A

Dissertation

on

“Real Time Power Quality Event Detection”

Submitted in

partial fulfilment of the requirement

for the award of the degree of

MASTER OF TECHNOLOGY

in

VLSI DESIGN & EMBEDDED SYSTEMS

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CERTIFICATE

This is to certify that the report titled **"Real Time Power Quality Event Detection"** is a bonafide record of Major Project-II submitted by Navin Singhal (Roll no: 2K13/VLS/14) as the record of the work carried out by him under my guidance. The said work has not been submitted anywhere else for the award of any other degree or diploma.

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DECLARATION

I hereby declare that work presented in this report, titled **"Real Time Power Quality Event Detection"**, in partial fulfillment for the award of degree of M.Tech. in VLSI Design & Embedded Systems, submitted in the Department of Electronics and Communication Engineering, Delhi Technological University, Delhi is my own work carried out during December, 2014 - May, 2015 under the guidance of Dr. Rajiv Kapoor, Professor, Department of Electronics and Communication Engineering, Delhi Technological University, Delhi.

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ACKNOWLEDGEMENTS

I express my deepest gratitude to my guide **Dr. RAJIV KAPOOR**, Department of Electronics and Communication Engineering, Delhi Technological University whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. His suggestions and ways of summarizing the things made me to go for independent studying and trying my best to get the maximum in my topic, this made my circle of knowledge very vast. I am highly thankful to him for guiding me in this project.

I am also grateful to **Prof. Prem R. Chadha**, HOD, Electronics and Communication Engineering Department, DTU for his immense support.

Finally, I take this opportunity to extend my deep appreciation to my family and friends, for all that they meant to me during the crucial times of the completion of my project.

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ABSTRACT

The quality of electric power and disturbances occurred in power signal has become a major issue among the electric power suppliers and customers. For improving the power quality continuous monitoring of power is needed which is being delivered at customer's sites. Therefore, detection of Power Quality Disturbances (PQD), and proper classification of PQD is highly desirable. The detection and classification of the PQD in distribution systems are important tasks for protection of power distributed network. Most of the disturbances are non-stationary and transitory in nature hence it requires advanced tools and techniques for the analysis of PQD. In this work S-Transform and Histogram of Oriented Gradients are used for detection of PQD. A number of power quality events are generated and S-Transform and Histogram of Oriented Gradients(HOG) are applied for accurate detection of disturbances. It is also observed that when the PQD are contaminated with noise the detection becomes difficult and the feature vectors to be extracted will contain a high percentage of noise which may degrade the classification accuracy. Distinct features common to all PQD like Energy, Standard deviation (SD) are extracted and are fed as inputs to the classifier system for accurate detection and classification of various power quality disturbances.

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Chapter 1

Introduction

Power quality measures the goodness of electronic devices and electrical power. Correctness of the amplitude, phase and frequency allows electrical systems to work properly. “Power Quality term is used to explain the electrical power that operates the electrical load and its ability to function properly”. “PQ disturbances/events have a wide range of frequencies and significantly variations in their magnitude and they can be stationary or non-stationary signals”. There are many causes which results in low electrical power quality. The Power industry comprises electricity generation, transmission and finally distribution to a user premises. The significance of power quality disturbance/event is mainly due to increased use of sensitive electronic equipments, increased use of SSD (solid state devices), automated and data processing equipments non linear loads and loads that are power electronically Switched, as well as rectifiers and inverters [2]. In on-line detection and identification of power quality disturbances/events it is necessary to know the source and cause of such disturbance for appropriate mitigation/corrective action. Power Quality (PQ) events like voltage sag, oscillatory transients, flicker, voltage swell, harmonics, spikes etc are the most frequent types of disturbances that appear in a system. Highly sensitive and costly equipment’s are connected with the power line are affected and damaged due to disturbances that occur randomly for very short interval of time. Voltage dips also known as voltage sag are amongst one of the most critical disturbances for the industrial equipment. “Over voltages also known as voltage swell can result in over heating and may destroy industrial equipments like electric motor, drives etc”. “Electronic systems are highly sensitive against harmonic disturbance as their control mainly depends either on the peak value or the zero crossing of the signal, and these both are extremely affected by the harmonic disturbance”.
“So, any kind of disturbance that takes place in the amplitude, phase or frequency may also affect the customer’s side which is called power quality problem”. Decrease in the quality of power is mainly supported by disturbances like Swell, Sag, harmonic distortions etc. Electric motor consume more current on starting as compared to current when they are operating at their rated speed. Therefore, switching on of an electric motor may result in voltage sag. Energization of vast capacitor bank may result in voltage swell. In practical distribution network power quality has to be very good therefore to achieve this disturbances should be detected and classified first before mitigation step can be taken. A practical way to reduce the problem of such disturbances is to apply detection capabilities in equipments so that the disturbance of interest can be identified, captured and classified automatically. Therefore, good performance monitoring systems must be able to detect, localize and classify the PQ events for minimizing their impact by devising suitable corrective and preventive measures.
Now a day’s computers have been tremendously used in our daily work, as they can handle a large amount of data and computations more accurately and efficiently than humans. So the capabilities should be exploited to do more intelligent tasks with high accuracy.

1.1 Literature Survey

Power "Quality disturbances/events are generally non-stationary in nature and exist for a very small duration of time". For "efficient identification of such short duration signals, both time and frequency domain analysis is required". "By using Fourier Transform, it is not possible to completely analyze a signal as fourier transform only provides frequency domain information but it does not give any time domain information. Time domain information is very important step for identifying the time and duration of the occurrence of disturbance [29]". "For studying non-stationary signal, Time frequency analysis is more efficient as it gives both time and frequency information of the signal". "Many researchers have used other techniques like Discrete Wavelet Transform (DWT) and Short Time Fourier Transform (SFT). In (SFT) analysis, a fixed size window is used to shift in time for analyzing the signal which is not efficient for power quality events, because power quality events contain wide range of frequencies". "In such cases DWT is more suitable for analysis of time-frequency variations as it contains a fixed window width [30]. For classifying transient disturbances wavelet based Radial Basis Neural Network method proposed by T.Jayasree is more effective. In this thesis, various PQ disturbances have been generated and HOG (Histogram of Oriented Gradients) and S Transform are applied to disturbance signal to detect the disturbance". Gaing [50], "used Multi-Resolution technique for breaking the signal into two coefficients, detail and approximation coefficients". "In that paper Probablistic Neural Network has been used for classification of disturbances based on the features obtained from the detail coefficients through multiple decompositions". Zhang Ming [60] used a method which involves RMS and FFT technique for obtaining the features from the detected disturbance signal. "In this thesis, HOG has been proposed to detect the disturbance and entropy along with Standard deviation are used(in case of S-Transform) as features extracted from the disturbance signal for classification of signal disturbance".

1.2 Objective of the Project

The main objective of this work is to propose a new technique that can detect and classify the power quality (PQ) fast and accurately.

Steps involved in detection and classification of PQD are :

1. Detection of PQ events (using S-Transform and HOG).

2. Feature extraction (Features like Standard Deviation, Entropy etc.)

3. Classification (using SVM, Fuzzy Logic etc.)

1.3 Chapter Outline

This thesis contain nine chapters overall.

Chapter 1 Describes the overview of the project. Few lines about introduction of power quality. Then, continued with introduction that gives some information regarding disturbances in PQ , then literature survey, and finally objective of the work has been discussed.

Chapter 2 Provides information regarding power quality events their cause of generation in real world and finally their generation details in MATLAB.

Chapter 3 Tells us about the Wavelet Transform.

Chapter 4 Tells us about the S-Transform.

Chapter 5 Tells us about the HOG.

Chapter 6 In this chapter different types of features has been discussed which are extracted after detection stage and behaves as input for classification stage.

Chapter 7 In this chapter classification process has been discussed.

Chapter 8 Simulation results showing detection of various power quality events using HOG and S-Transform are provided in this chapter.

Chapter 9 This chapter discuss about Conclusion and Future Scope of this thesis.

Chapter 2

Introduction on Power Quality

"PQ itself has many definitions from manufacturer, consumers and utility perspectives". "PQ is defined as idea of powering and grounding highly sensitive equipments in such a manner that is suitable for the operation of the equipment [70-8]". This chapter will describe what PQ is, the problems associated to PQ and How power quality events are generated in practical equipments and how they can be generated using MATLAB.

2.1 The significance of "Power Quality (PQ)"

"The standard of electric power has become main issue for both consumers and power generation companies". The consumers, in specific, are the party who faces a main damaging effect of their devices due the PQ problem or technically define as power disturbances". "These disturbances/events have decreased the performance and efficiency of consumer's device especially power electronics devices [15]". "In seeking relief, electric power utilities and consumers tries to inspect, monitor, record and study of the electric power to detect the problem and then apply mitigation technique in order to correct the occurrences of the disturbance".

2.2 Types of Power Quality (PQ) Problems

The most appropriate way to reduce the PQ disturbance is to install proper wiring and grounding systems for electrical consumers systems [10]. Another major factor that causes PQ problem is the use of electronic devices that are especially non-linear devices. The non-linear devices consumes harmonic currents, and as a result, harmonic voltages are generated when this harmonic current flows through the linear system [21]. The existance of harmonic results in many problems to consumer's electrical system and device [22]. Another approach that can enhance the quality of power is good knowledge of PQ area.

The theoretical situation of the performance and effect of the load usage in electrical equipment is very important. The performance of load relates to the size of cable used in the system, the appropriate mitigation technique and protective system used be used. One should realize that most of the PQ problems are originated from the load. Another problem in achieving high PQ level is that effects of natural causes like lightning, man-made etc problems. These problems cannot be avoided from the practical systems. A good protective system should be implemented to stop such problems in wider area.

