentary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than 1.4 per unit at 0.2756 second as shown in 5.29(a). The starting time of the event was noted and a counter was incremented for the number of events on phase B. The event lasted till 2.79994 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 2.52434 seconds which falls within the limits of 0.5 second to 3 seconds, it is flagged as Momentary Swell.

Similarly, on phase C the Momentary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than 1.4 per unit at 0.25948 second as shown in 5.29(a). The starting time of the event was noted and a counter was incremented for the number of events on phase C. The event lasted till 2.79994



(a) Instantaneous Swell occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Swell	0.30498	0.71084	0.40586

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Swell	0.31096	0.70772	0.39676

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Instantaneous Swell	0.30862	0.70694	0.39832

(b) Instantaneous Swell detected on three phases

Figure 5.27: Instantaneous Swell on Three Phases

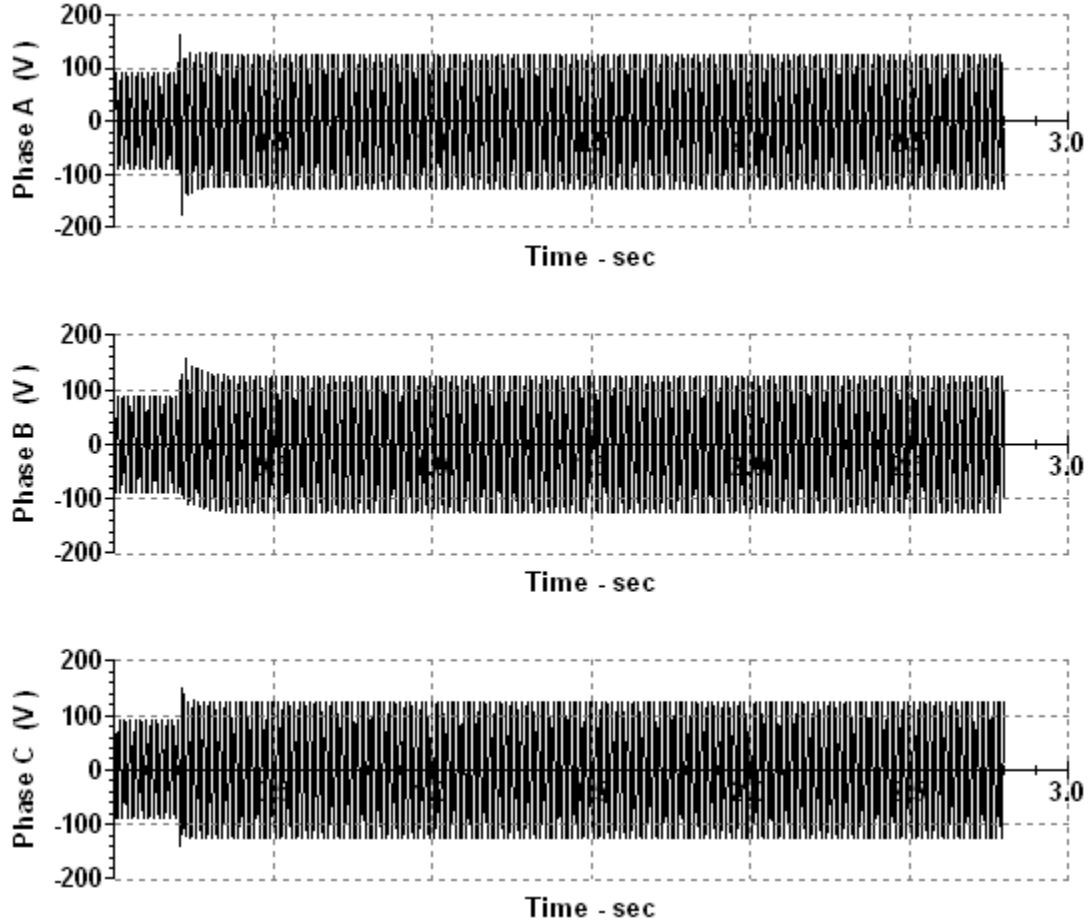


Figure 5.28: Momentary Swell Waveform

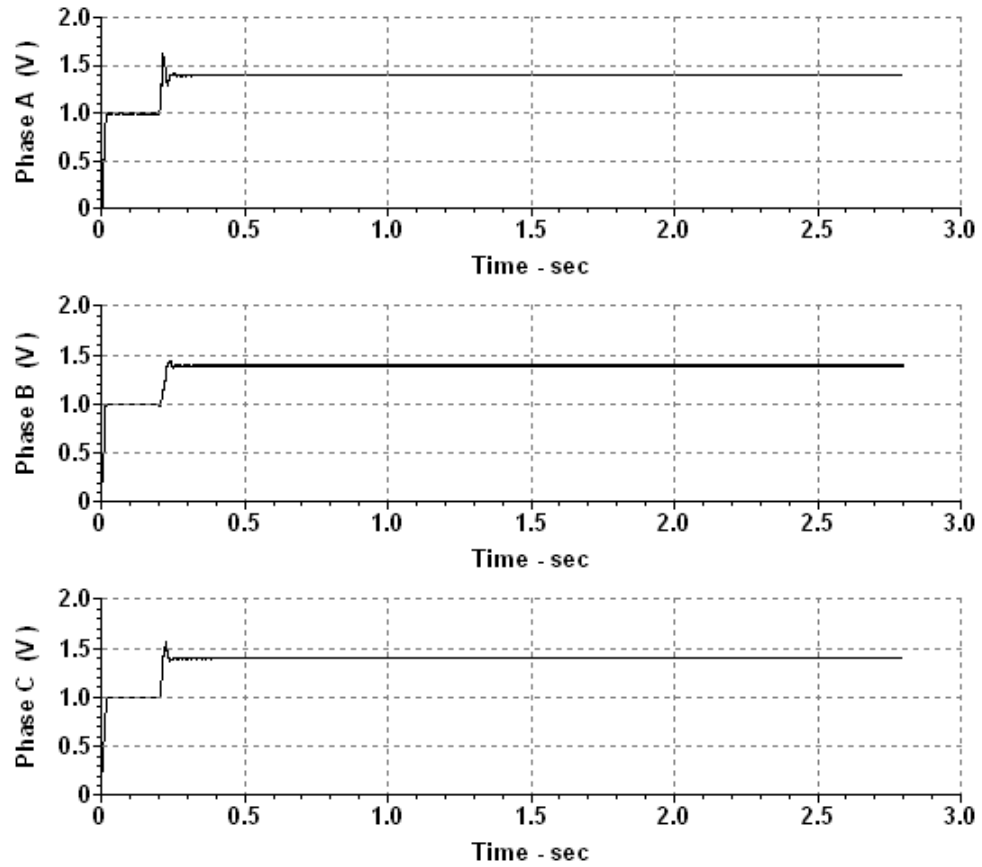
seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 2.54046 seconds which falls within the limits of 0.5 second to 3 seconds, it is flagged as Momentary Swell.

Figure 5.29(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.4.3 Temporary Swell

A three phase to ground fault was simulated on the line T_{r2} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of $50 \mu\text{s}$
2. Fault ON resistance of 0.001Ω
3. Fault OFF resistance 1000000Ω



(a) Momentary Swell occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Swell	0.273	2.79994	2.52694

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Swell	0.2756	2.79994	2.52434

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Swell	0.25948	2.79994	2.54046

(b) Momentary Swell detected on three phases

Figure 5.29: Momentary Swell on Three Phases

4. Transmission line T_{r2} of length 400 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 4 are shown in Figure 5.30. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.31(a).

The Temporary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.2 per unit on phase A at 0.22022 second as shown in 5.31(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The event lasted till 5.79982 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 5.5796 seconds which falls within the limits of 3 second to 60 seconds, it is flagged as Temporary Swell.

On phase B the Temporary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.2 per unit at 0.21814 second as shown in 5.31(a). The starting time of the event was noted and a counter was incremented for the number of events on phase B. The event lasted till 5.79982 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 5.58168 seconds which falls within the limits of 3 second to 60 seconds, it is flagged as Temporary Swell.

Similarly, on phase C the Temporary Swell algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than than 1.2 per unit at 0.22412 second as shown in 5.31(a). The starting time of the event was noted and a counter was incremented for the number of events on phase C. The event lasted till 5.79982 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 5.5757 seconds which falls within the limits of 3 second to 60 seconds, it is flagged as Temporary Swell.

Figure 5.31(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.5 Overvoltage

A three phase to ground fault was simulated on the line T_{r2} at a location of 25 km from Bus 1. The following parameters were used.

