

Harmonic Estimation Of Distorted Power Signals Using PSO - Adaline

A Thesis Submitted in Partial Fulfilment
Of the Requirements for the Award of the Degree of

MASTER OF TECHNOLOGY

in
Electrical Engineering
(Power Control & Drives)

by
G. S. C. TRINATH PRABHU
Roll No.-209EE2163



Department of Electrical Engineering
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Under the Supervision of
Prof. Prafulla Chandra Panda



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*Dedicated
To
My beloved Parents*

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G. S. C. Trinath Prabhu

M. Tech. (Power Control and Drives)

Contents	
ABSTRACT	i
List of Figures	ii
List of Tables	iv
CHAPTER 1	1
INTRODUCTION	
1.1 Introduction	2
1.2 Motivation	3
1.3 Organization of thesis	4
Chapter 2	5
Power Quality	
2.1 Definition	6
2.2 Power Quality	6
2.3 Electro Magnetic Phenomena	7
2.4 Power Quality Issue	9
2.4.1 Transients	9
2.4.2 Long-duration voltage variations	10
2.4.3 Short-duration voltage variations	11
2.4.4 Voltage Imbalance	11
2.4.5 Waveform Distortion	12
2.4.6 Voltage Fluctuations	13
2.5 Cost of Power Quality	13
2.6 Problems due to Power Quality	15
2.7 Solutions to Power Quality	18
Chapter 3	20
Harmonics	
3.1 Effects of harmonics on power system equipment	22
3.2 Causes of harmonics	22
3.3 Fourier analysis of waves	23
3.4 Discrete and Fourier Transforms	26
Chapter 4	26
Estimation of Harmonics	
4.1 FFT and DFT for Harmonic Estimation	27
4.2 Kalman Filtering Algorithm for Harmonic Estimation	28
4.3 Artificial Intelligence and optimization algorithms for Harmonic Estimation	28
Chapter 5	30
LSE, PSO and Adaline	
5.1 Principle of Least Squares	31
5.2 Method of Least Squares	31

5.3 Particle Swarm Optimization	33
5.3.1 Introduction to Particle Swarm Optimization	33
5.3.2 Basic Concepts of PSO	33
5.3.2.1 Swarm Intelligence	33
5.3.2.2 Computation of PSO	34
5.3.3 Implementation of PSO	34
5.3.3.1 Algorithm for PSO	35
5.3.3.2 Topology for PSO	35
5.3.3.3 Parameter selection for PSO	36
5.3.3.5 Selection of Acceleration constants	37
5.3.3.6 Selection of Inertia Constants	37
5.4 Adaline	39
5.4.1 Introduction to ANN	39
5.4.2 Why Neural Network	39
5.4.3 History	40
5.4.4 Artificial Neuron	41
5.4.5 Neural Network Structure	42
5.4.6 Neural Network Operation	43
5.4.7 Neural Network Learning	44
Chapter 6	46
Estimation Using LSE-PSOPC and LSE-Adaline	
6.1 Estimation of harmonics using LSE-PSOPC	47
6.2 Estimation of harmonics using LSE-Adaline	49
Chapter 7	51
Proposed Estimation technique	
Chapter 8	
Results And Conclusion	
8.1 Results	55
8.2 Conclusion	62
8.3 Future Work	62
References	63

Abstract

In recent times, power system harmonics has got a great deal of interest by many Power system Engineers. It is primarily due to the fact that non-linear loads comprise an increasing portion of the total load for a typical industrial plant. This increase in proportion of non-linear load and due to increased use of semi-conductor based power processors by utility companies has deteriorated the Power Quality.

Power Quality is related to voltage amplitude variations which include voltage sags/dips, related to frequency is harmonics in the power system. Frequencies in turn harmonics in a power system not only deal with power quality but it plays a key role in indicating system operating state. Transient and abnormal conditions may occur in power system which distorts the waveform of voltage and current. Harmonics directly relate them to effective power control and proper functioning of protective relays. Hence for assuring increased power stability fast and accurate harmonic estimation is very much necessary.

Harmonics are a mathematical way of describing distortion in voltage or current waveform. The term harmonic refers to a component of a waveform occurs at an integer multiple of the fundamental frequency. Several methods had been proposed, such as discrete Fourier transforms, least square error technique, Kalman filtering, adaptive notch filters etc; As a result, harmonic estimation of distorted signals may occur incorrectly or take longer to converge and even diverge.

Unlike above techniques, which treat harmonic estimation as completely non-linear problem there are some other hybrid techniques like Genetic Algorithm (GA), LS-Adaline, LS-PSOPC which decompose the problem of harmonic estimation into linear and non-linear problem. The results of LS-PSOPC and LS-Adaline has most attractive features of compactness and fastness. In both the techniques the amplitudes were estimated by linear estimator Least Square Estimator. Harmonic phases were estimated by their respective error reducing techniques. Our new proposed technique tries to reduce the pitfalls in the LS-PSOPC, LS-Adaline techniques. With new technique we tried to estimate the Amplitudes by Least square estimator, frequency of the signal by PSOPC and phases of the harmonics by Adaline technique using MATLAB program. Harmonic signals were estimated by using LS-PSOPC, PSOPC-Adaline. Errors in estimating the signal by both the techniques are calculated and compared with each other.

LIST TO FIGURES

	Title	Page No.
Figure 2.1	Possible consequences of poor Power Quality	14
Figure 2.2	Most Common PQ defects	14
Figure 2.3	Possible consequences of poor power quality according to survey across 1400 cities in Europe	15
Figure 2.4	CBEMA curve for limits in voltage variations for data processing equipment	16
Figure 2.5	Solution to power quality problems practiced by max % at 1400 cities in 8 European countries.	18
Figure 3.1	Waveforms of current and voltage of non-linear loads	21
Figure 3.2	Non-linear periodical sine wave shown as sum of sinusoidal waves	23
Figure 5.1	Swarm Topologies	36
Figure 5.2	Structure of biological neuron showing information flow	41
Figure 5.3	Simplified model of Artificial Neural Network	41
Figure 5.4	A model Neuron	42
Figure 5.5	Back Propagation Network	43
Figure 5.6	Sigmoid Function	44
Figure 5.7	Neuron weight adjustment	44
Figure 5.8	Adaline Neural Network	45
Figure 8.1	Comparision of estimated signal and original signal in presence of 20dB noise in measured signal when used proposed LSE-PSOPC-Adaline.	56
Figure 8.2	Comparision of estimated signal and original signal in presence of 20dB noise in measured signal when used proposed LSE-PSOPC.	56
Figure 8.3	Measured signal when 20dB noise is there in measurement.	56
Figure 8.4	Comparision of estimated signal and original signal in presence of 10dB noise in measured signal when used proposed LSE-PSOPC-Adaline.	57
Figure 8.5	Comparision of estimated signal and original signal in presence of 10dB noise in measured signal when used proposed LSE-PSOPC.	58
Figure 8.6	Measured signal when 10dB noise is there in measurement.	58

Figure 8.7	Comparision of estimated signal and original signal in presence of 0dB noise in measured signal when used proposed LSE-PSOPC-Adaline.	59
Figure 8.8	Comparision of estimated signal and original signal in presence of 0dB noise in measured signal when used proposed LSE-PSOPC.	59
Figure 8.9	Measured signal when 0dB noise is there in measurement.	60
Figure 8.10	Comparision of estimated signal and original signal in presence of No noise in measured signal when used proposed LSE-PSOPC-Adaline.	61
Figure 8.11	Comparision of estimated signal and original signal in presence of No noise in measured signal when used proposed LSE-PSOPC.	61
Figure 8.12	Measured signal when No noise is there in measurement.	61

List Of Tables

	Title	Page No.
Table 2.1	Principle phenomena causing Electro-Magnetic phenomena	7
Table 2.2	Categories and Characteristics of Electro-Magnetic phenomena	8
Table 8.1	Comparison of errors calculated using LS-PSOPC and LS-PSOPC-Adaline	55
Table 8.2	Comparison of estimated amplitude between LS-PSOPC and LS-PSOPC-Adaline for 20dB noise measurement.	55
Table 8.3	Comparison of frequency estimated using LS-PSOPC and LS-PSOPC-Adaline for 20dB noise measurement.	56
Table 8.4	Comparison of estimated amplitude between LS-PSOPC and LS-PSOPC-Adaline for 10dB noise measurement.	57
Table 8.5	Comparison of frequency estimated using LS-PSOPC and LS-PSOPC-Adaline for 10dB noise measurement.	58
Table 8.6	Comparison of estimated amplitude between LS-PSOPC and LS-PSOPC-Adaline for 0dB noise measurement.	58
Table 8.7	Comparison of frequency estimated using LS-PSOPC and LS-PSOPC-Adaline for 0db noise measurement.	59
Table 8.8	Comparison of estimated amplitude between LS-PSOPC and LS-PSOPC-Adaline for No noise measurement.	59
Table 8.9	Comparison of frequency estimated using LS-PSOPC and LS-PSOPC-Adaline for No noise measurement.	60

Chapter 1

INTRODUCTION

1.1 Introduction:

The operation of an electrical power system is very important task at present scenario. Electrical power is generated from remote areas which are fed to the common grid in parallel with many other generators and arrives at the point of use. Using several transformers, overhead lines or sometimes underground cables power is transferred to load points. Due to frequent occurrence of electromagnetic disturbances such as system faults, load/converter switching, lightning strikes and other intentional and unintentional events undesirable effects propagate throughout the network change the characteristics of voltage and current waveforms in the power system. Not only due to disturbances but also due to increasing using of power- electronic equipment produced by non-linearly operated electronic equipment, has significantly deteriorated the power quality (PQ). The electric utility companies should supply their customers with a supply having a constant frequency equal to the fundamental frequency, 50/60 Hz, having a constant voltage magnitude. Due to the presence of harmonics in the voltage or current waveform distorted signal for voltage or current happens. Then signal becomes non-sinusoidal signal which it should not be. The Power quality has it effects on malfunctioning of protective devices and metering equipment, interference with communication circuits and control devices and overheating of components.

The power system harmonics problem has been noticed since the establishment of the ac generators. It is not a new problem. Distortion in voltage and current waveforms is there from 20th century.

Harmonic estimation is the foundation of every active filter. For noise canceling in low-voltage power systems, it generates and re-injects reference currents in phase opposition through an active power line conditioner. Thus the study of power system harmonics is an important subject for power engineers.

To obtain the voltage and current frequency spectrum from discrete time samples, there are frequency domain harmonic analyses algorithms which are based on the Discrete Fourier Transform (DFT) or on the Fast Fourier Transform (FFT) method. However these two methods suffer three pitfalls, namely, aliasing, leakage and picket fence effect. There are some other methods suffering from these three problems and this is because of existing high frequency components measured in the signal however truncation of the sequence of sampled data, when only a fraction of the sequence of a cycle exists in the analyzed waveform, can boost leakage problem

of the DFT method. So, the need of new algorithms that process the data, sample-by-sample, and not in a window as in FFT and DFT, is of paramount importance. One of the methods is that Kalman Filter. A more robust algorithm for estimating the magnitudes of sinusoids of known frequency embedded in an unknown measurement noise which can be a measure of both stochastic and signals. As the above said algorithm will not be able to track abrupt changes in signals and its harmonics. However, it requires a priori knowledge of the statistics of the electrical signal and the state matrix needs to be defined accurately as well. Harmonics are decomposed from input signals by designed finite impulse response (FIR) filters where the FIR filter suffers the shortcoming of slow roll off speed which jeopardizes the accuracy of the cut frequency. In order to achieve desired precision, a high-order FIR filter has to be designed, which increases the complexity of the technique.

Techniques specified above should have a prior knowledge of system frequency. But transient and abnormal conditions may occur in power system, the waveform of voltage and current will not be sinusoidal and there may be sudden deviation in frequency every moment due to generation load mismatch, or by some other disturbances. There is a very need of estimating techniques which not only estimate harmonics in power system but also frequency of power system in parallel.

1.2 Motivation

The techniques which were proposed further degrade their ability to estimate harmonics when inter-harmonics and sub-harmonics come in the signal. By considering above pit falls of the different techniques proposed a technique is very much needed for estimation of inter-harmonics, sub-harmonics. An algorithm for the estimation of not only the phases and amplitudes of harmonics but also the phase, amplitude, as well as frequency has been proposed in this paper without any prior knowledge above the signal. New algorithm applies the hybrid iterating method between LS-based amplitude estimation and particle swarm optimizer with passive congregation (PSOPC)-based phase estimation; the parameters in the new model can be easily adjusted to get applied to different applications without increasing the computational complexity dramatically. Further, it was proposed to estimate the Amplitude using LS method, Phases with Adaline technique, Frequency will be estimated using PSOPC technique. And the output errors will be compared for

estimated harmonic signal by LS-PSOPC technique was compared with LS-PSOPC-Adaline technique.

1.3 Organization of Thesis:

This thesis majorly deals with the study of power quality and effects of harmonics in power quality, estimation of harmonics from sampled data. Chapter 2 introduces us to power quality issues in power system, onwards chapter 3 and further sections help us to know about the causes of harmonics, measurement and estimation in power system.

Chapter 2 gives introduction to power quality. Various power quality issues, problems caused by them and solution to these problems have been discussed in brief in this chapter.

Chapter 3 gives information about causes of harmonics and effects of harmonics in power system. How important is to estimate the harmonics in gaining better power system operation has also been given.

Chapter 4 tells us about classical methods to estimate the harmonics in power system. How harmonic content is calculated from a signal is described.

Chapter 5 deals with various methods available in harmonic estimation. How PSOPC and Adaline processes are having faster convergence with much lesser error when compared with other methods. Other Attractive features in estimating harmonics using PSOPC and Adaline are mentioned.

Chapter 6 tells us about how harmonics are estimated using Least squares and particle swarm optimization (PSO) techniques. How to implement this PSOPC technique and Adaline to a test signal are separately described.

Chapter 7 will describe about the new proposed LS, PSOPC, and Adaline technique to estimate a test signal. Algorithm and step by step procedure to calculate the frequency, amplitude and phases of harmonics is shown.

Chapter 8 comprises results obtained by using LSE-PSOPC and LS-PSOPC-Adaline technique. Comparison of errors obtained using both the techniques. Wave forms comparing the original signal with estimated signals.

Chapter 2

Power Quality

Introduction to power quality:-

Power quality means a perfect power supply which has no deviation from standard voltage or frequency and a noise free sinusoidal wave shape. Based on the specifications of equipment and users application deviation in the voltage wave form and frequency can be allowed.

2.1 Definition:

Institute of Electrical and Electronic Engineers (IEEE) Standard defines power quality as” The concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment.”

Power quality was defined in a book of power quality by R.C. Dugan, Mark F. McGranaghan as “Any power problem manifested in voltage, current or frequency deviations that results in failure or misoperation of consumer equipment”. A utility company may define power quality based on reliability and ask for a system that its system is 99.98% reliable. Likewise, there can be many more definitions for power quality. A manufacturer of load equipment may define power quality as those characteristics of the power supply that enable the equipment to work properly. Hence, power quality is ultimately a consumer-driven issue, and the end user’s point of reference takes precedence. Depending on one’s reference definition of the power quality completely changes.