2.3 Power Quality (PQ) Phenomena

"PQ has been defined in many ways in which it is used in the related field. Therefore PQ can be defined as less fluctuation, high performance of electrical system and less false operation of the system [33]". "This definition is obtained from consumers point of view, which is obtained from the system application. From the utility point of view, PQ is defined as the ability of the generator to deliver the power to the consumers". "PQ may also be defined with respect to both parties as the availability of the current or voltage in an electrical system to perform a sinusoidal characteristic [34]". "The high variation of current and voltage from the desired sinusoidal characteristic shows very low PQ of the system". "But since PQ problem, is defined as any change in terms of magnitude

and frequency in any of the both current or voltage that may cause any problem relating to the malfunctioning or false operation of the electrical system or equipment of the consumers". "It means that, the large variations in voltage or current may cause serious problems to the consumers equipments or the utility".
"PQ phenomena characterization is applicable for all utilities, manufacturers and consumers side to prepare them for proper mitigation action". "In this thesis work, eleven power disturbances have been discussed, which can have one or more characteristics as listed by PQ phenomena, these disturbances are selected for further analysis". "These eleven PQ disturbances are interruption, harmonics with flicker, oscillatory transient, flicker, harmonics, voltage sag, voltage swell, harmonics with sag, harmonics with swell, harmonics with interruption, and impulsive transient". The selection of disturbances was motivated by the vast literature available on disturbance waveform [08].

2.3.1 "Voltage Sag"

Voltage sag can be defined as "the deccrease in the nominal rms voltage between the value 0.1 p.u. to 0.9 p.u". "The time length of voltage sag can vary from 0.5 cycles to 1 minute". "Sag occurs mainly due to existence of Single Line to Ground (SLG) faults, heavy motor starting and over current drawn activities. Voltage sag may also be defined as the short duration decrease of the voltage level". "If the decrease in the voltage exists for more than 1-minute, we use a new term known as under voltage". However, voltage sag can be divided into three broad classes based on the duration of interval for which sag exists. "These classes are instantaneous , momentary and temporary sag [07]".

2.3.2 "Voltage Swell"

"Voltage swell" can be defined as "the increase in the nominal rms voltage between the value 1.1 p.u. to 1.8 p.u". The occurrence frequency of voltage swell is low as compared to occurrence of voltage sag. "The time length of voltage swell can vary from 0.5 cycles to 1 minute which is same as in case of voltage sag". "The factors that may result voltage swell includes light system loading, incorrect tap setting of the transformer etc". However, voltage swell can also be divided into three broad classes based on the duration of interval for which swell exists. "These classes are instantaneous, momentary and temporary swell as discussed in case of voltage sag". If the continuous duration of increased voltage is more than 1 minute, then overvoltage term is used preferable. "Placing fast acting tap changers in the electrical system can be used to mitigate voltage swell". "The severe effects of voltage swell event includes overheating of devices and high iron loss in maximum machines applications [07]".

2.3.3 Interruption

"Voltage Interruption" is can be defined as "the decrease in rms voltage less than that 0.1 p.u." "Mainly voltage interruption occurs after the occurrence of voltage sag". "The voltage interruption occurs as a result of loose connection, major faults and reclosing of circuit breaker". Reclosing of circuit breaker action results in transient phenomena followed by interruption can also be observed. "The voltage interruption results in inconvenience tripping and false operation of the overall system". "Voltage interruptions shows that there is almost zero voltages and no more power supply is available for the system".

2.3.4 Oscillatory Transient

"Oscillatory transient" event is another type of PQ phenomena "that occurs and is totally different from the previous phenomena" that have been discussed so far. "The transient is sudden change in magnitude of voltage". "The typical time length of this disturbance is between 5µs to 50ms". "The maximum magnitude in case of transient may reach up to 2.0 p.u". But, in most of the typical cases maximum magnitude of oscillatory transient remains between 1.2 to 1.5 p.u. "The sudden changes in the magnitude during the occurrence oscillatory transients can be positive or negative in polarity". "The transient may be generated as a result of capacitor switching, load switching and reclosing of circuit breaker [07]".

2.3.5 Impulsive Transient

"Impulsive transient" is another rapidly occurring disturbance that is experienced by the electrical users. "Impulsive transient is an instantaneous, non-power frequency variation of voltage". "The instantaneous change in magnitude of voltage for impulsive transient is unidirectional having positive polarity". "This disturbance is identified by its very short rise and decay times". The time length of the disturbance may be less than 50ns and can go up to the duration of more than 1 ms. The most common cause that generates impulsive transient is lightning strike [07].

2.3.6 Voltage Flicker

Voltage flicker or flickering can be defined as cyclic variations in amplitude of voltage with amplitude varying below 10% of the nominal value. Electrical devices are mainly not damaged by voltage fluctuations, but these fluctuations may result in the change in illumination intensity of light devices. Voltage flicker may result in a very unpleasant visual sensation, that becomes the source of complaints from utility customers. The disturbance level and unpleasant visual sensation depends on the type of lamp and characteristics (amplitude, frequency and duration) of the flickering.

2.3.7 Harmonics

Harmonics are generated in an electric power system due to the presence of non-linear loads. Harmonic voltages and currents "in the power grid system are one of the frequent causes of power quality problems". "Harmonics in systems causes over heating of the devices and conductors, false firing in variable speed drives, and torque variations in motors". "Reduction or complete removal of harmonics is considered desirable". "In a general the voltages vary sinusoidaly at a specific frequency, usually 50 or 60 hertz". "When a linear load is present to the system, it draws a sinusoidal current which has same frequency as that of voltage (phase may be different)".

Harmonics are generated because of the presence of non-linear electric loads that are connected to the system. “When a non-linear load, such as a rectifier is connected to the system, it takes current that is not necessarily sinusoidal”. “The resulting current waveform may be very complex in nature, depending on the type of load and how load interact with other components of the system”. Fourier series analysis decomposes the current waveform into a series sinusoids regardless of complexity of current waveform, as described by fourier series. The decomposed signal contains fundamental frequency and other frequencies that are “integer multiples of the fundamental frequency”.
Most common examples of devices that act as “non-linear loads includes common office equipment such as computers and printers, Fluorescent lighting, battery chargers etc”.

2.3.8 Other PQ Disturbances

1. Harmonics along with Sag
2. Harmonics along with Swell
3. Harmonics along with Flicker
4. Harmonics with Interruption

All above disturbances are called multistage events. Multistage events occurs due to occurrences of the more than one type of event at the same time many other types of disturbances can also occur due to various combinations of above events.

2.4 Generation of PQ disturbances

Synthetic data of PQ events is advantageous in estimating the generalization ability of the classifier so it is accepted and widely used [8, 13]. The availability of the real power quality event's data is limited as it requires a long monitoring time simultaneously at number of locations with uncertainty in the occurrence of the power quality events. So, numerical models of the power quality events are used for the simulation in MATLAB. These synthetically generated PQ events obtained from the mathematical models very are close to the real-time data and can be generated as per the international standards. Multiple power quality events are generated from summation of single stage power quality events. Numerical modeling of the simulated power single and multiple quality events [15]. Power quality events are simulated in MATLAB as per standard IEEE-1159 [2]
“The different types of power quality disturbances such as Interruption, Harmonics Voltage Sag, Voltage Swell, Harmonics with Sag and Swell etc”. have been generated with different characteristics using MATLAB 2013a. Fig2.1 shows the Flow chart how to generate “PQ signal disturbance using MATLAB 21013a”.

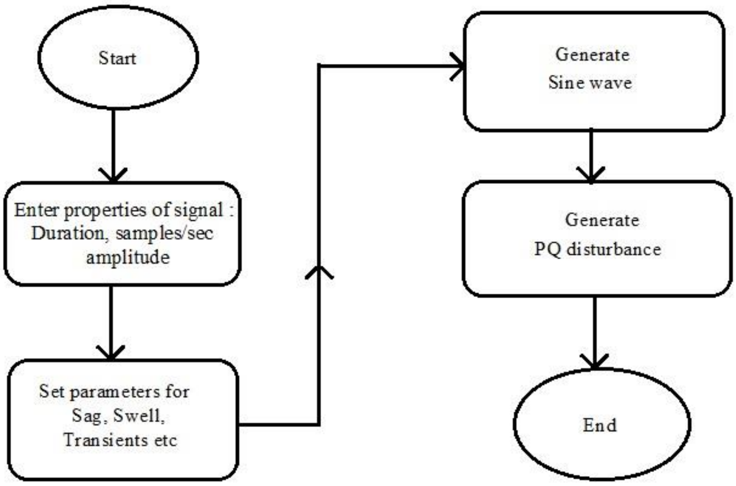

Fig.2.1 Flow chart for PQ signal disturbance generation using MATLAB

2.4.1 Signal Specification

Specification of all eleven events are listed in Table.1 . Figures from Fig.2.2 to Fig.2.13 shows the signals generated using parameters given in Table1. All these signals are generated using MATLAB 2013a.

Table.1 Signal Specification

PQ Disturbance	Model	Parameter
Sine	$f(t) = A\sin(\omega t)$	Frequency = 50Hz A=1
Sag	$f(t) = A(1 - a(u(t - t_1) - u(t - t_2)))\sin(\omega t)$	0.1≤a≤ 0.9; T≤ t_2 - t_1≤9T
Swell	$f(t) = A(1 + a(u(t - t_1)$-u(t-t2)))sin($\omega t$)	0.1≤ $\alpha \le 0.8$; T≤ t_2 - t_1≤9T
Interruption	$f(t) = A(1 - a(t\sin(\omega t)$	0.1≤a≤ 0.9; T≤ t_2 - t_1≤9T
Flicker	$f(t) = A(1 + \alpha_f \sin(\beta_f \omega t))\sin(\omega t)$	$\alpha_f = 0.1 - 0.2$ $\beta_f = 5 - 10Hz$
Harmonic	$f(t) = A(\alpha_1.\sin(\omega t) + \alpha_3\sin(3\omega t) + \alpha_5.\sin(5\omega t) + \alpha_7.\sin(7\omega t))$	0.05≤ $\alpha_3 \le 0.15$ 0.05≤ $\alpha_5 \le 0.15$ 0.05≤ $\alpha_7 \le 0.15$ $\sum \alpha_i^2 = 1$
Transient	$f(t) = A\sin(\omega t) + \alpha_{OSC}.\exp\left(-\left(\frac{t - t_1}{T_{OSC}}\right)\right).\sin\omega_{nosc}(t - t_1))$	$T_{osc} = 0.008 - 0.04s$ $\omega_{nosc} = 100 - 400Hz$
Swell with Harmonic	$f(t) = A\left(1 + \alpha\left(u(t - t_1) - u(t - t_2)\right)\right).\alpha_1\sin(\omega t) + \alpha_3.\sin(3\,\omega t) + \alpha_5.\sin(5\omega t) + \alpha_7.\sin(7\omega t))$	0.1≤ $\alpha \le 0.8$ T≤ $t_2 - t_1 \le 9T$ 0.05≤ $\alpha_i \le 0.15$ $\sum \alpha_i^2 = 1$
Sag with harmonics	$f(t) = A(1 - a(u(t - t_1) - u(t - t_2)))_* A(\alpha_1.\sin(\omega t) + \alpha_3\sin(3\omega t) + \alpha_5.\sin(5\omega t) + \alpha_7.\sin(7\omega t))$	0.1≤a≤ 0.9 T≤ t_2 - t_1≤9T 0.05≤ $\alpha_3 \le 0.15$ 0.05≤ $\alpha_5 \le 0.15$ 0.05≤ $\alpha_7 \le 0.15$ $\sum \alpha_i^2 = 1$