1. Calculation step of 50 μ s
2. Fault ON resistance of 50 Ω
3. Fault OFF resistance of 1000000 Ω

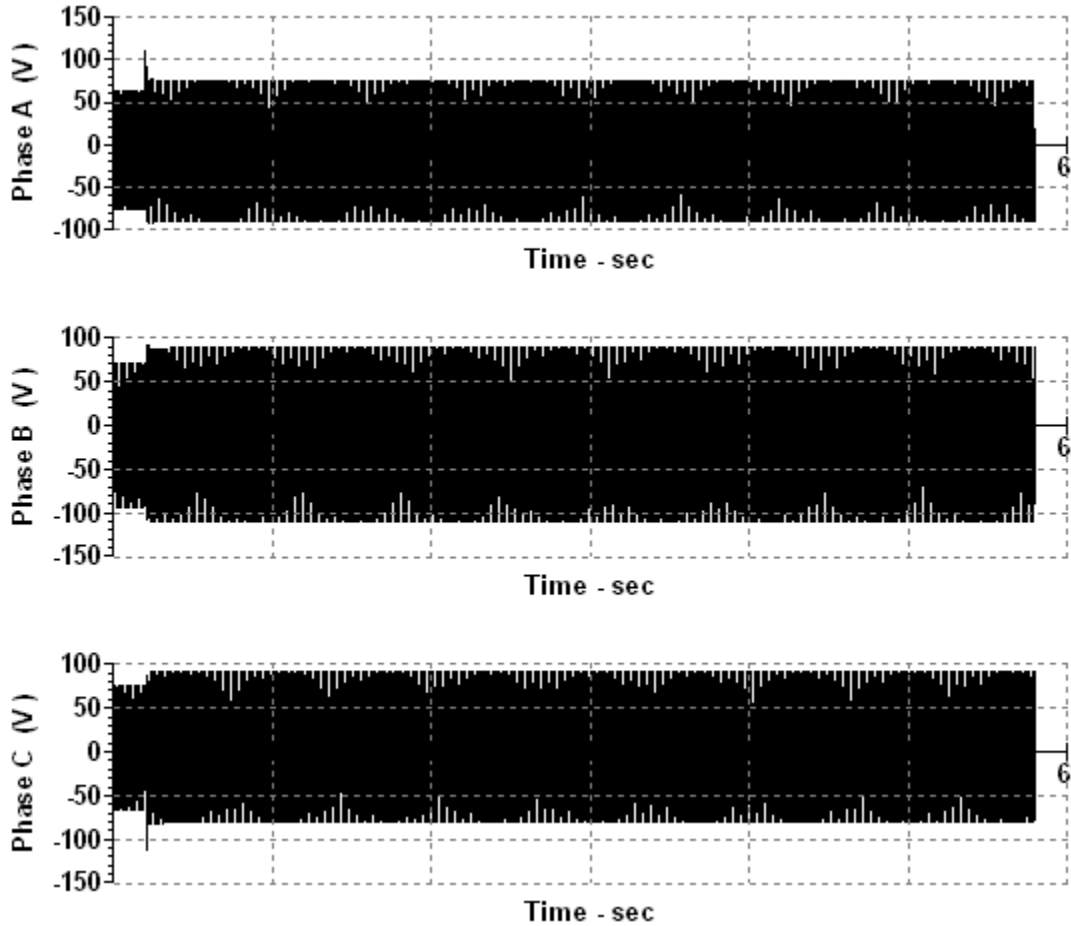


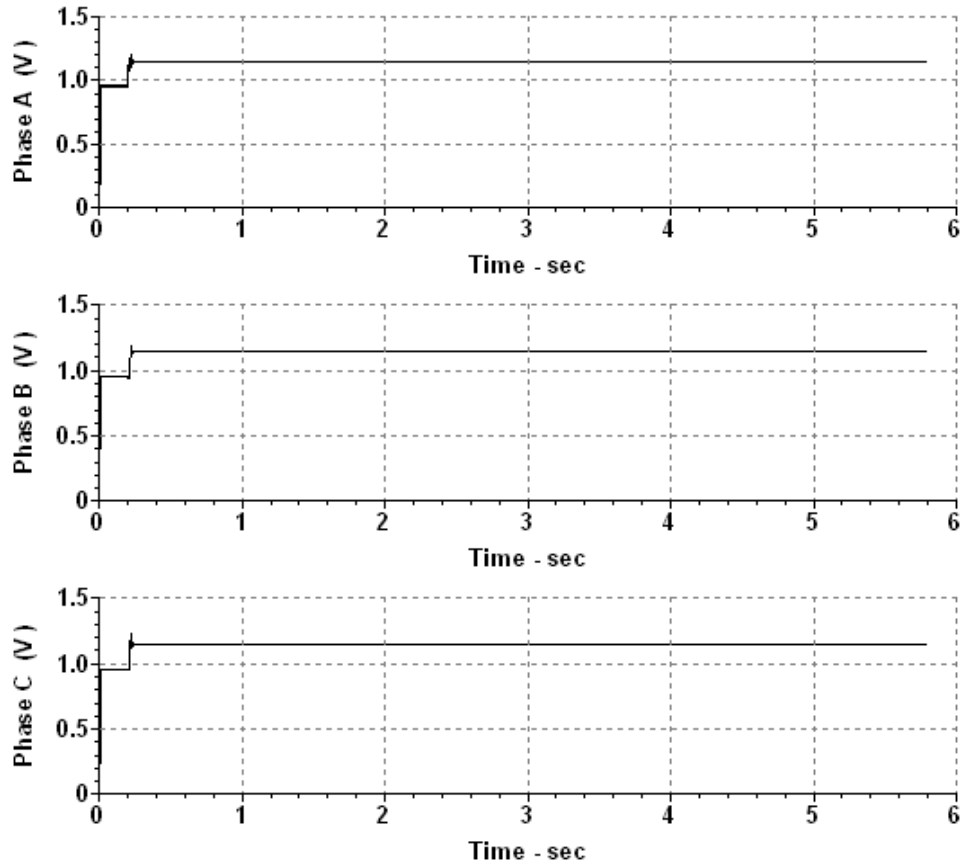
Figure 5.30: Temporary Swell Waveform

4. Transmission line T_{r2} of length 520 km

The voltage waveforms of phases A, B and C, as observed by Comtrade Recorder 4 are shown in Figures 5.32, 5.33 and 5.34. The waveforms of the outputs provided by the power quality analysis algorithms are shown in 5.35(a).

The Overvoltage algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than 1.2 per unit on phase A at 0.625 second as shown in 5.35(a). The starting time of the event was noted and a counter was incremented for the number of events on phase A. The event lasted till 62.5 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 61.875 seconds which is greater than 60 seconds, it is flagged as an Overvoltage.

On phase B the Overvoltage algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than 1.2 per unit at 0.63 second. The starting time of the event was noted and a counter was incremented for the number of



(a) Temporary Swell occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Temporary Swell	0.22022	5.79982	5.5796

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Temporary Swell	0.21814	5.79982	5.58168

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Temporary Swell	0.22412	5.79982	5.5757

(b) Temporary Swell detected on three phases

Figure 5.31: Temporary Swell on Three Phases

events on phase B. The event lasted till 62.5 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase B. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 61.87 seconds which is greater than 60 seconds, it is flagged as an Overvoltage.

Similarly, on phase C the Overvoltage algorithm implemented in the software detected the first voltage magnitude above 1.1 per unit and less than 1.2 per unit at 0.625 second. The starting time of the event was noted and a counter was incremented for the number of events on phase C. The event lasted till 62.5 seconds and the counter was stopped at this instant. In this case only one type of event occurs on phase C. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the event lasts for 61.875 seconds which is greater than 60 seconds, it is flagged as an Overvoltage.

Figure 5.35(b) shows the power quality events along with their start time, stop time and duration as detected by the software in phases A, B and C respectively.

5.6.6 Harmonic Analysis

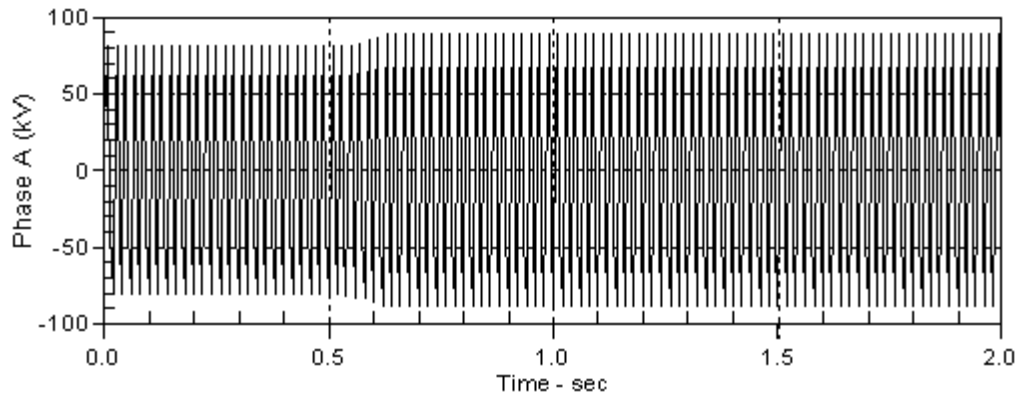
The total demand distortion (See equation 5.1) is used to measure the current harmonic distortion. The General Electric Multilin Relays do not have the peak or maximum demand load current available in the oscillography files. At present the algorithm is using the fundamental value of the current at the fundamental frequency. This is not an accurate representation of the TDD. Changes have been initiated to bring the peak or maximum demand load current in the oscillography files for future use.

$$\begin{aligned}
 TDD \text{ \% of peak demand} &= \left(\frac{I_{rms \text{ distorted}}}{I_{maximum \text{ demand}}} \right) \times 100 \\
 &= \frac{\sqrt{\sum_{h=2}^{25} I_h^2}}{I_d} \times 100
 \end{aligned} \tag{5.1}$$

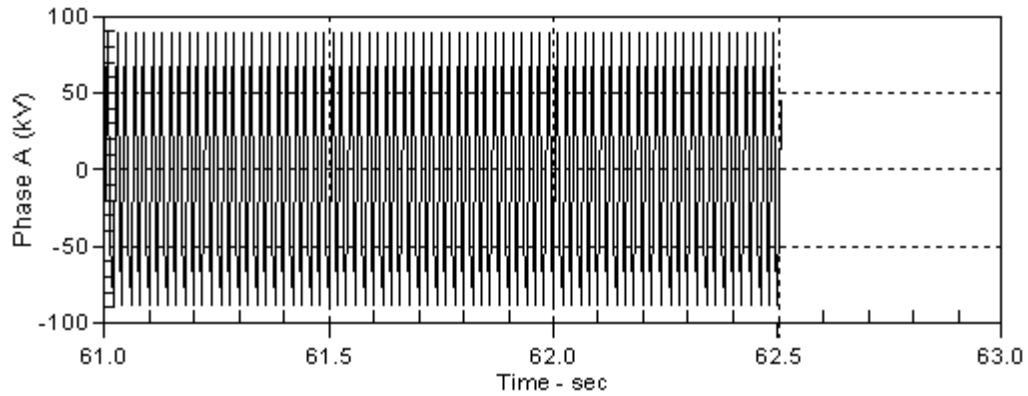
where, $I_{rms \text{ distorted}}$ is the rms value of the distorted waveform with the fundamental left out of the summation, and

I_d is the peak or maximum, demand load current at the fundamental frequency component measured at the point of common coupling. There are two ways to measure I_d

- With a load already present in the system, it is calculated as the average of the maximum demand current readings for the preceding 12 months.
- For a new facility where load is to be connected in the system, I_d has to be estimated based on the predicted load profiles.



