Optimal Placement of Phasor Measurement Units for Harmonic Source Identification

A Dissertation submitted in fulfillment of the requirements for the Degree

of

Master of Engineering

in

Power Systems

Submitted By

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Declaration

I hereby certify that the work which is presented in dissertation entitled, **"Optimal Placement of Phasor Measurement Units for Harmonic Source Identification"**, in partial fulfillment of the requirements for the award of the degree of **Master of Engineering** in **Power Systems**, submitted to **Electrical & Instrumentation Engineering Department** of **Thapar University, Patiala** is as authentic record of my own work carried under the supervision of **Dr. Sanjay K. Jain**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

Place: TU, Patiala

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Abstract

The nonlinear loads causes harmonic pollution in electrical power system. These harmonics or harmonic components affect the performance of power system components as well as the components causing harmonics. The line admittances get modified to unacceptable limits which thereby results in error during fundamental load flow calculations. In this dissertation, an efficient methodology to determine the harmonic sources and their injection levels has been implemented. The measurement data of phasor measurement units (PMUs) are considered as the time synchronised voltage and current phasor values of buses. Because of high cost associated with PMUs, optimal placement of PMUs has been investigated with index method, genetic method and binary particle swarm optimization approaches. The harmonic identification approach utilizes the direction of harmonic power flow at system buses. The effectiveness of the formulations is studied on 18-bus and 69-bus radial distribution systems and compared. The simulation is implemented in MATLAB.

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Anupam Dixit

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Nomenclature

h Order of harmonics

ξ Ratio of hysteresis loss to eddy current loss

ASD Adjustable speed drives

$BPSO$ Binary particle swarm optimization

$C(i, j)$ Connectivity matrix

C_M Mutual capacitance of capacitor bank

C_S Self capacitance of capacitor bank

D Desired measurement redundancy

DG Distributed generation

DP Dynamic programming

$FACTS$ Flexible ac transmission systems

GA Genetic algorithm

$gbest_i$ Global best position of i^{th} particle

HLF Harmonic load flow

HS Harmonic source

HSE Harmonic state estimation

I_h h^{th} order harmonic current injection

$I_{k,l}$ Harmonic current flow on line between bus k and l

IC_i Harmonic current absorbed by capacitor at i^{th} bus

Ih_i^h Linear load harmonic injection current at i^{th} bus

IPC In-plant point of coupling

L_i^h Localization index of i^{th} bus at h^{th} harmonic frequency

LAV Least absolute value

LB Location of buses

$lbest_i$ Local best position of i^{th} particle

LI Localization index

MR Measurement redundancy

N Number of PMUs

OPP Optimal PMU placement

P_1 Number of PMUs

P_2 Measurement redundancy

P_k^h Real harmonic power injection at k^{th} bus

PCC Point of common coupling

PMU Phasor measurement unit

PS Power system

PSO Partical swarm optimization

Q_C Reactive power of capacitor bank

Q_k^h Reactive harmonic power injection at k^{th} bus

R_g Generator's armature resistance

$S(i)$ State matrix

$S_i(t)$ Position vector of i^{th} particle

S_k^h Complex harmonic power injection at k^{th} bus

S_T Transformer rated power

SE State estimation

SVD Singular value decomposition

TCR Thyristor controlled reactors

THD Total harmonic distortion

U Observability matrix

V_h Bus voltage vector at h^{th} harmonic frequency

$V_i(t)$ Velocity vector of i^{th} particle

V_{max} Maximum velocity of particle

V_{min} Minimum velocity of particle

X_C Reactance of capacitive component

X_{g1} Positive sequence reactance of generator

X_{g2} Negative sequence reactance of generator

$X_{gd}^{'}$ Direct axis transient reactance of generator

X_{go} Zero sequence reactance of generator

X_g Impedance of generator

$y_{i,0}^h$ Admittance between i^{th} bus and ground

$y_{i,j}^h$ Admittance of line between i^{th} and l^{th} buses at h^{th} harmonic frequency

Z_h Impedance matrix of system at h^{th} harmonic frequency

$Z_{i,i}^h$ Driving point impedance of i^{th} bus at h^{th} harmonic frequency

$Z_{k,k}$ Driving point impedance of k^{th} bus

$Z_{k,l}$ Impedance of line between bus k and l

Z_L^h Impedance of transmission line

Z_T^+ Positive sequence impedance of transformer

Z_T^0 Zero sequence impedance of transformer

Chapter 1

Introduction

1.1 Overview

The increase in non-linear loads in the industrial, commercial and residencial power system has altered the utilities power flow conditions over the last decades. These non-linear loads are responsible for harmonic pollution in electrical power system. Though harmonics are present in the system for a long time, but have become a major concerning issue in the past few decades. Conventional harmonics generating loads are the transformers and electromechanical machines in which uneven distribution of airgap flux causes generation of non-sinusoidal voltages and currents. But nowadays even domestic equipments are responsible for harmonics. Many researchers have described the effect of the office and home equipments to the harmonic distortion in power systems [1], [2]. Individual contribution by these devices to harmonic distortion may be very less, but as a whole their contribution is substantial. Semiconductor technology has found huge applications in low powered devices. Also, with the increased efficiency and lowering cost in these technologies, they constitute the main components in power quality management and control of modern power systems. Modern power systems employ equipments which adjust and control the real and reactive power flow and also perform voltage regulation for efficient power generation and delivery. These equipments are known as Flexible AC Transmission Systems (FACTS). Since power electronics components contribute to the main components of these equipments, they generate distorted voltage and current waveforms. Interconnection of renewable energy sources like solar power and wind power which employ a large number of new power electronic devices also results in generation of harmonics. Other major sources of harmonics in power systems include converters, thyristor controlled reactors (TCR), and arc furnaces which produce non-characteristic harmonics.

Harmonic distortion created by these non-linear loads are responsible for many issues such as failure of equipments, increased losses, overheating, interference with communication circuits and miss-operation of protective relays that rely on voltage zero crossing detection. Along with the increase in harmonic producing sources, there has been considerable increase in the number of harmonic sensitive loads which may falsely trip due to harmonics. Another issue which arises is the occurrence of resonance condition in the power system. There is wide application of capacitor banks in the power systems for the purpose of power factor correction. These are not a source of harmonics, but can cause resonant condition which magnifies the harmonic distortion and also change the system response. Resonant condition causes high voltage across the capacitors resulting into the failure of the capacitor banks. As a result of these all problems, standards [3] have been made for harmonic level in order to limit it to acceptable value.

Measurement and identification of harmonic sources has become a major concern in electric power systems as these are widely spread across the whole power system. So, the challenge lies in obtaining the location of these sources and their magnitudes in order to place the phasor measurement units or design harmonic mitigation devices of proper specifications. Over the years, many researchers have used several methodologies to deal with the problem of identification of harmonic sources.

1.2 Literature Review

In the modern power systems, the harmonic sources can penetrate across the entire network because of its interconnected nature. Thus, the challenge lies in finding out the locations of harmonic sources along with their magnitudes. Many researchers suggested different methodologies in the literature. Herraiz *et al.* [4] summarized various methods for harmonic load flow and reported the merits and demerits of each method. He suggested that the complete harmonic load flow method, which considers the fundamental frequency power, requires less number of unknowns and has faster convergence. Najjar *et al.* [5] proposed a hybrid non linear least square method for identification of harmonic sources. The method is based on the kirchhoff current law and minimization of mismatch power. The method estimates the line currents and bus voltages. Harmonics upto 19^{th} order can be readily determined but estimation accuracy get deteriorated for higher order harmonics. Therefore, Islam *et al.* [6] identified the harmonic sources in the system based on reverse power flow procedure using computer program called HARMFIED. The program supports the investigation for higher order harmonics. In this, to trace the harmonics, each bus of the system is considered one by one as a harmonic source. Against all the power direction methods Xu *et al.* [7] mentioned that harmonic sources can not be detected by power direction methods and said them theoretically incorrect. He investigated closely the validity of method [8] and stated the cause of problem as: "the phase angle difference between the two sources decides the direction of active power flow while reactive power flow has better correlation with the source magnitude." Li *et al.* [9] reported the utilization of Critical Impedance/Critical Admittance criterion for identification of harmonic sources. This method requires the exact knowledge of internal impedances of the equivalent sources of the customer side and the supplier side. Similar methodology proposed in the literature [10], [11]. Antona *et al.* [12] proposed a methodology based on a Bayesian approach for harmonic source estimation. The method aims at reliably giving information of presence of non linear loads to the system operator. An improved version of methodology called Metropolis–Hastings approach is also presented which estimates the harmonic sources with a full uncertainty description. Farach *et al.* [13] presented state estimation techniques based on sensitivity analysis and a minimum variance approach to estimate the harmonic sources location along with the optimal placement of measurement devices. State estimation technique is also presented in [14], [15] to identify the new harmonic sources in power system. The method requires many measurement data of voltage and current which are expensive to obtain for larger power systems. Another harmonic state estimation technique based on sparsity maximization approach, which is solved using linear programming, is proposed by Liao *et al.* [16]. The technique locates the harmonic sources using harmonic meters lesser than unknown state variables. Haili *et al.* [17] addressed the dynamic estimate of the location of harmonic sources along with their injection level using kalman filter. Harmonic injection level is estimated by system error covariance analysis using kalman filter. The analysis further determines the optimal location of limited number of harmonic measurement devices. Using kalman filter, the instantaneous value of oscillating phasor and harmonics are estimated in [18], [19] while instance of occurrence of harmonics are determined in [20]. Gursoy *et al.* [21] looked into the use of a statistical signal processing technique, called independent component analysis (ICA) for identification and estimation of harmonic sources. The technique estimates the harmonic injections with few harmonic voltage measurements and without prior knowledge of network admittance or topology. Based on complex ICA, a method called scale factor calculation method is proposed in [22]. Baptista *et al.* [23] presented a useful computer tool named *"HarmoSim"* for simulation and prediction of behaviour of non-linear loads in low voltage power systems with main emphasize on residential electrical grids. The software allows to determine and visualize graphically the various parameters related with power quality like total harmonic distortion (THD), crest factors, circuit power factor, current and voltage in absolute value and the time domain current and voltage plots. Pyzalski *et al.* [24] proposed a method based on measurements at the Point of Common Coupling (PCC) for harmonic source identification. The method gives the idea about the contribution of harmonics by customers and utilities and therefore, dispute between customers and utilities on harmonic generation can be solved. The effectiveness of the method is investigated by calculating the probability of occurrence of wrong decision. Zhao *et al.* [25] reported a harmonic source model based on least squares approximation. The method utilizes this model and V-I characteristic of linear and non linear load for harmonic source identification along with harmonic current separation which is being absorbed by conventional linear loads. The method distinguishes the contributions of linear loads and non linear loads to harmonic voltage distortion. Herrera *et al.* [26] presented a index called load characterization index which calculates the harmonic distortion introduced by the load. The method involves the measurement of voltage and current at the point of common coupling. Using these measured values it can determine the location of harmonic sources even in the presence of capacitors which have a tendency to amplify the harmonics present in the system. Alammari *et al.* [27] proposed a constrained least absolute value (LAV) algorithm to identify the individual types of harmonic loads and their harmonics contribution to the power system. The problem formulation is done as least error squares parameter estimation using lagrange multiplier to include the equality constraints. Then, the resulting problem is solved based on constrained LAV. Alhaddad *et al.* [28] determined the optimal size and optimal locations for harmonic filters using Ant Colony algorithm for a radial distribution system to keep the total harmonic distortion (THD) and the effective harmonic voltage values within acceptable limits. The Ant Colony algorithm is performed in conjunction with a harmonic load flow (HLF) algorithm to see the impact of harmonic sources on total power loss. Madtharad *et al.* [29] performed the optimal measurement placement based on the minimum variance criterion and sequential solution. The methodology emphasizes on identifying best location for placing harmonic measurement device rather than optimizing the number of devices.