Flicker with harmonics	$f(t) = A(1 + \alpha_f \sin(\beta_f \omega t))\sin(\omega t) * A(\alpha_1.\sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5.\sin(5\omega t) + \alpha_7.\sin(7\omega t))$	$\alpha_f = 0.1 - 0.2$ $\beta_f = 5 - 10Hz$ $0.05 \le \alpha_3 \le 0.15$ $0.05 \le \alpha_5 \le 0.15$ $0.05 \le \alpha_7 \le 0.15$ $\sum \alpha_i^2 = 1$
Interruption with harmonics	$f(t) = A(1 - a(t \sin(\omega t) * A(\alpha_1.\sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5.\sin(5\omega t) + \alpha_7.\sin(7\omega t))$	$0.1 \le a \le 0.9$; $T \le t_2 - t_1 \le 9T$ $0.05 \le \alpha_3 \le 0.15$ $0.05 \le \alpha_5 \le 0.15$ $0.05 \le \alpha_7 \le 0.15$ $\sum \alpha_i^2 = 1$
Spikes	$f(t) = \sin(\omega t) + sign(\sin(\omega t)) * \sum k * (u(t - (t_1 + 0.02n)) - (u(t - (t_2 - 0.02n)))$	$0.1 \le k \le 0.4$ $0 \le t_1$ $t_2 \le 0.5T$, $0.01T \le t_2 - t_1 \le 0.05T$