(a) Waveform Showing the Beginning of Overvoltage in Phase A



(b) Waveform Showing the End of Overvoltage in Phase A

Figure 5.32: Overvoltage on Phase A

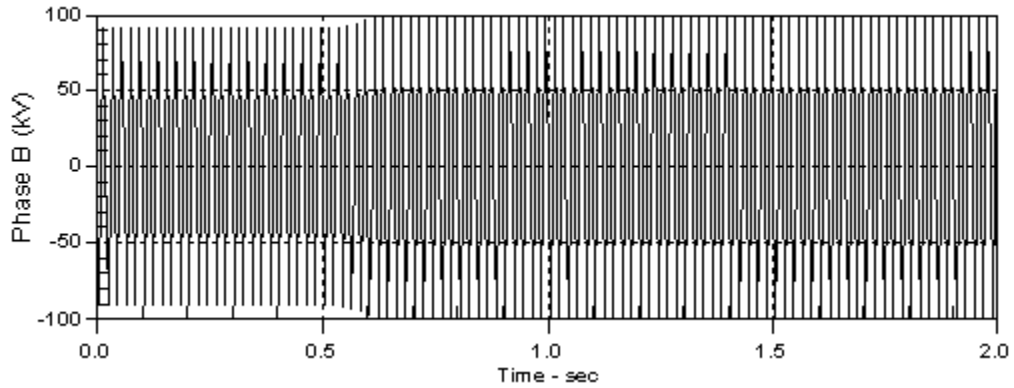
Usually, the higher order harmonics ranging from 25th and above are negligible for power system. They do not cause any damage to the power system. Figure 5.36 shows the THD variation in all the three phases. THD between 0 and 20 % is considered normal.

5.6.7 Unidentified Events

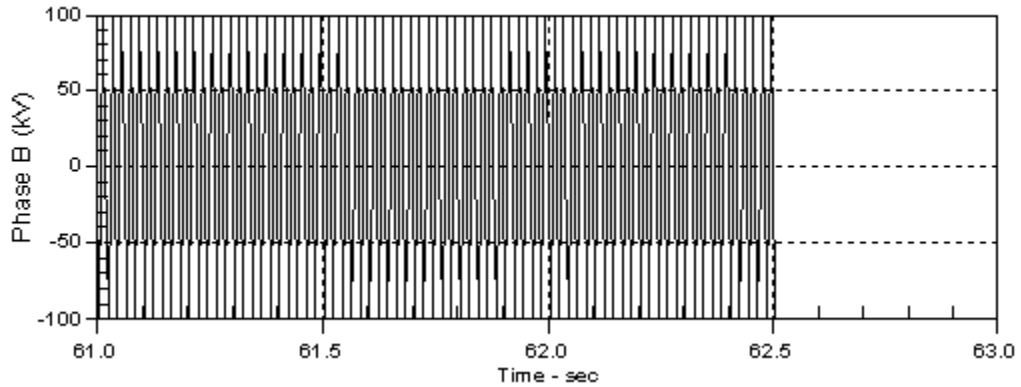
In case if any of the events cannot be identified by the algorithms they fall into the category of unidentified events. These type of events can then be further analyzed by human intervention from their waveforms.

5.7 Response of the Power Quality Analysis Tool

The results of one hundred fifty test studies are listed in Tables 5.7, 5.8, 5.9, 5.10, 5.11 and 5.12. When the event was correctly identified by the PQAT it is listed as “Event



(a) Waveform Showing the Beginning of Overvoltage in Phase B



(b) Waveform Showing the End of Overvoltage in Phase B

Figure 5.33: Overvoltage on Phase B

detected ”in the Result column. If the PQAT failed to correctly identify the event it is listed as “Event not detected ”. All the 150 different test studies were correctly identified by the PQAT.

5.8 Test Cases using Relay Recorded Data

The developed PQAT was applied to detect and classify the Power Quality Events from the data recorded by GE Multilin Universal Relays Family which includes the Bus Differential (B30 and B90), Controller (C30), Breaker Management (C60), Line Distance (D30 and D60), Multiple Feeder Management (F35), Feeder Management (F60), Generator Management (G30 and G60), Line Phase Comparison (L60), Line Current Differential (L90), Motor Management (M60), Network Stability and Synchrophasor Measurement (N60), Transformer Management - up to six winding power transformers (T35) and Transformer Management - two, three, or four winding power transformers (T60) relays [25]. The

Table 5.7: Result of Studies for Different Fault Types at Different Locations

Case No.	Fault Type	Fault Location	Result
1	Single Phase to ground fault	T_{r1} - 0 km	Event detected
2	Single Phase to ground fault	T_{r1} - 25 km	Event detected
3	Single Phase to ground fault	T_{r1} - 50 km	Event detected
4	Single Phase to ground fault	T_{r1} - 75 km	Event detected
5	Single Phase to ground fault	T_{r1} - 100 km	Event detected
6	Two phase fault	T_{r1} - 0 km	Event detected
7	Two phase fault	T_{r1} - 25 km	Event detected
8	Two phase fault	T_{r1} - 50 km	Event detected
9	Two phase fault	T_{r1} - 75 km	Event detected
10	Two phase fault	T_{r1} - 100 km	Event detected
11	Two phase to ground fault	T_{r1} - 0 km	Event detected
12	Two phase to ground fault	T_{r1} - 25 km	Event detected
13	Two phase to ground fault	T_{r1} - 50 km	Event detected
14	Two phase to ground fault	T_{r1} - 75 km	Event detected
15	Two phase to ground fault	T_{r1} - 100 km	Event detected
16	Three phase fault	T_{r1} - 0 km	Event detected
17	Three phase fault	T_{r1} - 25 km	Event detected
18	Three phase fault	T_{r1} - 50 km	Event detected
19	Three phase fault	T_{r1} - 75 km	Event detected
20	Three phase fault	T_{r1} - 100 km	Event detected
21	Three phase to ground fault	T_{r1} - 0 km	Event detected
22	Three phase to ground fault	T_{r1} - 25 km	Event detected
23	Three phase to ground fault	T_{r1} - 50 km	Event detected
24	Three phase to ground fault	T_{r1} - 75 km	Event detected
25	Three phase to ground fault	T_{r1} - 100 km	Event detected
26	Single Phase to ground fault	T_{r2} - 0 km	Event detected
27	Single Phase to ground fault	T_{r2} - 25 km	Event detected
28	Single Phase to ground fault	T_{r2} - 50 km	Event detected
29	Single Phase to ground fault	T_{r2} - 75 km	Event detected
30	Single Phase to ground fault	T_{r2} - 100 km	Event detected
31	Two phase fault	T_{r2} - 0 km	Event detected
32	Two phase fault	T_{r2} - 25 km	Event detected
33	Two phase fault	T_{r2} - 50 km	Event detected
34	Two phase fault	T_{r2} - 75 km	Event detected
35	Two phase fault	T_{r2} - 100 km	Event detected

Table 5.8: Result of Studies for Different Fault Types at Different Locations

Case No.	Fault Type	Fault Location	Result
36	Two phase to ground fault	T_{r2} - 0 km	Event detected
37	Two phase to ground fault	T_{r2} - 25 km	Event detected
38	Two phase to ground fault	T_{r2} - 50 km	Event detected
39	Two phase to ground fault	T_{r2} - 75 km	Event detected
40	Two phase to ground fault	T_{r2} - 100 km	Event detected
41	Three phase fault	T_{r2} - 0 km	Event detected
42	Three phase fault	T_{r2} - 25 km	Event detected
43	Three phase fault	T_{r2} - 50 km	Event detected
44	Three phase fault	T_{r2} - 75 km	Event detected
45	Three phase fault	T_{r2} - 100 km	Event detected
46	Three phase to ground fault	T_{r2} - 0 km	Event detected
47	Three phase to ground fault	T_{r2} - 25 km	Event detected
48	Three phase to ground fault	T_{r2} - 50 km	Event detected
49	Three phase to ground fault	T_{r2} - 75 km	Event detected
50	Three phase to ground fault	T_{r2} - 100 km	Event detected
51	Single Phase to ground fault	T_{r3} - 0 km	Event detected
52	Single Phase to ground fault	T_{r3} - 25 km	Event detected
53	Single Phase to ground fault	T_{r3} - 50 km	Event detected
54	Single Phase to ground fault	T_{r3} - 75 km	Event detected
55	Single Phase to ground fault	T_{r3} - 100 km	Event detected
56	Two phase fault	T_{r3} - 0 km	Event detected
57	Two phase fault	T_{r3} - 25 km	Event detected
58	Two phase fault	T_{r3} - 50 km	Event detected
59	Two phase fault	T_{r3} - 75 km	Event detected
60	Two phase fault	T_{r3} - 100 km	Event detected
61	Two phase to ground fault	T_{r3} - 0 km	Event detected
62	Two phase to ground fault	T_{r3} - 25 km	Event detected
63	Two phase to ground fault	T_{r3} - 50 km	Event detected
64	Two phase to ground fault	T_{r3} - 75 km	Event detected
65	Two phase to ground fault	T_{r3} - 100 km	Event detected
66	Three phase fault	T_{r3} - 0 km	Event detected
67	Three phase fault	T_{r3} - 25 km	Event detected
68	Three phase fault	T_{r3} - 50 km	Event detected
69	Three phase fault	T_{r3} - 75 km	Event detected
70	Three phase fault	T_{r3} - 100 km	Event detected

Table 5.9: Result of Studies for Different Fault Types at Different Locations

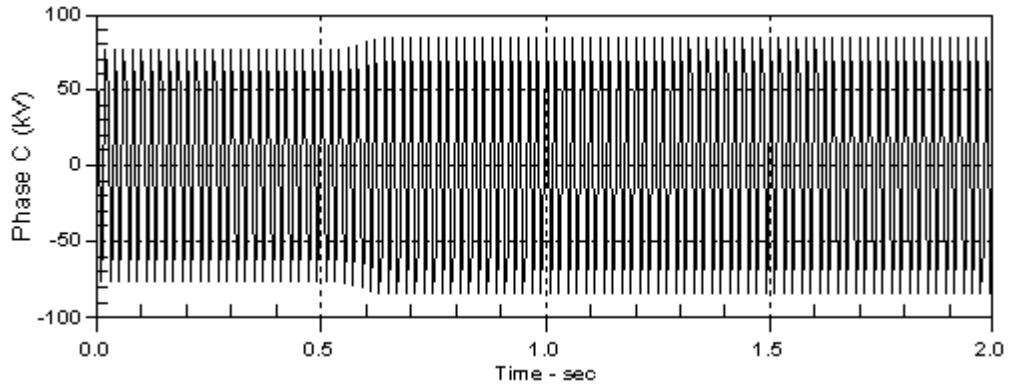
Case No.	Fault Type	Fault Location	Result
71	Three phase to ground fault	T_{r3} - 0 km	Event detected
72	Three phase to ground fault	T_{r3} - 25 km	Event detected
73	Three phase to ground fault	T_{r3} - 50 km	Event detected
74	Three phase to ground fault	T_{r3} - 75 km	Event detected
75	Three phase to ground fault	T_{r3} - 100 km	Event detected

