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Par : Mosbah LAOUAMER

Sujet

Contribution à l'utilisation des Unités de mesure du phaseur PMU pour l'amélioration du comportement dynamique du réseaux électrique

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ABBREVIATIONS

DFT: Discrete Fourier Transform

GA: Genetic Algorithm

SSA: Slaps Swarm Algorithm

GWO: Grey Wolves Optimizer

SCA: Sine Cosine Algorithm

GPS: Global Positioning System

PMU: Phasor Measurement Unit

RTDS: Real Time Digital Simulator

UTC: Coordinated Universal Time

WAMS: Wide Area Measurement System

OPP: Optimal PMU Placement

PDC: Phasor Data Concentrator

BUS: Binary Unit System

IEEE: Institute of Electrical and Electronics Engineers

SORI: system observability Redundancy Index

BOI: Bus observability Index

SCADA: Supervisory Control and Data Acquisition

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International Publications

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[3]. **Mosbah LAOUAMER**, Abdellah KOUZOU, Redha Djamel Mohammedi and Tlemcani Abdelhalime, A multi-objective genetic algorithm for optimal pmu placement in power System Algériens, International Conference on Communications and Electrical Engineering ICCEE'2018 ;17-18 December 2018,El Oued, Algeria

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[4]. **Mosbah LAOUAMER,** Imad Eddine Kaid, Nadji Hadroug, Ahmed Hafaifa, Modeling and simulation of the dual feed asynchronous machine - MADA -. The 2nd International Workshop on Signal Processing Applied to Rotating Machinery Diagnostics, SIGPROMD'2018, 29-30 April 2018, Djelfa, Algeria.

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ملخص:

تحتل وحدات قياس الطور مكانة كبيرة في عالم الكهرباء وأنظمة الطاقة حيث يتم استعمالها بشكل كبير في مراقبة نظام الطاقة وحمايته بصيفة متزامنة. وحدة قياس الطور(PMU) لديه قدرة فريدة من نوعها لتوفير قياسات الطور متزامنة للجهد والتيارات الكهربائية. هذه القدرة تميزها عن جميع أجهزة القياس الأخرى. واليوم، تجلب وحدة قياس الطور مزيدًا من الاهتمام لكل من المرافق ومؤسسات الأبحاث. حيث يبحثون عن أفضل الحلول لمشكلة تموضع هذه الاجهزة في الشبكات الكهربائية لتوفير أكبر قدر ممكن من تكلفة تنصيب هذه الأخيرة. نحن ندرس بعمق في هذه الاطروحة للوصول الى أفضل حل لمشكلة تموضع اجهزة وحدات قياس الطور على شبكات كهربائية عديدة مثل الشبكات الكهربائية القياسية المنتجة في معهد مهندسي الكهرباء والإلكترونيات(IEEE) وايضا لتقديم نتائج ناجعة وذات قيمة علمية رفيعة قمنا بتطبيق هذا العمل على شبكة كهربائية جزائرية حقيقة تحتوي على 114 ناقل للحصول على نتائج واقعية وذات مصداقية عالية وهذه الدراسة تمت باستخدام أربع طرق من الخوارزميات الحديثة. حيث تساهم هذه الاطروحة في إيجاد أفضل الحلول لتنصيب وحدات قياس الطور في نظام الطاقة الكهربائية بأقل تكلفة مادية.

Abstract

Recently, utilization of PMUs in a real time power system monitoring, protection and control has become significantly important. A phasor measurement unit (PMU) has a unique ability of providing synchronized phasor measurements of voltage and currents. This ability distinguishes it from all other metering devices. Today, PMU brings more attention to both utilities and research institutions. They are searching for the best solutions of OPP problem in electrical grids. In this thesis, we study in depth the best solution to the problem of the PMUs location applied on two networks from the IEEE and a real Algerian network 114-bus using four Meta-heuristic methods. The main contribution of the present thesis is to find the optimal placements of the PMUs in power system network to ensure the required measurements and hence the overall all control and monitoring of the power system with lowest cost.