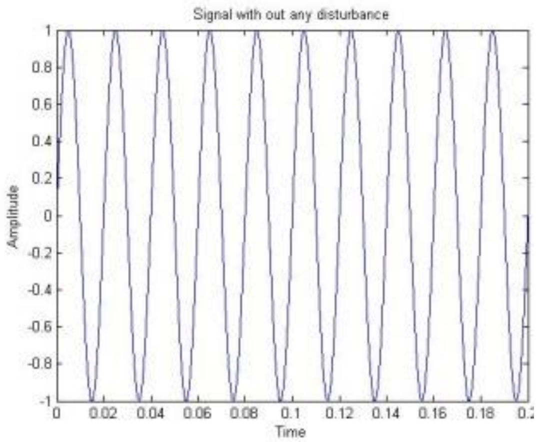

Fig.2.2 Pure Sine Wave

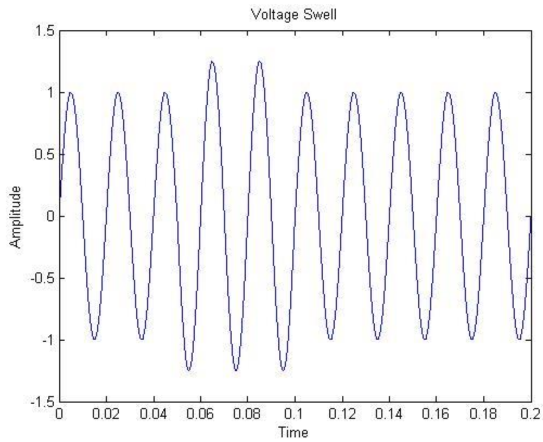

Fig.2.4 Voltage Swell

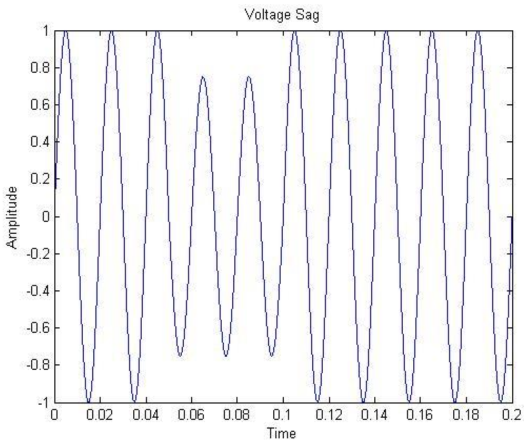

Fig.2.3 Voltage Sag

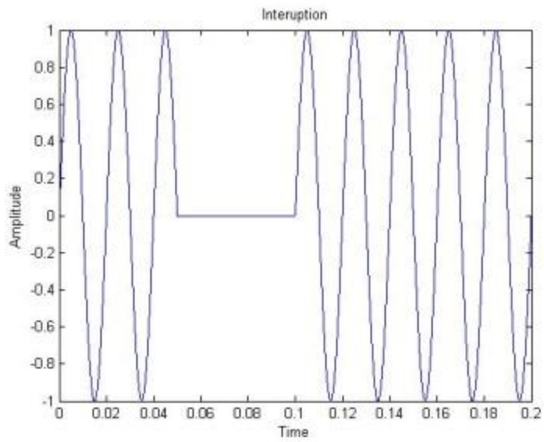

Fig.2.5Voltage Interruption

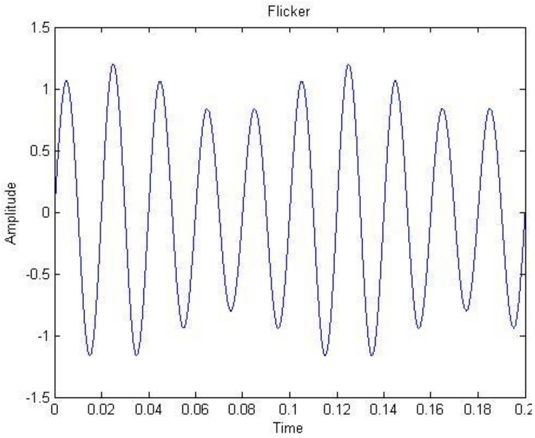

Fig.2.6 Voltage Flicker

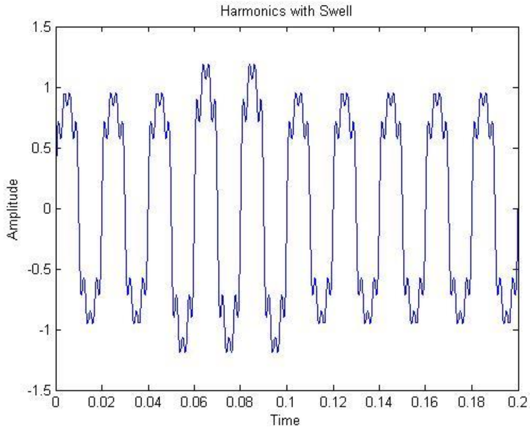

Fig.2.9 Harmonic with Swell

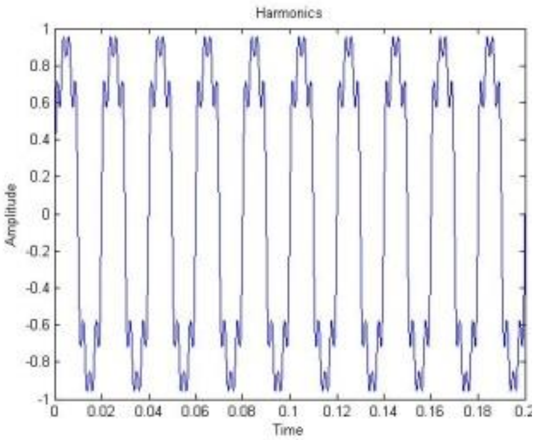

Fig.2.7 Harmonics

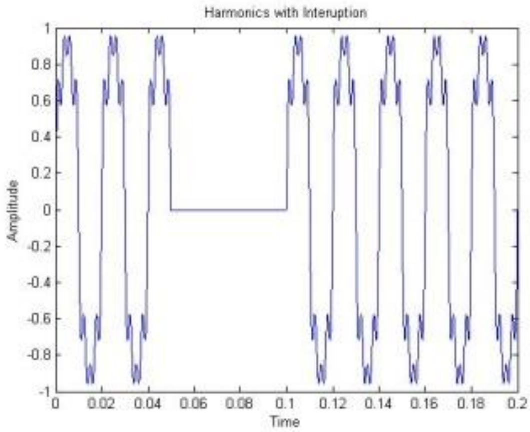

Fig.2.10 Harmonic with Interuption

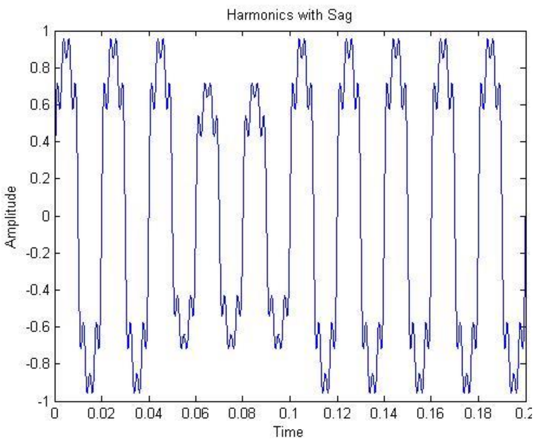

Fig.2.8 Harmonic with Sag

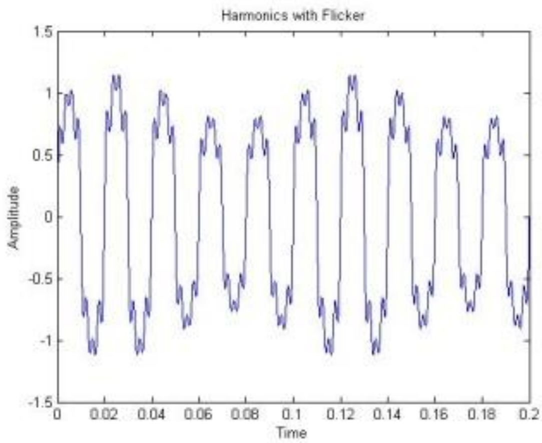

Fig.2.11 Harmonic with Flicker

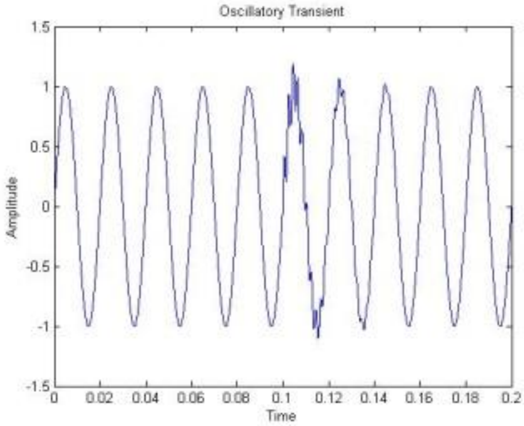

Fig.2.12 Oscillatory Transients

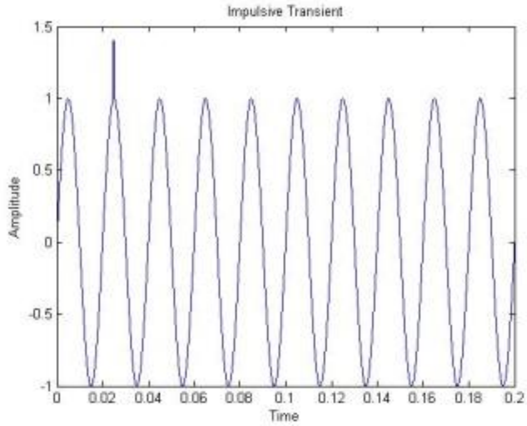

Fig.2.13 Impulsive Transient

Chapter 3

Wavelet transform (WT)

“Wavelet Transform has appeared as very strong signal processing tool that is used in the power quality area for analysis”. The WT can inspect different types of power quality events simultaneously in “time” and “frequency domain”, therefore giving the “time-frequency” representation of signal as given by “Short Time Fourier transform (STFT)”. STFT uses a fixed constant size frequency window function whereas the wavelet transform(WT) makes use of a variable size time frequency window, “whose window length depends on the frequency being analyzed using long windows for low frequencies and short windows for high frequencies”. Hence, “Wavelet transform(WT) provides accurate frequency resolution” and “poor time location at low frequency” , provides “accurate time location and poor frequency resolution at high frequency”. This property of “WT makes it highly effective for real events such as over voltages, under voltages, transients etc”. Wavelet transform based “online disturbance analysis” for power quality applications are more efficient as compared to conventional techniques in terms of speed and accuracy discrimination in the type of event [01]. In addition to detection of PQ events, wavelet transform is also effective in power system protection[], detection of high impedance faults[], and PQ data compression [].

3.1 “Wavelet transform and multi-resolution analysis”

Fourier analysis of a signal involves decomposing the signal into sine waves of different frequencies. In the same way, wavelet analysis involves breaking up the signal into scaled and shifted versions of the original wavelet also known as “mother wavelet”. The resulting wavelets are called “daughter wavelets”, these resulting wavelets are “localized in time and frequency both”. Therefore, “wavelet transform gives a local representation of signal in time and frequency both” whereas “Fourier transform only gives a global representation of signal in terms of frequency”. “Wavelet series (WS)”, “Continuous wavelet transform (CWT)”, and “Discrete wavelet transform (DWT)” are three different ways by which wavelet transform can be obtained. Continuous wavelet transform of any signal x(t) using the wavelet ψ(.) is represented by the following equation

$$CWT_x^{\psi}(a,b) = \psi_x^{\psi}(a,b) = \frac{1}{\sqrt{|a|}} \int_t f(t)\psi^*\left(\frac{t-b}{a}\right) dt \qquad (3.1)$$

where ‘a ’ is scale parameter, ‘b ’ is translation parameter and $1/\sqrt{a}$ is a normalization constant, ψ is the “mother wavelet”. All kernels can be obtained by shifting (translating) and/or scaling of the mother wavelet. The oscillation frequency and the wavelet length of wavelet is decided by the scaling parameter, ‘a ’, and the shift in position of wavelet is decided by the translation parameter, ‘b ’. Discrete wavelet transform is obtained by using discrete values of the scaling and translation parameter. This is achieved by replacing ‘a ’ by ‘a_0^m’ and ‘b’ by ‘$nb_0a_0^m$’ where ‘m ’ is the translation step describing frequency localization and ‘n ’ is scaling step describing time localization.

$$DWT(m,n) = \frac{1}{\sqrt[m]{a_0}} \sum_k f(k)\, \psi\left(\frac{k-nb_0a_0^m}{a_0^m}\right) \qquad (3.2)$$

“Wavelet transform” is also known as “dyadic-orthonormal” wavelet transform when $a_0 = 2$ and $b_0 = 1$ and this results in a very efficient algorithm known as “multi-resolution signal decomposition technique”. This technique “muli-resolution analysis (MRA)” was introduced by “Mallat [01]”. This technique “ decomposes the signal into scale with different time and frequency resolutions”. In MRA a signal f(n) can be entirely decomposed into (high frequency components) detailed version and (approximated versions)smoothed versions. The wavelet function acts as high pass filter with filter coefficients denoted by h(n), generates the detailed version of the input signal, whereas the scaling function associated with low pass filter with filter coefficient denoted by g(n), generate the approximated version of the input signal. Therefore by using MRA, "high frequency transient can easily be analyzed in the presence of low frequency components such as non-periodic wide-band signals and non-stationary signals". MRA can be implemented by using a set of successive filter banks as shown below in Fig.3.1.

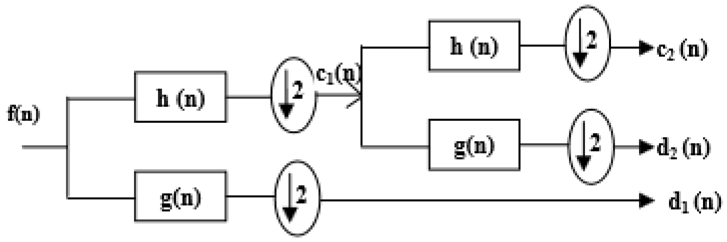

Fig.3.1 "Decomposition of f(n) into two scales"

The coefficients denoted by "h(n) and g(n)" are coefficients for the "low pass and high pass filters respectively". Let f(n) is the discrete version of continuous time signal f(t), from MRA we get the decomposed signals at scale 1 denoted "by $c_1(n)$ and $d_1(n)$", in which $c_1(n)$ represents the "smoothed version of the input signal", and $d_1(n\ )$ represents "the detailed version of the input signal down-sampled by a factor 2". Since high pass filter as well as low pass filters are half band, they decompose half the time resolution, therefore now only half number of sample are present to characterize the complete signal. But on the other hand "this operation doubles the frequency resolution" and hence the "frequency band of signal now have only half the previous frequency band", "effectively decreasing the uncertainty in the frequency domain by half". The next higher level/scale decomposition now depends on the signal $c_1(n\ )$ which act as input for second scale, which decomposes $c_1(n\ )$ further into $c_2(n\ )$ and $d_2(n\ )$. Therefore each scale, "this filtering and sub sampling operation results in half the number of samples from previous stage" and "thus makes half the time resolution and doubles the frequency resolution". The choice of "mother wavelet" plays a "significant role in localizing and detecting various types of power quality disturbances". "Daubechie's Wavelets" "with filter coefficients 4, 6, 8, and 10" work efficiently in almost all the disturbance detection cases. "At the first or lowest scale (scale 1)", the mother wavelet is the mostly localized in time and it "oscillates very rapidly within a very short interval of time". As we go in "higher scales the analyzing wavelets" become "less localized in time and they oscillates very less due to the dilation nature of the wavelet transform". "As a result of higher scale decomposition of signal", "the rapidly changing and short duration power quality disturbances will be captured at lower scales, whereas slow and long duration power quality disturbances are captured at higher scales". Therefore, both rapidly changing and slow changing power quality disturbances can be accurately detected. Since "Daubechie's 4 (Daub4)" has the lowest number of filter coefficients and it provides the shortest support.

Chapter 4

S Transform

S-transform[2] is considered among one of the best techniques used for "performing signal processing of non-stationary signals". "S-transform" is an advancement in the CWT (Continuous Wavelet Transforms) as it makes use of the information hidden in the phase of the CWT by suitably altering the phase of the mother wavelet function. It produces a "multi-resolution" analysis like "a bank of filters with constant relative bandwidth". It uniquely merges the frequency dependent resolution along with simultaneously localizing the real and imaginary spectrum. "Time frequency localizing property" is given by this transform, in computing both amplitude of discrete data and phase spectrum of discrete data samples. The "S-matrix" is generated for each power quality event by making use of advantages of two techniques, FFT and convolution theorem. The output result of the S-Transform is a complex matrix of size k x n and is represented as,

$$S(t_o, f) = B(t_o, f)e^{-j\emptyset(t_o,f)} \qquad (4.1)$$

where B(t_o, f) is the amplitude and Φ(t_o, f) is the phase. In S matrix rows represent the frequencies and the columns represents the time. Each column gives information about the different frequency components contained by the signal at a particular time. Each row gives information about the magnitude of a frequency with time changing from 0 to N-l samples.

4 .1 Continuous S-Transform

"The CWT w(t_o,d_o) of a function h(t) is represented as",

$$w(--t_o, d_o) = \int_{-\infty}^{+\infty} h(t)w(d_o, t - t_o)dt \qquad (4.2)$$

Width of the wavelet is determined by the scale parameter d_o and thus controls the resolution. t_o provides the position of the wavelet. The "S-transform" is defined as a "CWT" with a particular "mother wavelet function" multiplied by the phase factor as,

$$S(t_o, f) = e^{-j2\pi ft}w(d_o, t_o) \qquad (4.3)$$

$$w(t, f) = \frac{f}{\sqrt{2\pi}} e^{\frac{-t^2 f^2}{2}} e^{-j2\pi ft} \qquad (4.4)$$

Where mother wavelet w(t_o,d_o) is given as

The frequency f is the inverse of scale parameter d.
So the continuous S transform is given as

$$S(t_o, f) = \int_{-\infty}^{+\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{-t^2 f^2}{2}} e^{-j2\pi ft} dt \qquad (4.5)$$

and the Gaussian window has a width given as

$$\sigma(f) = T = \frac{1}{|f|} \qquad (4.6)$$

S-transform and Fourier Transform are related to each other by relation given below

$$S(t_o, f) = \int_{-\infty}^{+\infty} H(\beta + f)\, e^{\frac{-2\pi^2\beta^2}{f^2}} e^{j2\pi\beta t_o} dt \quad f\neq 0 \tag{4.7}$$

4.2 "Discrete S-Transform"

The power quality disturbance signal h(t) can be sampled as h(kT) where T is the sampling interval time and the discrete Fourier transform of the sampled signal h(kT), where k=O to N-l is as,

$$H\left[\frac{n}{NT}\right] = \frac{1}{N}\sum_{k=0}^{N-1} h(kT)\, e^{\frac{-j2\pi nk}{N}}$$

(4.8)

where n=0,l,. .. N-1.