Table 5.10: Result of Studies for Different Fault Resistances at Different Locations

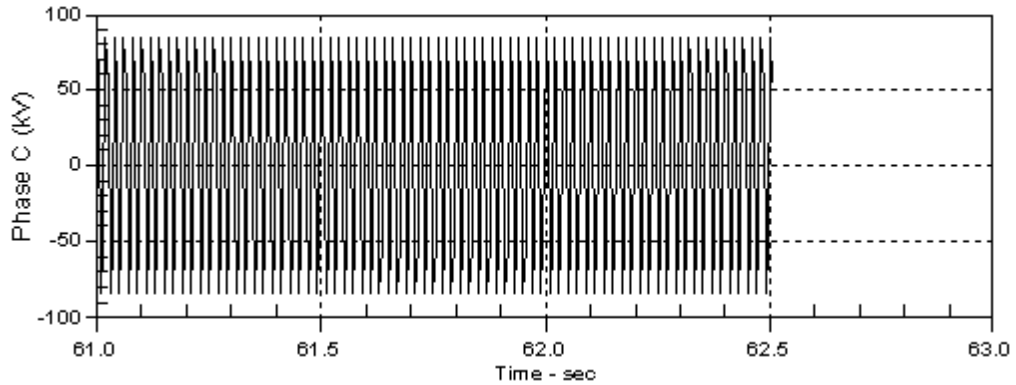
Case No.	Fault Location	Parameter Changed	Value of the parameter	Result
1	T_{r1} - 0 km	Fault Resistance	0.01 Ω	Event detected
2	T_{r1} - 25 km	Fault Resistance	0.01 Ω	Event detected
3	T_{r1} - 50 km	Fault Resistance	0.01 Ω	Event detected
4	T_{r1} - 75 km	Fault Resistance	0.01 Ω	Event detected
5	T_{r1} - 100 km	Fault Resistance	0.01 Ω	Event detected
6	T_{r1} - 0 km	Fault Resistance	10 Ω	Event detected
7	T_{r1} - 25 km	Fault Resistance	10 Ω	Event detected
8	T_{r1} - 50 km	Fault Resistance	10 Ω	Event detected
9	T_{r1} - 75 km	Fault Resistance	10 Ω	Event detected
10	T_{r1} - 100 km	Fault Resistance	10 Ω	Event detected
11	T_{r1} - 0 km	Fault Resistance	50 Ω	Event detected
12	T_{r1} - 25 km	Fault Resistance	50 Ω	Event detected
13	T_{r1} - 50 km	Fault Resistance	50 Ω	Event detected
14	T_{r1} - 75 km	Fault Resistance	50 Ω	Event detected
15	T_{r1} - 100 km	Fault Resistance	50 Ω	Event detected
16	T_{r1} - 0 km	Fault Resistance	70 Ω	Event detected
17	T_{r1} - 25 km	Fault Resistance	70 Ω	Event detected
18	T_{r1} - 50 km	Fault Resistance	70 Ω	Event detected
19	T_{r1} - 75 km	Fault Resistance	70 Ω	Event detected
20	T_{r1} - 100 km	Fault Resistance	70 Ω	Event detected
21	T_{r1} - 0 km	Fault Resistance	100 Ω	Event detected
22	T_{r1} - 25 km	Fault Resistance	100 Ω	Event detected
23	T_{r1} - 50 km	Fault Resistance	100 Ω	Event detected
24	T_{r1} - 75 km	Fault Resistance	100 Ω	Event detected
25	T_{r1} - 100 km	Fault Resistance	100 Ω	Event detected

Table 5.11: Result of Studies for Different Fault Resistances at Different Locations

Case No.	Fault Location	Parameter Changed	Value of the parameter	Result
26	T_{r2} - 0 km	Fault Resistance	0.01 Ω	Event detected
27	T_{r2} - 25 km	Fault Resistance	0.01 Ω	Event detected
28	T_{r2} - 50 km	Fault Resistance	0.01 Ω	Event detected
29	T_{r2} - 75 km	Fault Resistance	0.01 Ω	Event detected
30	T_{r2} - 100 km	Fault Resistance	0.01 Ω	Event detected
31	T_{r2} - 0 km	Fault Resistance	10 Ω	Event detected
32	T_{r2} - 25 km	Fault Resistance	10 Ω	Event detected
33	T_{r2} - 50 km	Fault Resistance	10 Ω	Event detected
34	T_{r2} - 75 km	Fault Resistance	10 Ω	Event detected
35	T_{r2} - 100 km	Fault Resistance	10 Ω	Event detected
36	T_{r2} - 0 km	Fault Resistance	50 Ω	Event detected
37	T_{r2} - 25 km	Fault Resistance	50 Ω	Event detected
38	T_{r2} - 50 km	Fault Resistance	50 Ω	Event detected
39	T_{r2} - 75 km	Fault Resistance	50 Ω	Event detected
40	T_{r2} - 100 km	Fault Resistance	50 Ω	Event detected
41	T_{r2} - 0 km	Fault Resistance	70 Ω	Event detected
42	T_{r2} - 25 km	Fault Resistance	70 Ω	Event detected
43	T_{r2} - 50 km	Fault Resistance	70 Ω	Event detected
44	T_{r2} - 75 km	Fault Resistance	70 Ω	Event detected
45	T_{r2} - 100 km	Fault Resistance	70 Ω	Event detected
46	T_{r2} - 0 km	Fault Resistance	100 Ω	Event detected
47	T_{r2} - 25 km	Fault Resistance	100 Ω	Event detected
48	T_{r2} - 50 km	Fault Resistance	100 Ω	Event detected
49	T_{r2} - 75 km	Fault Resistance	100 Ω	Event detected
50	T_{r2} - 100 km	Fault Resistance	100 Ω	Event detected
51	T_{r3} - 0 km	Fault Resistance	0.01 Ω	Event detected
52	T_{r3} - 25 km	Fault Resistance	0.01 Ω	Event detected
53	T_{r3} - 50 km	Fault Resistance	0.01 Ω	Event detected
54	T_{r3} - 75 km	Fault Resistance	0.01 Ω	Event detected
55	T_{r3} - 100 km	Fault Resistance	0.01 Ω	Event detected
56	T_{r3} - 0 km	Fault Resistance	10 Ω	Event detected
57	T_{r3} - 25 km	Fault Resistance	10 Ω	Event detected
58	T_{r3} - 50 km	Fault Resistance	10 Ω	Event detected
59	T_{r3} - 75 km	Fault Resistance	10 Ω	Event detected
60	T_{r3} - 100 km	Fault Resistance	10 Ω	Event detected



(a) Waveform Showing the Beginning of Overvoltage in Phase C



(b) Waveform Showing the End of Overvoltage in Phase C

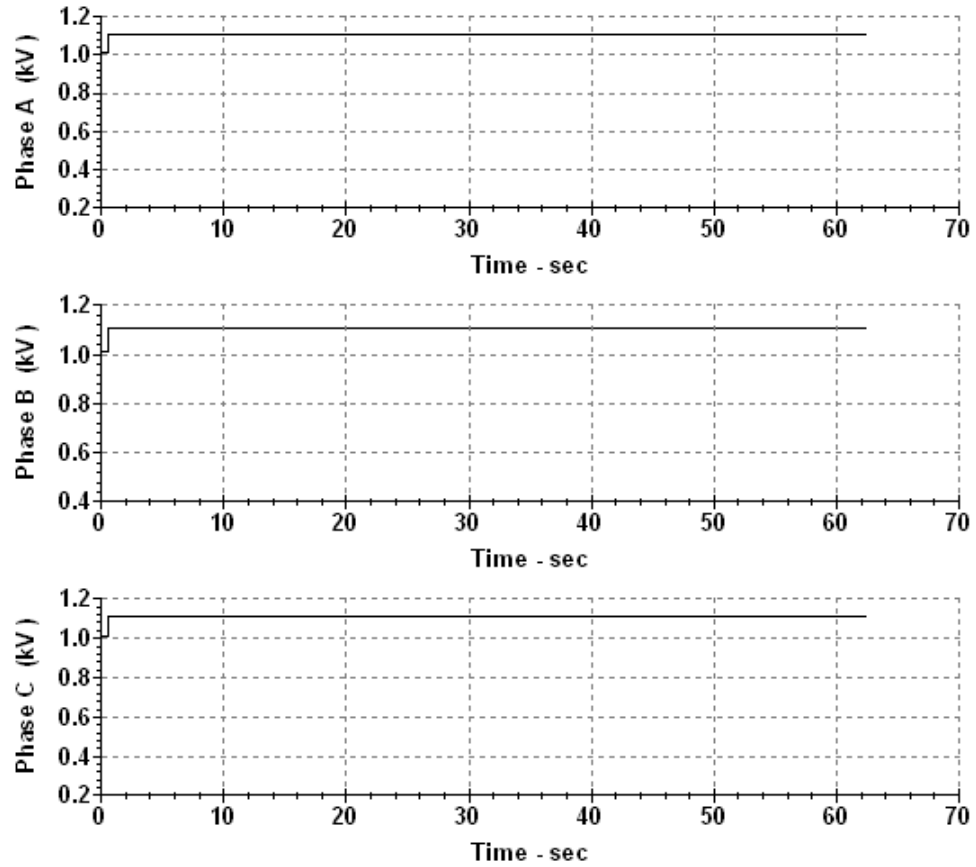
Figure 5.34: Overvoltage on Phase C

relay sampling rate is fixed at 64 samples per cycle. The AC input waveform (voltages and currents) are sampled at the rate of 64 samples per cycle. The performance of the tool was satisfactory in all cases. Two such case results showing Momentary Sag are described below.

5.8.1 Case I

The voltage waveform of phase A as recorded by the relay is shown in Figure 5.37.

The Momentary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit on phase A at 0.0019 second as shown in 5.38. The starting time of the event was noted and a counter was incremented for the number of events on phase A. The voltage magnitude reached to normal (The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal.) at 1.569929 second. The stopping time of the event was noted and the counter was stopped at this instant.