Wenbo *et al.* [30] conducted a interpolated FFT algorithm, based on Bartlett-Hann window. The algorithm accurately estimates the electrical harmonic parameters. Bartlett-Hann window takes the advantages of weighted Bartlett and Hann windows. The accuracy of electrical harmonic parameters like amplitudes, phases and frequencies determined by this algorithm meet the state standard of power quality. Hartana *et al.* [31] proposed a constrained neural networks for identifying the harmonic sources in power systems where sufficient direct measurement of phasors are not available. The neural networks are trained to estimate harmonic sources using available measurements. To improve their accuracy, the neural estimates are constrained to assure to available direct harmonic measurements. Other artificial neural networks based methodologies for harmonics and inter-harmonics estimation are reported in [32], [33]. Swain *et al.* [34] proposed a technique for identifying and estimating the harmonic components of a power signal in the presence of significant noise. The method employs the advantages of both orthogonal least squares (OLS) and singular value decomposition (SVD) algorithm. The algorithm determines the correct frequency component of the power signal by employing an error reduction ratio test. The other parameters of the power signal are determined at different levels of noise using SVD. Sahni *et al.* [35] presented an optimal sensor placement technique to identify the multiple harmonic sources on a radial distribution system. The method is based on the reverse power flow concept and does not require the disconnection of capacitors during the process of identification of harmonic sources as is the case in conventional methods. Kaneko *et al.* [36] established the experimental set up for measuring the harmonics in a communication factory using harmonic analyzers and optical harmonic measuring instruments for high voltage. Simultaneously, the patterns of the harmonics were measured at the distribution line in the vicinity of factory connected to the same distribution substation. The power factor was also measured and evaluated by the distortion factor in an industrial distribution line.

1.3 Motivation

Harmonics have become a major power quality issue in the power system because of the increased distortion levels. The distortion is continuously increasing to ever-increasing power electronic components in the system. The Indian situation is no different becuase of massive thrust on renewable and industrialization. The distribution companies often find it very difficult to provide harmonic free electric supply. Also harmonic distortion leads to financial expenses to electric power companies as well as customers. Hence, research in the field of identification of harmonic sources would be quite helpful for site engineers as they can easily place the harmonic mitigation devices or phasor measurement units optimally on a large power system.

1.4 Objective

The objective of this dissertation is to develop an efficient methodology for harmonic source identification based on direction of harmonic power flow in electric power systems. Also binary particle swarm optimization (BPSO) technique and genetic algorithm (GA) technique is to be applied for optimal placement of phasor measurement units (PMUs). The optimal placement problem have following objectives:

1. Minimize the number of PMUs.

2. Maximize the measurement redundancy of the system.

Both objectives must be satisfied with a constraint of complete system observability.

1.5 Dissertation Organization

The dissertation titled as -" Optimal Placement of Phasor Measurement Units for Harmonic Source Identification" has been elaborated in six chapters. Chapter 1 contains the detailed overview of the dissertation, brief literature review, motivation and objective of the dissertation. Harmonic analysis in the power systems and modelling of system components are explained in Chapter 2. Techniques for optimal placement of PMUs is described in Chapter 3. Chapter 4 introduces the estimation algorithm for the identification of harmonic source problem in power systems. Chapter 5 contains the results and discussion. Chapter 6 concludes the thesis with a summary followed by directions for future research.

Chapter 2

Harmonics in Power Systems

2.1 Introduction

Earlier harmonics were generated by transformers and rotating machines in which uneven distribution of airgap flux causes generation of non-sinusoidal voltage and currents but with the advancement in power electronics, the technology involved in power generation, transmission and distribution are rapidly changing. Growing penetration of distributed generation (DG) plants which are often based on renewable sources of energy have significant impact on power quality, regulation, reliability and other technical aspects. The huge employability of power electronic components in these DG plants are responsible for penetration of harmonics in power systems. Apart from generation side the load side is also responsible for penetration of harmonics in power systems. The basic behaviour of load have changed from linear to non linear. Small powered equipments such as computers adjustable speed drives (ASD), television, uninterruptible power supplies (UPS) and office equipment such as fax machines and printers draw non-sinusoidal voltages and currents. Individual contribution by these equipments to harmonic distortion may be negligible, but as a whole their contribution is substantial. Other major sources of harmonics in power systems include the High Voltage Direct Current Transmission (HVDC) technologies which consists of converters responsible for non-sinusoidal voltage and currents.

2.2 Non-Linear Loads

"A load is said to be non-linear when its impedance varies with the applied voltage". The changing impedance means even when sinusoidal voltage is applied across non linear load,

the load will draw non sinusoidal current. Nonlinearity is not the similar as the frequency dependence of impedance, that is, the value of reactance of an inductor or capacitor changes in accordance with the applied frequency, but they are linear at each applied frequency if we do not consider the fringing and saturation. However, non linear loads draw a current that may flow in the form of pulses for a part of the sinusoidal voltage cycle or even be discontinuous.
Mathematically, linearity implies two conditions:

1. Homogeneity

2. Superposition

Consider a system defined in the form of state equation as :

$$x = f[x(t), r(t), t] \tag{2.1}$$

If $x(t)$ is the solution to this differential equation with initial conditions $x(t_o)$ at $t = t_o$ and input $r(t), t > t_o$:

$$x(t_o) = \phi[x(t_o), r(t)] \tag{2.2}$$

then homogeneity implies that

$$\phi[x(t_o), \alpha r(t)] = \alpha\phi[x(t_o), r(t)] \tag{2.3}$$

This means that the solution $x(t)$ with input $\alpha r(t)$ is equal to α times of solution $x(t)$ with input $r(t)$ for any scalar constant α.
Superposition implies that

$$\phi[x(t_o), r_1(t) + r_2(t)] = \phi[x(t_o), r_1(t)] + \phi[x(t_o), r_2(t)] \tag{2.4}$$

That means that, the solution $x(t)$ with inputs $r_1(t) + r_2(t)$ is equal to the sum of solution $x(t)$ with input $r_1(t)$ and solution $x(t)$ with input $r_2(t)$. Thus, linearity is combination of superposition and homogeneity.

2.2.1 Increase in nonlinear load

Nonlinear loads are increasing continuously. According to a report by the Electric Power Research Institute, nonlinear load share was estimated to be 15–20 percent of the total load in 1992, and it is reported that this share would increase to 50–70 percent of the total loads in the recent years.

Concerns for harmonics begin from the need of a certain power quality, which leads to look forward for the related issues of:

- Effects on the operation of electrical equipment
- Harmonic analysis
- Harmonic control

A growing number of consumer equipments are sensitive to poor power quality. Their performance get deteriorated by the harmonics present in the power supply. Also it is estimated that industries bears loss of billion of dollars per year due to power quality problems. Although the increased use of power electronics and consumer automation equipment is resulted in higher productivity, these heavy loads are responsible for harmonics and electrical noise and are more affected by poor power quality. For example, adjustable speed drives (ASDs) are more affected by voltage sags and swells than an induction motor. A 10 % of voltage dip for a certain time duration may cause shutdown of ASD. This reveals that the nonlinear loads, which are a source of harmonics generation, are themselves relatively less tolerant to the poor power quality. Some examples of nonlinear loads are as follows:

- ASD systems
- Arc furnaces
- Computers, copy machines, television sets, and home appliances
- Cycloconverters
- Wind and solar power generation
- Rolling mills
- Switching mode power supplies
- HVDC transmission, harmonics originate in converters
- Static var compensators (SVCs)
- Thyristor controlled reactors (TCRs)

- Slip frequency recovery schemes of induction motors
- Electric traction, chopper circuits
- Fluorescent lighting
- Battery charging and fuel cells

2.3 Point of Common Coupling (PCC)

The term “point of common coupling” (PCC) which is sometimes known as “point of common connection” became popular and important after the release of IEEE 519, “Standard Practices and Requirements for Harmonic Control in Electrical Power Systems,”. According to IEEE-519, “PCC is the interface between sources and loads in a power system” which means PCC should be accessible to both the utility and the consumer for direct measurement. The PCC is a point in the electrical power system where multiple electrical loads or multiple customers may be connected. Although generally PCC is considered at the metering point, facility transformer or service entrance, according to IEEE-519 “the PCC is the point between the linear and non-linear loads within an industrial plant.” Often PCC is at the service transformer. Since there is usually one service transformer, hence, there is typically one PCC . At the point of common coupling, the ratio of short circuit current to load current is very large. When the PCC is located near the utility metering point, the total harmonic distortion (THD) limits are typically lower.
The PCC is important because at this point the nonlinear load’s distorted current waveform create the voltage waveform’s distortion. In other words, it is the point where, because of source internal impedance, different harmonic frequency currents develops a corresponding distorted voltages which are algebraically additive to the fundamental voltage produced at the output of the source. This fundamental voltage combined with the distorted voltages is then provided to the bus or feeder. From there, it can propagate to the whole power system and create power quality problems.

2.4 Standards for Harmonics

There are some standards set by IEEE and IEC in order to limit the harmonics for both i.e voltage and current waveforms.

2.4.1 Voltage distortion limits

IEEE 519

Although the harmonic current injection into the utility system is in a certain amount by the consumer side, the utilities must meet requirements of distortion free power supply to the consumers. The recommended voltage distortion limits are mention in Table 2.1:

Table 2.1: Harmonic voltage limits for utilities

Bus Voltage at PCC	Maximum % for Individual harmonic	Voltage THD, %
$V < 69KV$	3.0	5.0
$69 \leq V < 161KV$	1.5	2.5
$V \geq 161KV$	1.0	1.5

Total harmonic voltage distortion (THD) is expressed as a percentage of fundamental frequency voltage. For medium-voltage systems, the limits of distortion are 5 %. The consumer loads may accept a higher voltage distortion according to their sensitivities. It is worth noting that the IEEE 519 does not impose any limits of voltage distortion at the PCC.

IEC Voltage Distortion Limits

IEC 61000-2-2 provides the acceptable distortion levels for different types of power quality characteristics. On the low-voltage systems the acceptable distortion level is 8 %. For a public low-voltage networks (IEC-61000-2-2), the voltage harmonic distortion limits are given in Table 2.2. These limits are the same as in IEC 61000-2-4 for class 2. For class 3, as per this standard, the limits are shown in Table 2.3. The THD (voltage) is less than 8 % for class 2 and less than 10 % for class 3.

Class 2 : applies to PCC and IPC (in-plant point of coupling) in industrial environment, in general.

Class 3 : applies to IPCs in industrial environment

$x = 0.2 + 12.5/h$, for $h = 29, 31, 35, and\ 37$; $V_h = 0.63, 0.60, 0.56, and\ 0.54$.

$y = 5\sqrt{11}/h$, for $h = 29, 31, 35, and\ 37$; $V_h = 3.1, 3.0, 2.8, and\ 2.7$.