2.2 Power Quality:

Since the last late 1980s, power quality has become one of the most protruding issues in the power industry. Power engineers are attempting power quality as a system issue rather than handling it as individual problem.

Increased concern during these years was due to four major reasons:

- 1) New generation and load equipment with microprocessor- based controls and power electronic devices are more sensitive to power quality variations than was equipment used in the past.
- 2) For high-efficiency, adjustable-speed motor drives and shunt capacitors were kept in service for power factor correction and to reduce losses. Subsequently there is increase in harmonic levels on power systems. This makes many people concerned about the future of system capabilities.

- 3) Utility consumers are being informed about interruptions. Due to improved knowledge in end users about power quality. It became a challenge to the utilities to provide a very good quality of power to the consumers
- 4) Load points and generating points are now interconnected in a network. Failure of any component has very important consequences on power quality.

2.3 Electro Magnetic Phenomena:

The IEC classifies electromagnetic phenomena into following groups shown below in Table 2.1. First four categories are considered more important.

Electro Magnetic Phenomena	Cause of the disturbance
Conducted low-frequency phenomena	Harmonics, interharmonics, Signal systems(power line carrier), Voltage fluctuations, Voltage dips and interruptions, Voltage imbalance, Power frequency variations, Induced low-frequency voltages, DC in ac networks.
Radiated low-frequency Phenomena	Magnetic fields, Electric fields
Conducted high-frequency Phenomena	Induced continuous-wave voltages or currents, Unidirectional transients, and Oscillatory transients
Radiated high-frequency phenomena	Magnetic fields, Electric fields, Electro Magnetic fields, Continuous waves, Transients
Electrostatic Discharge phenomena	
Nuclear Electromagnetic pulse(NEMP)	

Table 2.1 Principal Phenomena Causing Electromagnetic Phenomena [1].

Electromagnetic phenomena will be described in steady-state by following attributes

- Amplitude
- Frequency
- Spectrum
- Modulation
- Source Impedance

- Notch depth
- Notch area

Electromagnetic phenomena will be described in transient state by following attributes

- Rate of rise
- Amplitude
- Duration
- Spectrum
- Frequency
- Rate of occurrence
- Energy potential
- Source impedance

Table 2.2 provides information regarding different categories of electromagnetic phenomena. It gives us about the spectral content, duration, and magnitude for every category that comes under the phenomena. Along with the attributes provided above this table will help us to know completely about the electromagnetic disturbance.

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 μ s	
1.1.2 Current	> 5 kHz	< 200 μ s	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.2.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.2.2 Momentary		30–120 cycles	0.1–1.8 pu
2.2.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

Table 2.2 Categories And Characterizations Of Electromagnetic Phenomena In A Power System [1]

Power quality problems are may be due to interconnected network. For example, a fault on the line or equipment in a network may cause a dip that will affect some customers nearby the fault, the higher the fault more number of customers will be experiencing the power quality issue. If there is a problem in one of the customer's area the problem will spread to other customers in the same subsystem. There are some other problems like harmonics, due to installation of electronic equipment which may or may not propagate harmonics in to the network. Harmonic problems can be solved by having well proven reduction equipment like Active Filters.

For having energy efficiency usage of nonlinear equipment's has become a part of world's directives. It is expected that almost all the loads in distribution systems will have a nonlinear character in coming years. These harmonics, inter-harmonics, and other forms of energy pollution are proliferating into electrical networks in epidemic proportions. Hence power system operation and stability have been paid with more attention in recent years. New challenges coming up in power system grabbed more interest from power system engineers to make the power system more reliable.

2.4 Power Quality Issues:

2.4.1 Transients:

Any event which is undesirable and momentary in nature in power system is known as transient. The notion of a damped oscillatory transient due to an RLC network is probably what power engineers think of when they hear the word transient. Transition from one steady state operating condition to another steady state condition of a variable is termed as transient. Another word synonymous to transient is "surge"

From sags to swells and interruptions in system most common word used by end user is transient. In maintaining power quality these transient behavior of the network has to be studied. Transients are categorized into two kinds, impulsive and oscillatory. These terms represent wave shaping of current or voltage transient.

Impulsive transient is a sudden change (non-power frequency) in the steady-state condition of voltage, current, or both. Impulsive transients can be revealed by spectral content characterized by their rise and decay times. Lightning is common example which causes impulsive transients. Impulsive transients are involved with

high frequencies. Impulsive transients can excite the natural frequency of power system circuits and produce oscillatory transients.

An oscillatory transient is a sudden change (non-power frequency) in the steady-state condition of voltage, current. Oscillatory transients with a primary frequency component greater than 500kHz and a typical duration measured in microseconds are considered as high frequency transients. A transient with primary frequency component between 5 and 500kHz with duration measured in tens of microseconds is termed as medium-frequency transient.

Back-to-back capacitor energization results in oscillatory transient currents in the tens of kilohertz. Cable switching results in oscillatory voltage transients that are in same range of frequency. Medium-frequency transients can also be the result of a system response to an impulse transient.

2.4.2 Long-Duration Voltage Variations:

ANSI C84.1 specifies the steady state voltage tolerances for root means square voltages expected on a power system. A voltage variation is considered as long duration only when the ANSI limits are exceeded and it exists for more than 1 min.

Due to load variations on the system and system switching operations Long – duration voltage variations happen. Long- duration variations in voltage are either over voltage or under voltage.

An overvoltage is termed as rise in rms ac voltage of system to more than 110 percent at the power frequency for time longer than 1min. Over voltages may be a result of load switching like switching off a large load or energizing a capacitor bank. Over voltages may be due to too poor voltage regulation or incorrect operation of tap changer on transformers.

An under voltage is termed as fall in rms ac voltage of system to less than 90 percent at the power frequency for time longer than 1min. Under voltages are the results of switching events that are the opposite of the events that cause over voltages. Switching on a load or making capacitor bank off might be the events for under voltage. Over loaded circuits will also result in under voltage of system voltage.

Long term duration voltage variation is termed as sustained interruption when the supply voltage has been zero for a period of time excess of 1 min. It requires human intervention to repair the system for restoration.

2.4.3 Short - Duration Voltage Variations:

This category covers the IEC category of voltage dips and interruptions which are for short duration. These variations can be described as instantaneous, momentary, or temporary, depending on the duration as defined in table 2.2.

Short-duration voltage variations are caused by fault conditions due to energization of large loads requiring high starting currents, or improper wiring. Based on the fault location and system conditions fault will make temporary voltage drops, voltage rises, or a complete loss of voltage.

A power outage is termed as interruption when supply voltage or load current decreases to less than 0.1pu for a period of time not exceeding 1min. Interruptions may be due to faults, malfunction of control equipment or failure of equipment. Duration of fault depends on the protective devices operating, Auto reclosure time provided by the utility companies. Some interruptions may be preceded by voltage sag when these interruptions are due to faults on the source system.

When the rms voltage or current falls to 0.1 to 0.9pu rms at the power frequency for durations from 0.5 cycles to 1min is called voltage sag. Voltage sags may occur due to system faults, energization of heavy loads or starting of large motors, loss of generation.

An increase in voltage is called swell when there is an increase in voltage goes to 1.1 to 1.8 Pu in rms at the power frequency for durations from 0.5cycles to 1min. Swells are not as common as voltage sags. These are usually associated with system fault conditions. Swells are characterized by their magnitude and duration.

2.4.4 Voltage Imbalance:

Voltage imbalance is defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three phase voltage or currents, expressed in percent.

The main cause of voltage unbalance of less than 2 percent is single-phase loads on a three-phase circuit. Voltage imbalance can also be due to the result of blown fuses in one of the phases of a three-phase capacitor bank. Severe voltage unbalance results mainly from single-phasing conditions.

2.4.5 Waveform Distortion:

Steady-state deviation of a wave from ideal sine wave at power frequency characterized by the deviation of spectral content is defined as Waveform distortion. Distortion in waveform is 5 types:

- DC Offset
- Harmonics
- Interharmonics
- Notching
- Noise

DC offset is presence of a dc voltage or current in an ac power system. This may happen due to geo magnetic disturbance or asymmetry of electronic power converters. Transformers get heated up due to the presence of DC offset. Direct Current causes the electrolytic erosion of grounding electrodes.

Sinusoidal voltages or currents' having frequencies as integer multiplies of the fundamental frequency are called harmonics. Distorted waveforms which are periodical can be represented into a sum of the fundamental frequency wave and the harmonics. Non-linear characteristics of the devices and loads on power system generate Harmonic distortion. To measure harmonics in power system Total Harmonic Distortion (THD) is the parameter to be considered.

Interharmonics are voltages or currents having frequency components that are not integer multiples of the fundamental frequency are called interharmonics. These are present in every electrical network. Causes of interharmonics are static frequency converters, cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as interharmonics.

Periodic voltage disturbance caused due to normal operation of power electronic equipment i.e. when current is commutated from one device to another cause the Notching phenomena. Notching phenomena can be characterized from the voltage spectrum of the effected wave form. Frequency components associated with notching are quite high which cannot be measured by normal harmonic analysis instruments.

Noise is defined as unwanted electrical signals with broadband spectral content lower than 200kHz superimposed upon the power system voltage or current in power conductors or neutral conductors or signal lines.

2.4.6 Voltage fluctuation:

Voltage fluctuations specified by ANSI C84.1 are systematic variations of the voltage or a series of random voltage changes and the magnitude voltage does not be out of range of 0.9 to 1.1pu.

Loads that exhibit rapid variations in the load current magnitude cause voltage variations that are often referred to as flicker. Flicker is termed from the impression of the voltage fluctuation on lamps such that they are seen by the human eye to flicker. Voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage fluctuation in some loads. Voltage fluctuation is commonly named as voltage flicker.

2.4.7 Power frequency variations:

Power frequency variations can be defined as the change of the power system fundamental frequency from the nominal value i.e. 50Hz specified in India. The system frequency is related to the generators supplying system and loads connected to the system. Very slight variations in frequency are due to dynamic balance between load and generation changes.

2.5 Cost of Poor Power Quality:

Poor power quality can be described as any event related to the electrical network that ultimately results in financial loss. Probable consequences of poor Power quality are

- Unexpected power supply failures(breaker tripping, fuses blowing)
- Equipment failure or malfunctioning
- Equipment Over heating (transformers, motors etc.) leading to their life time reduction.
- Damage to sensitive equipment(PC's, production line control systems)
- Electronic Communication interfaces.
- Increase of system losses.
- Need to increase capacity during installation to cope with additional electrical stress with consequential increase of installation and running cost and associated higher carbon footprint.
- Penalties will be imposed by utilities to user as the site pollutes the supply network too much

- Connection refusal of new sites as the site would infect the supply network too much.
- Impression of unsteadiness of visual sensation induced by light stimulus whose spectral distribution fluctuates with time (flicker).
- Health issues, reduced efficiency of operating person.



Fig 2.1 Possible Consequences Of Poor Power Quality [4]

The five most common PQ defects are:

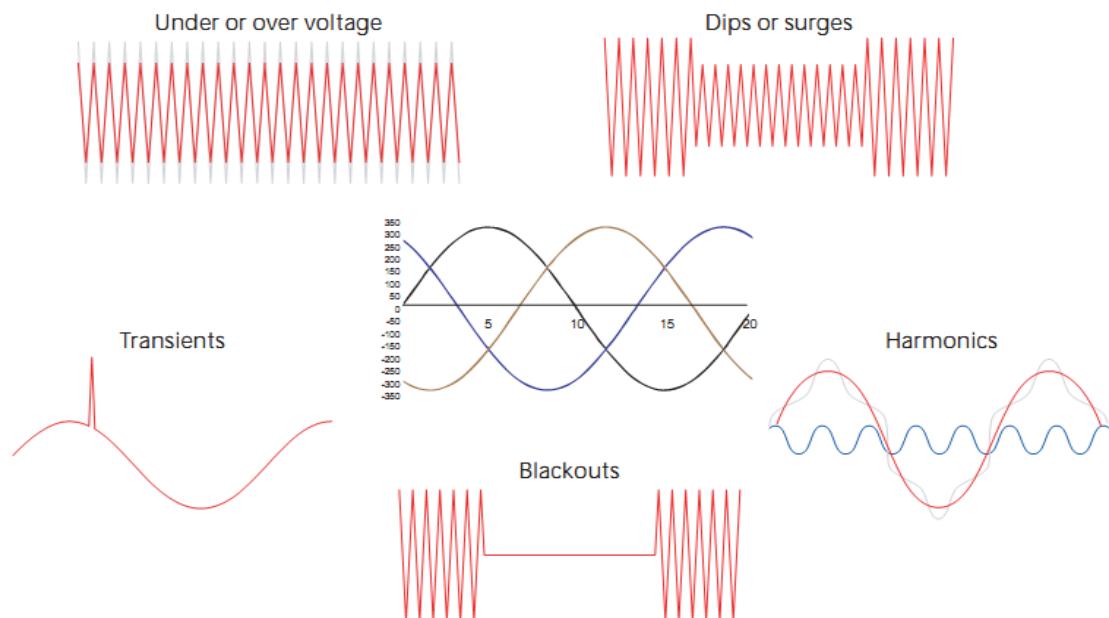


Fig 2.2 Most Common PQ Defects [5]

2.6 Problems due to poor Power Quality:-

- **Computer Lockup**

Due to originating earth current in the equipment there will be a voltage drop between the equipment and true earth. Even a very small voltage is very significant in IT equipment. PC hardware is designed to minimize sensitivity for this kind of disturbances but it cannot be eliminated entirely, especially when noise frequency rises. Modern equipment has communication protocols, error detection and correction algorithms built in, requiring retransmission of erroneously received data

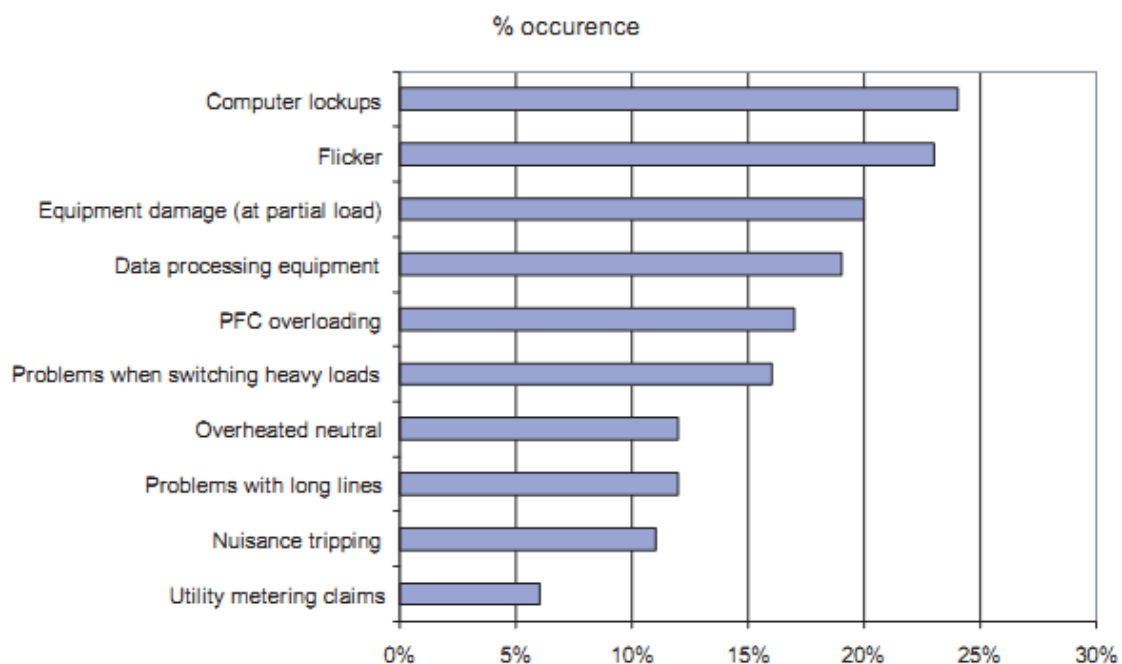


Fig 2.3 Possible Consequences Of Poor Power Quality According To Survey Across 1400 Cities In Europe [5]

- **Flicker**

Triple-n harmonic currents get summed up in the neutral conductor. In a TN-C configuration the protective and neutral conductor are combined and connected in many places to the structure of the building. These create a uncontrolled magnetic fields resulting in flickering of computer screens.