(a) Overvoltage occurred on three phases

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Over Voltage	0.625	62.5	61.875

Events Detected - Phase B

S.No	Event Type	Start Time	End Time	Duration
1	Over Voltage	0.63	62.5	61.87

Events Detected - Phase C

S.No	Event Type	Start Time	End Time	Duration
1	Over Voltage	0.625	62.5	61.875

(b) Overvoltage detected on three phases

Figure 5.35: Overvoltage on Three Phases

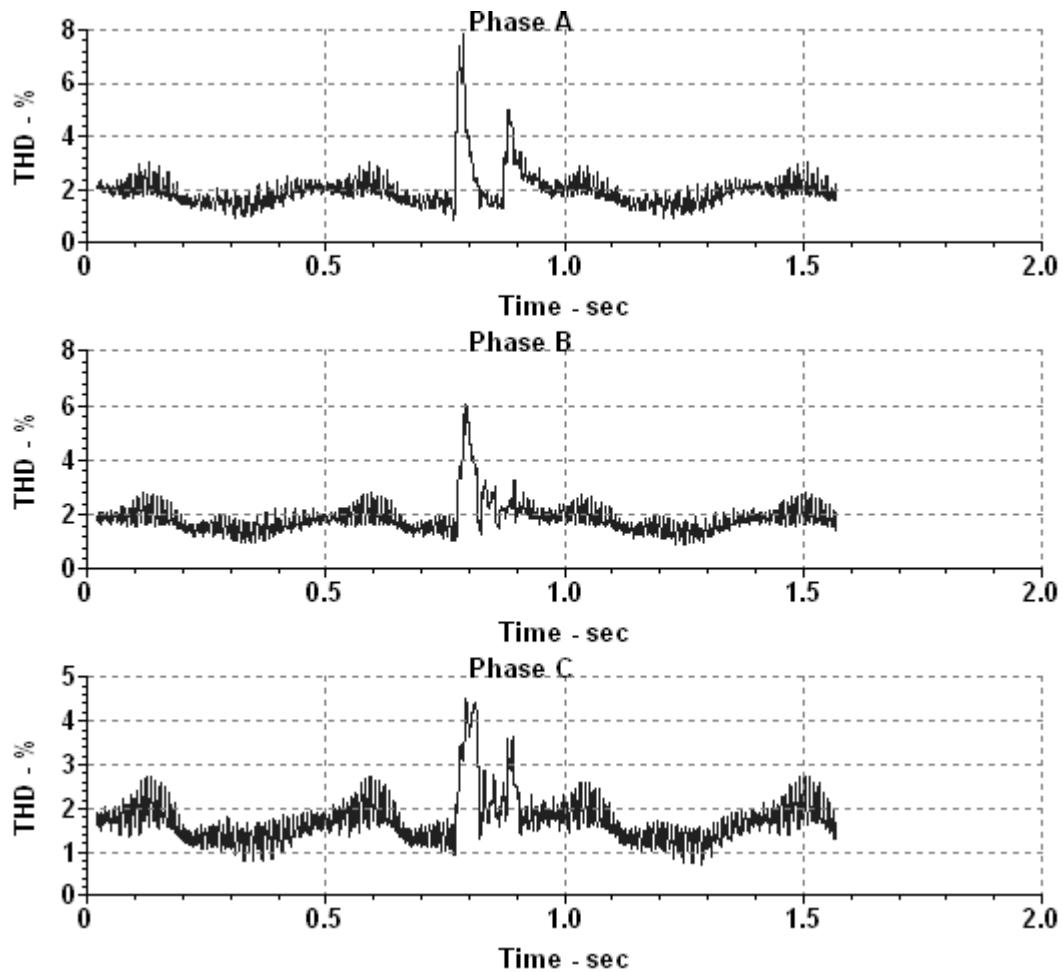


Figure 5.36: Harmonics in the Voltage Supply

In this case only one type of event occurs on phase A. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 1.5501902 seconds, it falls within the Momentary Sag limits of 0.5 second to 3 seconds.

Figure 5.39 shows the power quality event along with their start time, stop time and duration as detected by the software in phase A.

5.8.2 Case II

The voltage waveform of phase A as recorded by the relay is shown in Figure 5.40.

The Momentary Sag algorithm implemented in the software detected the first voltage magnitude below 0.9 per unit and greater than 0.1 per unit on phase A at 0.00196845 second as shown in 5.41. The starting time of the event was noted and a counter was incremented for the number of events on phase A. The voltage magnitude reached to normal (The voltage magnitude between 0.9 per unit and 1.1 per unit is considered normal.) at

Table 5.12: Result of Studies for Different Fault Resistances at Different Locations

Case No.	Fault Location	Parameter Changed	Value of the parameter	Result
61	T_{r3} - 0 km	Fault Resistance	50 Ω	Event detected
62	T_{r3} - 25 km	Fault Resistance	50 Ω	Event detected
63	T_{r3} - 50 km	Fault Resistance	50 Ω	Event detected
64	T_{r3} - 75 km	Fault Resistance	50 Ω	Event detected
65	T_{r3} - 100 km	Fault Resistance	50 Ω	Event detected
66	T_{r3} - 0 km	Fault Resistance	70 Ω	Event detected
67	T_{r3} - 25 km	Fault Resistance	70 Ω	Event detected
68	T_{r3} - 50 km	Fault Resistance	70 Ω	Event detected
69	T_{r3} - 75 km	Fault Resistance	70 Ω	Event detected
70	T_{r3} - 100 km	Fault Resistance	70 Ω	Event detected
71	T_{r3} - 0 km	Fault Resistance	100 Ω	Event detected
72	T_{r3} - 25 km	Fault Resistance	100 Ω	Event detected
73	T_{r3} - 50 km	Fault Resistance	100 Ω	Event detected
74	T_{r3} - 75 km	Fault Resistance	100 Ω	Event detected
75	T_{r3} - 100 km	Fault Resistance	100 Ω	Event detected

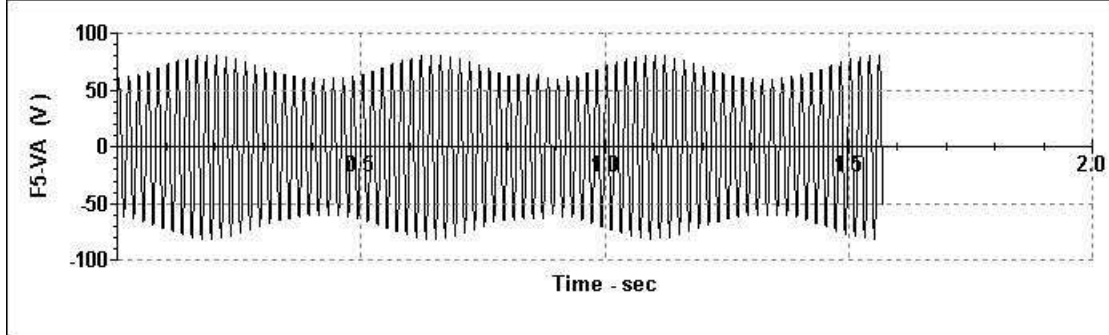


Figure 5.37: Relay Recorded Momentary Sag Waveform

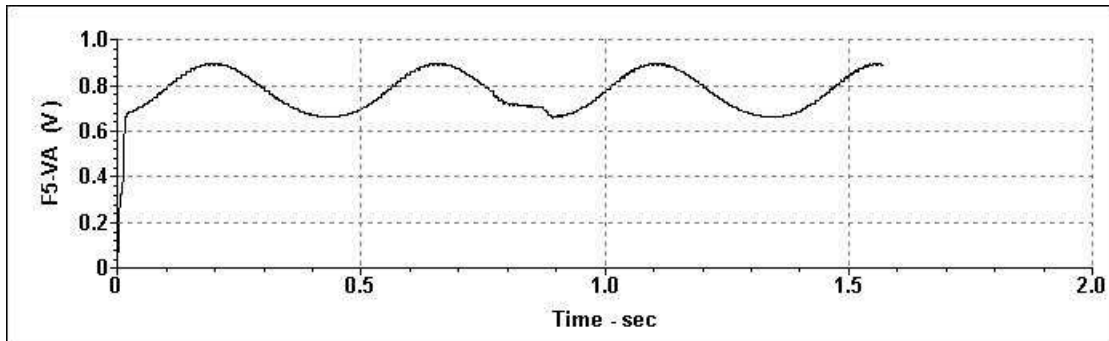


Figure 5.38: Relay Recorded Momentary Sag Occurred on Phase A

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Sag	1.973875e-002	1.569929	1.55019025

Figure 5.39: Relay Recorded Momentary Sag Detected on Phase A

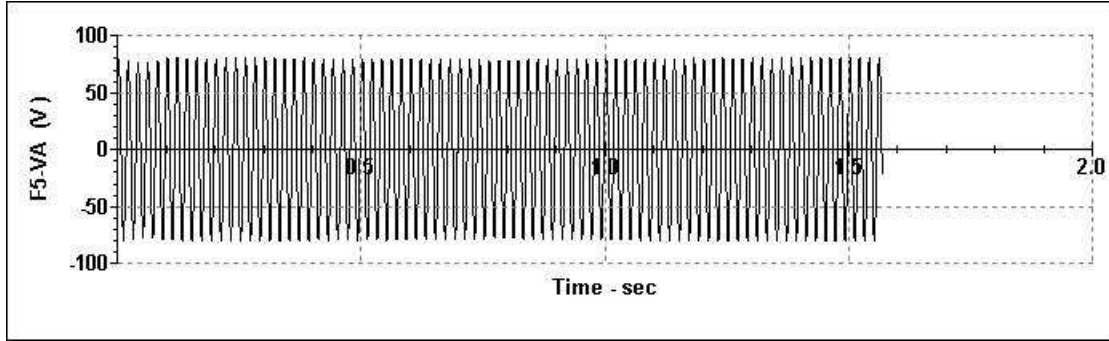


Figure 5.40: Relay Recorded Momentary Sag Waveform

1.56834875 second. The stopping time of the event was noted and the counter was stopped at this instant. In this case only one type of event occurs on phase A. The time duration of the whole event was calculated by subtracting the starting time from the stopping time. Since the duration of the event is 1.54866425 seconds, it falls within the Momentary Sag limits of 0.5 second to 3 seconds.