Table 2.2: IEC 61200-2-2 harmonic voltage limits for public low-voltage network

Odd Harmonics		Even Harmonics		Triplen Harmonics	
h	V %	h	V %	h	V %
5	6	2	2	3	5
7	5	4	1	9	1.5
11	3.5	6	0.5	15	0.3
13	3	8	0.5	> 21	0.2
17	2	10	0.5		
19	1.5	> 12	0.2		
23	1.5				
25	1.5				
> 29	x				

Table 2.3: IEC 61200-2-4 harmonic voltage limits, class 3

Odd Harmonics		Even Harmonics		Triplen Harmonics	
h	V %	h	V %	h	V %
5	8	2	3	3	6
7	7	4	1.5	9	2.5
11	5	≥ 6	1	15	2
13	4.5			21	1.75
17	4			≥ 27	1
19	4				
23	3.5				
25	3.5				
> 29	y				

2.4.2 Current harmonic distortion limits

IEEE 519

Table 2.4: IEC 61200-2-4 harmonic current limits, class 3

Maximum Harmonic Current Distortion in % of Fundamental Harmonic Order (Odd Harmonics)						
I_{sc}/I	< 11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

Current distortion limits given in above Table 2.4 are for odd harmonics. Even harmonics should not exceed 25 percent of the odd harmonic limits above.

I_{sc} is maximum short circuit current at point of common coupling. I is the maximum load current (fundamental frequency) at point of common coupling.

2.5 Modelling of System Components

The main purpose of harmonic studies are to determine the branch harmonic currents, bus harmonic voltages, total harmonic distortion (THD) for voltage and current phasors and resonance conditions. Thus, to get the accurate harmonic distortion results, the correct modelling of power system components are very important during harmonic studies. The figure of typical industrial power system is shown in Fig. 2.1, where the two transformers supplied the high voltage switchgear and in turn supplied the various high voltage motors, few low voltage distribution boards and several filters and converter drives.

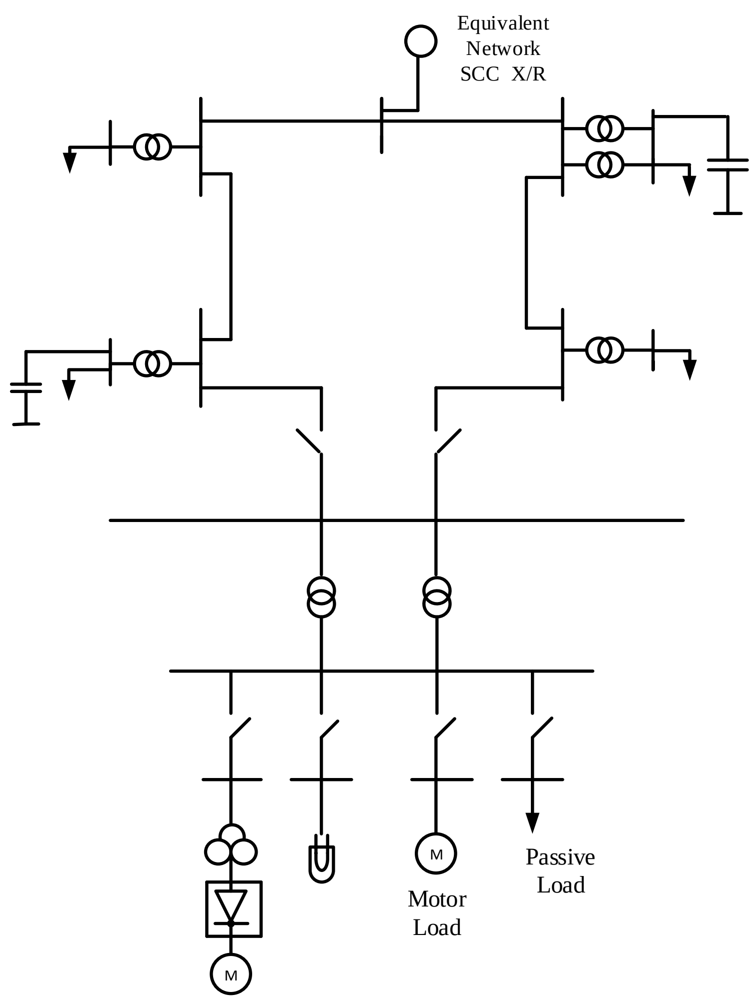

Figure 2.1: Industrial power system

Modelling of the power system components is a crucial factor in harmonic studies. This section deals with the modelling of system components like generators, transformers, induction motors, shunt and series capacitor banks and linear and non-linear loads.

2.5.1 Impedance in the presence of harmonics

At fundamental frequency, the impedance of inductive component having resistance R and reactance X_L is given as $Z = R + jX_L$. But in the presence of harmonics, the impedance of such components becomes

$$Z(h) = R + jhX_L \tag{2.5}$$

where h is the order of harmonics.
While at fundamental frequency, the reactance of capacitive component is given as $X_C = 1/(2\pi fC)$. The reactance of such components in the presence of harmonics becomes

$$X_C(h) = \frac{X_C}{h} \tag{2.6}$$

2.5.2 Skin effect

With the increase in frequency, the concentration of current increases near the surface of conductors, hence, the internal inductance of the conductor decreases and ac resistance increases. So, considering the skin effect, the impedance of generator and transformer in the presence of harmonics can be given as

$$Z(h) = \begin{cases} \sqrt{h}.R_g + jhX_g), & \text{in case of generator} \\ h.(R_t + jX_t), & \text{in case of transformer} \end{cases} \tag{2.7}$$

2.5.3 Modelling of transmission lines

Short transmission lines can be modelled by lumped parameters while long transmission lines can be modelled by distributed parameters [37]. The equivalent π model of transmission line is shown in Fig. 2.2.

In the above π model of transmission line, Z_L^h is the coupled impedance of all phases including ground conductors at h^{th} harmonic frequency, Y_L^h is the admittance of all phases including ground conductors at h^{th} harmonic frequency. For balanced harmonic analysis, the single phase π model can be obtained from the multiphase model using the positive sequence impedance values of transmission line. Taking into account the skin effect, the resistance of the line at h^{th}

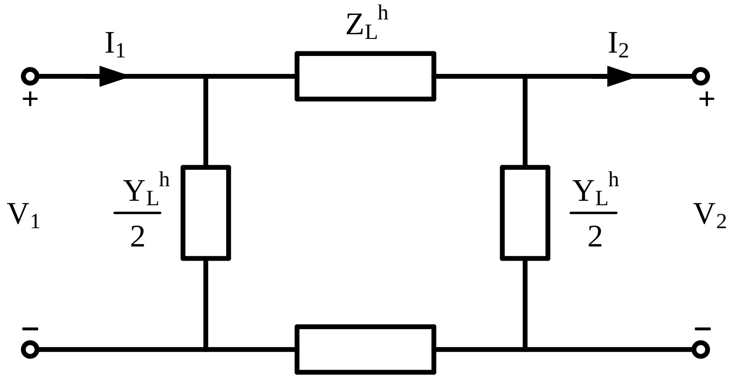

Figure 2.2: Equivalent π model of transmission line

harmonic frequency [38] can be expressed as

$$R_L^h = R(1 + \frac{0.646h^2}{192 + 0.518h^2}) \tag{2.8}$$

where R is the fundamental frequency resistance of line and h is the harmonic order. For simplicity the approximate impedance of the transmission line can be expressed as

$$Z_L^h = \sqrt{h}.(R_L + jX_L) \tag{2.9}$$

2.5.4 Modelling of generator

Assuming that the generator does not cause any harmonic voltages or currents, generator can be modelled simply by shunt impedance connected to the generator bus. For harmonic analysis there are various synchronous generator models obtained from the negative sequence or subtransient impedances of the generator.

$$X_g(h) = h.X_{gd}^{'} \tag{2.10}$$

$$X_g(h) = h.X_{gd}^{''} \tag{2.11}$$

$$X_g(h) = \frac{1}{2}h(X_{gd}^{''} + X_{gq}^{''}) \tag{2.12}$$

where $X_{gd}^{'}$ and $X_{gd}^{''}$ are direct axis transient and subtransient reactances respectively. $X_{gq}^{''}$ is the quadrature axis subtransient reactance of synchronous generator. On neglecting the skin effect, the positive, negative and zero sequence impedance of generator in the presence of harmonics can be expressed as

$$Z_g = \begin{cases} Z_1(h) = R_g + jhX_{g1}^{"}, & h = 3m+1 = 1,4,7,... \\ Z_2(h) = R_g + jhX_{g2}, & h = 3m-1 = 2,5,8,... \\ Z_0(h) = R_g + jhX_{g0} & h = 3m = 3,6,9,... \end{cases} \tag{2.13}$$

where

R_g is the generator's armature resistance.

X_{g2}, X_{g0} are negative and zero sequence reactance.

$X_{g1}^{"}$ is the subtransient reactance.

On considering the skin effect, the armature resistance becomes $\sqrt{h}$ times its value at fundamental frequency as mention in equation (2.7).

2.5.5 Modelling of transformer

The connection of the primary and secondary windings of two-winding transformer is a crucial factor during modelling of two-winding transformers. Hence, following points must be considered during harmonic analysis:

1. In the absence of grounded star connection, zero sequence currents can not flow.
2. In case of delta connection, zero sequence current is absent in line and flows inside the delta connection.
3. In $\Delta - Y$ and $Y - \Delta$ transformers, the negative and positive sequence harmonic currents get phase shifted.
4. Triplen harmonics must be suppressed in case of Δ or ungrounded Y connections.

With skin effect neglected, the transformer impedance in the presence of harmonics can be expressed as

$$Z_T(h) = \begin{cases} Z_T^0(h), & h = 3m = 3,6,9... \\ Z_T^+(h), & \text{otherwise } (h = 3m \pm 1) \end{cases} \tag{2.14}$$

where $Z_T^0(h)$ and $Z_T^+(h)$ are the zero sequence and positive sequence impedances of the transformer respectively. On considering the skin effect, the transformer resistance becomes h times its value at fundamental frequency as mention in equation (2.7).

Because of the phase shift effects and different types of connections, transformer modelling becomes complicated for harmonic analysis. In case of single phase analysis, its modelling can be done by its short circuit impedance. Below are some transformer models mentioned in the literature [39], [40]: In Figure 2.3, R_T is the resistance and X_T is the leakage reactance of the

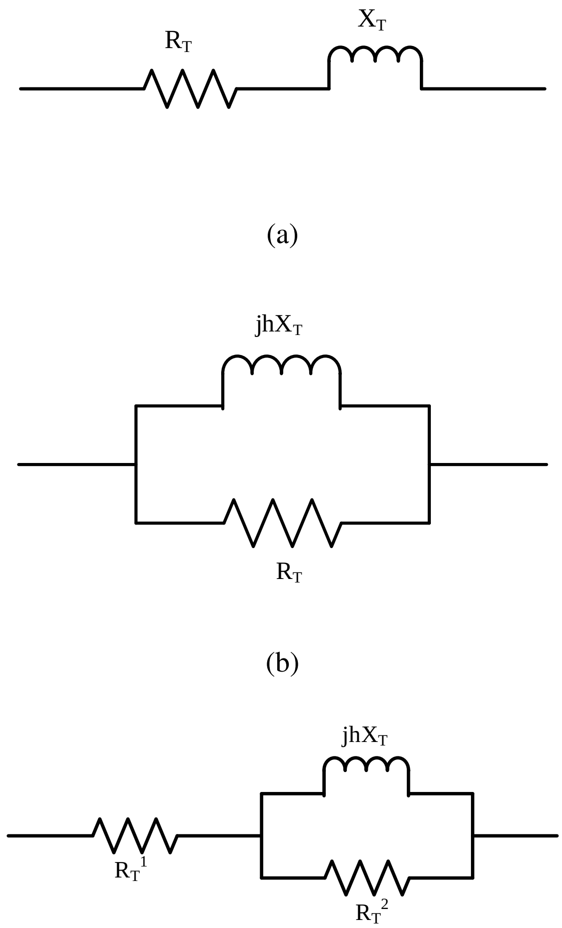

Figure 2.3: Different models of transformer

transformer at fundamental frequency. In Figure 2.3 (a) $R_T = 0.1026mhX_T(\xi + h)$, ξ being the ratio of hysteresis loss to eddy current loss, $m = 1/(1+\xi)$ and for model in figure (b), a factor 80 is mentioned for the reactance. In Figure 2.3 (c), R_T^1 and R_T^2 are the resistances independent of frequency whose values can be calculated from $90 < V^2/S_T R_T^1 < 110$ and $13 < V^2/S_T R_T^2 < 30$ respectively with S_T being the transformer rated power. If the harmonics produced by the transformer is significant, saturation effect should be taken into account. This harmonic producing characteristic of transformer can be represented by including a current source in the magnetizing branch.