Some sudden changes in voltage levels due to switching, short circuits and load changing may result in light flicker. Excessive flicker can cause many health related problems to humans like migraine and some sick building syndrome.

- **Overheating of equipment (at moderate loads)**

When transformer is operating at maximum load, harmonics causes additional losses which lead to overheating and hotspots in winding. This will lead in reduced life time of transformer. Harmonic pollution is very high in case of low-voltage networks. Harmonics affect the magnetic losses in the transformer core eddy current losses and resistive losses in the windings. As eddy current losses are directly proportional to square of its frequency, presence of harmonics drastically increases eddy current losses.

In induction motor 5th harmonic creates a counter – rotating field, 7th harmonic creates a rotating field beyond motors synchronous speed. Due to these fields pulsating torque is produced which wears and tears couplings and bearings. Energy contained in these harmonics is dissipated as extra heat which causes damage to the motor. Variable speed drives get affected due to sharp voltage rise times.

From the 7th harmonic i.e., 350Hz and upwards the losses in conductor due to skin effect losses in the conductor are more. Hence overloading of conductor happens whenever harmonics are present in the current.

- **Data processing equipment**

Limits for voltage variations for data- processing equipment are characterized by CBEMA curve. Duration and magnitude of voltage variations that can be tolerated are given by CBEMA curve

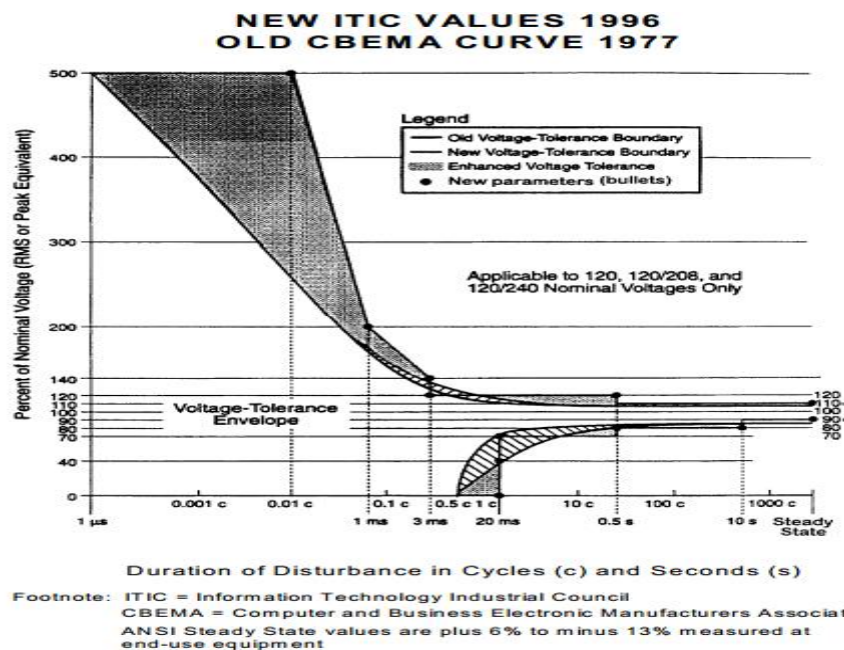


Fig 2.4 CBEMA Curve -Limits for Voltage Variations in Data Processing Equipment [6].

- **PFC Overloading**

Power factor correction equipment create excessive voltage or current when resonant frequencies coincide with the harmonic frequencies. Due to this coincidence stray inductance will have a very bad effect on PFC. Measurement devices will not work perfectly due to the presence of harmonic current.

- **Overheated neutral**

In a 3-phase circuit neutral conductor carries the unbalance current of the 3 phase network. Triple-n harmonics have significant amount of currents flowing in neutral conductor. As the size of the neutral conductor is very less, when the phase conductors are operating at full load and a slight unbalance will cause overloading of neutral conductor.

- **Problems with long lines**

Heavy loads located at end of the lines when switched on or off creates a surge in voltage. These result in higher harmonic voltage distortion. And to reduce voltage loss at the end of the line we need to increase the size of the conductor, which has an added advantage of lower power loss.

- **Nuisance Tripping**

Nuisance trips can be defined as unwarranted circuit breaker trips with either no electrically based reason for the trips, or, the breaker gets pulse to trip even though there is no fault exists.

Example for nuisance tripping is AFCI / GFCI breakers trip because of events that mimic trip conditions. There are different causes of breaker tripping. Voltage drop on a circuit fed by a GFCI Breaker can cause the breaker to trip due to loss in the electrical wiring greater than 6ma. Cheap surge protector power strips can cause GFCI and AFCI breakers to trip due to the MOV shunting to ground at a low clamping voltage. Any surge in the electrical system can cause a temporary malfunction of a GFCI and AFCI which can be called "NUISANCE TRIPPING".

- **Utility metering claims**

Harmonics are not charged for end users as they are only charged for reactive power. But the harmonic pollution created by the users makes power system not to operate optimally. Hence, in future power quality problems caused by users are charged.

- **Surge Suppressors**

Transient Voltage Surge Suppression (TVSS) provides protection against transient surges, which can happen so quickly that they do not register on normal electrical testing equipment. Surge suppressors or surge protectors are the most basic form of power protection. A surge suppressor is often used to shield important, but less critical or highly sensitive equipment. It is also used as a complement to more comprehensive power protection solutions. They are passive electronic devices that protect against transient high-level voltages. Transients are often the cause of “unexplained” equipment problems, computer lock-up, data loss, and other “gremlins” inside a facility. Transient voltage surge suppressors can be incorporated into voltage regulators, power conditioners, and UPS for added protection.

2.7 Solutions to poor Power Quality:-

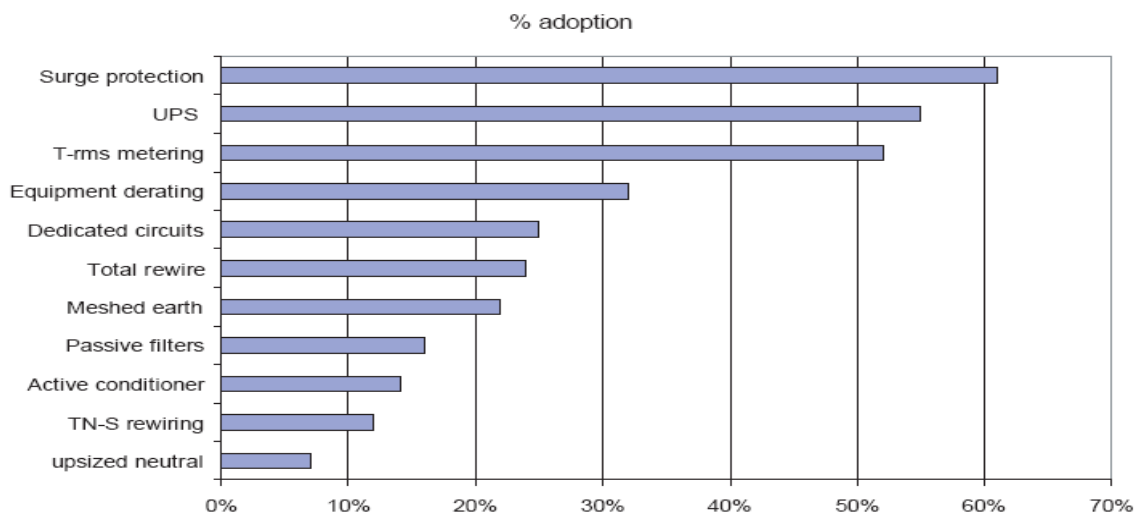


Fig 2.5 Solution To Power Quality Problems Practiced By Most In % At 1400 Cities In 8 European Countries [5]

- **Voltage Regulators**

A voltage regulator may also be referred to by the labels “power conditioner”, “line conditioner”, “voltage stabilizer”, etc. Regardless the term used, these devices are all essentially the same in that they provide voltage regulation and one or more additional power quality-related functions.

A voltage regulator can correct and/or provide protection from power problems such as:

- Over/Under voltage

- Voltage Fluctuations
- Sags and Dips
- Line Noise and Swells
- Phase Imbalance
- Short Circuits
- Brownouts and Surges

- **Uninterruptable Power supplies**

There are three basic types of UPS: Standby (or Offline), Line Interactive, and Double Conversion (or Online).

The Standby UPS consists of a basic battery/power conversion circuit and a switch that senses irregularities in the electric utility. The equipment to be protected is usually directly connected to the primary power source, and the power protection is available only when line voltage dips to the point of creating an outage. Some of the off-line UPS have surge protection circuits for better protection.

Line Interactive UPS are hybrid devices that offer a higher level of performance by adding better voltage regulation and filtering features to the standby UPS design. Like standby models, line interactive UPS protect against power surges by passing the surge voltage to the equipment until it hits a predetermined voltage, at which point the unit goes to battery. They provide moderate protection against high voltage spikes and switching transients.

Double conversion UPS, often called “Online” provide the highest level of power protection and are an ideal choice for shielding important computing and equipment installations. This technology uses the combination of a double conversion (AC to DC/DC to AC) power circuit and an inverter, which continuously powers the load to provide both conditioned electrical power and outage protection. Online UPS offer complete protection and isolation from all types of power problems. In addition, they provide digital-quality power not possible with offline systems. For these reasons, they typically are used for mission critical applications that demand high productivity and system availability.

Chapter 3

Harmonics

Introduction to Harmonics

The main objective of the electric utility is to deliver sinusoidal voltage at fairly constant magnitude for every end user wherever they are. This objective is complicated as there are loads on the system that produce harmonic currents. These harmonic currents produce distortion voltages and currents of power system. Such a system having harmonics will perform sub-optimally. In recent years, Harmonic pollution produced by non-linear electronically controlled equipment increased and deteriorated the power quality. Hence during any new installation additional changes have to be made in the network to nullify the effects of harmonics. To fully understand the impact of harmonics, two important concepts have to be studied. The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

In a power system a load is called a linear load if the current is proportional to the voltage. This means that the current wave shape will be the same as the voltage without any phase difference. Typical examples of linear loads are motors, heaters and incandescent lamps.

On the other hand, the current wave shape on a non-linear load is not the same as the voltage. Typical examples of non-linear loads include rectifiers (UPS units , , discharge lighting, power supplies), ferromagnetic devices, adjustable speed motor drives, arcing equipment and DC motor drives.

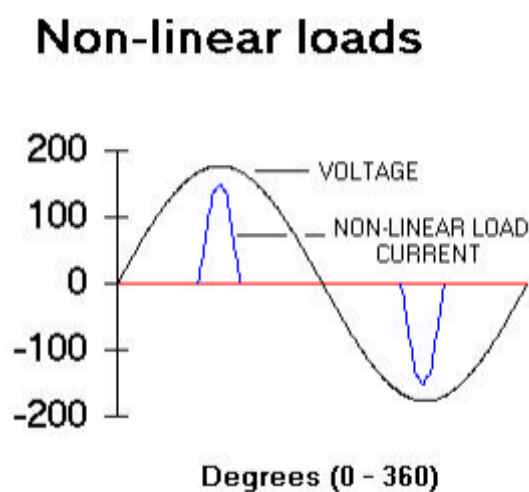


Fig 3.1 Waveforms Of Current And Voltages Of Non-Linear Loads

The current drawn by non-linear loads is periodic, meaning that the current wave repeats itself in every cycle. Periodic waveforms are mathematically described as a series of sinusoidal waves that have to be summed. The sinusoidal components are integer multiples of the fundamental frequency where the fundamental, in the India, is 50 Hz.

3.1 Effects of Harmonics on power system Equipment:

Harmonic effects on power system equipment mainly effects of voltage distortion. Effects of voltage distortion on equipment can be divided into three general categories

- Thermal stress
- Insulation stress
- Load disruption

Harmonic have the effect of increasing equipment losses and thus the thermal stress. Harmonics result in increased losses and equipment loss of life. Triplen harmonics result in the neutral carrying a current which might equal or exceed the phase currents even if the loads are balanced. This urges us to oversize the neutral wires. Moreover, resonance due to harmonics may damage equipment.

Harmonics further interfere with the working of metering devices, protective relays, control and customer electronic equipment, and communication circuits. Sensitive equipment would experience mal-operation or component failure.

Harmonics in the distribution system may cause:

- Transformer heating
- Transformer secondary voltage gets distorted
- Increased power losses
- Overloaded neutrals and capacitors
- Noise in telephone and communication systems.

3.2 Causes of Harmonics:

In power system there are many types of equipment which act as harmonic current emitters or sources which distort the voltage wave. Sources of harmonic emissions include large industrial loads, smaller commercial and residential customer loads, distributed generation systems. Harmonic current emissions originate Non-linear loads which draw non-sinusoidal current even when the supply voltage is

perfectly sinusoidal. Non-linear loads include saturated magnetic circuits, such as those in power system transformers and rotating machines, arc furnaces, fluorescent lighting and of course power electronic loads. Power electronic loads by far are the most significant harmonic contributors relative to the amount of energy they draw. Some of the more common power electronic loads include

- i. Switch mode power supplies(SMPS)
- ii. Rectifiers
- iii. Inverters
- iv. Static VAr compensators
- v. Cyclo-converters, and
- vi. High voltage DC transmission converters.

Emissions resulting from the above mentioned causes have to be mitigated to bring better power quality in power system.