Résumé

Récemment, l'utilisation des PMUs dans un système de surveillance, de protection et de contrôle en temps réel du réseau électrique est devenue très importante. Une unité de mesure de phaseur (PMU) a la capacité unique de fournir des mesures synchronisées de phaseur de tension et de courant. Cette capacité le distingue de tous les autres appareils de mesure. Aujourd'hui, Les PMUs attirent davantage l'attention des transporteurs d'énergie électrique et les institutions de recherche. Ils cherchent des meilleures solutions au problème de l'OPP dans les réseaux électriques. Dans cette thèse, nous étudions en profondeur la meilleure solution au problème de la localisation des PMUs appliquée sur deux réseaux de IEEE et réseau Algérien 114-bus réel en utilisant quatre méthodes méta-heuristiques. La principale contribution de la présente thèse est de trouver les emplacements optimaux des PMUs dans le réseau électrique pour assurer les mesures nécessaires et donc le contrôle et la surveillance globale du réseau électrique au moindre coût.

1.General introduction

The electric power industry has been transforming rapidly in recent years. Several renewable energy sources are getting integrated into electric power grids along with new loads and storage elements. This has increased the complexity of power systems by raising its dynamics and uncertainties. This, in turn, has caused concerns regarding the reliability and stability of power systems.

In order to address these concerns, a concept of the smart grid is in the process of constant development for some years now. State Estimation (SE) is one of the critical applications of power systems. it is also a key function in modern energy management systems (EMS). SE creates a complete and accurate database of measurements which can be used as an input for other applications of EMS. To calculate voltage phasors, conventional state estimators utilizes a set of measurements consisting of bus voltages, real-reactive power flows and injections. Until recently, the supervisory control and data acquisition (SCADA) system were the only mean to obtain these measurements. SCADA systems can gather these measurements in real-time through remote terminal units (RTUs) which are installed at substations [1].

As shown within the biggest blackout in North American history, one amongst the factors that causedthe incident was the dearth of time period information gathering throughout the incident. This prevented thenecessary steps from being taken before the incident happened, resulting in the catastrophicblackout. Fifty million individuals in eight America states and 2 Canadian provinces were affectedby the incident [90].Following that incident, the phasor measurement unit (PMU) became an interesting solutionbecause of its ability to be used as a mensuration tool which will give synchronous phasor measurements [91].

The advent of the global positioning system (GPS) has made possible the inclusion of time synchronized phasor measurements provides by phasor measurement units (PMUs) into the set of measurements.

A PMU measures voltage phasor of the bus-bar at which it is installed and current phasors of some or all branches incident to that bus depending on the number of available channels. Use of PMUs at substations can significantly improve monitoring, protection, and control of interconnected power systems [1].

As PMUs have a number of advantages over other smart measuring devices such as intelligent electronic devices (IEDs) and smart power meters, its planned installation in near future has grown

significantly. However, from an economic point of view, the high cost of PMU limits the number of installation sites [2]. In order to obtain a sufficient amount of observability of a power system, PMU installation sites are dispersed over a wide area. The data generated by these PMUs is then communicated to remotely located phasor data concentrators (PDCs) over a dedicated or a shared communication network [3].

1.2 Objectives

The main objectives of this thesis are:

1. Studying available literature review on phasor measurement units.
2. Studying available PMU placement techniques and the topologic of full observability.
3.Studying the different Meta-heuristic four resolved this problem of OPP.
4. Simulating PMU placement problem for complete and incomplete observability with MATLAB.

1.3 Thesis Outline

Chapter 1 presents a literature review on phasor measurement units. Where, the phasor measurement unit are outlined, a brief historic of the phasor measurement units is exposed and so the status of PMUs in power grid is emphasized. On the other side, this chapter discusses the wide area monitoring systems and strategies and then the communication system that completes the PMU main function and permits the transfer of the obtained measurements in real time, it is a part of.

Chapter 2 focuses mainly on presenting the PMUs placement techniques, which are known as the OPP problems (Optimized placement of PMUs). The OPP problem is formulated as optimization problem to achieve the complete system observability by placing a minimal number of PMUs as well as maximizing the measurement redundancy of the buses, simultaneously. The minimal number of PMUs and their optimal locations are selected by using any good optimization technique. In this chapter we explain techniques of optimal placement of PMUs.