2.5.6 Modelling of loads

The linear passive loads are not responsible for generation of harmonics but at higher frequencies they may have effect on resonance condition of the network. So, the aggregate of all the individual loads are modelled either in series or in parallel. The equivalent series and parallel load models are shown in Fig. 2.4.

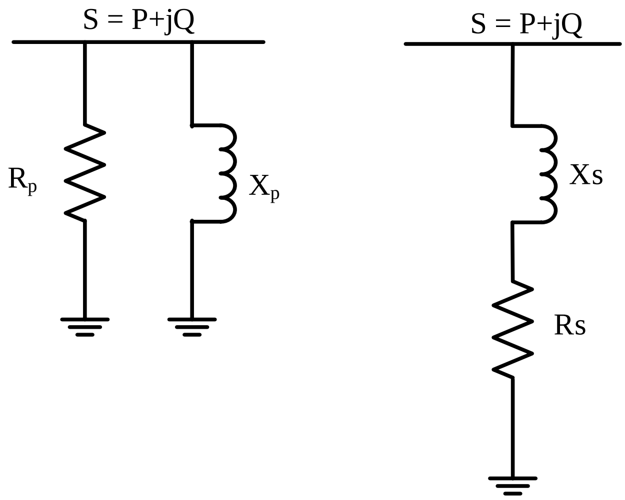

Figure 2.4: Equivalent models of loads

Series load model

The series load model is best suited to represent the individual loads. The equivalent impedance can be determined by active and reactive powers, and voltages obtained from load flow solutions at fundamental frequency.

$$Z_L = R_L + jX_L = \frac{V^2}{P_L - jQ_L} = \frac{V^2(P_L + jQ_L)}{P_L^2 + Q_L^2} = \frac{V^2(P_L + jQ_L)}{|S_L|^2} \tag{2.15}$$

so that

$$R_L = \frac{V^2}{|S_L|^2}.P_L \tag{2.16}$$

$$X_L = \frac{V^2}{|S_L|^2}.Q_L \tag{2.17}$$

where $S_L = P_L + jQ_L$ is the complex power.

In the presence of harmonics

$$Z_L(h) = R_L + jhX_L \tag{2.18}$$

Parallel load model

The parallel load model is most suitable for representing lumped loads.

$$Y_L = \frac{1}{R_L} - j\frac{1}{X_L} = \frac{P_L - jQ_L}{V^2} \tag{2.19}$$

so that

$$R_L = \frac{V^2}{P_L} \tag{2.20}$$

$$X_L = \frac{V^2}{Q_L} \tag{2.21}$$

In the presence of harmonics

$$Y_L(h) = \frac{1}{R_L} - jh\frac{1}{X_L} \tag{2.22}$$

2.5.7 Modelling of capacitor banks

If the values of self and mutual capacitances of balanced capacitor banks are given, then, in the presence of harmonics the capacitive reactance is expressed as

$$X_{C_h} = \frac{X_C}{h} = \begin{cases} \dfrac{1}{hw(C_S - 2C_m)}, & h = 3m = 3, 6, 9... \\ \dfrac{1}{hw(C_S + C_m)}, & \text{otherwise } (h = 3m \pm 1) \end{cases} \tag{2.23}$$

If the reactive power Q_C and capacitor rated voltage in KV is given, then, the capacitive reactance is determined as

$$X_C = \frac{KV^2}{Q_C} \tag{2.24}$$

In the presence of harmonic of order 'h'

$$X_C(h) = \frac{X_C}{h} \tag{2.25}$$

Chapter 3

Optimal Placement of PMUs

3.1 About Phasor Measurement Units (PMUs)

A phasor measurement unit is a device which measures voltage and current phasors on an electricity grid. PMUs are provided with the Global Positioning System (GPS) to give the time synchronised (real time) measurement of voltage and current phasors. The device gives the 48 samples of resulting measurements per second which depicts its accuracy. The total error in the measurement of phasor (magnitude and angle) is less than 1 %. Individually magnitude and phasor contributes error < 1 % and $< 0.573^{o}$ respectively. The results obtained by the device is known as a synchrophasor. That's why the terms "PMU" and "synchrophasor" are sometimes used interchangeably though they are two separate technical terms.

3.1.1 Applications of PMU

- Wide-area situational awareness
- Voltage monitoring and trending
- State estimation
- Power oscillation monitoring
- Special protection schemes and islanding
- Frequency stability monitoring and trending

- Event detection and avoidance

3.2 Optimal Placement of PMUs

With the increasing demand of quality power, the use of phasor measurement units (PMUs) has increased a lot ever since it came into existence in 1980s. With this advanced meter, the operation, protection, monitoring and control of power system becomes accurate and easy. Using the PMUs data in state estimation (SE) equation make the SE algorithm linear which is easy to solve as compared to the non linear state estimation equations. Since it makes the SE algorithm linear, no iteration is required in getting the solution. Because of PMUs promising accuracy, its role is very crucial in SE algorithm. It is predicted that in the coming days SE technique will rely more on results of PMUs. However due to expensive nature of device (Rs. 27 lacs/PMU) they can not be installed at all the buses. Therefore, a suitable technique is required to minimize the number of PMUs with complete observability of power system. A power system is said to be completely observable when the phasor voltage of all the buses in the system can be determined uniquely either directly or indirectly. Therefore observability study in the PMUs placement problem is important before the deployment of PMUs. After assuring the complete system observability, it is necessary to find the optimal locations of the PMUs to maximize the measurement redundancy. The term "measurement redundancy" for a particular bus represents the number of times that bus is observed by PMUs. For example, if a bus observed by one PMU is make to observe by one more PMU, then the measurement redundancy of that bus will increase by one. The increase in value of measurement redundancy will ensure the observability of system in case of branch outage or PMU failure. References [41–44] considered only complete system observability without taking into account the measurement redundancy parameter. This approach may result in not having complete system observability in case of branch outage. In [45], conventional method of measurements are reported, which raises the number of PMUs. Also in [46], the immunity genetic algorithm is applied, but complete system observability is not achieved. Therefore, minimizing the number of PMUs with complete system observability and maximizing the measurement redundancy will result in a more complicated optimization problem.

3.2.1 Problem formulation for optimal placement of PMUs

Defining objective function

For defining an objective function to minimize the number of PMUs, there are some efficient rules which need to be considered to improve the topological analysis. These rules are as follows:

1. A PMU installed at a particular bus can measure the voltage phasor of that bus and the current phasor of all the branches incident on that bus. This type of measurement is called direct measurement.

2. If voltage phasor and current phasor values at one end of a line are available, then the voltage phasor value at the other end of line can be easily determined using ohm law. This type of measurement is called pseudo measurement.

3. If voltage phasor values at both ends of a line are available, then the line current phasor value can be determined using known line impedance.

Therefore, the main objective function can be mathematically defined as follows:

$$Minimize \qquad w_1P_1 + w_2P_2 \tag{3.1}$$

$$Subject\ \ to \qquad CS^T \geqslant U \tag{3.2}$$

where U is an observability matrix of order $(n \times 1)$, each element of which is equal to unity. w_1 and w_2 are weights of two objectives i.e P_1 and P_2 respectively. C is the connectivity matrix for a n bus system of order $(n \times n)$ which is expressed as:

$$C(i,j) = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if bus } i \text{ and bus } j \text{ are connected} \\ 0 & \text{otherwise} \end{cases}$$

P_1 represents the number of PMUs and mathematically expressed as:

$$P_1 = \sum_{i=1}^{i=n} S_i \tag{3.3}$$

where n is the number of buses and S is the state matrix which is given as:

$$S(i) = \begin{cases} 1 & \text{if PMU is installed at bus } i. \\ 0 & \text{otherwise} \end{cases}$$

P_2 is the measurement redundancy function which is mathematically expressed as:

$$P_2 = \sum(D - SC) \tag{3.4}$$

D is the desired measurement redundancy vector of order $(n \times 1)$. Each element of D are set equal to the value of desired measurement redundancy.

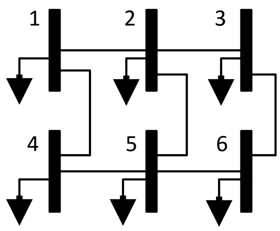

Figure 3.1: 6-bus system

For example, the first part of equation (3.1) i.e P_1 for a 6-bus test system (Fig.3.1), by taking w_1 as unity, can be formulated as follows:

$$min \quad [S_1 + S_2 + S_3 + S_4 + S_5 + S_6] \tag{3.5}$$

where $S_1 - S_6$ are elements of S matrix which can be either 0 or 1. So, equation (3.5) denote the minimum number of PMUs.

Similarly, the second part of equation (3.1) i.e P_2 can be formulated as follows:

$$min \quad \sum[D - SC] \tag{3.6}$$

where D = [4 4 4 4 4 4] represents the desired measurement redundancy of 4. Product 'SC'represents the actual measurement redundancy.

The observability constraint expressed in equation (3.2) can be defined as follows:

Bus 1 : $S_1 + S_2 + S_4 \geq 1$

Bus 2 : $S_1 + S_2 + S_3 + S_5 \geq 1$

Bus 3 : $S_2 + S_3 + S_6 \geq 1$

Bus 4 : $S_1 + S_4 + S_5 \geq 1$

Bus 5 : $S_2 + S_4 + S_5 + S_6 \geq 1$

Bus 6 : $S_3 + S_5 + S_6 \geq 1$

The above mentioned inequality constraints represents the number of observable buses when PMUs are installed at buses 1-6.

The sets of equal number of PMUs may make the system completely observable but the redundancy parameter may vary from one set to another. For example, in the above considered system (Fig. 3.1), PMUs placement sets can be (1, 6), (2, 5) and (3, 4) which can make the whole system observable. But among all these sets, (2, 5) is the optimal location because buses 2 and 5 are observed two times by PMUs. Therefore, placement of PMUs at buses 2 and 5 will increase the measurement redundancy of the system.