Figure 5.42 shows the power quality event along with their start time, stop time and duration as detected by the software in phase A.

5.9 Summary

Some of the limitations hindering the full usage of the relay for power quality monitoring have been described. Portable power quality monitors would still serve the useful purpose

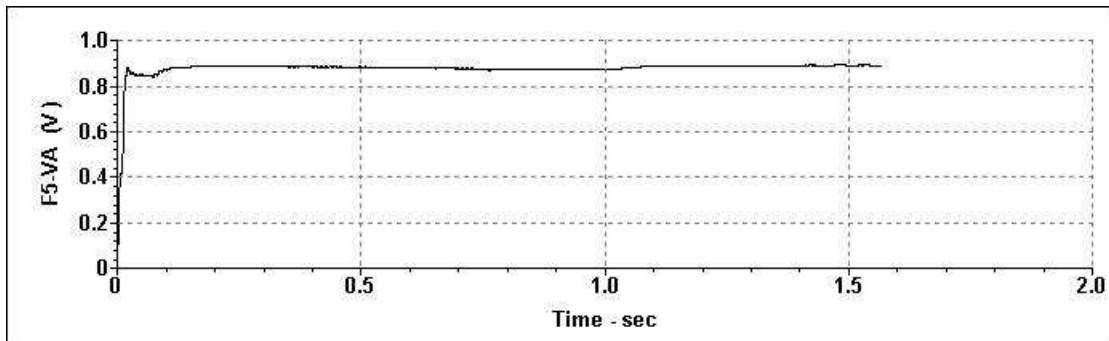


Figure 5.41: Relay Recorded Momentary Sag Occurred on Phase A

Events Detected - Phase A

S.No	Event Type	Start Time	End Time	Duration
1	Momentary Sag	1.96845e-002	1.56834875	1.54866425

Figure 5.42: Relay Recorded Momentary Sag Detected on Phase A

of monitoring transient disturbances at key locations throughout the system to detect and troubleshoot problems before they lead to equipment damaged and loss in production.

CHAPTER 6

CONCLUSIONS

6.1 Introduction

This chapter provides a brief summary of all the previous chapters. Some of the limitations of the PQAT are also described in detail. Suggestions are given concerning the future direction for the power quality area.

6.2 Summary

Chapter 1 of the thesis described the history and importance of the Power Quality. The benefits of monitoring the power quality in the microprocessor based relays is also described. Chapter 2 describes the microprocessor - based relays, also called numerical relays. The relaying algorithms used in those relays have been presented. All those algorithms estimate the voltage and current phasors using data - windows of one-quarter to one cycle of the fundamental frequency. Reasonably accurate estimates are obtained when the data-window is approximately one cycle of the fundamental frequency. Chapter 3 introduces several related terms to the area of power quality. An important distinction is made between the terms “variations” and “events”. An overview of the various types of power quality disturbances is also given. The characteristics of various events are explained along with an in depth explanation of the use of Information Technology Industry Council Curve. Chapter 4 provided a description of the Power Quality Analysis Tool. It discusses the main features of the Power Quality Analysis Tool. Many screen shots of the tool are provided to aid in the explanation. Chapter 5 presented the performance evaluation of the proposed tool. Data generated for a power system model simulated on an electromagnetic transient program, EMTDC, were used for this purpose. A program written in C++ was used to implement the proposed detection of events based on the IEEE Standard 1159. Test studies were carried for different types of operating conditions. Test results shows that the developed algorithms correctly detects various power quality events. The limitations in the detection of the Impulsive(Nanosecond, Microsecond and Millisecond) and Oscillatory(Medium Frequency and High Frequency) Transients are pointed out. This is not a limitation of the algorithm but a limitation of the slow sampling rate of the relay. When higher sampling rates become available, the algorithm would be

able to detect these transients. Chapter 6 gives a brief sketch of the future developments in the area of the power quality.

The specific contributions made by this thesis are as follows:

- Algorithms have been developed based on the voltage duration and magnitude as specified in the IEEE Std. 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality, of three phases to detect and classify the power quality events.
- The Graphical User Interface was developed using the Microsoft Visual C++ Programming environment using the Microsoft Foundation Classes.
- Quinn Curtis Graphics Library was used to program and display the results of the detection and classification algorithms in the form of plots.

6.3 Limitations

In spite of the ability of the software to automatically detect and classify most of the power quality events, there are some precincts too. Transients have been explained in detail in section 3.3.3. Some of the Impulsive Transients and Oscillatory Transients cannot be identified by the software. It is not a shortcoming of the PQAT but a limitation of the relay sampling rate. The software has inherent capability to read the data from the Comtrade files for any type of event. In the future when higher sampling rates are used, full capability of the software could be exploited.

6.3.1 Impulsive Transients

The characteristics for the Impulsive Transients are shown in Table 6.1. When the sampling rate is 3840 Hz [64 samples / cycle], the difference between consecutive samples is 0.2 msec. The Impulsive Transients have a rise time or event duration that lasts less than 0.2 msec. None of these impulsive transients can be detected at this sampling rate. When the sampling rate is 7680 Hz [128 samples / cycle], the time difference between consecutive samples is 0.1 msec. As the duration of the events is less than one sampling interval the impulsive transients cannot be detected.

6.3.2 Oscillatory Transients

The characteristics for the Oscillatory Transients are shown in Table 6.2. When the sampling rate is 3840 Hz [64 samples / cycle], the difference between consecutive samples is 0.2 msec. The Medium Frequency and High Frequency Oscillatory Transients have a duration that lasts less than 0.2 msec. These oscillatory transients can not be detected at this sampling rate. When the sampling rate is 7680 Hz [128 samples / cycle], the

Table 6.1: Impulsive Transient Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Voltage Rise Time</i> (in per unit)
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Impulsive Transients				
Nanosecond	< 0.0000003	< 0.000000050	< 0.000050	5 ns rise
Microsecond	0.0000003 - 0.06	0.000000050 - 0.001	0.000050 - 1	1 μ s rise
Millisecond	0.06	> 0.001	> 1	0.1 ms rise

time difference between consecutive samples is 0.1 msec. As the duration of the events is less than one sampling interval the medium and high frequency oscillatory transients cannot be detected. Low Frequency Oscillatory Transients have a duration between 0.3 and 50 msec, which is greater than one sampling interval. Hence these can be detected by the software.

Table 6.2: Oscillatory Transient Characteristics

<i>Event Type</i>	<i>Event Duration</i>			<i>Event Voltage Magnitude</i> (in per unit)
	<i>cycles</i>	<i>seconds</i>	<i>milliseconds</i>	
Oscillatory Transients				
Low Frequency	0.018 - 3	0.000300 - 0.050000	0.3 - 50	0 - 4
Medium Frequency	0.0012	0.000020	0.020	0 - 8
High Frequency	0.0003	0.000005	0.005	0 - 4

6.3.3 Sampling Interval

Most of the present day relays have a sampling rate of upto 128 samples per cycle. The sampling interval when sampling at 64 samples per cycle and 128 samples per cycle are

given below.

$$\begin{aligned} \textit{LineFrequency} &= 60\textit{Hz} \\ \textit{Samplespercycle} &= 64 \\ \textit{SamplingRate} &= \textit{LineFrequency} \cdot \textit{Samplespercycle} \\ &= 60 \cdot 64 \\ &= 3840\textit{Hz} \\ \textit{OneSamplingInterval} &= 0.000260416\textit{seconds} \\ &= 0.260\textit{milliseconds} \end{aligned}$$

$$\begin{aligned} \textit{LineFrequency} &= 60\textit{Hz} \\ \textit{Samplespercycle} &= 128 \\ \textit{SamplingRate} &= \textit{LineFrequency} \cdot \textit{Samplespercycle} \\ &= 60 \cdot 128 \\ &= 7680\textit{Hz} \\ \textit{OneSamplingInterval} &= 0.000130208\textit{seconds} \\ &= 0.130\textit{milliseconds} \end{aligned}$$

6.3.4 Detection Requirements

In order to detect and classify impulsive and oscillatory transients the relay should have the following features:

High Sampling Rate A very high sampling rate is required for the detection of transients as transients having duration less than one sampling interval cannot be detected. Table 6.3 shows the minimum sampling rate requirements for detecting and classifying Impulsive and Oscillatory Transients. Impulsive transients are often shorter in duration and require higher sampling rates ranging from 16kHz to 252 MHz. On the other hand the sampling rate requirements for oscillatory transients vary from 4 kHz to 0.3 MHz. At present such high speed sampling is not available in the relays.

Large Onboard Memory The relay must have higher onboard memory to store the larger number of samples and the associated rms data while still performing data logging functions e.g., load profiling, energy usage, etc. for standard monitoring

Table 6.3: Minimum Sampling Rate Requirements for Transients

<i>Event Type</i>	<i>Samples per cycle</i>	<i>Sampling Rate</i>	<i>Sampling Interval</i>
Impulsive Transients			
Nanosecond	4194304	251,658,240 Hz	3.97 ns
Microsecond	32768	1,966,080 Hz	0.5 μ s
Millisecond	256	15360 Hz	0.065 msec
Oscillatory Transients			
Low Frequency	64	3840 Hz	0.260 msec
Medium Frequency	1024	61,440 Hz	0.016 msec
High Frequency	4096	245,760 Hz	0.004 msec

purposes.

6.4 Future Developments in the Area of Power Quality

As discussed earlier in the thesis, the power quality analysis tool utilizes the information stored by the relay in COMTRADE record to characterize the power quality events in an offline mode.

6.4.1 Real Time Power Quality Monitoring

In the near future, the know-how gained from offline power quality analysis would eventually lead to real time power quality monitoring. Based on the results of this project, changes in the design of the relays will be initiated to ensure that the existing relays throughout the system can monitor power quality online in a cost effective manner. The immediate need is for higher sampling rates, more onboard memory and higher processing power.

6.4.2 Utility Customer Contracts

Several utilities have already entered into contracts with their bigger industrial customers, whereby the utility pays compensation to its customers when the quality of supply drops below a certain level. In 1995 Detroit Edison entered into long-term pricing and service quality agreements with Chrysler Corporation, Ford Motor Company, and General Motors. The contract specifies the maximum number acceptable for the voltage interruptions and voltage dips. When this number is exceeded within the year, Detroit Edison pays a pre-defined amount of compensation for each additional event. Detroit Edison has installed

a power quality monitoring system at 58 of the three customers locations throughout its territory. The power quality monitoring system allows Detroit Edison to determine the frequency and severity of voltage dips that occur at the customer locations. With Real time power quality monitoring in future such contracts can be entered with other customers utilizing the existing relays and without the need of expensive additional power quality monitors.