3.3 Fourier Analysis of waves:

Any periodic signal which is not a perfect sinusoid can be expressed in a Fourier series as a sum of sinusoids which have frequencies as integer multiples of fundamental frequencies called harmonic frequencies. Figure 3-2 shows a fundamental sine-wave with third and fifth harmonics.

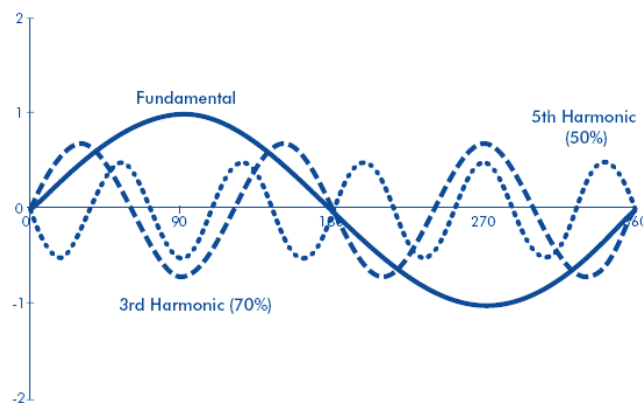


Fig 3.2 Non-Linear Periodical Wave Shown As Sum Of Harmonic Sinusoidal Waves

If a function $f(t)$ is periodic with period Tp i.e.,

$$f(t + Tp) = f(t) \quad (3.1)$$

For a finite interval $f(t)$ has finite number of discontinuities and a finite number of maxima and minima (dirichlet's conditions), and in addition,

$$\text{If } \int_0^{T_p} f(t) dt < \infty \quad (3.2)$$

Then $f(t)$ can be expressed in the form of

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n w_0 t + b_n \sin n w_0 t) \quad (3.3)$$

$$\text{Where } w_0 = 2\pi / T_p \quad (3.4)$$

Where the Fourier coefficients a_n and b_n are determined by the following equations

$$a_n = 2/T \int_{t_0}^{t_p} f(t) \cos n w_0 t \cdot dt, \quad n=0,1,2,3 \quad (3.5)$$

$$b_n = 2/T \int_{t_0}^{t_p} f(t) \sin n w_0 t \cdot dt, \quad n=0,1,2,3 \quad (3.6)$$

Equation (3.3) is trigonometric Fourier series; the term $a_0/2$ is the dc component of the signal. Average value of the signal is the dc component. The terms in equations 3.5 and 3.6 is called n^{th} harmonic component. The fundamental component is obtained when $n=1$. I.e., fundamental component is when fundamental frequency is w_0 . When $n=2$, it is the 2^{nd} harmonic component and respective harmonic components for $n=3,4,5, \dots, n$

3.4 Discrete and Fast Fourier Transform:

If $f(t)$ is a non-periodic deterministic signal expressed as a function of time t , then the Fourier transform of $f(t)$ is given by the integral expression [3.2]. The discrete time Fourier transform of a discrete time signal $f(n)$ is given by

$$f(w) = \sum_{n=-\infty}^{n=\infty} g[n] \cdot \exp(-jwn) \quad (3.7)$$

Hence we can formulate N point Discrete Fourier Transform(DFT) as follows

$$F(k) = \sum_{n=0}^{n=N-1} g[n] \exp(-j2\pi kn/N); \quad k=0,1,2,\dots,(N-1) \quad (3.8)$$

The inverse discrete Fourier transform, $f(n)$ is

$$f[n] = 1/n \sum_{k=0}^{N-1} G(k) \exp(j2\pi kn/N-1); \quad n=0,1,2,3,\dots,(N-1) \quad (3.9)$$

Where N is number of time sequence values of $f(n)$, It is also the total number frequency sequence values in $F(k)$.

Time interval 'T' is the time between two consecutive samples of the input sequence $f(n)$.

F is the frequency interval between two consecutive samples of the output sequence $F(K)$.

$$N, F \text{ are related as } NT=1/F \quad (3.10)$$

Chapter 4

Estimation of Harmonics

As explained in chapter 3 there are several disadvantages due to the presence of harmonics in power system and leads to reduced power quality. In order to improve power quality there is urging to identify the sources of harmonic current emitters and nullify them. For nullifying the harmonic currents in power system we have several methods available. Filters are one of the available possibilities to nullify the harmonic currents. For proper action of these filters harmonic estimation is the primary thing because for injecting harmonic current 180° out of phase with harmonic currents firstly we need have the data of harmonic currents. For harmonic estimation firstly we need to identify the sources and capacitor banks situated in the power system. After identifying the sources, then we need to have the sampled data of the current. Hence some sensitive measuring equipment should be provided for sampled data. Then we should analyse the data. There a lot of methods to analyse the data and estimate the harmonic signal. This chapter tries to help us different ways of estimation of signal and pitfalls in each method.

4.1 FFT and DFT for harmonic estimation:

The DFT and FFT algorithms are the basic estimation algorithms which are already applied to many applications in power system to know phasor measurements and harmonic analysis. Improper application of FFT algorithm would lead to incorrect results. Some basic conditions or assumptions have to be made before applying DFT and FFT. These assumptions are:

- i. The signal is having constant magnitude.
- ii. Fundamental frequency should be assumed by the algorithm.
- iii. The sampling frequency of any signal should be greater than twice the highest frequency for getting complete information about the signal.
- iv. Each frequency in the signal is an integer multiple of the fundamental frequency.

Basically, the fundamental frequency is the reciprocal of the window length of data (T).

When these assumptions are satisfied, the results of the DFT or FFT are accurate.

Three major pitfalls in FFT application to a signal:

- i. Aliasing,
- ii. Leakage, and
- iii. Picket-fence effect.

Aliasing is eliminated by increasing the sampling frequency (f_s). Aliasing occurs at the higher frequencies which will resemble same as frequencies less than fundamental frequency. Hence the FFT spectrum may be erroneous.

The term "leakage" refers the apparent spreading of energy from one frequency into adjacent frequencies. It arises due to the improper selection of window width. The resulting error is known as spectral "leakage". The DFT and FFT of such a sampled waveform will incorrectly indicate non-zero values for all of the harmonic frequencies.

The picket-fence effect occurs if the analysed waveform includes a frequency which is not one of the discrete frequencies (an integer times the fundamental). This influences the accuracy of the magnitudes of each harmonic.

4.2 Kalman filtering algorithm for optimal harmonic estimation

Application of Kalman filtering for estimation of harmonics was started in 90's. Tracking of time varying parameters and estimation of phasors is possible with Kalman filtering approach. The signal is represented in state space form. State space theory is applied to the signal in state space form in order to estimate the harmonics. Approach is simple, linear, and robust; but it requires *a priori* knowledge of electrical signal. State matrix has to be defined accurately. To overcome the short comings of Kalman filter, we require a higher order FIR filters. Ability of computer to perform calculations in real time is limited. Hence, there is a limit for higher order FIR filters that can be used.

4.3 Artificial Intelligence and optimal algorithms for harmonic estimation

Artificial neural networks, evolutionary algorithms, optimization techniques became popular in recent years for controlling and estimation. Identifying the voltage/current signals are nonlinear in phase and linear in amplitude, a hybrid algorithm iterating between genetic-algorithm (GA)-based phase estimation and LS-based amplitude estimation was proposed. As GA is population-based algorithm, it does not rely on the gradient information of an objective function; thus, it will not be

trapped in local minima. GA will converge prematurely when it is used to estimate the parameters which are highly correlated. Efficiency of GA is significantly degraded in this case.

A hybrid algorithm based on particle swarm optimization with passive congregation (PSOPC) was also used by some of the authors to estimate harmonics. They proposed PSOPC to optimize the phase of each individual harmonic, because the particle swarm optimizer (PSO) has faster convergence rate than evolutionary algorithms. The major advantage in PSOPC is that it has very few parameters to adjust. With the introduction of passive congregation, the information sharing mechanism between the particles is improved and the optimization results are very accurate.

Chapter 5

LSE, PSO and Adaline

Most of the techniques explained so far in the above chapters treat estimation technique as a completely non-linear problem. Hybrid techniques like LSE-PSOPC and LS- Adaline techniques have divided the estimation of harmonics as two parts. In the first part Amplitudes are estimated linearly by using Least Square Estimation technique. Phases of harmonics are estimated by using population based algorithm using PSOPC in LSE-PSOPC technique. In LSE-Adaline, phases of harmonics are estimated using weighted vectors by continuously calculating the errors using Adaline algorithm. Detailed explanation of how these techniques are used to estimate the harmonics is explained in this chapter.

5.1 Principle of least squares

Gauss the principle of least squares says to know the unknown parameters of a model should be chosen in such a way that

The sum of the squares of the differences between the actually observed and computed values multiplied by numbers that measure the degree of precision is a minimum.

5.2 Method of least squares:

Least squares estimation is very simple and robust technique of estimation. To be able to give an analytic solution, the computed values must be linear functions of the unknown parameters.

$$y(t)=P_1(t).\theta_1+ P_2(t).\theta_2+.....+P_n(t) \theta_n =\Phi^T. \theta \quad (5.1)$$

Where $y(t)$ is observed variable

$\theta_1, \theta_2, \dots, \theta_n$ are Unknown parameters

P_1, P_2, \dots, P_n are known functions that may depend on other known variables.

The variables P_1, P_2, \dots, P_n are called regression variables and the equation is called regression model.

Define

$$\Phi^T=[P_1(t), P_2(t), \dots, P_n(t)]$$

$$\theta^T=[\theta_1, \theta_2, \dots, \theta_n]$$

Then we can write

$$y(t)= \Phi^T_{1 \times n} \cdot \theta_{n \times 1} \quad (5.2)$$

If N measurements are taken then equation can be written as

$$y(1) = [P_1(1), P_2(1), \dots, P_n(1)] \cdot [\theta_1, \theta_2, \dots, \theta_n]^T$$

$$y(2) = [P_1(2), P_2(2), \dots, P_n(2)] \cdot [\theta_1, \theta_2, \dots, \theta_n]^T$$

$$y(3) = [P_1(3), P_2(3), \dots, P_n(3)] \cdot [\theta_1, \theta_2, \dots, \theta_n]^T$$

or, $Y = N \times I$ vector

$\Phi = N \times n$ Matrix

And

$$\Phi = \begin{bmatrix} P_1(1) & \dots & P_n(1) \\ \vdots & \ddots & \vdots \\ P_n(N) & \dots & P_n(N) \end{bmatrix}$$

$$\Phi = \begin{bmatrix} \Phi^T(1) \\ \Phi^T(2) \\ \vdots \\ \Phi^T(N) \end{bmatrix}$$

Problem here is to determine θ so as the error between the computed equation and original equation are as close as possible by taking the measured values $y(i)$.

In order to obtain the least square estimation error as minimum

$$\text{Cost function } J = \frac{1}{N} \sum_{t=1}^N (y(t) - \Phi^T(t) \cdot \theta)^2$$

In vector form, we want to minimize

$$J = \frac{1}{N} (Y - \Phi \hat{\theta})^T (Y - \Phi \hat{\theta}) = \frac{1}{N} [Y^T Y - Y^T \Phi \hat{\theta} - \hat{\theta}^T \Phi^T Y + \hat{\theta}^T \Phi^T \Phi \hat{\theta}]$$

In the above expression all terms are scalars. Transposition of matrix is possible without any changes to it. So,

$$(Y^T \Phi \hat{\theta})^T = \hat{\theta}^T \Phi^T Y = Y^T \Phi \hat{\theta}$$

Therefore,

$$J = \frac{1}{N} [Y^T Y - \hat{\theta}^T \Phi^T Y - \hat{\theta} \Phi^T Y + \hat{\theta}^T \Phi^T \Phi \hat{\theta}]$$

For getting minimum value for the function J first derivative of cost function J should be equal to zero and we should get a solution for $\hat{\theta}$.

$$\frac{\delta J}{\delta \hat{\theta}} = -2 \Phi^T Y + 2 \Phi^T \Phi \hat{\theta} = 0$$

Or,

$$\Phi^T Y = \Phi^T \Phi \hat{\theta}$$

Or,

$$\hat{\theta} = (\Phi^T \Phi)^{-1} \Phi^T Y$$

For getting minimum value for the cost function J second derivative of the function should be positive. Hence,

$$\frac{\delta^2 J}{\delta \hat{\theta}^2} = 2(\Phi^T \Phi) > 1$$

Hence, by using least squares and finding the minimum for cost function J we will be able to find the optimum solution.

5.3 Particle Swarm Optimization:

5.3.1 Introduction to Particle swarm optimization:

The particle swarm optimizer (PSO) is a population-based algorithm invented by Kennedy and Eberhart in 1995. It is inspired from social behaviour of animals, such as bird flocking. Like other population-based algorithms (evolutionary algorithms) PSO is also capable of solving a variety of problems related to non-linear optimization. In many optimization problems PSO has shown a faster convergence rate than any other evolutionary algorithms. Main advantage in PSO algorithm is it has very few parameters to adjust to come to optimum solution making it easy to implement.

The foundation of PSO is based on the hypothesis that social sharing of information among con-specifics offers an evolutionary advantage. Every particle remembers its best previous position and global best position. PSO is more efficient to maintain diversity among the swarm.

5.3.2 Basic Concepts of PSO:

PSO is based on swarm intelligence concept, which is property of a social behaviour in which collective behaviours of swarm particles will create a local environment that create a global function patterns. Hence concept of PSO can be explained as follows.

5.3.2.1 Swarm Intelligence:

Basically, swarm intelligence concept can be explained by 5 fundamental rules [14]

I. Proximity Principle: Swarm should be capable to carryout simple space and time computations

II. Quality Principle: Swarm should be able to respond to Quality factors in the neighbourhood or environment.

III. Diverse Principle: Swarm should not commit to activities which makes it to go through narrow channels of search space.

IV. Stability Principle: Swarm should not change its behaviour for every environment change.

V. Adaptability Principle: Swarm should be able to change its mode of behaviour when it is worth of computation ease.

Particles in PSO mean a pseudo particle which carries only information. Particles have no mass or volume

5.3.2.2 Computation of PSO:

Swarm intelligence is an extension of evolutionary computational algorithms, it also includes the logical operators like AND, OR, and NOT. PSO is a concept extension of cellular automata (CA). Similar, to cells in CA particles in PSO randomly change their dimensions simultaneously.

Computational attributes in PSO:

- I. Individual particles are updated in parallel.
- II. Each new value of each particle depends on its previous value and its neighbour's value.
- III. All updates should be made by same rules.