The discrete version of the S transform is obtained as t_o→jT and is f→n/(NT) as,

$$S\left[jT, \frac{n}{NT}\right] = \sum_{k=0}^{N-1} H\left[\frac{m+n}{NT}\right] G(m,n)\, e^{\frac{j2\pi mk}{N}} \quad n\neq 0 \tag{4.9}$$

where G(m,n)= $e^{\frac{-2\pi^2 m^2}{n^2}}$

For n=0, equation (4.9) is modified as,

$$S[jT, 0] = \frac{1}{N}\sum_{k=0}^{N-1} H\left[\frac{m}{NT}\right] \tag{4.10}$$

This equation (eqn.(4.10)) makes the "constant average of the time series into the zero frequency voice", thus assuring the inverse is exact. The "inverse of the discrete S transform" is given by

$$h[jT] = \frac{1}{N}\sum_{n}^{N-1}\left[\sum_{k=0}^{N-1}\left\{S\left(jT, \frac{n}{NT}\right)\right\}\right] e^{\frac{j2\pi nk}{N}} \tag{4.11}$$

Complex form of S-transform matrix is calculated for each power quality event and then absolute S-matrix is obtained for extracting the time frequency information. "The maximum value of each column gives the information regarding the main frequency present in the signal at a particular time". "The maximum value of each row gives the information regarding the maximum amplitude of that frequency in the whole sample time". The frequency of the event can be found by multiplying the sampling frequency with the frequency scale value corresponding to the maximum amplitude of the row. Scale value is the "normalized frequency" value which is the ratio of the frequency amplitude to the sampling frequency.

Chapter 5

“Histogram of Oriented Gradient”

"Histogram of Oriented Gradient descriptors", or "HOG descriptors", are "feature descriptors" mainly used for the purpose of "object detection" in "computer vision and image processing". This technique counts existence of "gradient orientation in limited portion of an image".

This chapter deals with the feature extraction using "histogram of oriented gradients (HOG)". This technique gives the normalized value of the "histograms of gradients". "HOG features" was initially introduced by "Navneed Dalal and Bill Triggs [01]" they have developed this technique and tested several variants of "HOG descriptors", with different kind of "spatial organization, and normalization methods".

The "key idea" behind this technique "HOG descriptors" is that the appearance of local object and its shape in an image can be represented by "the distribution of intensity gradients or edge directions". "Execution of these descriptors can be achieved by, dividing the image into small but connected regions, "known as cells", and for each and every cell compiling a "histogram of gradients directions" or "edge orientations" for the pixels within the cell". The resultant combination of these histograms is then called "as descriptor". For "improved performance", the small local histograms can be "contrast normalized by calculating a measure of the intensity across a bigger region of the image", known as a "block", and then utilizing this value to "normalize all the cells within the block". This type of normalization results in better invariance to changes in the illumination or shadowing.

5.1 Algorithm

5.1.1 Preprocessing

Preprocessing is initially used to reduce the noise coming in the image. The reduction is compulsory otherwise it will give false output of the gradient vectors. Preprocessing is mainly done with the help of the filters by convolving the image with the filter noise will get reduced. Multiplication of image with the filter can also be called as a kernel or mask. The multiplication or convolving the image is simply sliding the filter over the image. To reduce noise various filters are used such as Gaussian filters etc.

5.1.2 Gradient Computation

In order to get the accurate shape and appearance gradient computation is useful. This is the primary step in calculation feature extraction of the image. "The simplest and the most common method to obtain gradient" is to "apply the one dimensional centered point discrete derivative mask" in "horizontal and vertical directions". This function is based on calculating the derivatives of each function. $\partial f / \partial x$ And $\partial f / \partial y$ at each and every pixel coordinate is calculated. This technique "needs filtering" of the "grayscale image" with the given below "filter kernels":

$D_X = [-1\ 0\ 1]$ and $D_Y = [1\ \ 0 - 1]'$

So, for the given image I, we must obtain "the x and y derivatives" with the help of "convolution operation":

$I_X = I * D_X$ and $I_Y = I * D_Y$

The Gradient magnitude is given by $G = \sqrt{{I_X}^2 + {I_Y}^2}$

Gradient orientation is given by $\theta = \arctan(I_Y/I_x)$

Original image is shown in Fig.15(a) then gradients is estimated with the help of above expression in x direction as well as y direction. After finding the gradients in both the directions then resultant magnitude will be calculated. Gradient in x as well y direction is shown in Fig.15(b) and 15(c). Resultant magnitude is shown in
Fig.15(d) and the orientation of gradient is calculated by trigonometry expressions explained above. The images come out after gradient which expresses the boundaries of the image.

Fig .5.1(a)

Fig .5.1(b)

Fig .5.1(c)

Fig .5.1(d)

5.1.3 “Orientation Binning”

In “HOG” analysis “weighted magnitude & binning orientation” plays important role. “Each pixel inside the cell provides a weighted vote” for “orientation-based histogram channel”, which is based on the values found in “gradient computation”. The cells are generally “rectangular” and the “histogram channels are spreaded evenly between 0 to 180 degrees or 0 to 360 degrees”, which is decided on the basis of gradient whether the gradient is “unsigned” or “signed”. “Dalal and Triggs” found that unsigned gradients should be used in “conjunction with 9 histogram channels” for best performance in their experiments[]. As for the “vote weight, pixel contribution can itself be the gradient magnitude”, or the “square or square root” of the gradient magnitude.

5.1.4 “Descriptor Blocks”

In order to “account for variation in illumination and contrast”, the “strength of gradients” must be “normalized locally”, which needs “grouping of the cells” together to form “large spatially-connected blocks”. Then “HOG descriptor” is the “vector of the components of the obtained normalized cell histograms” from each and every block region. These blocks generally “overlap, resulting that each cell contributes more than once to form the final descriptor”.

5.1.5 Block Normalization

Generally there are various types of variations in the images such as illumination, background and foreground contrast and brightness. It varies the gradient strength over a wide range. Without applying normalization result is not that much accurate. So the normalization is necessary to get desired result. Below figures shows the normalization result.

There are various methods to perform normalization techniques.

$$L2-norm: \quad \nu \rightarrow \nu / \sqrt{\|\nu\|_2^2 + \epsilon^2}$$

$$L1-norm: \quad \nu \rightarrow \nu / (\|\nu\|_1 + \epsilon)$$

$$L1-sqrt: \quad \nu \rightarrow \nu / \sqrt{\|\nu\|_1 + \epsilon}$$

By using these equations normalization is performed where v is the vector representing the histogram of the block after combining. Î is a very small constant. After calculation of above equation we get the normalized featured vector of HOG.

Chapter 6

Feature Extraction

"Feature extraction" of a power quality disturbance signal helps us to obtain "information that detects the responsible fault". An "accurate and fast" feature extraction tool helps "power engineers" to "monitor, control and maintain power quality disturbances more efficiently". The selection of extracted parameters "(magnitude, duration, frequency component, or waveform shape)" "plays an important role in deciding the complexity of the classifier structure". "Feature extraction plays a critical role in designing of intelligent systems that can be used for pattern recognition". The ability of the classifier to classify is badly affected if the extracted features are not selected wisely. Further, to enhance computing ability and accuracy of correctly recognizing a PQ event the feature extractor must convert the original signal to a lower dimension which has the most useful information of the original signal. The features obtained by signal processing algorithms are used as input to PQ classification system. Feature extraction is defined as conversion of the raw signal, from its original form to a new form, from where suitable information can be obtained. Carefully selected feature set reduces the pressure from the classifiers. Therefore, good consideration of PQ related problems demands an highly effective signal processing technique.

Many different features have been obtained with various detection techniques for the purpose of classification like Standard Deviation, Mean, Maximum value, Min value, Entropy, THD(Total Harmonic Distortion) etc have been used rapidly in power quality event detection.

Like standard deviation, maximum value and mean have been used as given below for S-Transform matrix[01]

(a) F_1 represents: "Standard deviation" of "time-maximum amplitude" plot representing the "amplitude of fundamental frequency component".

(b) F_2 represents: "Maximum value" of "frequency in the time-frequency plot".
(c) F_3 represents: "Frequency-maximum" amplitude plot.
(d) F_4 represents: "Mean value" of "time-maximum amplitude plot".

Similarly other features like "THD, Energy" have been frequently used many times for wavelet transform [01]

6.1 "Total Harmonic Distortion or THD"

The "total harmonic distortion", is a "measurement of the harmonic distortion present in a signal" and it is "defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency".

$$THD = \frac{\sqrt{\frac{1}{N_f}\sum n\left[cD_f(n)\right]^2}}{\sqrt{\frac{1}{N_f}\sum n\left[cA_f(n)\right]^2}} \qquad (6.1)$$

Where cDj is obtained from wavelet decomposition and is known as detail coefficient.

and cAj is obtained from wavelet decomposition and it is known as approximation coefficient.

6.2 “Energy”

In wavelet transform the original signal is decomposed into two components represented as the “approximate” and “detailed coefficients”. “Therefore energy dissipated by the signal in terms of approximate and detail coefficients represented by the following equation”

$$E = \sum_k |C_j(k)|^2 + \sum_{j=1}^{I} \sum_k |D_j(k)|^2 \quad (6.2)$$

Where C j (k) and Dj (k) represents “approximate coefficient” and “detail coefficient” at jth level respectively.

Chapter 7

Classifier

Classifier plays an important role in pattern recognition. The goal of classifier used is to classify event on the basis of some characteristics to which classes they belong. The classifier classify the desired patterns based on the value of characteristics also known as features.