3.2.2 Solution techniques

To solve this optimal PMU placement (OPP) problem, various optimization techniques have been discussed in the existing work which are mainly classified as conventional techniques and heuristic techniques. Conventional techniques basically comprises of linear programming (LP), dynamic programming, non linear programming (NLP), and combinational technique. Advanced heuristic techniques are better than conventional methods as they can overcome the problems associated with conventional ones like PMU failure or branch outage.

Dynamic Programming

Dynamic programming (DP) is an optimization approach for solving a complex problem by making a sequence of interrelated conclusions in an optimal style. DP convert the complex problems into a collection of simpler sub-problems.

The three most important features of DP problems are:

1. **Stage**

   It is a multistage optimization procedure in which each sub-problem is solved just once, and the solution obtained is stored using a memory-based data structure. Although each one-stage problem is solved as an ordinary optimization problem, its solution helps to define the characteristics of the next one-stage problem in the sequence. In the problem's planning horizon, stages represent different time periods.

2. **States**

   The states of the algorithm are related with each stage of the optimization problem. The states provide the necessary information required to know the consequences of current conclusion upon future actions. The detailing of the states of the algorithm is perhaps the most important design parameter of the DP model. The essential features that should consider during the selection of states are:

   i) The states should provide enough information to make future decisions without considering how the algorithm reached the current state.

   ii) Since the computational effort associated with the DP approach increases with increase in number of variables, therefore, the number of state variables chosen should be small.

3. **Recursive Optimization**

   In a recursive optimization procedure, one stage is solved and one stage is sequentially included at a time. Solving one-stage problems continues until the overall optimum is found. Recursive optimization procedure can be based on either a forward induction process or a backward induction process. In the former one, problems are carried out by solving one stage at a time and moving in forward direction until all the stages are completed. Hence, the first stage is solved in the initial stage of the problem. While in backward induction process all the stages are included while moving in backward direction, solving one stage at a time. Hence, the first stage is solved in the last stage of the problem.

   DP saves the computation time by looking at the stored solutions of sub-problems, each time the sub-problems occur. But computational effort increases with increase in number of state variables which limits the application of DP approach in practice.

Genetic Algorithm (GA)

A genetic algorithm (GA) is a search heuristic that is invented to mimic some of the processes observed in natural evolution. In GA, an intelligent exploitation of a random search is employed to solve optimization problems. Although randomised, they exploit previous information to direct the search into the zone of better solution within the solution space. The basic techniques are incorporated into GA in such a way as to simulate processes necessary for evolution of a population, specially the principles of “survival of the fittest”, laid down by Charles Darwin. Since in nature, competition among creatures for limited resources results in the fittest creatures dominating over the weaker ones.

Following are some key terms which need to know first in order to understand the GA.

Search Space - All possible solutions to the problem

Individual - Any possible solution

Chromosome - Blueprint for an individual

Genome - Collection of all chromosomes for an individual

Population - Group of all individuals

Allele - Possible settings for a trait

Trait - Possible aspect of an individual

Locus - The position of a gene on the chromosome

A population of randomly generated individuals usually starts evolution. Evolution is an iterative process and in each iteration the population generated is called generation. In each iteration, the fitness is evaluated for every individual in the population. Fitness is nothing but the value of objective function in the optimization problem being solved. Individuals giving more better fitness are selected from the current population and genome of each individual is modified to generate the new population. Similar procedure perform with the new generation of candidate solutions in the next iterations until the algorithm terminates. The algorithm terminates when either a satisfactory fitness level has been achieved or a maximum number of generations has been produced.

To perform the above stated algorithm, GA repetitively applies following three operators on the initialized population.

1. Reproduction

2. Crossover

3. Mutation

Reproduction : During each successive iteration, a proportion of the current population is selected to reproduce a new generation. Based on the fitness (as measured by a fitness function),

individual solutions are selected. These individual solutions needs to be fittest as they have to carry out reproduction which would result in inherit of important and relevant information by the successive generations.
Crossover : It is also called recombination. From the existing population, a pair of individuals, called *parent solutions*, are selected for breeding. These parent solutions produce the new solutions called child solutions which typically inherit many of the characteristics of its "parents".
Mutation : This behaves as a secondary operator. The purpose of this operator is to maintain diversity within the population. Random changes in the elements of individuals introduces diversity in the solutions which helps to explore the new regions of solution space.

Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) technique [47] is a metaheuristic technique developed by Dr. Eberhart and Dr. Kennedy for optimization of problem. PSO shares many similarities with genetic algorithms. However, PSO has no evolution operators like crossover and mutation which are used in GA. PSO technique is a robust stochastic optimization technique which takes its inspiration by collective movement and intelligence of a swarm of bees, a school of fish, or a flock of bird. Consider the following scenario: a group of birds roaming over an area in the search of food and there is only one piece of food in the area being searched. The birds do not know the exact location of food but they know the distance of food in each iteration. So what's the best scheme to find the food? The scheme followed by birds is in such a way as one who is nearest to the food tweets the loudest and the other birds chase that one. If any of the other birds comes nearer to the food than the first, it tweets louder and the others changes their direction toward him. Hence, the best way to find the food is to chase the bird nearest to the food. This tightening scheme continues until one of the birds reaches to the food.

PSO learned from the scenario and mimics the behaviour of bird flocking to solve the optimization problems. In PSO, each single solution is associated with a "bird" in the search space. We call it "particle". The objective is defined by a fitness function which is evaluated for each position of particles. The evaluated values of fitness function corresponding to each particle is called fitness values. The particles in the search space learned from two sources, one is from it's own experience which is known as cognitive learning and the other is from the combined learning of the whole swarm which is known as social learning. Cognitive learning is denoted by personal best (pBest) and social learning is denoted by the global best (gBest) value. The pBest value is the particle's individual best position it has ever achieved in its history. The gBest value is the best position ever achieved by any particle in the swarm. The particles fly through the search space by following the current best particle. Therefore, the value of parameter gBest guides the swarm. Cognitive and social learning together used to calculate the velocity of particles. These velocities of randomly moving particles decides the direction of the particles. Therefore, each particle of the swarm follow very simple rules of communicating and cooperating with other particles of the swarm. When all the iterations get completed, the result so obtained is the optimal solution of problem under consideration.

Characteristics of PSO

• For the problem being optimized, PSO makes few or no assumptions, therefore, it is a meta-heuristic technique.

• PSO does not require the problem being optimized to be differentiable as it does not use the gradient for optimization like other gradient based techniques.

• PSO is faster, cheaper and require few parameters to adjust.

Binary PSO (BPSO)

This is binary version of PSO developed by Kennedy and Eberhart in 1997 [48] which can handle discrete binary variables.

Application of BPSO to solve a complex PMU placement problem can be summarised briefly in the steps given below:

Step 1 : A random population of particles is initialized, which is a matrix of dimension $(n \times m)$. Where n is the number of particles and m is the number of buses. Each element in the initialized population is either 0 or 1.

Step 2 : With the help of objective function, defined the expression of fitness function as below:

$$F = w_1 P_1 + w_2 P_2 \tag{3.7}$$

$$Subject\ \ to \qquad CS^T \geqslant U \tag{3.8}$$

Every symbol used in above expression have same meaning discussed in previous section.

The bus observability constraints, given by equation (3.7), is included in the fitness function using penalty method and thus the problem is transformed into an unconstrained optimization

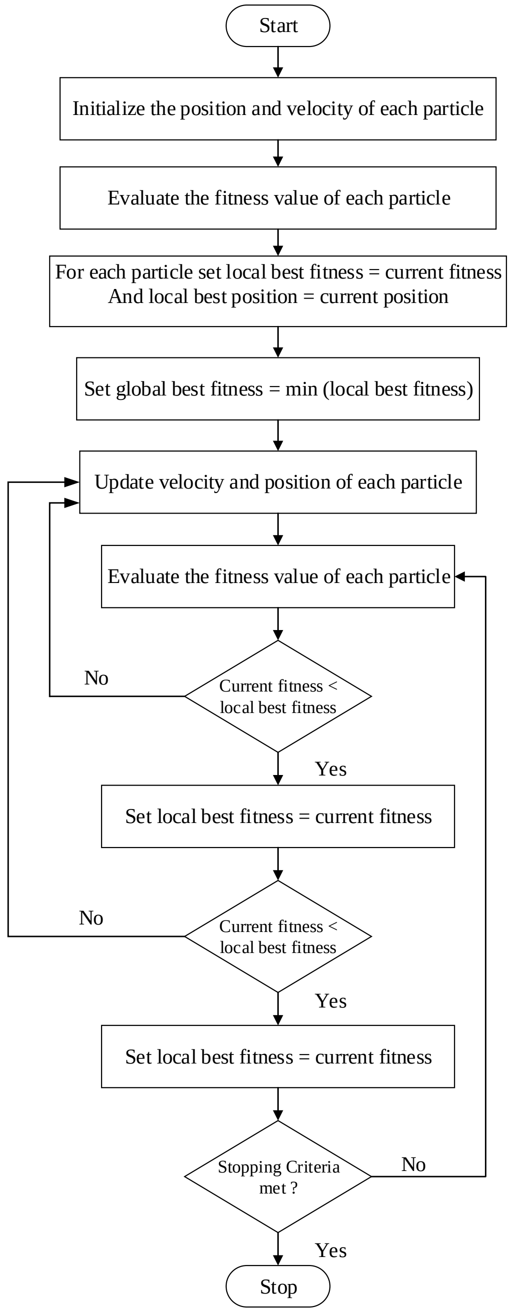

Figure 3.2: Flowchart of BPSO

problem. Therefore, the fitness function expressed by equation (3.7) becomes:

$$F = w_1 P_1 + w_2 P_2 + P_3 \tag{3.9}$$

Step 3 : For each particle, the value of fitness function is evaluated which represents the local best values (lbest) and the position of particles represents the local best positions. The best among the local best values represents the global best value (gbest) the position of particle represents the global best position.

Step 4 : Start the iteration count and the positions and velocities of the particles get updated as below:

$$S_i(t) = S_i(t-1) + V_i(t) \tag{3.10}$$

where $S_i(t)$ and $S_i(t-1)$ are the position vectors of the ith particle at the instant t and $t-1$ respectively, and $V_i(t)$ is the velocity vector of the particle.

The velocity of the particle is updated by using the experience of its own, as well as the experience of the other particles in its neighbourhood. Hence, velocity is updated as below:

$$V_i(t) = V_i(t-1) + C_1R_1(lbest_i - S_i(t-1)) + C_2R_2(gbest_i - S_i(t-1)) \tag{3.11}$$

where C_1 and C_2 are adjustable parameters called individual and social acceleration constant respectively; R_1 and R_2 are random numbers in the range [0, 1].

Step 5 : Set the velocities as follows:

$$V(i) = \begin{cases} V_{max} & \text{if } V_i > V_{max} \\ V_{min} & \text{if } V_i < V_{min} \end{cases}$$

Step 6 : The value of fitness function is evaluated for each particle's updated position and comparison is made between the new obtained fitness values and the old ones. Now the more suitable values obtained after comparison is set as lbest and the best of lbest is set as gbest.

Step 7 : If iteration count is reached maximum, then go to next step. Otherwise go to Step 4.

Step 8 : Particle position obtained corresponding to the final value of gbest represents the optimal location of PMUs.

The flow chart of the BPSO algorithm is shown in Fig.3.2.

Applications of PSO

The following are the major fields in which PSO is applied:

• Economic dispatch and unit commitment problems.

• Optimization of reactive power flow in the power system so that the real power losses in the system can be minimized.