6.4.3 Database Integration

Database integration is important to store the various event parameters for further statistical analysis later. The database can be managed on a central server or each PC can have its own localized database [26], [27]. The central server database is recommended for the simple reason of ease in database management and maintenance.

6.4.4 Statistical Analysis

The most important useful parameter for analysis is the frequency of occurrence of a particular type of event during a certain period of time e.g one day, one week, one month, one year etc. for a single site or multiple sites.

This information / analysis would lead to appropriate changes in power system application and design.

6.5 Conclusion

Electronic equipment is continuously being developed to provide improved industrial productivity and reliability. As each generation of product evolves, it is promptly adopted by industry, with the promise of higher productivity, greater reliability and lower production costs. As the sensitive end use equipment is increasing day by day, the power quality problems are going to be on the rise as well. The huge amount of data generated would require more memory and higher processing power in the relay itself. It has been clearly shown relay recorded data, along with the developed software and algorithms, can be used for Power Quality Analysis in offline mode.

Most of the attention till date has been focused on solving the power quality problems through the usage of mitigation equipment. An effort has to be made to manufacture equipment that has higher tolerance to the voltage variations in the power system and also does not cause disturbances in the supply side of the system. At this point, it looks like it is not going to happen anytime sooner. Till then the power quality problem is here to stay.

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APPENDIX A

MICROSOFT VISUAL C++

This appendix gives a brief description about the integrated development environment (IDE) Microsoft Visual Studio 6.0, which was used for programming and building the graphical user interface. The wide ranging scope of the Windows Application Programming Interface (API) requires an object oriented programming language like C++ which has become the professional Windows programmer's language of choice.

The built in library, Microsoft Foundation Class (MFC) Library, provides a comprehensive set of classes representing everything from windows to ActiveX controls in order to simplify Microsoft Windows programming. MFC is continually updated to incorporate the latest changes to Windows itself.

Programs written for traditional operating environments use a procedural programming model in which programs execute from top to bottom in an orderly fashion. The path taken from start to finish may vary with each invocation of the program depending on the input it receives or the conditions under which it is run. In a C++ program, execution begins with the first line in the function named *main* and ends when *main* returns. In between, *main* might call other functions and these functions might call even more functions, but ultimately it is the program - not the operating system - that determines what gets called and when.

Windows program operates differently. They use *event-driven programming model* in which applications respond to events by processing messages sent by the operating system. An event could be a keystroke, a mouse click, or a command for a window to repaint itself, among many other things. The entry point of the Windows program is a function named *WinMain*, but most of the action takes place in a function known as the window procedure. The window procedure processes messages sent to the window. *WinMain* creates that window and then enters a message loop, alternatively retrieving messages and dispatching them to the window procedure. Messages wait in a message queue until they are retrieved. A typical windows application performs the bulk of its processing in response to the messages it receives, and in between messages, it does little except wait for the next message to arrive.

The message loop ends when a *WM_QUIT* message is retrieved from the message queue, signaling that it's time for the application to end. This message usually appears because the user selected *Exit* from the *File* menu, clicked the close button (the small button with

an X in the window's upper right corner), or selected Close from the window's system menu. When the message loop ends, WinMain returns and the application terminates.

The window procedure typically calls other functions to help process the messages it receives. It can call functions local to the application, or it can call API functions provided by Windows. API functions are contained in special modules known as dynamic-link libraries, or DLLs. The Win 32 API includes hundreds of functions that an application can call to perform various tasks such as creating a window, drawing a line, and performing file input and output. The code provided to process an application message is known as message handler. Messages that an application doesn't process are passed on to an API function named DefWindowProc, which provides default responses to unprocessed messages.

APPENDIX B

QUINN CURTIS GRAPHICS LIBRARY

B.1 Introduction

Quinn-Curtis Charting Tools for Windows are a collection of general purpose graphics and user interface functions. The charting tools enables the user to create and incorporate sophisticated graphs into the Windows application. It has been designed for development of Windows NT, Windows 98, and Windows 95 applications using Microsoft Visual C++ or Borland C/C++.

The main part of this software is in the form of a Windows dynamic link library (DLL) , and a very small portion comes as C or C++ source code that has to be compiled and linked with a user application. Multiple applications using these tools can run simultaneously - all supported by the same DLL. The DLL is automatically loaded by the first application that needs it, and is unloaded when the last application using it exits.

Main features of the Charting Tools for Windows are:

- Functions for easy creation of numerous plot types including line plots, scatter plots, several kinds of bar graphs, pie charts, area plots, stacked lines, high-low-close, contour plots, etc.
- Graphs can be enhanced with various kinds of labels, legends, text, arrows, geometric drawings. Bitmaps and metafiles can also be incorporated into graphs.
- Graphical objects can be positioned in coordinates representing data values.
- Automatic axes scaling and labelling.
- Exchange of images with other applications.
- Freedom from managing graph windows.
- Multiple pages and graphs Collection of dialog boxes for editing graphs and individual objects.
- Serialization Mouse support WYSIWYG (What you See Is What You Get) printing.

B.2 Functions

There are numerous functions in the Quinn Curtis Graphics Library. The mathematical functions in the Quinn Curtis Graphics Library used in the PQAT are described below.

B.2.1 FFT Functions

These functions perform direct and reverse Fourier transforms and related operations.

- **WGComplexFFT** Computes direct and inverse fast Fourier transform of a set of complex data values. It uses a modified Cooley-Tukey algorithm.
- **WGFFTFrequency** Calculates the frequency associated with a given harmonic index and sampling frequency.
- **WGFFTMagnitude** Calculates the FFT magnitude associated with a given harmonic index.
- **WGFFTPhase** Calculates the FFT phase associated with a given harmonic index.
- **WGPowerSpectrum** Calculates the power spectrum periodogram of a sampled data set.
- **WGRealFFT** Computes direct and inverse fast Fourier transforms of an array of real data values.
- **WGDSPWindow** Applies a specified windowing function to data array.

APPENDIX C

POWER QUALITY STANDARDS

This appendix gives a brief description of the existing standards related to power quality developed by various organizations. The homepage of the standards developing committee for the standards are listed wherever available. Not all of them were used in the preparation of this thesis work.

C.1 IEEE Power Quality Standards

The Institute of Electrical and Electronics Engineer (IEEE) homepage can be visited at <http://www.ieee.org/>.

- IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book) (ANSI).
- IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) (ANSI).
- IEEE Std 241-1990, IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (IEEE Gray Book) (ANSI).
- IEEE Std 242-1986, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book) (ANSI).
- IEEE Std 399-1990, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (IEEE Brown Book) (ANSI).
- IEEE Std 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book) (ANSI).
- IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire Line Communications Facilities Serving Electric Power Stations.
- IEEE Std 493-1990, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book) (ANSI).

- IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (Reaff 1990) (ANSI).
- IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI).
- IEEE P519A, Guide for Applying Harmonic Limits on Power Systems.
- IEEE Std 602-1986, IEEE Recommended Practice for Electric Systems in Health Care (ANSI).
- IEEE Std 739-1995, IEEE Std 739-1995 IEEE Recommended Practice For Energy Management In Industrial And Commercial Facilities (The Bronze Book) (ANSI).
- IEEE Std 929-2000, IEEE Recommended Practice for Utility Interface Photovoltaic (PV) Systems (ANSI).
- IEEE Std 1001-1988, IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems (ANSI).
- IEEE Std 1035-1989, IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters (ANSI).
- IEEE Std 1050-1989, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI).
- IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (Emerald Book) (ANSI).
- IEEE Std 1159-1995, IEEE Recommended Practice for Monitoring Electrical Power Quality
- IEEE Std 1159.1-2003, IEEE Guide For Recorder and Data Acquisition Requirements for Characterization of Power Quality Events
Status: Under Preparation.
- IEEE Std 1159.2-2003, IEEE Power Quality Event Characterization
Status: Under Preparation.
- IEEE Std 1159.3-2003, IEEE Recommended Practice for the transfer of power quality data
- IEEE Std 1250-1995, IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances (ANSI).
- IEEE P1346-1998, Recommended Practice or Evaluating Electric Power System Compatibility With Electronic Process Equipment

- IEEE P1433, Power Quality Definitions
Status: Under Preparation.
- IEEE P1453, Voltage Flicker
Status: Under Preparation.
- IEEE Std C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI).
- IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).
- IEEE Distribution, Power, and Regulating Transformers Standards Collection, 1995 Edition (C57) (ANSI).
- IEEE Surge Protection Standards Collection, 1995 Edition (C62) (ANSI).

C.2 ANSI Power Quality Standards

ANSI homepage can be visited at <http://www.ansi.org/>.

- ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment - Voltage Ratings (60 Hz).
- ANSI C141 Flicker (1975 Edition).
- ANSI/NFPA 70-1993, National Electrical Code (NEC).

C.3 IEC Power Quality Standards

The (IEC) International Electrotechnical Commission homepage can be visited at <http://www.iec.ch/>.

- IEC 1000 Series, Electromagnetic Compatibility (EMC).

C.4 SEMI Power Quality Standards

The Semiconductor Equipment and Material International (SEMI) homepage can be visited at <http://wps2a.semi.org/wps/portal/>.

- SEMI F47-0200, Specification for Semiconductor Processing Equipment Voltage Sag Immunity.
- SEMI F42-0600, Test Method for Semiconductor Processing Equipment Voltage Sag Immunity.

C.5 UIE Power Quality Standards

The International Union for Electricity Applications (UIE) homepage can be visited at <http://www.uie.org/>.

- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 1: General Introduction to Electromagnetic Compatibility (EMC)
- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 2: Voltage Dips and Short Interruptions
- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 3: Voltage Distortion (to be published)
- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 4: Voltage Unbalance
- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 5: Flicker
- UIE-DWG, Guide to Quality of Electrical Supply for Industrial Installations, Part 6: Transients and Temporary Overvoltages and Currents

C.6 Miscellaneous Power Quality Standards

C.6.1 FIPS Power Quality Standards

The US Federal Information processing (FIPS) homepage can be visited at <http://www.itl.nist.gov/fipspubs/>.