Many classifiers have been used in past for power quality event classification like ANN, SVM, Fuzzy Logic etc Their main motive is to determine a decision boundary between pattern classes. In order to get good results of decision boundary, the best way is used to minimizing the error level that is reducing mean squared error.

7.1 “Support Vector Machine (SVM)”

“Support vector machine” is an algorithm with many great advantages “in the area of classification” and it has been developed from “Statistical Learning Theory” by “Vapnik [7]”. The main advantages include “firstly”, it provides “accurate classification” with support vectors, “which is not affected by noise”. “Secondly”, the use of “kernel function” “helps SVM to solve nonlinear problems” efficiently without making a “feature space with explicit high dimension”. “Thirdly”, SVM has “capability to be applied for both” “binary and multiclass” classification. “Support vector machine classifier” is used widely in power quality event detection task. “The main procedures of SVM classifier” are showed as Fig.7.1. It “minimizes the edge of linear hyperplane” and “tries to find out best separation between the patterns” and “provides higher accuracy in classification” according to “F. Qi et al. [8]”, Although there are some mistakes when considering for small sample, nonlinear and high dimensional pattern recognition issues. The application of Linear SVM (support vector machine) has been used with various features sets. There is another type of SVM which is non linear uses polynomial and radial basis function to map the sample to get the higher dimensional space. Hence the performance will get boost up. But the main disadvantage of this method is that it is a binary classifier that is it can classify only two classes at one time. If more than one class has to be classified than complexity of system increases and also increases computation costs and memory. SVM constructs hyperplane in N-dimension. Mainly SVM model uses sigmoid or linear function. When kernel function is used support vector machine can be applied to polynomial, weights of a network has been found out by quadratic programming problem. The aim of SVM modelling is to separates clusters of vectors. The one category of the desired variable is on the one side and the other category of the vectors on another side. The vectors distribute on plane. The simplest application work in two dimensional spaces. A classification is performed, when the data is having two categories and these are two known and continuous values. The SVM analysis separates the cases based on their target values. Generally high dimensional and irregular vectors are present which cannot be divided by those SVM which are linear so the separation has been done with the help of the non linear curves.

If the clusters cannot be completely separated, then a third predictor variable is added, its value will be used in third dimension and points can be plotted in three dimension cube. Here points in 3-D can be separated by 2-D. According to this rule of SVM predictor value is added with the data points in an N-Dimensional space, and a (N-1) dimensional plane can separate them. The decision function is non linear function of the data that’s the reason of non linear hyperplane is used for separation. A variety of kernels is used in many researchers’ topics. A few kernels considered for having good performance in many applications for example linear, polynomial, and sigmoid.

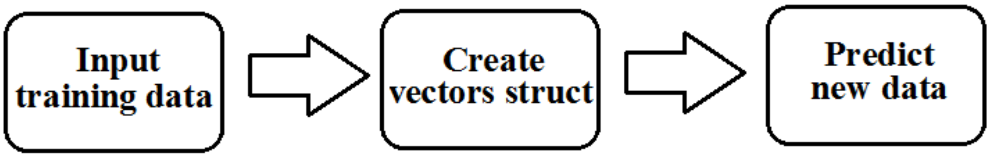

Fig.7.1 Operating Procedures of Classifiers

Chapter 8

Results

8.1 Simulation Results

All the simulation of power quality events have been done according to IEEE standards and are done in MATLAB 2013a.

8.1.1 Simulation results of detection of various events using S-Transform.

Power quality events generated according to Table.1 have been detected successfully using S-transform. S-Transform extracts information both in time and frequency domain. In each Fig.8.1 to Fig.8.9 plot 1 shows the disturbance signal plot 2 shows time domain information obtained by applying S-Transform and plot 3 shows the frequency domain information obtained by applying S-Transform.