• Optimal power flow (OPF) problem.

• In the design of power system controller.

• In different areas of sensor networks which includes optimization and control [49], localization of wireless sensor networks [50], network coverage, and clustering of nodes.

Chapter 4

Identification of Harmonic Sources

4.1 Overview

In order to determine the effective influence of harmonics on the power system, it is essential to find out the location of harmonics first. Also one can not suppress the harmonics without knowing its location. Therefore, determination of location of harmonic sources is a crucial part of harmonic studies. Based on number of measurements, the methods to determine the harmonic sources is classified into two groups:

• Single point measurement methods i.e methods based on measurement at PCC only.

• Multiple point measurement methods.

Taking into account the criterion used for localization of harmonic sources, the methods in first group can be further classified based on [51]:

• the Current Criterion (utilization of direction of a harmonic current).

• the Critical Impedance Criterion (utilization of so-called 'Critical Impedance' [9]).

• the Active Power Direction Criterion (utilization of direction of an harmonic active power flow).

• the Source Criterion (utilization of parameters of the equivalent harmonic sources).

The method based on current criterion is suitable for finding the location of harmonic sources when there is only one source present. In case of multiple sources the method gives erroneous results. The critical impedance criterion is suitable for finding the dominating harmonic sources location by comparing the critical impedance with the total impedance of customer and utility. This criterion gives less erroneous results as compared to the previous one. Source criterion theoretically seems effective but is not easy to utilize and implement. Therefore, a method based on direction of active and reactive harmonic power flow combined with the nature of reactive part of impedance is implemented to determine the location of harmonic sources.

4.2 Methodology for Harmonic Sources Identification

4.2.1 Assumptions

Following assumptions are taken into account while implementing the methodology:

1. A balanced network is considered. Hence, study of any one phase will give the knowledge of all other phases.
2. In the analysis, the load side and utility side is not separated.
3. Value of line capacitance is very small in case of distribution system. Therefore, line capacitance is not considered.
4. Line is modelled as lumped $R-L$ series circuit and load as a series $R-L$ load.
5. The value of impedance of all the lines are known at any harmonic frequency.
6. Harmonic voltage phasor values are known for all the buses.

4.2.2 System modelling and formulations

The modelling of all the power system components have done in the same manner as explained in chapter 2. Non linear loads are modelled as constant current sources. Current injections by each non linear load needs to represented for a specific frequency spectrum. Under non-sinusoidal condition the system can be represented by following linear equation:

$$V_h = Z_h I_h \tag{4.1}$$

where h is the order of the harmonic, V_h is the bus voltage vector, I_h represents the harmonic current injection into system, Z_h is the h^{th} order system impedance matrix. With the help of available data of power system line parameters, loads data and harmonic current injection data by PMUs, the harmonic voltage at all the buses can be determined easily.

Suppose a single harmonic source is injecting I_L magnitude of current at i^{th} bus of an n bus system, then, the harmonic voltage vector can be expressed as:

$$\begin{bmatrix} V_1 \\ . \\ . \\ . \\ V_i \\ . \\ . \\ . \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & . & . & . & Z_{1n} \\ . & . & & & & \\ . & . & & & & \\ . & . & & & & \\ Z_{i1} & Z_{i2} & . & . & . & Z_{in} \\ . & . & & & & \\ . & . & & & & \\ . & . & & & & \\ Z_{n1} & Z_{n2} & . & . & . & Z_{nn} \end{bmatrix} \cdot \begin{bmatrix} . \\ . \\ . \\ . \\ I_L \\ . \\ . \\ . \\ . \end{bmatrix}$$

where, diagonal elements of the bus impedance matrix represents the driving point impedances while off diagonal elements represents the transfer impedances between buses.
Since the harmonic voltage at any bus is influenced by all the harmonic sources present in the system, the total harmonic voltage at any bus will be the sum of harmonic voltage produce by all sources at that bus.

Suppose that there are $'k'$ number of harmonic sources are present in the system then, the total harmonic voltage at a bus i can be expressed as:

$$V_i^h = \sum_k Z_{k,i}^h I_k^h \tag{4.2}$$

The six and twelve pulse converters are the main sources of harmonics in the system which injects harmonics of order $(6c \pm 1)$ and $(12c \pm 1)$ respectively, where n is an integer, into the system. Thus, in the analysis, even order harmonics are not taken into account. Moreover, triplen harmonics are not considered for three-phase three-wire system. As the magnitude of injected harmonics decreases with increase in its order, greater contribution of harmonics in the system is by lower order harmonics such as 5^{th}, 7^{th}, 11^{th}, and 13^{th}only. Therefore, identification of only lower order harmonic sources will accomplish the task of identification of non linear loads.

Suppose that there is only one harmonic source present in the system which is connected to k^{th} bus. The complex harmonic power injection by this source into the system at h^{th} harmonic frequency will be given by:

$$S_k^h = V_k^h \times (I_k^h)^* \tag{4.3}$$

From equations (4.2) and (4.3), complex harmonic power injection can be expressed as:

$$S_k^h = Z_{k,k}^h \times \mid I_k^h \mid^2 \tag{4.4}$$

From complex harmonic power injection, real and imaginary harmonic power injections can be obtained as

$$P_k^h = Re(Z_{k,k}^h) \times \mid I_k^h \mid^2 \tag{4.5}$$

$$Q_k^h = Im(Z_{k,k}^h) \times \mid I_k^h \mid^2 \tag{4.6}$$

Bus impedance matrix is always a square matrix having dimension $n \times n$, where n is number of buses. The diagonal element$Z_{k,k}^h$ represents the driving point impedance of k^{th} bus. For any network, the real part of $Z_{k,k}^h$ will always be positive which state that the active harmonic power injection into the system by a non linear load will always be positive, until unless no other dominating non linear load is present in the system. In the presence of other dominating non linear loads, it may be possible that the sign of active harmonic power injection get altered at some buses which would result in wrong identification of buses. Reactive part of $Z_{k,k}^h$ can have any sign either positive or negative, depending on the magnitude, nature and location of loads, magnitude and location of reactive power support, values of line parameters, connection and phase shifting type of transformer, tap settings etc. Therefore, by just looking at the sign of reactive part of $Z_{k,k}^h$, it can be determined that whether the injected reactive harmonic power is positive or negative, until unless no other dominating non linear load is present in the system. Again, in the presence of other dominating non linear loads, the sign of reactive harmonic power may get reversed. The bus impedance matrix of the system can be formed either by Z-bus building algorithm or by using admittance matrix of system at any harmonic frequency. However its exactness can not be ensured because of uncertainty in load modelling at higher frequencies. Thus, elements of calculated impedance matrix Z^h may differ from actual impedance matrix Z^h. Once the harmonic voltage is obtained at all the buses by (4.2), the harmonic current flow on any line can be determined with the help of line parameters as:

$$I_{k,l} = \frac{V_k - V_l}{Z_{k,l}} \tag{4.7}$$

where $I_{k,l}$ is the harmonic current flow on line between bus k and l. V_k and V_l are harmonic voltages at bus k and l respectively. $Z_{k,l}$ is impedance of line between bus k and l.

The magnitude of harmonic current flow on the system lines can be more than the harmonic current injected by the non linear load at any frequency. At lower order harmonics, the magnitude of current flow is depends on the input impedance at the non linear load for that frequency. If the magnitude of this input impedance become very high at any particular frequency, then large harmonic voltage may appear on some components of system which will result in flow of large harmonic current through them. Also, in case of line reaches a resonant frequency, the injected harmonic currents by the non linear loads gets amplified to a large value.

In harmonic analysis, non linear loads are treated as harmonic current sources while the shunt components like linear loads and capacitors are expressed as injection currents. For example, if a linear load having impedance Z_i^h at harmonic frequency h is connected at i^{th} bus, its equivalent injection current can be expressed as

$$Ih_i^h = \frac{V_i^h}{Z_i^h} \tag{4.8}$$

Similarly, if a capacitor having capacitive reactance X_i^h at h^{th} harmonic frequency is connected at bus i, then, the harmonic current absorbed by it can be expressed as

$$IC_i^h = \frac{V_i^h}{X_i^h} \tag{4.9}$$

Therefore, it can be concluded that the harmonic currents by non linear loads and linear impedances along with absorption by shunt capacitors contributes to total system harmonic current. Hence, the total harmonic current flowing out of the i^{th} bus into the system at h^{th} harmonic frequency

Table 4.1: Categorization of buses

Bus Category	Probability of harmonic source
Category-A	Very High
Category-B	Moderate
Category-C	Low
Category-D	Very Low

can be expressed as

$$I_i^h = \sum_{l \in e} (V_i^h - V_l^h) \times y_{i,l}^h \tag{4.10}$$

where e represents set of branches connected to i^{th} bus. V_i^h is the harmonic voltage at i^{th} bus at h^{th} harmonic frequency. $y_{i,l}^h$ is the admittance of line between i^{th} and l^{th} buses at h^{th} harmonic frequency.
After determining the harmonic current injection and harmonic voltages at buses, the complex harmonic power injection S_i^h at h^{th} order can be determined using (6). And by separating the real and imaginary components of S_i^h, the active and reactive harmonic power injection of h^{th} order frequency can be expressed as

$$P_i^h = Re(V_i^h \times (I_i^h)^*) \tag{4.11}$$

$$Q_i^h = Im(V_i^h \times (I_i^h)) \tag{4.12}$$

Assign a category to each bus, as listed in Table 4.1, depending on the signs of P_i^h, Q_i^h, $\text{Im}(y_{i,0}^h)$ and $\text{Im}(Z_i^h)$. This categorization will depict whether the bus is linear or non linear one. $y_{i,0}^h$ is the admittance connected between the ground and i^{th} bus. The flow chart for categorization of buses is shown in Fig. 4.1.

4.3 Harmonic Source Locations and Injection Levels

Following the flow chart shown above, categorization of each bus can be done [52]. Sign of real harmonic power injection, reactive harmonic power injection along with sign of $\text{Im}(Z_{i,i}^h)$ and

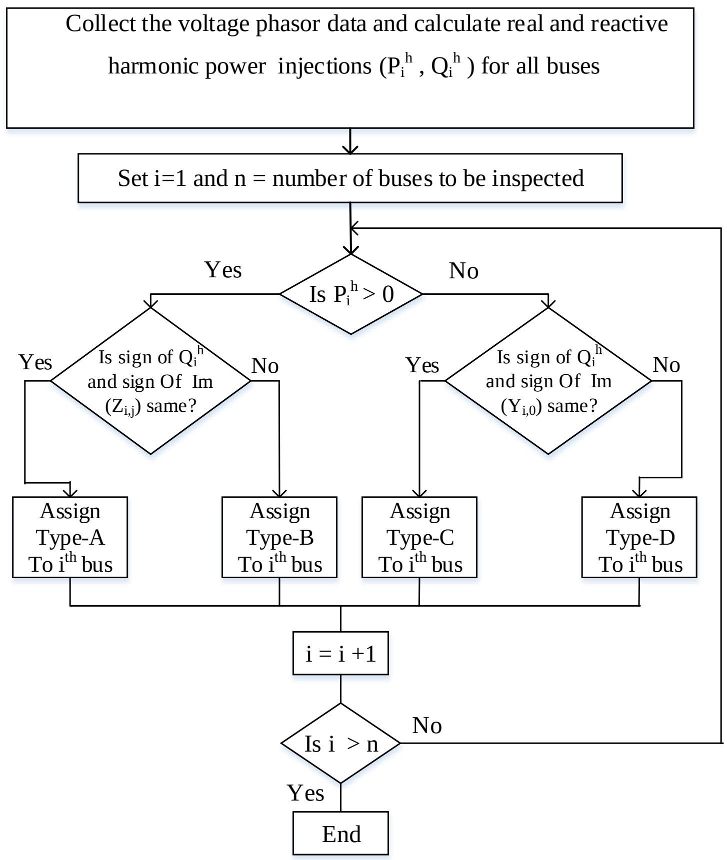

Figure 4.1: Flow chart for bus categorization

$\text{Im}(y_{i,0}^h)$ are deciding factors for bus categorization.