- FIPS PUB 94, Guideline on Electrical Power for ADP Installations, 1983.

C.6.2 NEMA Power Quality Standards

The National Electrical Manufacturers Association (NEMA) homepage can be visited at <http://www.nema.org/>.

- NEMA-PE1 (1992), Uninterruptible Power Systems.
- NEMA MG1 (1993), Motors and Generators.

C.6.3 NFPA Power Quality Standards

The National Fire Protection Association (NFPA) homepage can be visited at <http://www.nfpa.org/>.

- NFPA-75 (1995), Protection of electronic computer data processing equipment.
- NFPA-780-95, Lighting protection code.

C.6.4 NIST Power Quality Standards

The National Technical Information Service (NIST) homepage can be visited at <http://www.ntis.gov/>.

- NIST-SP768, Information poster on power quality. electrical equipment.

C.6.5 UL Power Quality Standards

The Underwriters Laboratories, Inc.(UL) homepage can be visited at <http://www.ul.com/>.

- UL 1449 (1995), Transient voltage surge suppressors.

C.6.6 US Military Power Quality Standards

The United States (US) Military Power Quality Standards apply mostly to the shipboard and aircraft power.

- MIL-STD-1399, Interface Standard for Shipboard Systems.
- MIL-STD-704E, Interface Standard: Aircraft Electric Power Characteristics.
- MIL-E-917E(NAVY), Electric Power Equipment: Basic Requirements.
- MIL-HDBK-454A, General Guidelines: Electronic Equipment.
- MIL-PRF-28800F(SH), Test Equipment for use with Electrical and Electronic Equipment.
- MIL-HDBK-411B, Power and the Environment for Sensitive Department of Defense Electronic Equipment.
- MIL-M-24116B(SH), Monitors, Voltage and Frequency, 400 Hz Electric Power.
- MIL-PRF-24021K "Electric Power Monitors, External, Aircraft"
- MIL-M-24350B(SH), Monitors, Reverse Power and Power Sensing.

APPENDIX D

COMTRADE RECORD

Each Comtrade record consists of four files. All the files have the same name but different extensions. These files are :

- Header
- Configuration
- Data
- Information

The file names are in the form NAME.EXT. The “NAME” field is the “name of the file” used to identify the Comtrade record. The “EXT” field is the extension which identifies the “type of file”. The file names have a limitation of eight characters and the extensions are limited to three characters. The “EXT” field is represented by the following set of three characters: HDR for Header file, CFG for Configuration file, DAT for Data file and INF for Information file.

D.1 Header File

The header file is an ASCII text file for the storage of supplementary narrative information, provided for the user to better understand the conditions of the transient record. The header file is not intended to be manipulated by an applications program. It is created through the use of a word processor program by the originator of the COMTRADE data. The creator of the header file can include any information in any order desired. Examples of information that may be included in the header file are as follows:

1. Description of the power system prior to disturbance
2. Name of the station
3. Identification of the line, transformer, reactor, capacitor, or circuit breaker that experienced the transient
4. Length of the faulted line

5. Positive and zero-sequence resistance and reactance, capacitance
6. Mutual coupling between parallel lines
7. Locations and ratings of shunt reactors and series capacitors
8. Nominal voltage ratings of transformer windings, especially the potential and current transformers
9. Transformer power ratings and winding connections
10. Parameters of the system behind the nodes where the data was recorded (equivalent positive- and zero-sequence impedance of the sources)

D.2 Configuration File

The configuration file is an ASCII text file intended to be read by a computer program. The configuration file contains information needed by a computer program in order to properly interpret the data (.DAT) file. One field in the first line of the configuration file identifies the year of the COMTRADE standard revision with which the file complies (e.g., 1991 or 1999). If this field is not present or it is empty, then the file is assumed to comply with the original issue of the standard (1991). The configuration file also contains a field that identifies whether the companion data file is stored in ASCII or binary format. The configuration file includes following information:

1. Station name, identification of the recording device, and COMTRADE Standard revision year
2. Number and type of channels
3. Channel names, units, and conversion factors
4. Line frequency
5. Sample rate(s) and number of samples at each rate
6. Date and time of first data point
7. Date and time of trigger point
8. Data file type
9. Time Stamp Multiplication Factor

D.3 Data File

The data file contains the value for each input channel for each sample in the record. The number stored for a sample is a scaled version of the value presented to the device that sampled the input waveform. The data is stored in either ASCII or Binary format. The data file type field defined in the configuration file specifies the file type. For ASCII and Binary data files it is set to ASCII and Binary respectively [5].

D.3.1 ASCII Data File

The ASCII data file is divided into rows and columns. The number of data rows varies with the length of the recording. The number of columns is dependent upon the recording system and also affects the file length. Each row is divided into $TT+2$ columns where TT is the total number of channels, analog and status, in the recording. The other two columns are for the sample number and time stamp.

Each data file record consists of following layout:

$n, timestamp, A_1, A_2, \dots, A_k, D_1, D_2, \dots, D_m$

1. The first column contains the sample number represented by ‘ n ’.
2. The second column is the time stamp for the data of that sample number shown by ‘ $timestamp$ ’.
3. The third set of columns contain the data values that represent analog information. A_1, A_2, \dots, A_k are the analog channel data values separated by commas.
4. The fourth set of columns contain the data for the status channels. D_1, D_2, \dots, D_m are the status channel data values separated by commas. The state of the status input is represented by a number “1” or “0” in the data file.

If all the columns containing data values do not fit on the same line, they are continued without a carriage return/line feed until all data values for that sample have been displayed. The last value shall be terminated with carriage return/line feed. The next row (line) begins with the next sample number followed by the next data set. An ASCII end of file (EOF) marker (“1A” HEX) shall be placed immediately following the carriage return / line feed (CR/LF) of the last data row of the file.

D.3.2 Binary Data File

For the most part the binary data file has the same structure as the ASCII data file. The main difference is in the status channel data being compacted. The data within a binary sample record is not separated by commas. The binary data file is a continuous stream of

binary data. Data translation is determined by sequential position within the file. If any data element is missing or corrupt, the sequence of variables is lost and the file is unusable.

The format of the binary data file is

$n, timestamp, A_1, A_2, \dots, A_k, D_1, D_2, \dots, D_m$

The sequential data in the binary format represent the following:

1. Sample number and time stamp data are stored in unsigned binary form of four bytes each.
2. Analog channel sample data are stored in two's complement binary format of two bytes each.
3. Status channel sample data are stored in groups of two bytes for each 16 status channels for each 16 or part of 16 status channels continued until data for all status channels are displayed.

D.4 Information File

The Information file (.INF) file provides information regarding the event recorded in the COMTRADE record that may enable enhanced manipulation or analysis of the data. This optional information is stored in a separate file. The information file is divided into sections. Each section consists of a header line followed by a number of entry lines. There is no limit to the number of sections but there shall be at least one section per file. Each section is identified by a unique section header line. Any program reading data from information files shall be able to recognize any public section header, entry, or other data defined in this standard, and take any action in response to that data.

APPENDIX E

POWER SYSTEMS COMPUTER AIDED DESIGN

EMTDC, Electromagnetic Transients including DC, represents and solves differential equations for both electromagnetic and electromechanical systems in the time domain. Solutions are calculated based on a fixed time step, and its program structure allows for the representation of control systems, either with or without electromagnetic or electromechanical systems present.

PSCAD is a powerful and flexible graphical user interface to the EMTDC solution engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment. Online plotting functions, controls and meters are also included, so that the user can alter system parameters during a simulation run, and view the results directly. PSCAD comes complete with a library of pre-programmed and tested models, ranging from simple passive elements and control functions, to more complex models, such as electric machines, FACTS devices, transmission lines and cables. If a particular model does not exist, PSCAD provides the flexibility of building custom models, either by assembling them graphically using existing models, or by utilizing an intuitively designed Design Editor.

Compilation of the PSCAD network generates FORTRAN source code. The source code is then compiled using EMTDC, which generates executable code that runs in the Windows environment on a PC.

APPENDIX F

SIMULATED SYSTEM PARAMETERS

The data for transmission lines and other system components in the power system model shown in Figure 5.7.

F.1 Transmission Lines

Table F.1: Transmission Line parameters

<i>Name</i>	<i>Length (km)</i>	<i>No Of Con- ductors</i>	<i>Sub- conductors in a bundle</i>	<i>Shunt Con- ductance (mhos/m)</i>
T_{r1}	100	3	1	1.0E-10
T_{r2}	100	3	1	1.0E-10
T_{r3}	100	3	1	1.0E-10

The frequency dependant (phase) model was used for all the transmission lines.

F.2 Generator

Table F.2: Generator Parameters

<i>Name</i>	<i>Power</i>	<i>Power Factor</i>	<i>Voltage (L-L)</i>
G1 - Source	100 MW	0.866 lagging	13.8 kV
G2 - Source	100 MW	0.866 lagging	13.8 kV

F.3 Current Transformers

The model can be represented as shown in Figure F.1. The model has two wire labels for representing the primary and secondary currents of the current transformer respectively.

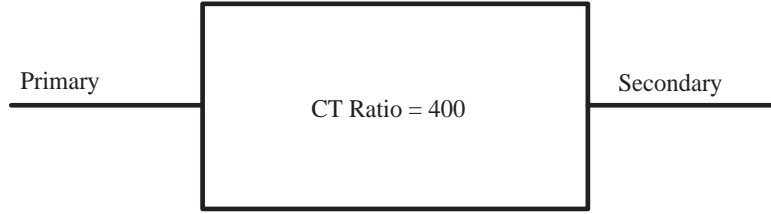


Figure F.1: Current Transformer Model

The primary wire label is given the same name as the current label used in the EMTDC simulation model. The secondary wire label then gives the equivalent CT output for the given input current. The CT ratio can be selected in the model. The input current is in kA and the output current is in A.

F.4 Transformers

Table F.3: Transformer

<i>Name</i>	<i>MVA Rating</i>	<i>Voltage Ratio</i>	<i>X_Tp.u.</i>
T_{rf1}	1000	13.8 kV / 230 kV	0.1

F.5 Loads

Table F.4: Load

<i>Name</i>	<i>Power (MW)</i>	<i>Voltage</i>
L1	200	230 kV
L2	200	230 kV