5.3.3 Implementation of PSO:

Firstly we have to define the particle. A particle can be n-dimensional according to our requirement. This particle should have limits for search space which should be defined by us. And particles movement is defined by velocity for each particle.

$$x_i(k) = x_i(k-1) + v_i(k) \quad (5.3)$$

$$\text{where, } x_i(k) \in R^n$$

$$v_i(k) \in R^n$$

Information available for each particle is based on its own experience and the experience of other particles in the swarm. As, the relative importance of these two experiences from the swarm will vary the decision, random weights should be applied to each experiences for varying $v_i(k)$.

$$v_i(k) = v_i(k-1) + \psi_1 \cdot \text{rand}_1 \cdot (p_i - x_i(k-1)) + \psi_2 \cdot \text{rand}_2 \cdot (p_g - x_i(k-1)) \quad (5.4)$$

Where ψ_1, ψ_2 are two positive numbers with uniform distribution to range [0,1]. $\text{rand}_1, \text{rand}_2$ are two random numbers with uniform distribution in the range of [0,1]

Equation (5.4) shows velocity updating equation has three components

I. First component is inertia or momentum. It models the tendency of the particle to move in the same direction it has been travelling.

II. The second component is a moving the particle towards the best position ever found by the particle itself, scaled by $\psi_1, rand_1$. This component can be termed as self-knowledge.

III. The third component is a moving the particle towards the best position ever found by the any particle, scaled by $\psi_2, rand_2$. This component can be termed as group-knowledge.

5.3.3.1 Algorithm for PSO

By formulating the above computations, algorithm of implementing the PSO is by the following procedure

1. Initialize the swarm by assigning random positions in the space to each particle
2. Evaluate the fitness function accordingly for each particle
3. For each individual particle, compare the particle fitness value with it P_{best} . And the current position of the particle's position to x_i as P_i .
4. Identify the particle that has the best fitness value in the swarm. The value of best fitness is identified as g_{best} . And its position as P_g .
5. Update the velocities and positions of all the particles using equations 5.3, 5.4
6. Repeat 2 to 5 until criteria for stopping is obtained.

5.3.3.2 Topology for PSO:

Particles in PSO are studied in two general types of neighbourhoods

- 1) Global best (gbest) and
- 2) Local best (lbest).

In swarm gbest is the optimum solution found by any member in the swarm. This signifies a fully inter-connected network in which each particle will have access to the information of all the particles in the swarm as shown in Fig 5.1.

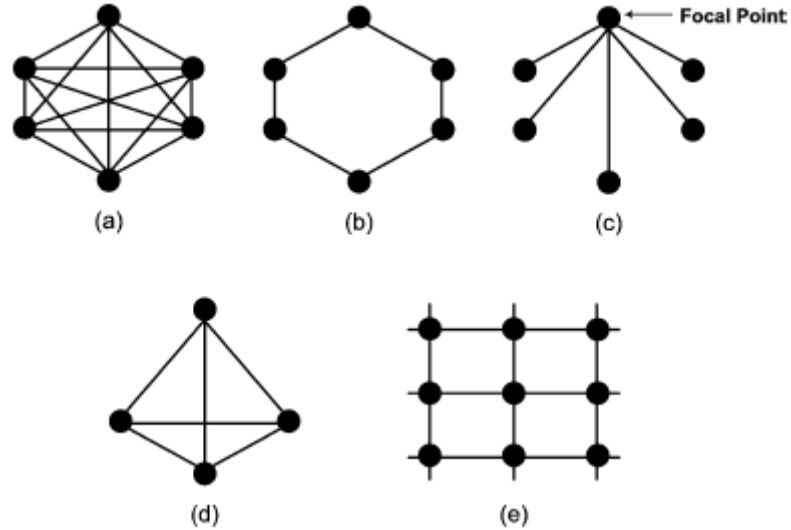


Fig 5.1 Swarm Topologies A) Global Best B) Ring Topology C) Wheel Topology D) Pyramid Topology E) Von Neumann Topology

In case of Local best (lbest), each particle has access to information immediate neighbour particle, so it has to follow some swarm topology.

Different types of swarm topology are mentioned in fig5.1 (b) to (e)

- I. Fig 5.1(b) represents ring topology where each particle is connected to two of its immediate neighbours
- II. Fig 5.1(c) represents wheel topology in which individuals are isolated from each other and there will be a focal point for information sharing.
- III. Fig 5.1(d) shows pyramid topology
- IV. Fig 5.1(e) shows von Neumann topology

5.3.3.3 Parameter selection for PSO:

During implementation of PSO, Several considerations have to be taken into consideration for early convergence and to prevent search out of limits of the swarm. These limitations include search space, Maximum and minimum velocities, Accelerating constants, constriction factor or inertia constant.

5.3.3.4 Selection of maximum and minimum velocity:

For each iteration step, algorithm adjusts the velocity that each particle should move in the some direction in hyper space. The velocity of the particle is a stochastic variable and can be out of bounds from problem space. In order to limit the particle movement, upper and lower limits are specified for the velocity v_i ,

Hence after computation of equation 5.4 we have to check for

If $v_i > v_{max}$ then $v_i = v_{max}$.

Else if $v_i > -v_{max}$ then $v_i = -v_{max}$.

v_{max} is selected empirically according to the characteristics of the problem defined. It is important to note that if the value is too high, then the particles may move erratically and convergence of the problem may not be possible. On the other hand if the velocity v_{max} is too small then particles movement is limited and optimal solution will never be found. Usually v_{max} is selected by

$$v_{max} = (x_{max} - x_{min}) / N \quad (5.5)$$

Where N is the number of intervals in the k^{th} dimension selected by the user and x_{max}, x_{min} are maximum and minimum values found so far by the particles.

5.3.3.5 Selection of acceleration constants:

Acceleration constants ψ_1, ψ_2 , in the equation 5.4 will control the movement of each particle towards its individual and global best positions, respectively. Small movement in the particle will confine the particle and whereas large movement will diverge the particle from solution. Hence we have to select a value for ψ_1, ψ_2 such that convergence is obtained as soon as possible. The two constants are considered into one single constant and limitation is kept for that constant.

$$\psi_1 + \psi_2 = \psi \quad (5.6)$$

Since the individual and global best positions are the same. Authors concluded that by an increase in the value acceleration constant, the frequency of oscillations around the optimal point increases, to a sinusoidal waveforms; however, if the value is increased, the complex paths of cyclic trajectories appear. The trajectory leads to infinity for values given to ψ greater than 4.0.

The effect of considering a random value for acceleration constant will help to create an uneven cycling for the trajectory of search for the particle when it is searching around optimal value.

5.3.3.6 Selection of inertia constants:

Studies on PSO indicate that, improperly defining the maximum velocity and acceleration constants make the particles to diverge and go to infinity. That is called explosion phenomena. There are two methods defined in order to constrict the particles not to explode

Constriction factor: The first method to control the explosion of the swarm was developed by cleric and Kennedy. It introduces a constriction coefficient which defines constriction coefficient χ . And the update rule for the velocity is defined as

$$v_i(k) = \chi [v_i(k-1) + \psi_1 \cdot \text{rand}_1 \cdot (p_i - x_i(k-1)) + \psi_2 \cdot \text{rand}_2 \cdot (p_g - x_i(k-1))] \quad (5.7)$$

$$x_i(k) = x_i(k-1) + v_i(k)$$

$$\text{where, } \chi = 2 / (2 - \psi - \sqrt{\psi^2 - 4\psi}), \psi_1 + \psi_2 = \psi > 4 \quad (5.8)$$

Typical value of χ is around 1.49445

Inertia factor: Second method proposes a new parameter which only multiplies the velocity at the previous time step i.e $v(k-1)$ rather than having one parameter multiplying the whole velocity term. This parameter is termed as inertia constant (ψ_{ic}) This results to a modified equation as shown below

$$v_i(k) = \psi_{ic} v_i(k-1) + \psi_1 \cdot \text{rand}_1 \cdot (p_i - x_i(k-1)) + \psi_2 \cdot \text{rand}_2 \cdot (p_g - x_i(k-1)) \quad (5.9)$$

$$x_i(k) = x_i(k-1) + v_i(k)$$

Inertia constant can be either constant or continuously changing. Essentially, this parameter controls the exploration of search space, therefore inertia weight should be chosen in such a way that it has high value, which allows the particle to find optimum neighbourhood. Then after some iterations it can be chosen as low value in order to limit the particle to optimum solution. But main disadvantage of this method is that once inertia weight is decreased the swarm loses its ability to search new areas because it is not able to recover its exploration capability.

Recently Chen and Li used stochastic approximation theory to analyze dynamics of PSO. Authors proposed a decreasing coefficient that is reduced to zero as number of iterations increases. This facilitates the particles to spread around the problem space at the beginning of search; the stochastic velocity term provides additional exploration ability, thus helping the particles to escape from local minima.

There are many other developments in finding the optimum solution in minimum iterations and less convergence time. These are mentioned below.

- 1) Standard Particle Swarm Optimizer (SPSO)
- 2) Gaussian Particle Swarm Optimizer (GPSO)
- 3) Dissipative PSO (DPSO)
- 4) PSO with passive congregation (PSOPC)
- 5) Co-operative PSO (CPSO)

5.4 Adaline:

5.4.1 Introduction to ANN:

A Neural Network is an artificial representation of human brain, trying to simulate the learning process. An artificial neural network (ANN), often called the neural network or simply neural net (NN) is the most generic form of Artificial Intelligence.

The word neural network is referred to network of biological neurons in the nervous system of human body. Nervous system in human body process and transmit the information from brain to other parts of body and from other parts of body to brain. These are called biological neurons. Similar types of neurons created artificially are called artificial neurons. Using some computational models or mathematical models artificial neurons try to process the information and computes the solution for required problem.

The artificial neurons are simple processing elements sharing some properties of biological neurons. By interconnecting them, they can form into a network capable to exhibit complex global behavior, determined by the connections, processing elements and element parameters.

Neural computing is large number of highly interconnected processing elements called neurons working together in order to solve specific problems. And ANN's are just like humans which learn by examples and repetition of solutions when same problem is faced again.

Learning in biological systems involves adjustments of synaptic connections existing between the neurons. Similarly in ANN, neurons are configured for specific problems like pattern recognition or data classification by a through learning process.

5.4.2 Why Neural Network:

Neural networks uses different paradigm for computing. Neural networks are based on the parallel architecture of biological brains, which have properties of processing or memory extraction like human thinking process. Though the conventional computers are good for fast arithmetic and do what programmer asks to do. But computers have pitfalls in the following cases like noisy data or data from environment, massive parallelism. Adaption to changes to circumstances is not

possible with conventional computers. There comes the need for some algorithm which leads all these backdrops and finds solution what the user needs.

Neural network helps us to find solution where there is not definite algorithm solution, only if we have lot of examples that can expect the behaviour of the system.

Neural networks are a form of multiprocessor computer system, with

- Simple processing elements
- A high degree of interaction between neurons
- Simpler messages and
- Adaptive interaction between elements.

5.4.3 History:

McCulloch and Pitts (1943) are the designers of the first neural network. By combining many simple processing units they lead to an overall increase in computational power. They suggested many ideas like threshold level for neurons. It is still the fundamental way of implementing fixed set of weights for ANN operation.

Hebb (1949) developed first learning rule, “If two neurons are active at the same time then the strength between them should be increased”.

In 1950 and 60's, many researchers worked on perceptron. Neural network model is able to converge to correct weights, in turn solves the problem. The learning algorithm is nothing but weight adjustment used in the perceptron was found powerful than other learning rules said earlier than this. Perceptron made the thought that programs could think. Then, Minsky and Papert (1969) proved that perceptron could not learn those functions which are not linearly separable.

Multi-layer networks called back propagation gained importance in 1985-86 which is able to solve some of the problems that were not linearly separable.

5.4.4 Artificial Neuron:

The human brain consists of a large number more than a billion of neural cells that process information. Each cell works like a simple processor. The massive interaction between all cells and their parallel processing only makes the brain's abilities possible.

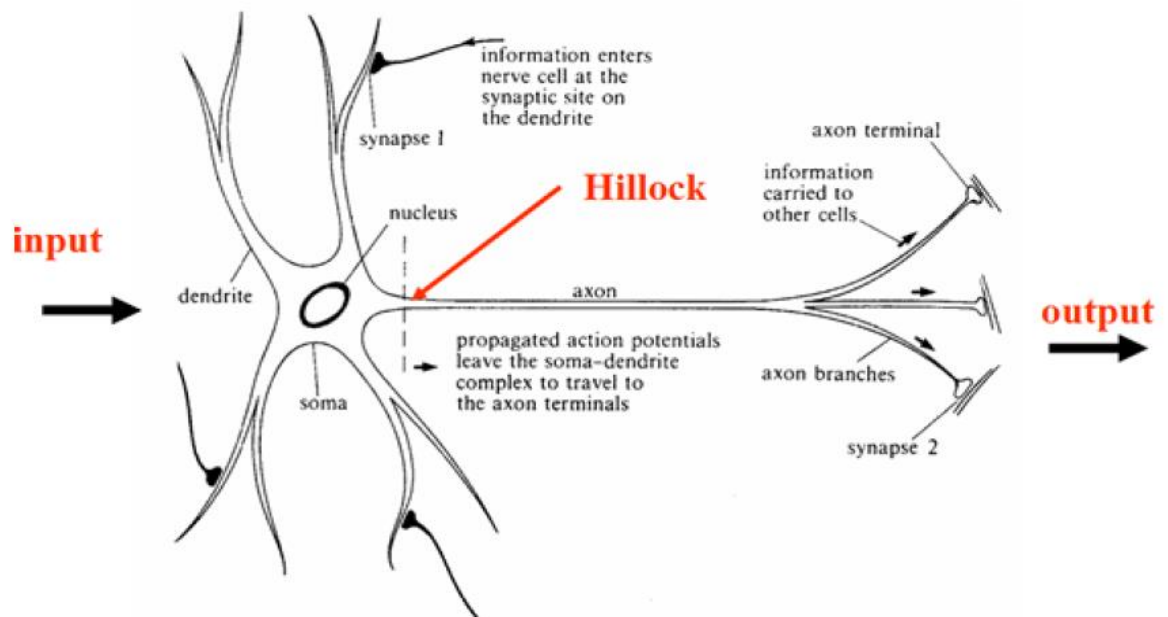


Fig 5.2 Structure Of A Biological Neuron Showing Information Flow.

In biological neuron dendrites receive the activation from other neurons. Soma processes the incoming activations and converts them into output activations. Axon acts as transmission lines to send activation to other neurons. Synapses the junctions allow signal transmission between the axons and dendrites. The process of transmission is by diffusion of chemicals called neuro-transmitters.

Artificial neuron is a mathematical function representing a simple model of a real biological neuron

The McCulloch-Pitts proposed simplified model of real neurons, known as a threshold Logic unit.

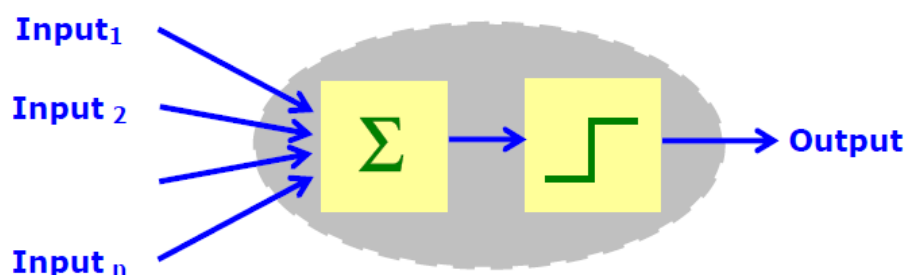


Fig 5.3 Simplified Model Of Artificial Neural Network

The set of input connections brings activations from other neurons. Processing unit tries to sum the inputs and process using some non-linear activation function (i.e. squashing/transfer/threshold function). Output is characterized and transmitted to other neurons.