Chapter 3 Focuses in giving a general literature review of the Meta-heuristic algorithms. This chapter denotes a wide-ranging outline to deterministic optimization methods and global optimization techniques (meta-heuristics). It describes a global sight on their philosophy, their implementation, their characteristics and advantages. Then the main used algorithms are presented in details such as the genetic algorithms optimization, the Gray Wolf Optimizer algorithm, sine cosine algorithm and slaps swarm algorithm.

Chapter 4 presents the application of Meta-heuristic algorithms for PMUs placement. Indeed, in this chapter we are interested in solving the problem of optimization for finding the best solution of optimal PMUs placement in power system using the four optimization algorithms explained in the second chapter. All the proposed approaches have been developed by simulation.

Finally, the thesis ends by a conclusion summarizing all accomplished tasks and provides a short overview on eventual perspectives.

CHAPTER I

LITERATURE REVIEW OF PMUs

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I.1-Introduction

The power system network is on the edge of a significant transformation due to the appearance of modern technologies which are providing many improved and new options of operation, monitoring and control of such vital systems. The PMUs are presenting a part among these technologies which are used mainly for the measurement of the main parameters of the power system which can help in analyzing the actual state of the power system. Where, the objective is to improve the decision making in real time in case of any deviation from the normal operation of the power system based on the obtained instantaneous PMU data. Indeed, this data will go through instantaneous simulations and advanced visualization tools which will help the system operators in assessing accurately the dynamic challenges of the system stability.

Up to currently, monitoring and control of power systems is conducted through the supervisory control and data acquisition (SCADA) system. The SCADA system collects the real-time measurements from the remote terminal units (RTU) placed in substations of the power system. Conventional RTU measurements include power flows, power injections, as well as voltage and line current magnitudes. The phase angle cannot be easily measured due to technical difficulties associated with the synchronization of measurements at RTUs.

Global Positioning System (GPS) helped to overcome these difficulties and led to the development of Phasor Measurement Units. Synchrophasor technology uses PMUs to measure voltage and current waveforms and calculate phasors. Each measurement is time-stamped and thus synchronized against Coordinated Universal Time (UTC) using a time source such as the GPS. PMU data is collected at 30 to 120 samples per second and sent to data concentrators and archives.

Synchrophasor applications have among the most stringent precision time and time interval requirements of all timing uses on the electric power system, due to high-frequency reporting, phasor precision needs, and the wide geographic distribution of PMUs.

In this section, a brief history of PMUs is given therefore the importance of PMUs in power systems is highlighted, the chapter place along discusses the evolution PMUs Technology and PMU Equipped System compared to SCADA Equipped System. finally, we find detailed illustration of PMU application and application in Worldwide

I.2- Historical Overview of Evolution PMUs Technology

Historically, electric grid planners and operators had limited information for understanding the status and behavior of the electric grid. Available information included measurements from supervisory control and data acquisition (SCADA) systems, typically available at several-second intervals from substations, and model data based on equipment ratings and specifications. The physical state variables of the a.c. network – specifically, the complex voltages, or time-shifted voltage waveforms at every node – were not directly observable, but could be estimated through these models. This solution worked well enough for many years. But given the growing uncertainties and complexities in grid planning and operations, these methods are increasingly becoming inadequate in time resolution, precision, accuracy and scope [4,5].

Planners and operators must first move the power system recognize the need for new tools that rely on advanced sensors and more comprehensive monitoring to better observe, understand and manage the grid. The challenge in transmission systems was comparing measurements across long distances (hundreds of miles) that would reveal physical interactions such as oscillations between generators, and be able to describe power flows and stability across an entire synchronous a.c. network. By comparison, distribution systems were simple and posed little need to observe their operation with much granularity in space or time [5].

A high-value grid monitoring system will possess several characteristics:

• A high degree of time granularity, on the order of a sample per cycle, compared to current SCADA and EMS, which provide samples every few seconds.

• Fast communications access for real-time streaming of data for system recovery following disturbances.

• High-resolution data for off-line engineering analysis, and preferably in near real-time to enable operation support analytics.

• Deployment of a large number of measurement devices across the system, which implies both low-cost devices and easy installation.

• Precise time synchronization of measured data to enable comparison across many electrical locations on the grid.