Buses consisting of large number of harmonic sources will come under type A category. However it may be possible that a bus with lot of harmonic sources may come under a category other than type A because of error in phasor measurements by PMUs, dominance of other harmonic sources or error in Z-bus formation. By categorization of buses it becomes convenient to observe for location of non linear loads on a large power system because it leads the observation restricted to limited areas on a large network. But the method is not full fledged as it may give erroneous results sometimes which may result in loss of time and effort. Therefore, in order to be more precise about the location of harmonic sources, a unique index called *localization index* is defined for each bus. The greater the value of localization index for a particular bus, greater will be the possibility of non linear loads at it.

The localization index of the i^{th} bus at h^{th} harmonic frequency is mathematically defined as

$$L_i^h = | I_i^h + V_i^h \times y_{i,0}^h + IC_i^h | \tag{4.13}$$

where I_i^h is the total harmonic current flowing out of the i^{th} bus into the system at h^{th} harmonic frequency, IC_i^h is the h^{th} order harmonic current absorbed by the capacitor at i^{th} bus and the multiplying component $(V_i^h \times y_{i,0}^h)$ represents the harmonic current absorbed by shunt admittance at i^{th} bus. Ideally, when there will be no any non linear load present in the system, the harmonic generation term I_i^h will be nullify by the harmonic absorption term $(V_i^h \times y_{i,0}^h + IC_i^h)$, resulting in localization index being zero. Therefore, the localization index, apart from identifying the harmonic sources location, also gives the information regarding harmonic injection levels at respective locations. However, because of error in measurements, exact value of harmonic injection level can not be ensured.

Chapter 5

Results and Discussion

5.1 Optimal Location of PMUs

In this work, genetic algorithm (GA) and binary particle swarm optimization (BPSO) algorithm as described in section 3.2.2 is proposed for solving optimal PMU placement problem and optimizing the total number of PMU and measurement redundancy of the system. The formulation of objective function along with the constraints considered have been mentioned in detail in section 3.2.1. The optimization algorithms has been tested on 18-bus and 69-bus radial distribution systems. The randomization parameters required for the implementation of genetic algorithm and BPSO are shown in Table 5.1 and Table 5.2 respectively.

Table 5.1: Genetic algorithm parameters

Parameter	Optimal value
Number of chromosomes	100
Number of iterations	1000
Crossover probability	0.5
Mutation probability	0.1
weight w_1	0.9
weight w_2	0.01

5.1.1 Case 1: 18-bus system

The single line diagram of 18-bus radial distribution system, with location of non linear loads are shown in Fig. 5.1. All buses are of PQ type except first one which is slack bus. All buses

Table 5.2: BPSO parameters

Parameter	Optimal value
Number of particles	5*N_{bus}
Number of iterations	1000
acceleration constants ($\phi_1 = \phi_2$)	2
weight w_1	1
weight w_2	0.01
Measurement redundancy D	4

except 1 and 2 are at 12.5 KV and system base MVA is 10 MVA. Bus data and line data are given in appendix.

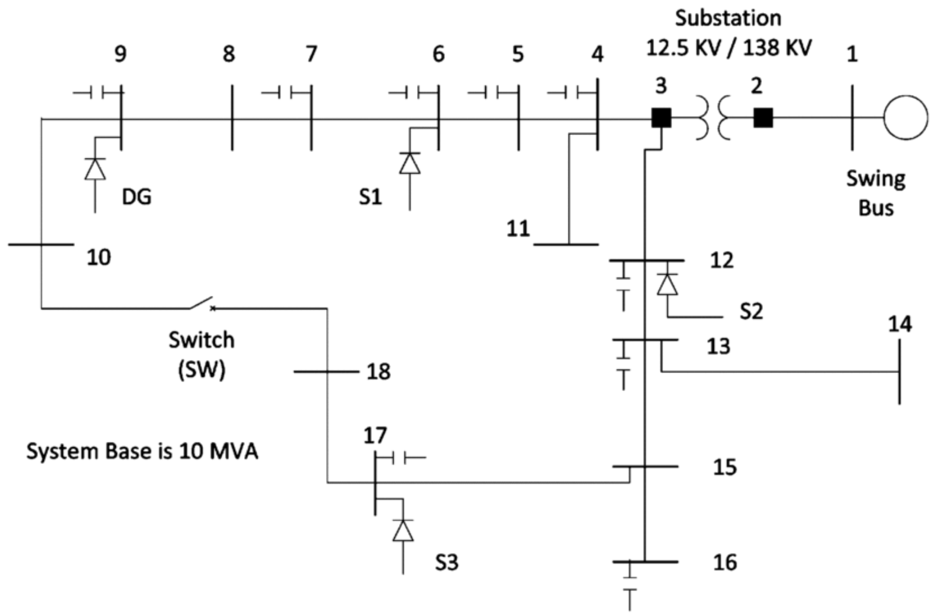

Figure 5.1: 18-bus radial distribution system

For this test system, the result of optimization of total number of PMUs for complete system observability using genetic algorithm and BPSO has been shown in Table 5.3. Now, in the shown table, there are altogether five columns. Explanation of second and third column are mentioned below the table. The last column represent the time taken by each method. In this work, the size of chromosomes taken is equal to the number of buses and the size of population is hundred in each generation of GA. From the results shown in Table 5.3, it is observed that the number of devices to be placed comes more with index method while it is same with GA and BPSO. The optimal location for PMUs placement are also same by GA and BPSO while index method shows all those bus locations obtained by other two algorithm with additional two bus locations. Therefore for optimal placement of PMUs, metaheuristic algorithms are more efficient as compared to the index method. Moreover, it can be observed that the computational time taken by BPSO is least as compared to GA. Therefore, though the both metaheuristic algorithm give the same locations but BPSO is computationally more efficient.

Table 5.3: OPP for 18-bus system

Method	N	LB	Iteration	Time (s)
Index method	8	2,4,6,7,9,13,15,17	1	0.04
Genetic algorithm	7	2,4,6,9,13,15,17	1000	6.90
BPSO algorithm	7	2,4,6,9,13,15,17	1000	1.6

N - number of PMUs, LB - location of buses

5.1.2 Case 2: 69-bus system

The single line diagram of 69-bus radial distribution system is shown in Fig. 5.2. All buses are of PQ type except first one which is slack bus. The base values of the system are taken as 12.66 kV and 10 MVA. Bus data and line data are given in [53].

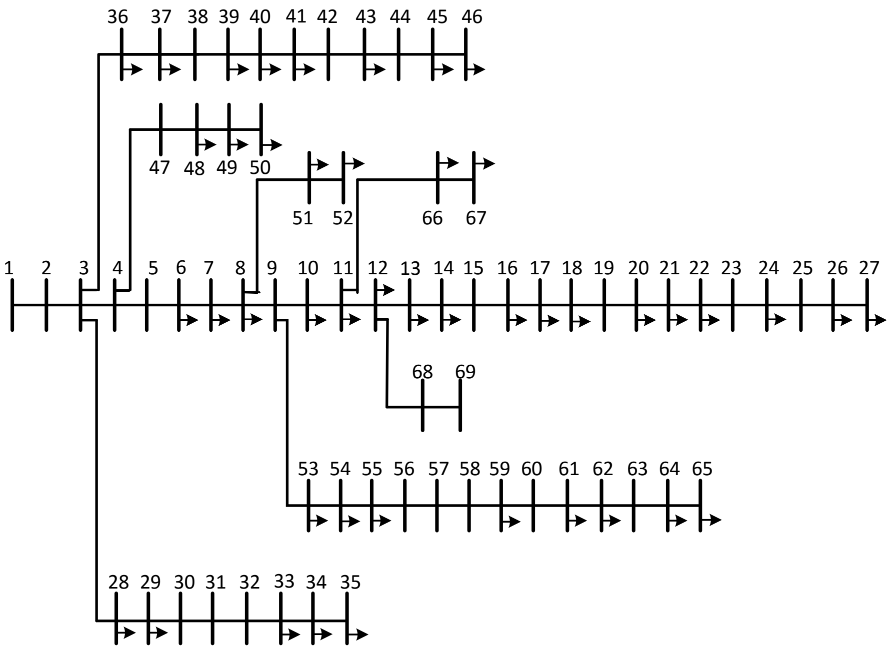

Figure 5.2: 69-bus radial distribution system

The results obtained with the different methods are shown in Table 5.4. In this case also the size of chromosomes taken is equal to the number of buses and the size of population is three hundred in each generation of GA. Here again the number of PMUs obtained by index method is more as compared to GA and BPSO algorithm. Between GA and BPSO, BPSO result in same number of PMUs and also the computational time taken by BPSO is less as compared to GA. Therefore, for any power system, BPSO is more efficient as compared to GA algorithm.

Table 5.4: OPP for 69-bus system

Method	N	LB	Iteration	Time (s)
Index method	26	2,3,4,9,10,13,15,17,20,22,26, 29,31,34,36,38,40,43,45, 49,51,53,57,64,66,68	1	0.2
Genetic algorithm	23	2,6,9,13,16,18,21,25,27, 30,33,37,40,43,45,47, 50,54,57,61,64,66,68	1000	27.87
BPSO algorithm	23	2,5,7,11,13,15,17,20,22,25, 27,29,32,34,38,42,45, 48,51,54,56,60,64	1000	10.06

N - number of PMUs, LB - location of buses

5.2 Identification of Harmonic Sources

After optimal placement of PMUs, a harmonic state estimation technique is implemented for identifying the location of harmonic sources. The detail of the technique is presented in section 4.2. As the technique may give wrong location of harmonic sources in the presence of other dominating harmonic sources, therefore, a index called *localization index* is introduced which determines the location of harmonic sources along with their injection levels.

5.2.1 Case 1: 18-bus system

For the same system considered in section 5.1.1, location of non linear loads are determined using harmonic state estimation technique. The harmonic injection has been made at four buses (shown in Table 5.5) to create harmonic voltage distortions at different buses of the system.

In practice, we would neither be having the data on the locations of non linear loads nor the harmonic current source data, but we will have measurement of harmonic voltage data across the network. That's why, during the identification of harmonic source location, we have only used the harmonic voltage data (obtained from equation 4.2) which can be measured in reality.

Simulation results are shown in Table 5.6 and Table 5.7. Since no loads are connected at buses 1, 2 and 3, they are not considered in the results. Following the flow chart shown in Fig. 4.1, a category to each bus is assigned which is shown in Table 5.6. Categorization of buses,

Table 5.5: Harmonic current injection for 18-bus system

Bus No.	Harmonic current injection (in p.u)			
	5^{th}	7^{th}	11^{th}	13^{th}
5	0.0135+j0.0063	0.0092+j0.0065	0.0037+j0.0056	0.0023+j0.0051
9	0.0090+j0.0042	0.0061+j0.0043	0.0025+j0.0037	0.0015+j0.0034
13	0.0045+j0.0021	0.0031+j0.0022	0.0013+j0.0019	0.0008+j0.0017
17	0.0018+j0.0008	0.0012+j0.0008	0.0005+j0.0007	0.0003+j0.0006

based on the values of localization index, is also done which is shown in Table 5.7.