5.4.5 Neural Network Structure:

Neural networks are models of biological neural structures. The starting point for most neural networks is a model neuron, as in Figure 5.4, which consists of multiple inputs and a single output. Every input will be modified by a *weight*, which multiplies it with the input value. The neuron will combine these weighted inputs and, with reference to a threshold value and activation function, use these to determine its output. Watching the behavior closely makes us to understand how real neurons work.

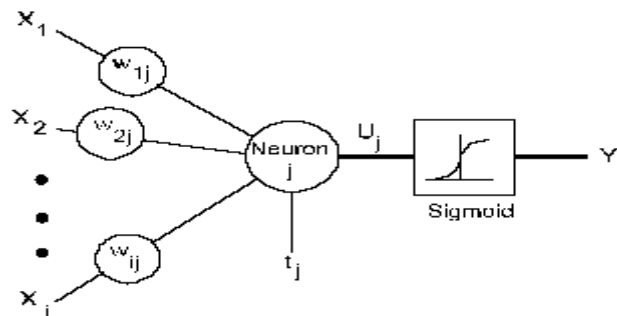


Fig 5.4: A Model Neuron

While there is a fair understanding of how an individual neuron works, there is still a great deal of research and mostly conjecture regarding the way neurons organize themselves and the mechanisms used by arrays of neurons to adapt their behavior to external stimuli. There are a large number of experimental neural network structures currently in use reflecting this state of continuing research.

In our case, we will only describe the structure, mathematics and behavior of that structure known as the *back propagation network*. This is the most prevalent and generalized neural network currently in use.

To build a back propagation network, proceed in the following fashion. First, take a number of neurons and array them to form a *layer*. A layer has all its inputs connected to either a preceding layer or the inputs from the external world, but not both within the same layer.

A layer has all its outputs connected to either a succeeding layer or the outputs to the external world, but not both within the same layer.

Next, multiple layers are then arrayed one succeeding the other so that there is an input layer, multiple intermediate layers and finally an output layer, as in Figure 3. Intermediate layers, that are those that have no inputs or outputs to the external world, are called *hidden layers*.

Back propagation neural networks are usually *fully connected*. This means that each neuron is connected to every output from the preceding layer or one input from the external world if the neuron is in the first layer and, correspondingly, each neuron has its output connected to every neuron in the succeeding layer.

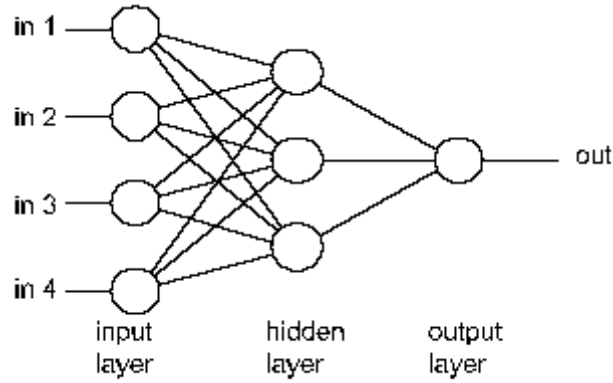


Figure 5.5. Back Propagation Network

Generally, the input layer is considered a distributor of the signals from the external world. Hidden layers are considered to be categorizers or feature detectors of such signals.

$$Y_j = F_{th}(U_j + t_j)$$

The output layer is considered a collector of the features detected and producer of the response. While this view of the neural network may be helpful in conceptualizing the functions of the layers, you should not take this model too literally as the functions described may not be so specific or localized. With this picture of how a neural network is constructed, we can now proceed to describe the operation of the network in a meaningful fashion.

5.4.6 Neural Network Operation:

The output of each neuron is a function of its inputs. In particular, the output of the j th neuron in any layer is described by two sets of equations.

For every neuron, j , in a layer, each of the i inputs, X_i , to that layer is multiplied by a previously established weight, w_{ij} . These are all summed together, resulting in the internal value of this operation, U_j . This value is then biased by a previously established threshold value, t_j , and sent through an activation function, F_{th} . This activation function is usually the sigmoid function, which has an input to output mapping as shown in Figure 4. The resulting output, Y_j , is an input to the next layer or

it is a response of the neural network if it is the last layer. Neuralyst allows other threshold functions to be used in place of the sigmoid described here.

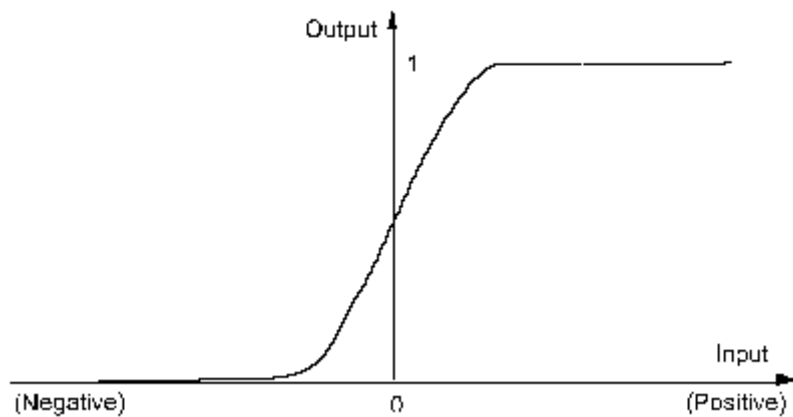


Figure 5.6. Sigmoid Function

A predetermined set of weights, a predetermined set of threshold values and a description of the network structure (that is the number of layers and the number of neurons in each layer), it is possible to compute the response of the neural network to any set of inputs. Then we can get the required response.

5.4.7 Neural Network Learning:

Learning in a neural network is called *training*. Like training in athletics, training in a neural network requires a coach, someone that describes to the neural network what it should have produced as a response. From the difference between the desired response and the actual response, the *error* is determined and a portion of it is propagated backward through the network. At each neuron in the network the error is used to adjust the weights and threshold values of the neuron, so that the next time, the error in the network response will be less for the same inputs.

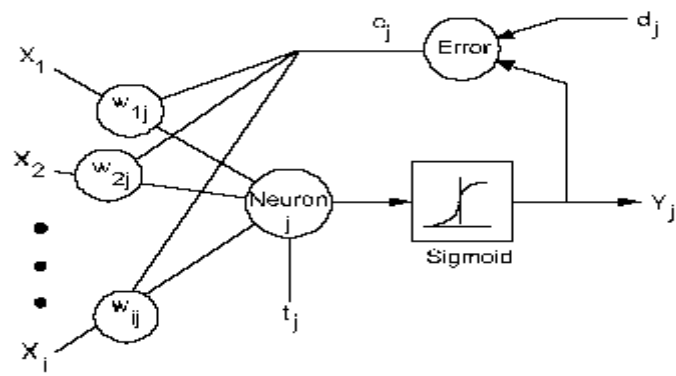


Figure 5.7 Neuron Weight Adjustments

This corrective procedure is called *back propagation* (hence the name of the neural network) and it is applied continuously and repetitively for each set of inputs and corresponding set of outputs produced in response to the inputs. This procedure continues so long as the individual or total errors in the responses exceed a specified level or until there are no measurable errors. At this point, the neural network has learned the training material and you can stop the training process and use the neural network to produce responses to new input data.

5.4.8 Adaline:

ADALINE (Adaptive Linear Neuron or later Adaptive Linear Element) is a SINGLE layer neural network. It was developed by Professor Bernard Widrow based on the McCulloch–Pitts neuron. Adaline simply consist of weight, a bias and a summation function. Main difference between Adaline and the standard McCulloch–pitts perceptron is, in the learning phase the weights are adjusted according to the weighted sum of the inputs. In the standard perceptron, the net is passed to the activation transfer function and the function's output is used for adjusting the weights. Here in this thesis we tried to use this Adaline technique in estimation of phases of harmonics.

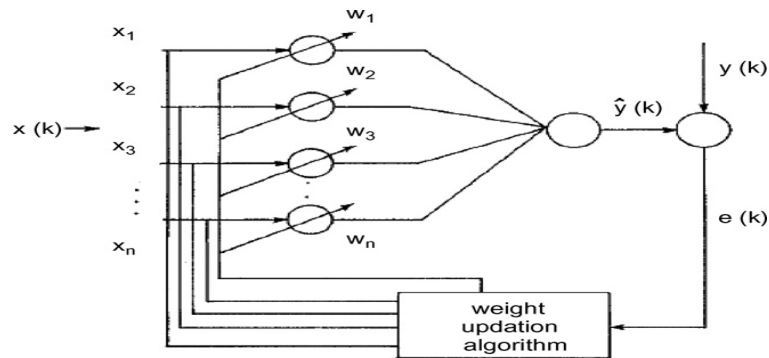


Fig 5.8 Adaline Neural Network

Chapter 6

***Estimation using
LSE-PSO
And
LSE-Adaline***

6.1 Estimation using LSE-PSOPC:

LSE-PSOPC is a hybrid technique which is capable of estimating phases, amplitudes and frequency of inter-harmonics. Deviation of frequency can also be estimated using this technique. This technique tries to estimate phases using PSOPC technique and amplitude is estimated based on Least Squares. The parameters in this technique are adjusted so easily without increasing the complexity. This is possible even with conventional PSO technique. Information sharing between the particles in the swarm is increased by using Passive Congregation in to the PSO.

Assume an electrical signal $Z(t)$ described as below

$$Z(t) = \sum_{n=1}^N A_n \sin(w_n t + \Phi_n) + v(t) \quad (6.1)$$

Where $n=1,2,\dots,N$ represents the order of the harmonic; A_n , Φ_n , and w_n represent amplitude, phase angle, and angular frequency of the n^{th} harmonic, respectively, $w_n = 2\pi f_n$; and $v(t)$ is additive noise.

To estimate the A_n , Φ_n , and w_n of each harmonic, the following function is constructed

$$\hat{Z}(t) = \sum_{n=1}^N \hat{A}_n \sin(\hat{w}_n t + \hat{\phi}_n) \quad (6.2)$$

Thereby original signal can be represented as

$$Z(t) = \hat{Z}(t) + r(t) = \sum_{n=1}^N \hat{A}_n \sin(\hat{w}_n t + \hat{\phi}_n) + r(t) \quad (6.3)$$

Where $r(t)$ is the estimation difference which indicates the difference between $Z(t)$ and $\hat{Z}(t)$. Our goal is to estimate for best of $\hat{A}_n, \hat{w}_n, \hat{\phi}_n$ by minimizing $r(t)$. Phases of the harmonics in the expression above are nonlinear. Phases are restricted to $[0, 2\pi)$. Phases will be estimated by using the recursive algorithm. Once the phases and the frequencies are estimated, after iteration the amplitude \hat{A}_n is obtained by using standard Least Square method.

$$Z(k) = H(k).A + v(k), \text{ where } k=1,2,3,\dots,K \quad (6.4)$$

And

$$H(k) = \begin{bmatrix} \sin(w_1 t_1 + \phi_1) & \dots & \sin(w_N t_1 + \phi_N) \\ \sin(w_1 t_2 + \phi_1) & \dots & \sin(w_N t_2 + \phi_N) \\ \vdots & \dots & \vdots \\ \sin(w_1 t_k + \phi_1) & \dots & \sin(w_N t_k + \phi_N) \\ \vdots & \dots & \vdots \\ \sin(w_1 t_K + \phi_1) & \dots & \sin(w_N t_K + \phi_N) \end{bmatrix} \quad (6.5)$$

Where $Z(k)$ is the k^{th} sample of the measured values with additive noise $v(k)$;

$A = [A_1, A_2, \dots, A_n]^T$ is the vector of the amplitudes needing to be estimated;

$H(k)$ is the system structure matrix. To find the best estimated matrix the difference between $z(k)$ and

$$\hat{z}(k) = \hat{H}(K) \cdot \hat{A}, \text{ Should be minimized.} \quad (6.6)$$

Once the values of $\hat{w}_n, \hat{\phi}_n$ are evaluated using optimization algorithm respectively, $\hat{H}(K)$ is calculated consequently. Assuming $\hat{H}(K)$ as full-rank matrix, the estimation of \hat{A} can be obtained via standard LS algorithm as

$$\hat{A} = \hat{H}^T(K) \cdot \hat{H}(K)^{-1} \cdot \hat{H}(K) \cdot Z(k) \quad (6.7)$$

Then by having all the three estimates one can calculate the $\hat{z}(k)$ by using equation 6.6.

The cost function or error function can be calculated using

$$J = \sum_{k=1}^K (z(k) - \hat{z}(k))^2 \quad (6.8)$$

This process is continued until final convergence condition is obtained.

For PSOPC technique of frequency estimation a current position for frequency has to be set in an N-dimensional search space.

1) Current position in a N-dimensional space for frequency is defined as f_i^k ,

$f_i^k \in [l_n, u_n]$ where l_n and u_n are lower and upper bounds for the n^{th} dimension, respectively.

2) A current velocity $v_i^k, v_i^k \in [v_{\max}, v_{\min}]$.

- 3) By calculating the error one should update the global best and local best.
- 4) In each iteration of PSO, the swarm is updated by the following equations 5.9
- 5) Iterate from 2 to 4 until optimum solution is obtained.

6.2 Estimation using LSE-Adaline:

In LSE-Adaline prior knowledge of fundamental frequency is needed. By having the fundamental frequency and by using weighted vector principle phases of the harmonics are estimated first. Then by using the conventional Least Square algorithm one can easily find out the optimum solution for harmonics estimation.

As in LSE-PSO sinusoidal signal is estimation of Amplitude is same. But when it comes to estimation of phases following procedure is followed.