• Data quality, availability and volume that are appropriate to serve the high-priority uses and monitoring needs of operational and planning tools.

In three papers s [1,2,3], in early 1980 the focus was on research and development of measurement devices – PMUs and PDCs.

During the same period, the focus moved to utilization of phasors for wide-area monitoring, in the Western Interconnection, especially with the 1996 blackout, During the 90's, the focus shifted to data networking and addressing the technology issues associated with utilizing multiple PMUs and PDCs.

The first prototypes of the modern "phasor measurement units" (PMUs) using GPS were built at Virginia Tech in early 1980s, and two of these prototypes are shown in Figure 01. The prototype PMU units built at Virginia Tech were deployed at a few substations of the Bonneville Power Administration, the American Electric Power Service Corporation, and the

New York Power Authority. The first commercial manufacture of PMUs with Virginia Tech collaboration was started by Macro dyne in 1991 [7], In 1995 PMU technology prompted the development of a standard to define the use of phasor measurement technology in power system applications. The standard has been revised and is technically referred to by its trademark IEEE Standard C37.118 [8].

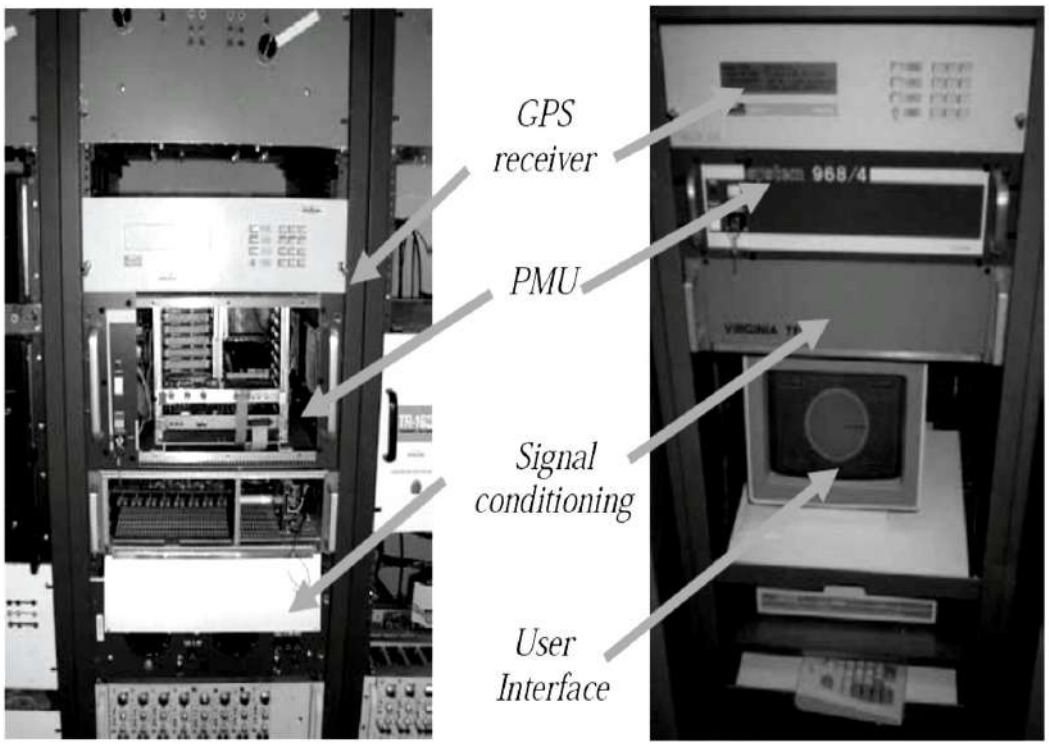


Figure I.1 The first phasor measurement units (PMUs).

Synchrophasor technology, using phasor measurement units (PMUs) offers all of the above characteristics. An individual PMU measures grid conditions at high speeds at a specific location and

gives each measurement a precise time-stamp; a network of PMUs sharing data through a phasor data concentrator (PDC) or other aggregating platform enables the calculation of time-synchronized voltage and/or current magnitudes and phase angles (known as synchrophasors).