Table 5.6: Harmonic power injection for 18-bus system

Bus No.	$P_i^5 * 10^4(pu)$	$Q_i^5 * 10^3(inpu)$	Bus Category
4	-0.0053	0.0248	C
5	-0.0046	0.0217	C
6	0.1526	-0.1046	A
7	-0.0045	0.0211	C
8	-0.0045	-0.0017	C
9	0.0203	0.0042	A
10	-0.0045	-0.0017	C
11	-0.0053	-0.0020	C
12	0.0389	-0.0743	A
13	-0.0091	0.0659	C
14	-0.0090	-0.0034	C
15	-0.0120	-0.0045	C
16	-0.0142	0.1024	C
17	-0.0424	0.0174	B
18	-0.0123	-0.0046	C

5.2.2 Case 2: 69-bus system

For the same system considered in section 5.1.2, location of non linear loads are determined using harmonic state estimation technique. The harmonic injection has been made at fourteen buses (shown in Table 5.8) to create harmonic voltage distortions at different buses of the system.

Simulation results are shown in Table 5.9 and Table 5.10. Since no loads are connected at buses 1, 2 and 3, they are not considered in the results.
Following inferences can be drawn from the result.

1. The real harmonic power injections are positive at non linear buses if any other dominant non linear source is not present. Type-B category occurs due to these dominant sources.

Table 5.7: Localization index based bus ranking

Bus No.	Bus Category	Localization Index	Bus No.	Bus Category	Localization Index
4	C	0.0053	12	A	0.0040
5	C	0.0049	13	D	0.0106
6	A	0.0103	14	D	0.0006
7	C	0.0048	15	D	0.0007
8	D	0.0004	16	D	0.0132
9	D	0.0029	17	B	0.0074
10	D	0.0004	18	D	0.0007
11	D	0.0004			

2. All the linear buses comes under Type-D category.
3. Localization index gives clear information about harmonic injection level at non linear buses.
4. Ideally, localization index should be zero for linear buses but due to load modelling error it has a very small value for buses with linear loads.

Table 5.8: Harmonic current injection for 69-bus system

Bus No.	Harmonic current injection (in p.u)			
	5^{th}	7^{th}	11^{th}	13^{th}
7	0.0145+j0.0073	0.0072+j0.0015	0.0033+j0.0051	0.0019+j0.0044
13	0.0090+j0.0042	0.0056+j0.0041	0.0027+j0.0034	0.0011+j0.0031
17	0.0045+j0.0021	0.0036+j0.0026	0.0019+j0.0015	0.0010+j0.0019
22	0.0018+j0.0008	0.0022+j0.0010	0.0009+j0.0007	0.0012+j0.0009
27	0.0092+j0.0065	0.0035+j0.0046	0.0025+j0.0013	0.00013+j0.0006
33	0.0037+j0.0056	0.0052+j0.0038	0.0025+j0.0017	0.0013+j0.0011
42	0.0067+j0.0043	0.0062+j0.0038	0.0035+j0.0027	0.0023+j0.0016
45	0.0112+j0.0068	0.0082+j0.0058	0.0046+j0.0031	0.0021+j0.00012
49	0.0081+j0.0022	0.0053+j0.0029	0.0045+j0.0021	0.0026+j0.0011
54	0.0055+j0.0037	0.0034+j0.0012	0.0027+j0.0013	0.0013+j0.0010
57	0.0025+j0.0034	0.0021+j0.0013	0.0015+j0.0004	0.0009+j0.0006
61	0.0020+j0.0009	0.0017+j0.0007	0.0013+j0.0004	0.0010+j0.0006
64	0.0122+j0.0078	0.0092+j0.0076	0.0075+j0.0067	0.0053+j0.0036
68	0.0039+j0.0026	0.0032+j0.0019	0.0023+j0.0013	0.0016+j0.0008

Table 5.9: Harmonic power injection for 69-bus system

Bus No.	$P_i^5 * 10^4(pu)$	$Q_i^5 * 10^3(pu)$	Bus Category	Bus No.	$P_i^5 * 10^4(pu)$	$Q_i^5 * 10^3(pu)$	Bus Category
4	0.0000	0.0000	D	37	0.0000	0.0110	C
5	-0.0004	-0.0017	D	38	-0.0107	-0.0379	D
6	-0.0091	-0.0339	C	39	-0.0118	-0.0166	C
7	0.0576	0.2053	A	40	-0.0005	0.0234	C
8	-0.0093	-0.0230	D	41	0.0000	0.1188	C
9	-0.0091	-0.0203	D	42	0.1432	0.5181	A
10	-0.0230	-0.0770	D	43	0.0000	0.0000	C
11	-0.0234	-0.0839	D	44	-0.1335	-0.4113	D
12	-0.0036	-0.0113	C	45	0.0957	0.3012	A
13	0.1071	0.2777	A	46	0.0000	0.0794	D
14	0.0000	0.0193	D	47	-.0132	-0.0472	D
15	-0.0182	-0.0475	D	48	-0.0195	-0.0677	C
16	-0.0272	-0.0792	D	49	-0.0016	0.0016	A
17	0.0031	0.0207	A	50	-0.0015	-0.0037	D
18	0.0000	0.0160	C	51	-0.0011	0.0089	C
19	-0.0005	-0.0015	D	52	-0.0012	0.0082	C
20	-0.0489	-0.1590	C	53	-0.0085	-0.0175	D
21	-0.0029	0.0029	C	54	0.0469	0.0922	A
22	0.0155	0.0485	A	55	0.0000	0.0000	C
23	-0.0178	-0.0380	D	56	0.0000	0.0117	D
24	0.0000	0.0326	C	57	0.0346	0.0431	A
25	-0.0166	-0.0115	D	58	-0.0037	-0.0122	D
26	-0.0193	-0.0133	D	59	0.0000	0.0000	D
27	0.1926	0.2855	A	60	-0.0077	-0.0272	D
28	-0.0047	-0.0167	D	61	0.0014	0.0130	A
29	0.0000	0.0000	D	62	0.0000	0.0024	D
30	0.0000	0.0000	D	63	-0.0169	-0.0590	D
31	0.0000	0.0000	D	64	0.0859	0.2265	A
32	-0.0045	-0.0162	D	65	-0.0067	-0.0111	D
33	0.0814	0.1190	A	66	-0.0027	-0.0098	D
34	-0.0025	-0.0083	C	67	-0.0043	-0.0152	C
35	-0.0082	-0.0184	C	68	-0.0356	0.0507	A
36	-0.0048	-0.0108	D	69	0.0000	0.0000	D

Table 5.10: Localization index based bus ranking

Bus No.	Bus Category	Localization Index	Bus No.	Bus Category	Localization Index
4	D	0	37	D	0.0011
5	D	0.0001	38	D	0.0011
6	D	0.0021	39	D	0.0009
7	A	0.0107	40	D	0.0021
8	D	0.0008	41	C	0.0046
9	D	0.0007	42	A	0.0115
10	C	0.0055	43	D	0.0027
11	C	0.0060	44	B	0.0072
12	D	0.0006	45	A	0.0156
13	A	0.0101	46	D	0.0013
14	D	0.0016	47	D	0.0033
15	D	0.0019	48	B	0.0092
16	D	0.0036	49	A	0.0105
17	A	0.0110	50	D	0.0005
18	D	0.0012	51	D	0.0011
19	D	0.0007	52	D	0.0011
20	B	0.0075	53	D	0.0005
21	D	0.0009	54	A	0.0157
22	B	0.0092	55	D	0.0000
23	D	0.0015	56	D	0.0006
24	D	0.0021	57	A	0.0146
25	D	0.0011	58	D	0.0019
26	D	0.0012	59	D	0.0001
27	A	0.0105	60	D	0.0016
28	D	0.0011	61	B	0.0082
29	D	0.0000	62	D	0.0006
30	D	0.0000	63	B	0.0063
31	D	0.0000	64	A	0.0113
32	D	0.0009	65	D	0.0004
33	B	0.0060	66	D	0.0004
34	D	0.0004	67	D	0.0012
35	D	0.0011	68	A	0.0126
36	D	0.0004	69	D	0.0000

Chapter 6

Conclusions and Future Scope

6.1 Conclusions

Optimal placement of phasor measurement units have been carried out using BPSO technique and genetic algorithm to observe the complete system economically. The work has been carried out for minimizing the total number of devices and simultaneously maximizing the measurement redundancy of the system. The method is described to locate the harmonic sources along with their injection level in the system. Linear and non linear buses are identified with the applied method. The effectiveness of the presented methodology is demonstrated on 18-bus and 69-bus test systems. The following conclusions are drawn from the study:

• The comparative study shows that BPSO is more efficient compared to GA algorithm and requires less computational time.

• The real power injections at non linear buses are positive for specified harmonic.

• Localization index gives information about harmonic injection level at non linear buses.

6.2 Future Scope

The scope of the further work after completion of presented work is identified as:

• Optimal placement of PMUs are done without considering other aspects like zero-injection buses, single-line outages and loss of PMUs. Further work can be extended by considering these aspects.

• In the presented work, the errors in load modelling and voltage phasor measurement are neglected. At higher frequencies, there shall be load modelling and voltage phasor measurement errors and therefore there is a scope to account these in algorithm.

List of Publications

International Conference

1. A. Dixit, "Harmonic Source Identification with Optimal Placement of PMUs," accepted and presented in *IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems*, July 2016.

International Journal

1. A. Dixit and S. K. Jain "Optimal Placement of Phasor Measurement Units for Harmonic Source Identification," communicated to *Electric Power System Research*, ISSN: 0378-7796, listed in SCI.

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Appendix-A

Table 1: Bus data of 18-bus test system

Bus No.	Linear Load P (%)	Linear Load Q (%)	Shunt Load Q (%)
1	0	0	0
2	0	0	0
3	0	0	0
4	6.18	4.63	-6.5
5	6.18	4.63	-6.5
6	6.18	4.63	-6.5
7	6.18	4.63	-6.5
8	6.18	4.63	0
9	6.18	4.63	-6.5
10	6.18	4.63	0
11	6.18	4.63	0
12	6.18	4.63	-6.5
13	6.18	4.63	-9.5
14	6.18	4.63	0
15	6.18	4.63	0
16	6.18	4.63	-9.5
17	6.18	4.63	-9.5
18	6.18	4.63	0

Table 2: Line data of 18-bus test system

Bus No.		Resistance (in pu)	Reactance (in pu)
From	To		
1	2	0.00309	0.07049
2	3	0.00429	0.01304
3	4	0.00608	0.01592
4	5	0.00320	0.00876
5	6	0.00889	0.02610
6	7	0.00297	0.00865
7	8	0.0169	0.0221
8	9	0.0411	0.03105
9	10	0.01701	0.02301
4	11	0.0289	0.03678
3	12	0.0231	0.02736
12	13	0.0490	0.07102
13	14	0.0401	0.0501
13	15	0.0293	0.03675
15	16	0.0380	0.04378
15	17	0.0231	0.0273
17	18	0.0380	0.04613

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