For estimation of phase of the signal, Adaline technique will be used. For using Adaline equation (1) will be written as

$$Z(K) = \sum [A_n \sin(\omega_n kTs) \cos \Phi_n + A_n \cos(\omega_n kTs) \sin \Phi_n] \quad (6.9)$$

This equation gives us the idea of using an adaptive linear combiner comprising a neural network called ‘Adaline’ to estimate the phases of harmonics. The block diagram of the Adaline is shown in Fig. 5.4. The input to the network is:

$$\mathbf{x}(t) = [A_1 \sin(\omega_1 t) \ A_1 \cos(\omega_1 t) \ \dots \ A_N \sin(\omega_N t) \ A_N \cos(\omega_N t)]^T \quad (6.10)$$

The weight vector of this network is:

$$\mathbf{W}(k) = [W_1(k) \ W_2(k) \ \dots \ W_{2N-1}(k) \ W_{2N}(k)]^T \quad (6.11)$$

Weight vector is updated using a modified Widrow–Hoff delta rule [2] as:

$$\mathbf{W}(k+1) = \mathbf{W}(k) + \frac{\alpha e(k) \mathbf{X}(k)}{\lambda + \mathbf{x}^T(k) \mathbf{x}(k)} \quad (6.12)$$

Where $\mathbf{X}(k) = \text{SGN}(\mathbf{x}(k))$

And for $i = 1, 2, \dots, 2N + 2$

$$\text{SGN}(x_i) = \begin{cases} +1 & \text{if } x_i > 0 \\ -1 & \text{if } x_i < 0 \end{cases}$$

And α is chosen to lie in between $0 < \alpha < 2$, for making the tracking error $J(k)$ to converge asymptotically to zero. The learning parameter α can be made adaptive using the following expression:

$$\alpha(k) = \alpha_0 / (1 + k/\beta) \quad (6.13)$$

Where α_0 is initial learning rate and β is decaying rate constant. To make learning rate adaptive α_0 is chosen as 1.5 and β is chosen as 100.

λ is usually a small quantity chosen as 0.01 in this case. It is chosen to make

$$\lambda + \mathbf{x}^T(k)\mathbf{x}(k) \neq 0 \quad (6.14)$$

In this way, amplitude and phase of nth harmonic parameters are derived as follows:

$$\varphi_n = \tan^{-1} \left(\frac{W_{2n}}{W_{2n-1}} \right) \quad (6.15)$$

The magnitudes of α_0 and β control the rate of convergence and the quality of noise rejection. Other nonlinear functions like $\tanh(\mathbf{x})$ and $\text{sig}(\mathbf{x})$ can be used. $\text{SGN}(\mathbf{x})$ is chosen because of its simplicity in implementation.

Chapter 7

Proposed Estimation technique

Advantages of PSOPC and Adaline are discussed. Most of the techniques treat estimation of harmonics as totally non-linear problem, Hence they converge very slowly. In implementing LS-PSOPC technique or LS- Adaline technique the problem will be decomposed into a linear problem and non-linear problem.

In both LS-Adaline and LS-PSOPC techniques a linear estimator, i.e., Least Squares (LS), which is simple, fast and does not need any parameter tuning to follow harmonics amplitude changes, is used for amplitude estimation.

In LS-Adaline method an adaptive linear combiner called ‘Adaline’, which is very fast and very simple, is used to estimate phases of harmonics. An improvement in convergence and processing time is achieved using this algorithm. Moreover, better performance in online tracking of dynamic and abrupt changes of signals is the result of applying this method. But this technique requires a prior knowledge of the system frequency.

In LS-PSOPC technique particle swarm optimizer is applied to optimize the phase of each individual harmonic. By introducing passive congregation, the information sharing mechanism is improved and the optimization result is more accurate. LS-PSOPC technique was implemented by taking samples of a harmonic signal. It was observed that with no noise in measurement the results were very accurate, when it comes to signal measured with noise the error with the estimated signal is on very high side.

Proposed method of LS-PSO and Adaline technique is introduced and it is dealt exhaustively with logical and mathematical approaches. In the present proposed technique estimation process of the harmonic phases are estimated using Adaline technique, Frequency Estimation is by nonlinear optimization algorithm and Amplitude is estimated using linear LS method.

As LSE-Adaline technique there is no need of priori knowledge of frequency in this technique. When a new sample is acquired the iteration process starts firstly random initializations take place then error function is calculated and compared with original signal. Updating the best solutions and by updating the errors. Iteration process continues until required output is obtained.

The algorithm that we are going to use for the proposed technique is explained step wise in the below.

Set $t_s=0$, Set $k=0$
Randomly initialize weighted vectors; Randomly initialize frequency for different particles and set limits for positions and velocity for all particles.
While ($t_s < \text{program Running time}$)
While ($k < \text{no. of iterations}$)
For each particle i in the swarm
Calculation of phases: From Randomly initialized weighted vectors, Phase of harmonic components are calculated for different particles.
Calculate fitness: Calculate the fitness value of current particle: $J(f_i)$
Update pbest for frequency: Compare the fitness value of pbest with $J(f_i)$. If $J(f_i)$ is better than the fitness value of pbest, then set pbest to current position f_i
Update gbest for frequency: Compare the fitness value of pbest with $J(f_i)$. If $J(f_i)$ is better than the fitness value of gbest, then set gbest to current position f_i
Update R_i : Randomly select a particle from the swarm as R_i
Update Velocities for frequency: Calculate velocities V_i using Equation (7). If $V_i > V_{\max}$ then $V_i = V_{\max}$, and if $V_i < V_{\min}$ then $V_i = V_{\min}$
Update Positions of frequency: Calculate position f_i using equation 7.
End For
$k=k+1$
End While
Update Phase Positions: Randomly initialized positions for phases are updated with Equations (11).
Update the Sampling time: Measure the new sample
End While

Chapter 8

Results and Conclusion

8.1 Results:

SNR	PSOPC(ϵ)	Hybrid(PSOPC-Adaline)
No Noise	1.5752×10^{-5}	0.17
20dB	1.85	1.14
10dB	15.24	9.09
0dB	64.49	32.88

Table 8.1 Comparison Of Errors Calculated Using LS-PSOPC And LS-PSOPC-Adaline

Harmonic Order	Amplitude	PSOPC	PSOPC-Adaline
1	1	0.9975	0.9985
2	0.07	0.0697	0.0643
3	0.03	-0.0370	0.0254
4	0.00	0.0048	-0.0037
5	0.01	$8.1359e^{-04}$	0.0072
6	0.00	0.0061	0.0058
7	0.02	0.0175	0.0160
8	0	-0.0071	-0.0061
9	0	$1.887e^{-04}$	-0.0062
10	0	-0.0074	-0.0045

Table 8.2 Comparison Of Estimated Amplitude Between LS-PSOPC And LS-PSOPC-Adaline For 20db Noise In Measurement

frequency	PSOPC(ϵ)	Hybrid(PSOPC-Adaline)
50Hz	50.0094	49.9053

Table8.3 Comparison Of Frequency Estimated Using LS-PSOPC And LS-PSOPC-Adaline For 20db Noise In Measurement

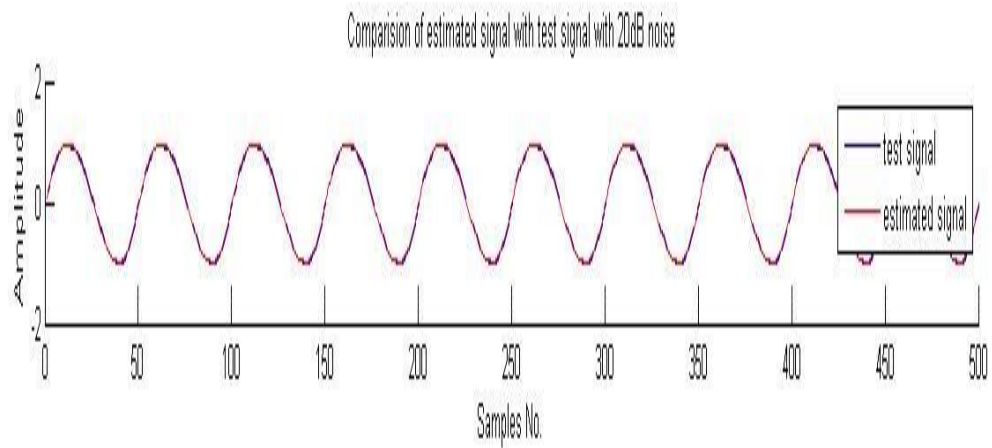


Fig 8.1 Comparison Of Estimated Signal And Original Signal In Presence Of 20db Noise In Measured Signal When Used Proposed LSE-PSOPC-Adaline.

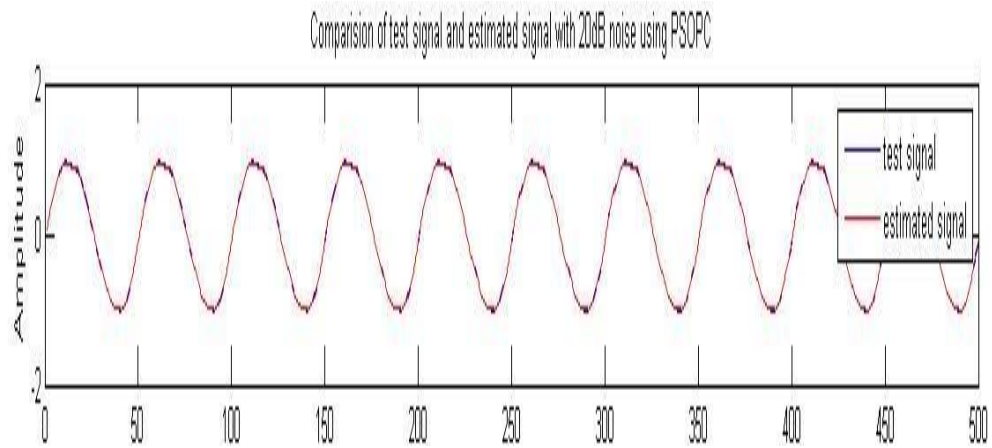


Fig 8.2 Comparison Of Estimated Signal And Original Signal In Presence Of 20db Noise In Measured Signal When Used Proposed LSE-PSOPC.

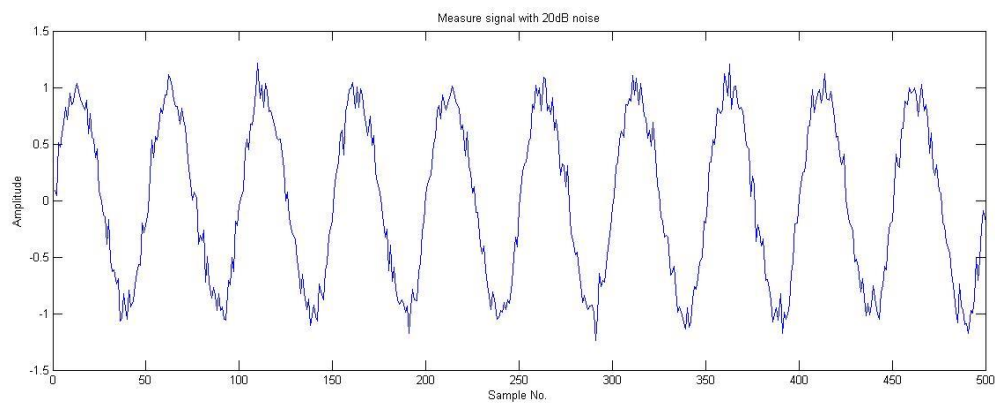


Fig 8.3 Measured Signal When 20db Noise Is There In Measurement.

Harmonic Order	Amplitude	PSOPC	PSOPC-Adaline
1	1	-1.024	1.0001
2	0.07	-0.0847	0.0775
3	0.03	-0.0389	0.0324
4	0.00	0.0052	-6.3091e ⁻⁰⁵
5	0.01	-5.5132e ⁻⁰⁴	0.0040
6	0.00	-0.0120	-0.0194
7	0.02	-0.0330	-0.0079
8	0	0.0205	0.0128
9	0	-0.0235	0.0078
10	0	0.0161	0.0034

Table 8.4 Comparison Of Estimated Amplitude Between LS-PSOPC And LS-PSOPC-Adaline For 10db Noise In Measurement

frequency	PSOPC(ϵ)	Hybrid(PSOPC-Adaline)
50Hz	50.0019	49.9822

Table8.5 Comparison Of Frequency Estimated Using LS-PSOPC And LS-PSOPC-Adaline For 10db Noise In Measurement

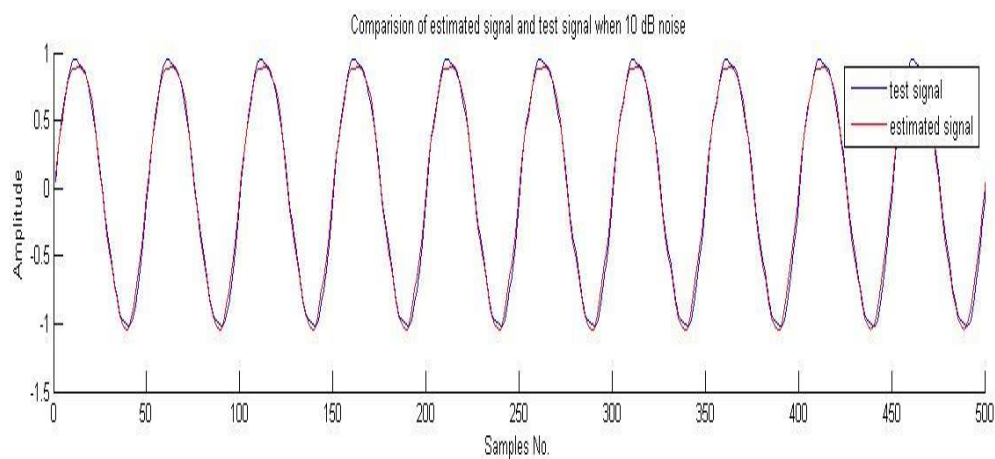


Fig 8.4 Comparison Of Estimated Signal And Original Signal In Presence Of 10db Noise In Measured Signal When Used Proposed LSE-PSOPC-Adaline.

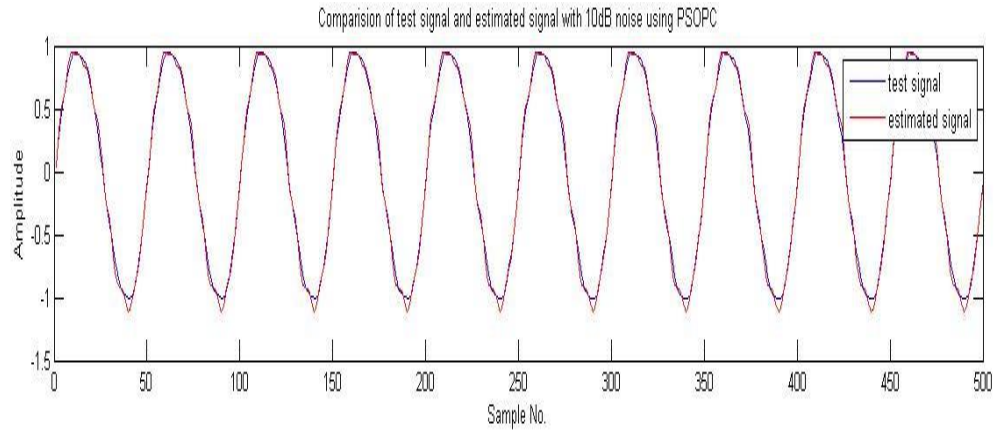


Fig 8.5 Comparison Of Estimated Signal And Original Signal In Presence Of 10db Noise In Measured Signal When Used Proposed LSE-PSOPC.