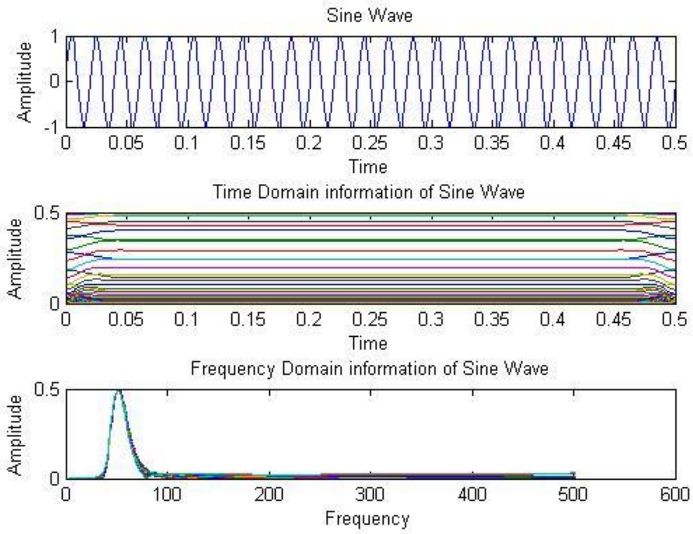

Fig.8.1 Sine wave and its detection using S-Transform

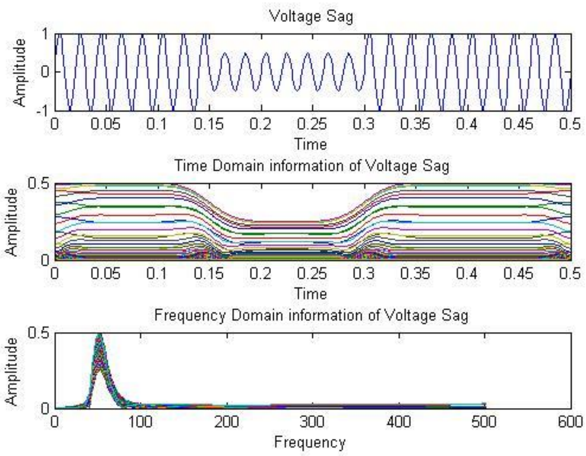

Fig.8.2 Voltage Sag and its detection using S-Transform

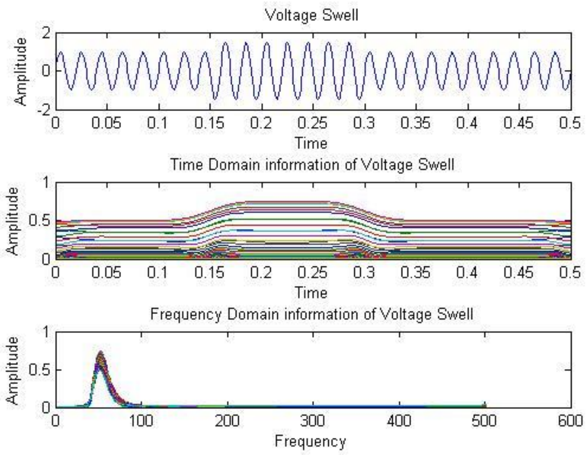

Fig.8.3 Voltage Swell and its detection using S-Transform

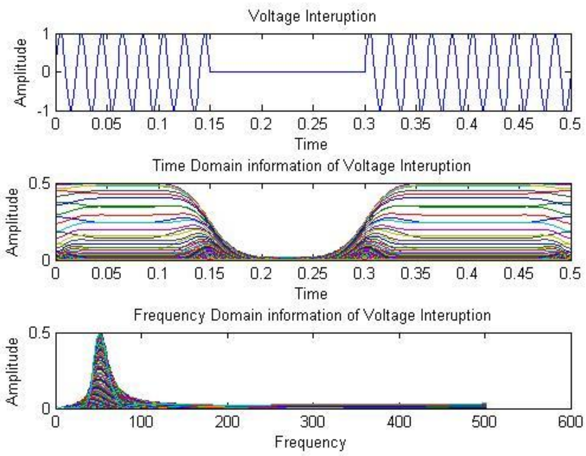

Fig.8.4 Voltage Interuption and its detection using S-Transform

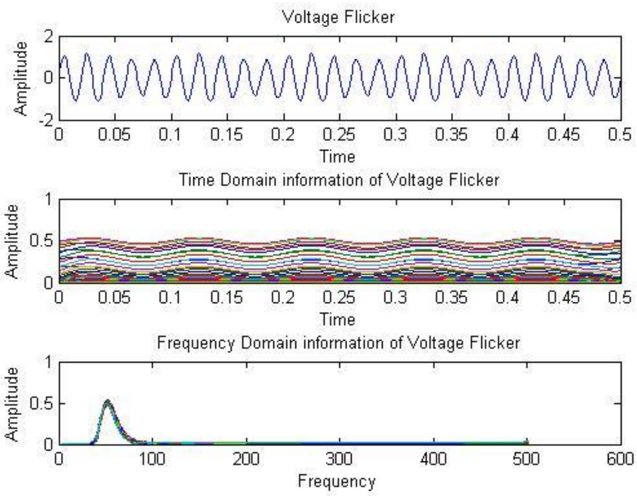

Fig.8.5 Voltage Flicker and its detection using S-Transform

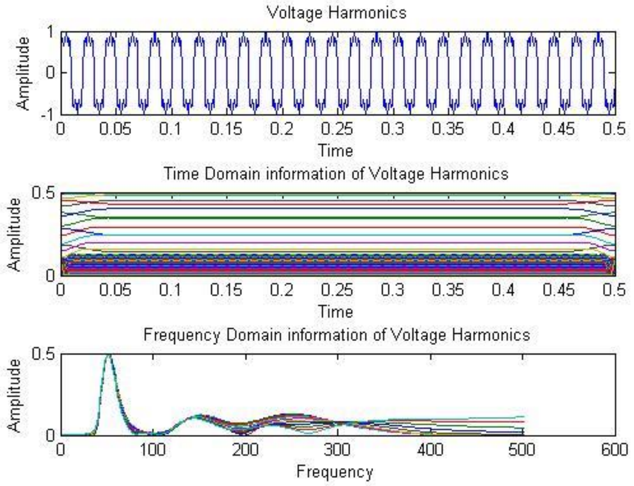

Fig.8.6 Voltage Harmonics and its detection using S-Transform

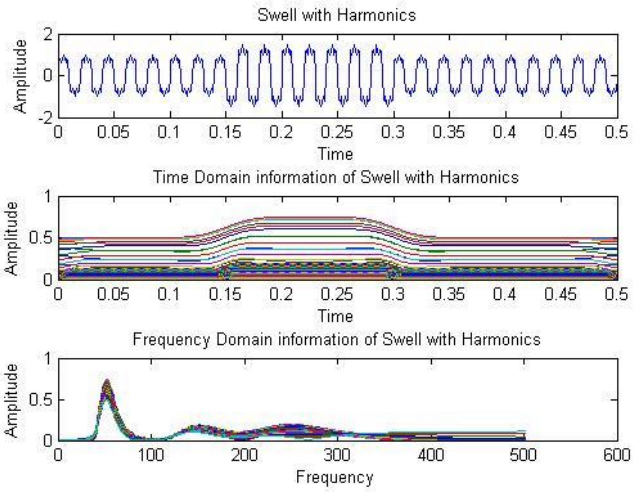

Fig.8.7 Voltage Swell and its detection using S-Transform

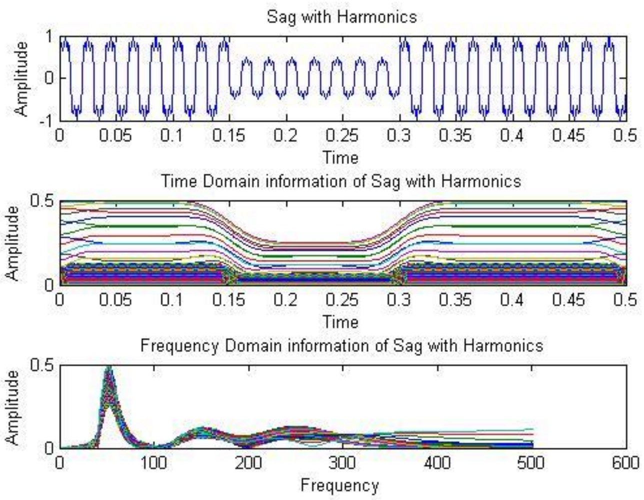

Fig.8.8 Sag with Harrmonics and its detection using S-Transform

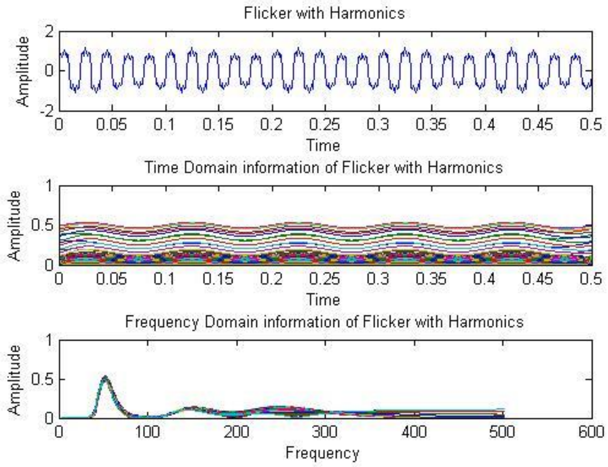

Fig.8.9 Flicker with Harmonics and its detection using S-Transform

8.1.2 Simulation results of detection of various events using HOG.

HOG extracts information in time domain. In each Fig.8.9 to Fig.8.15 plot 1 shows the disturbance signal plot 2 shows time domain information obtained by applying HOG.

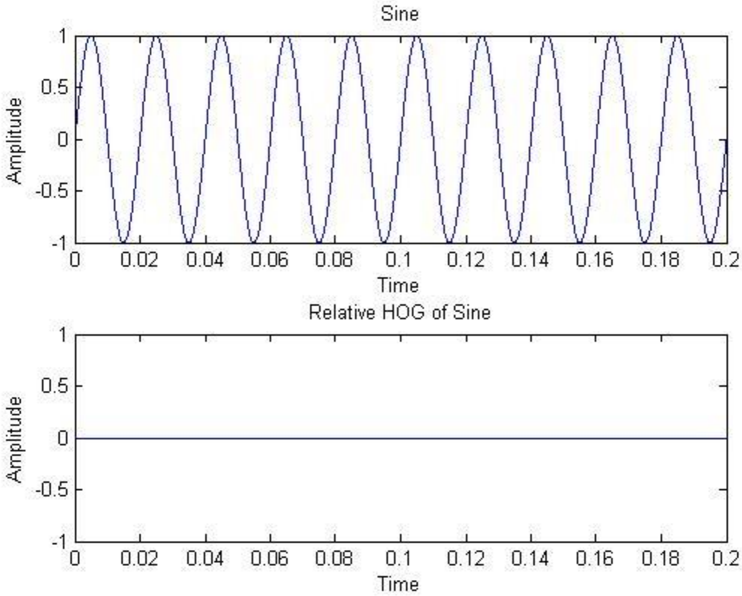

Fig.8.10 Sine wave and its detection using HOG.

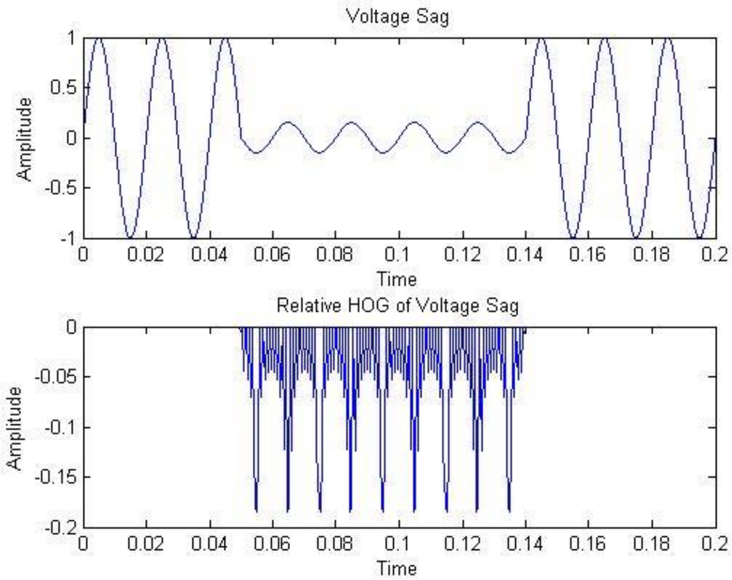

Fig.8.11 Voltage Sag and its detection using HOG.

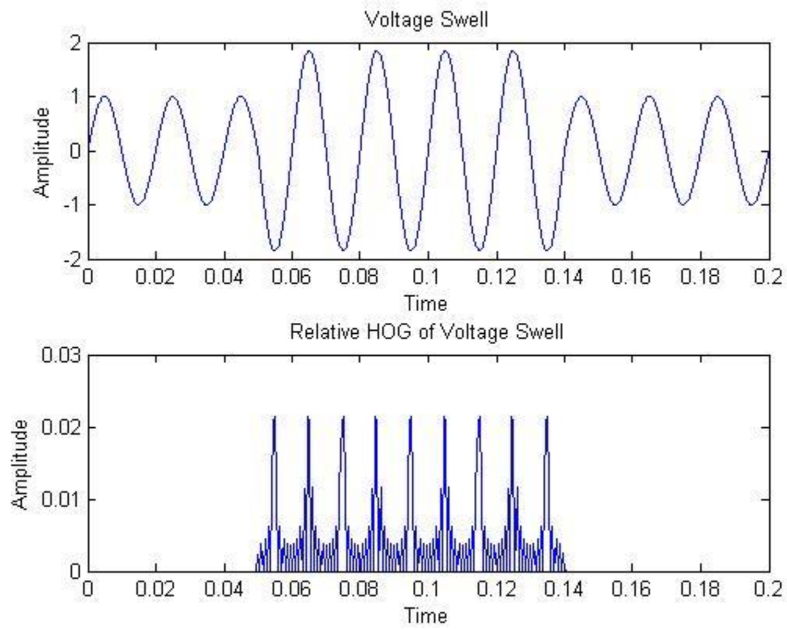

Fig.8.12 Voltage Swell and its detection using HOG.

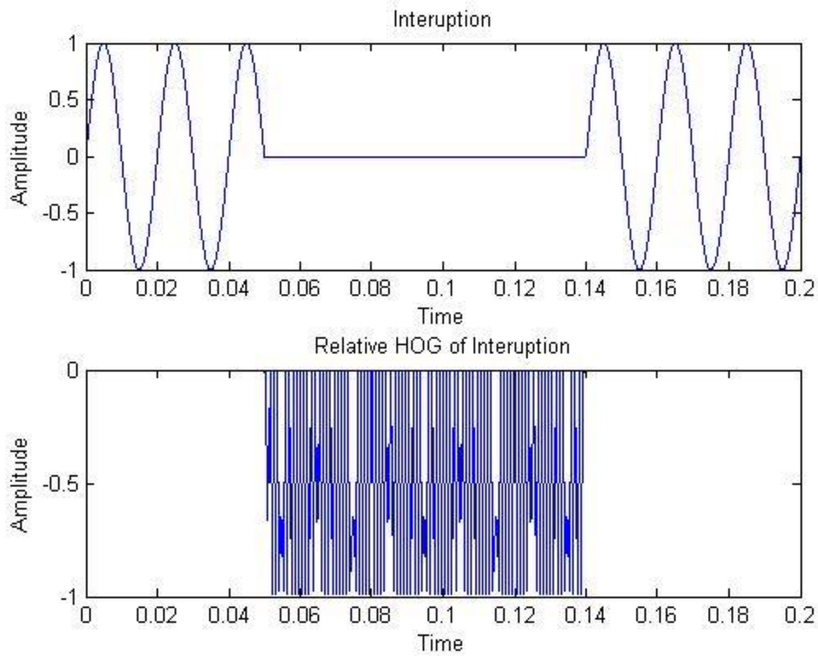

Fig.8.13 Interuption and its detection using HOG.