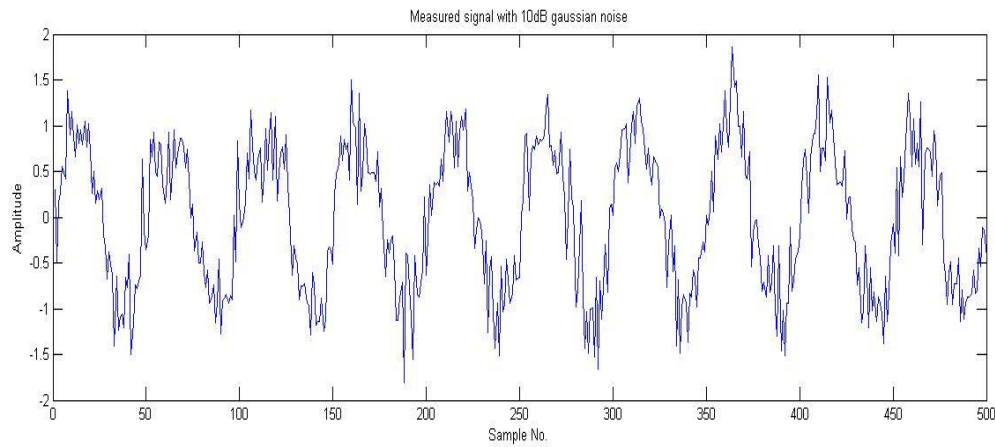


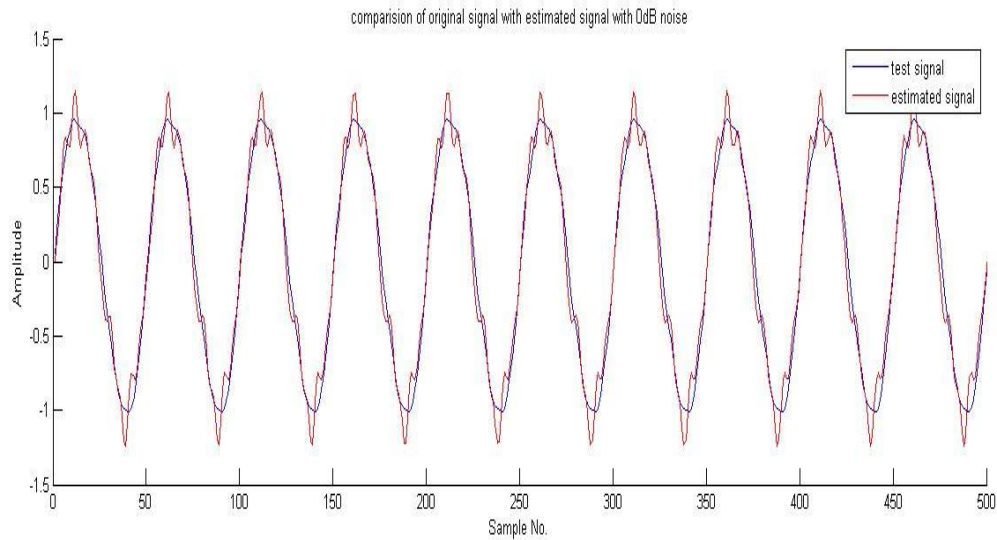
Fig 8.6 Measured Signal When 10db Noise Is There In Measurement.

Harmonic Order	Amplitude	PSOPC	PSOPC-Adaline
1	1	-0.9582	0.9532
2	0.07	-0.0746	0.0068
3	0.03	0.1023	0.0149
4	0.00	-0.0042	0.0706
5	0.01	0.0950	0.0596
6	0.00	-0.0669	0.0864
7	0.02	0.0401	0.0168
8	0	-0.0268	0.0215
9	0	-0.0765	0.0063
10	0	-0.0526	0.0340

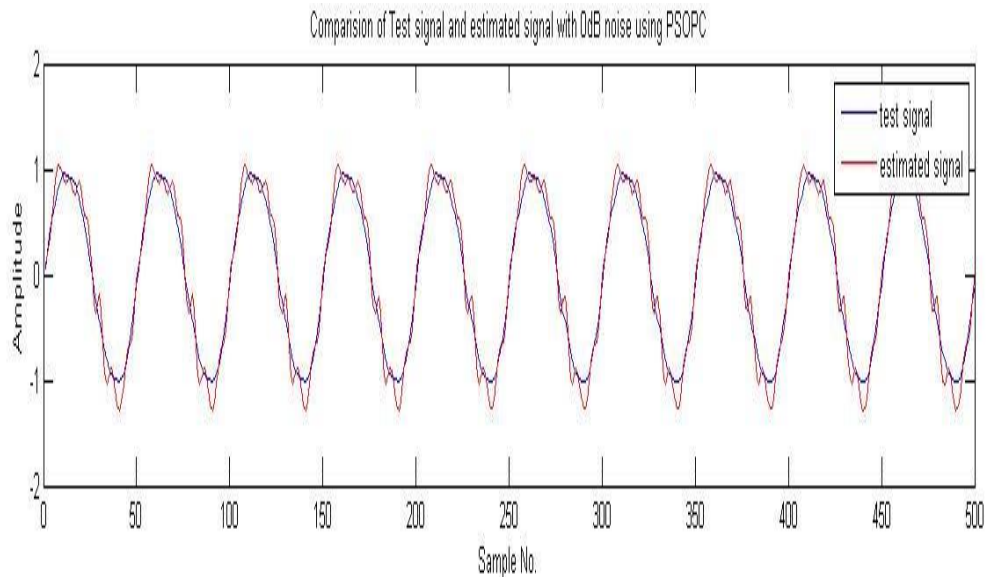
Table 8.6 Comparison Of Estimated Amplitude Between LS-PSOPC And LS-PSOPC-Adaline For 0db Noise In Measurement

frequency	PSOPC(ϵ)	Hybrid(PSOPC-Adaline)
50Hz	50.0190	49.9978

**Table8.7 Comparison Of Frequency Estimated Using LS-PSOPC And LS-PSOPC-Adaline
For 0db Noise In Measurement**



**Fig 8.7 Comparision Of Estimated Signal And Original Signal In Presence Of 0db Noise In
Measured Signal When Used Proposed LSE-PSOPC-Adaline.**



**Fig 8.8 Comparision Of Estimated Signal And Original Signal In Presence Of 0db Noise In
Measured Signal When Used Proposed LSE-PSOPC.**

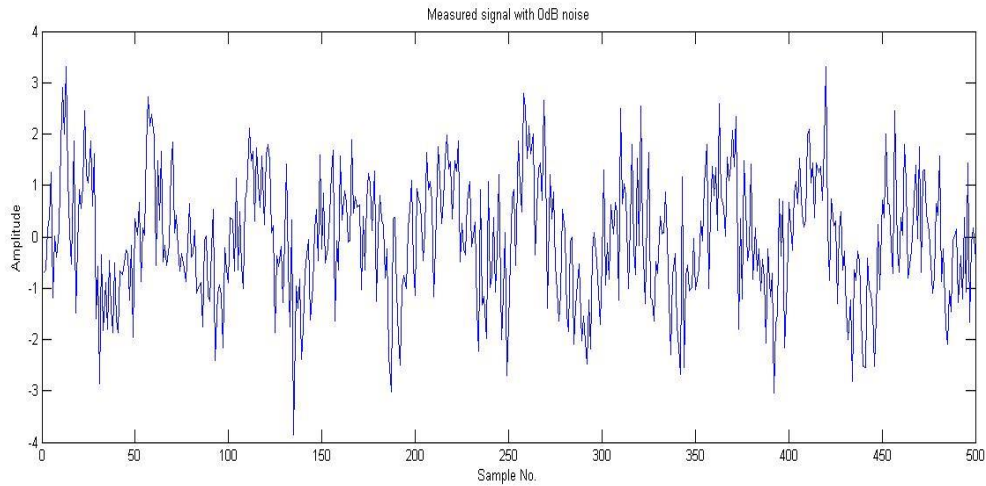


Fig 8.9 Measured Signal When 0db Noise Is There In Measurement.

Harmonic Order	Amplitude	PSOPC	PSOPC-Adaline
1	1	1.00000	0.9992
2	0.07	0.0698	0.0690
3	0.03	0.0222	0.0297
4	0.00	$2.771e^{-06}$	$8.6045e^{-05}$
5	0.01	0.0099	0.0068
6	0.00	$1.6250e^{-05}$	$7.6695e^{-05}$
7	0.02	0.028	0.0190
8	0	$2.2762e^{-05}$	$1.4272e^{-04}$
9	0	$3.0401e^{-05}$	$1.1176e^{-04}$
10	0	$2.7016e^{-05}$	$7.8285e^{-05}$

Table 8.8 Comparison Of Estimated Amplitude Between LS-PSOPC And LS-PSOPC-Adaline For No Noise In Measurement

frequency	PSOPC(ϵ)	Hybrid(PSOPC-Adaline)
50Hz	50.0033	49.9850

Table8.9 Comparison Of Frequency Estimated Using LS-PSOPC And LS-PSOPC-Adaline For No Noise In Measurement

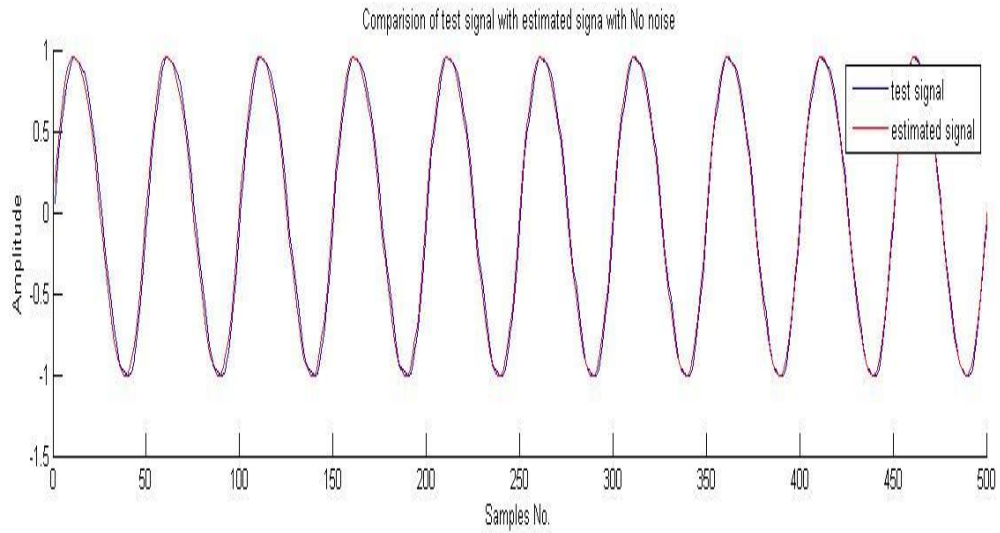


Fig 8.10 Comparison Of Estimated Signal And Original Signal In Presence Of No Noise In Measured Signal When Used Proposed LSE-PSOPC-Adaline.

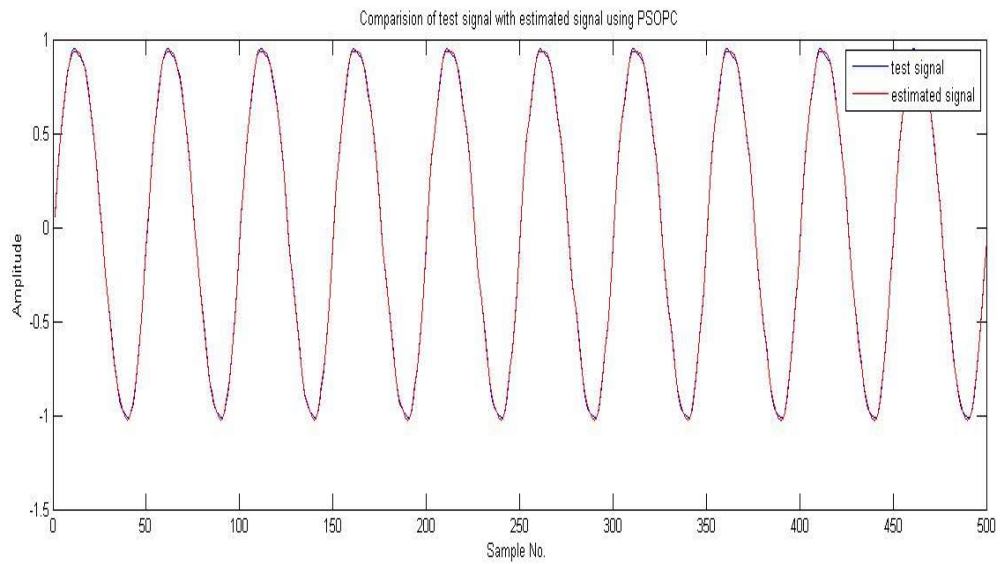


Fig 8.11 Comparison Of Estimated Signal And Original Signal In Presence Of No Noise In Measured Signal When Used Proposed LSE-PSOPC.

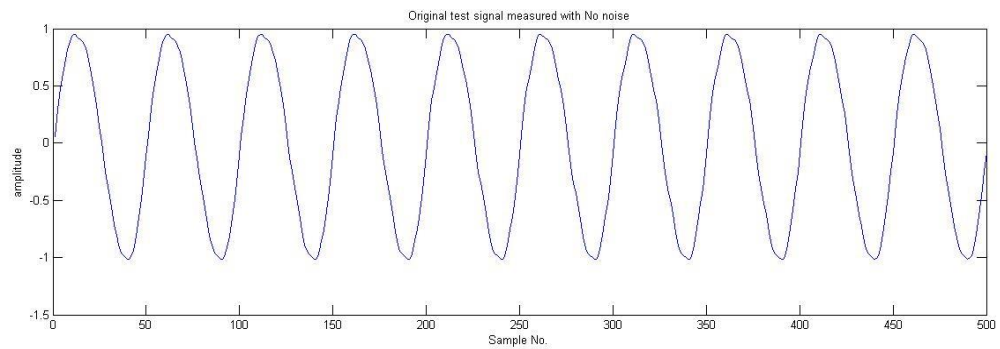


Fig 8.12 Measured Signal When No Noise Is There In Measurement.

8.2 Conclusion

This new technique presented harmonic estimation for distorted power system signals using LS-PSOPC-Adaline technique and compared with LS-PSOPC through computer simulations. Both these techniques are capable of estimating the signal very accurately. When noise in the measuring signal is more LS-PSOPC technique has more error when compared to LS-PSOPC-Adaline technique. And this present technique evaluates the phase, frequency and amplitude for every new sample acquired.

8.3 Future Work

Only static signal with various noises has been implemented in the above work. It can be extended to real time data. One can use this algorithm as online estimator of the signal harmonics by taking the samples online. Deviation in system frequency can also be estimated by using LS-PSOPC. Inter- harmonics and sub-harmonics can also be estimated using the proposed technique. Deviation of frequency can also be estimated using the above proposed technique. Online real time data can be collected in samples and our proposed algorithm can be implemented and the credibility of the program can be checked.

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