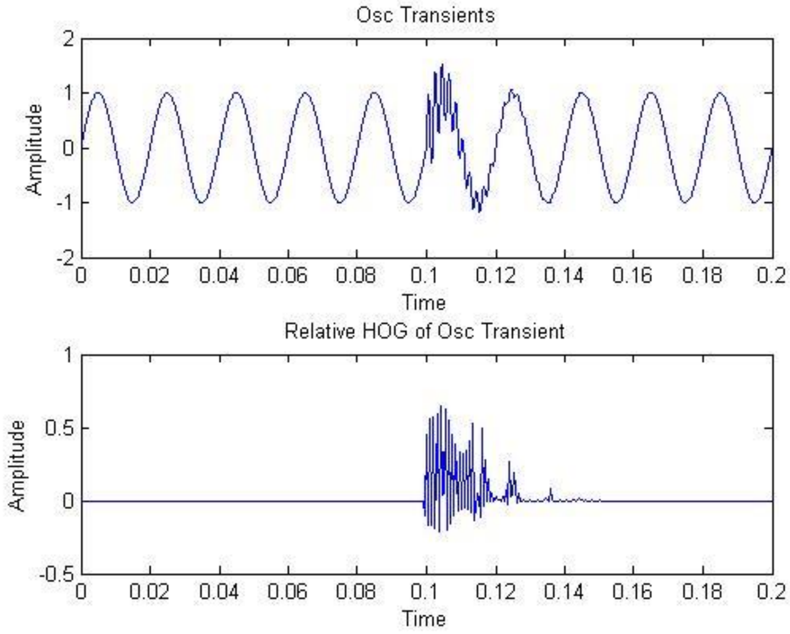

Fig.8.14 Osc Transient and its detection using HOG.

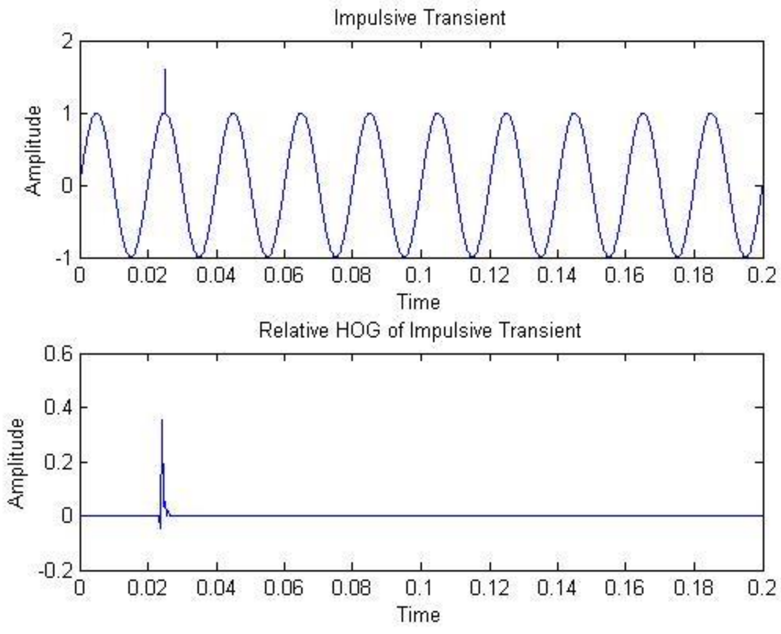

Fig.8.15 Impulsive Transient and its detection using HOG.

Chapter 9

Conclusion and Future scope of work

9.1 Future scope of work

1. “In this work” “wavelet transform”, “S-Transform” and “HOG” has been discussed although “HOG” is “less complex” and “fast” as compared to S-Transform and Wavelet Transform but “it is not so efficient to detect harmonics” therefore some new technique should be merged with HOG to make it efficient for harmonics detection also.

2. “In this thesis”, effect due to “noise” has not been considered. “In the future research work, the effect of noise will be included”. In this thesis simulated signal have been used in future work instead of simulated signals, “the real distorted signal can be used which can be obtained by digital recorder” and “through a dsPIC based hardware system”, “it can be implemented for real time”.

9.2 Conclusion

In this thesis, firstly it has been tried to detect pure sinewave and all the PQ disturbances that commonly appear in a system such as voltage sag, voltage with harmonics, transients, voltage swell, and flicker at power system frequency.
Before classification, First S-Transfrom, Wavelete Transform or HOG is applied to PQ disturbances and pure sine wave. Then after getting the feature matrix of all the disturbances matrix of sine wave is taken as reference. To get the information of disturbance features are extracted from the feature matrix. After obtaining feature vector, classification of disturbance is carried out by using a powerful classifier.

REFERENCES

[1]P.S.Wright,"Short time fourier transform and wigner-ville distributions applied to the calibration of power frequency harmonic analyzers," IEEE Trans.instrum.meas. (1999) 475-478.

[2]Y.Gu,M.Bollen, "Time Frequency and Time Scale Domain Analysis of Voltage Disturbances," IEEE Transactions on Power Delivery, Vol 15, No 4, October 2000, pp 1279-1284.

[3] G.T.Heydt, P.S. Fjeld, C.C.Liu, D.Pierce, L.Tu, G.Hensley,"Applications of the Windowed FFT to Electric Power Quality Assessment," IEEE Trans.Power Deliv.Vol.14 (4) (1999) 1411-1416.

[4]R. Polikar, The Engineer's Ultimate Guide to Wavelet analysis, The Wavelet Tutorial.March 1999.

[5]S.Santoso, W.M.Grady,E.J.Powers,J.Lamoree and S.C.Bhatt,"characterization of distribution power quality events with fourier and wavelet transforms," IEEE Trans.power delivery,Vol.15,pp 247-254,jan.2000.

[6]Abdelazeem A.Abdelsalam, Azza A.Eldesouky,Abdelhay A.Sallam,"characterization of power quality disturbances using hybrid technique of linear kalman filter and fuzzy expert system," ELSEVIER Electric power system Reaserch 83 (2012) 41-50.

[7]L.C.Saikia, S.M.Borah, S.Pait,"detection and classification of power quality disturbances using wavelet transform and neural network," IEEE annual india conference 2010.

[16] IEEE 1159: 1995, Recommended practice for monitoring electric power quality, 1995.

[9] M. Gouda, M. M. A. Salama, M. R. Sultan, and A. Y. Chikhani, "Power quality detection and classification using wavelet multiresolution signal decomposition," IEEE Trans. Power DelivelY, vol. 14, no. 4, pp. 1469-1476, Oct.l999.

[10] R.G. Stockwell, L. Mansinha and R.P. Lowe, "Localization of the complex spectrum: the S-transform," iEEE Transactions on Signal ProceSSing, vol. 4, pp. 998-1001,1996.

[11] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power quality analysis using S-transform," IEEE Trans. on Power Delivery, vol.18, no.2, pp.406-411, Apr.2003.

[12] P. Janik and T. Lobos, "Automated classification of power quality disturbances using SVM and RBF networks," iEEE Trans. Power Delivery, vol. 21, no. 3, pp. 1663-1669,J uly 2006.

[13] F. Z. Zhao and R. G. Yang, "Power-Quality Disturbance Recognition Using S-Transform," IEEE Trans on Power Del., vol. 22, no. 2, pp.944-950, Apr.2007.

[14] S. Mishra, C. N. Bhende, and B. K. Panigrahi, "Detection and Classification of Power Quality Disturbances Using S-Transform and Probabilistic Neural Network," iEEE Trans. Power Delivery, Vo1.23, pp. 280-287, Jan. 2008.

[15] Rodney H.G. Tan and V.K. Ramachandramurthy, "Numerical Model Framework of Power Quality events," European Journal of Scientific Research, vol. 43. no.l, pp.30-47, 2010.

[17]Karimi M., Mokhtari H., and Iravani M.R., 2000, Wavelet based on-line disturbance detection for power quality application, IEEE Trans.on Power Del., vol.15, no. 10, pp. 1212-1220.

[18]Charri O., Meunier M., and Brouaye F., 1996, Wavelets: A new tool for the resonant grounded power distribution system relaying, IEEE Trans on Power Del., vol. 11, pp. 1301-1308.

[19]Michalik M., Rebizant W., Lukowicz M., Sang-Jae L., Sang- Hee K., 2006, High impedance fault detection in distribution networks with use of wavelet- based algorithm, IEEE Trans. on Power Del., vol. 21, pp.1793-1802.

[20]Santoso S., Powers E. J., and Grady W. M., 1997 Power quality disturbance data compression using wavelet transform methods, IEEE Trans. on Power Del.,vol.12, pp. 1250-1257.

[21]Mallat S., 1989, A theory for multiresolution signal decomposition: The wavelet representation, IEEE Trans. Pattern Anal. Mach. Intell. Vol.11, no.7, pp 674-693.

[22] Jiaqi Li, M. V. Chilukuri, Power Supply Quality Analysis Using S-Transform and SVM Classifier, Journal of Power and Energy Engineering, 2014, 2, 438-447 Published Online April 2014 in SciRes. http://www.scirp.org/journal/jpee http://dx.doi.org/10.4236/jpee.2014.24059.

[23]N.Dalal, B.Triggs: Histograms of oriented gradients for human detection, IEEE Computer Society Conference on Computer visionand Pattern Recognition, 2005.

[24] Sharmistha Sarkar, Power Quality Disturbance Detection And Classification Using Signal Processing and Soft Computing Techniques, June 2014.

[25] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power quality analysis using S-transform," IEEE Trans. on Power Delivery, vol.18, no.2, pp.406-411, Apr.2003.

[26] P. Janik and T. Lobos, "Automated classification of power quality disturbances using SVM and RBF networks," IEEE Trans. Power Delivery, vol. 21, no. 3, pp. 1663-1669,J uly 2006.

[27] F. Z. Zhao and R. G. Yang, "Power-Quality Disturbance Recognition Using S-Transform," IEEE Trans on Power Del., vol. 22, no. 2, pp.944-950, Apr.2007.

[28] S. Mishra, C. N. Bhende, and B. K. Panigrahi, "Detection and Classification of Power Quality Disturbances Using S-Transform and Probabilistic Neural Network," iEEE Trans. Power Delivery, Vo1.23, pp. 280-287, Jan. 2008.

[29] Murat Uyar, Selcuk Yildirim and Muhsin Tunay Gencoglu, "An expert system based on S-transform and neural network for automatic classification of power quality disturbances," Expert Systems with Applications, vol. 36, Issue 3, Part 2, pp. 5962-5975, April 2009.

[30]Vapnik, V.N. (1995) The Nature of Statistical Learning Theory. Springer-Verlag, New York. http://dx.doi.org/10.1007/978-1-4757-2440-0

[31]Qi, F., Bao, C. and Liu, Y. (2004) A Novel Two-Step SVM Classifier for Voiced/Unvoiced/Silence Classification of Speech.