Synchrophasors are currently being used by utilities around the world for system model validation, situational awareness, stability analysis, islanding detection, disturbance analysis, and wide-area measurement and control. PMU technology has become cheaper over the years. Therefore, many modern power system utilities around the world is planning or in the process of installing wide-area measurement systems (WAMS)strengthened by a backbone of PMU devices. The device must provide real-time data outputs that meet the requirements of IEEE C37.118 [5] and other new versions We will address them in detail in the appendix.

I.3. Definition of Synchrophasor, Frequency And ROCOF

I.3.1-Synchrophasor Definition

Phasor is an important concept in Electrical Engineering that represents a sinusoidal signal represented by the quantity of its magnitude and phase with respect to a reference. In the figure of sinusoidal waveform as depicted in Figures 02 and 03,[8] the distance between the sinusoidal peak of signal and the time reference (E.g. time = 0) is defined as a phase angle and it is transferred to an angular measurement in the phasor representation

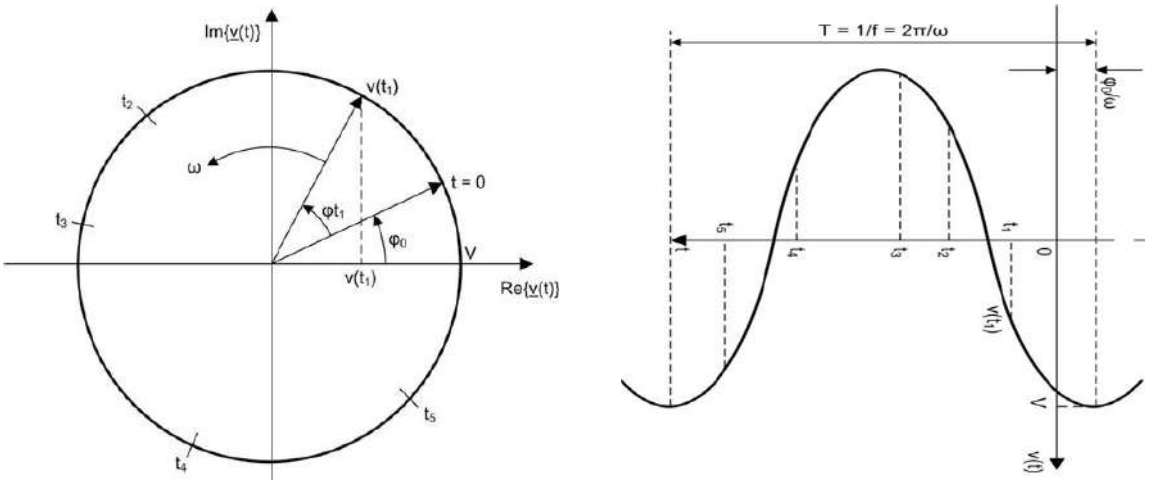


Figure I.2 Geometric Representation of a Phasor

A sinusoidal signal can be defined by the following formula:

$$x(t) = X_m * \cos(2\pi f t + \varphi) \quad \text{(I.1)}$$

where X_m is the amplitude and f is the frequency. Such signal is commonly represented as the complex phasor:

$$X = \frac{X_m}{\sqrt{2}} e^{j\varphi} = \frac{X_m}{\sqrt{2}} * (\cos\varphi + j \sin\varphi) = X_r + j X_i \quad \text{(I.2)}$$

where the magnitude is the root-mean-square (rms) value, $\frac{X_m}{\sqrt{2}}$, and the X_r and X_i are the real and imaginary parts of the complex value (its rectangular components). The value of phase angle φ depends on the time reference. Particularly, when t = 0 is assumed, for the standard the synchrophasor can be defined as:

The synchrophasor representation of the signal x(t) in Equation (I.1) is the value Xin Equation (3.2) where ϕ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to UTC.

Figure 03 shows the convention for the synchrophasor representation: the cosine functions X_{1m}has a maximum at t = 0, so the synchrophasor angle is 0 degrees when the maximum of X_{1m}occurs at the UTC second rollover (1 PPS time signal). Instead, the synchrophasor angle of the sine X_{2m}function is –90° degrees when the positive zero crossing occurs at the UTC second rollover.

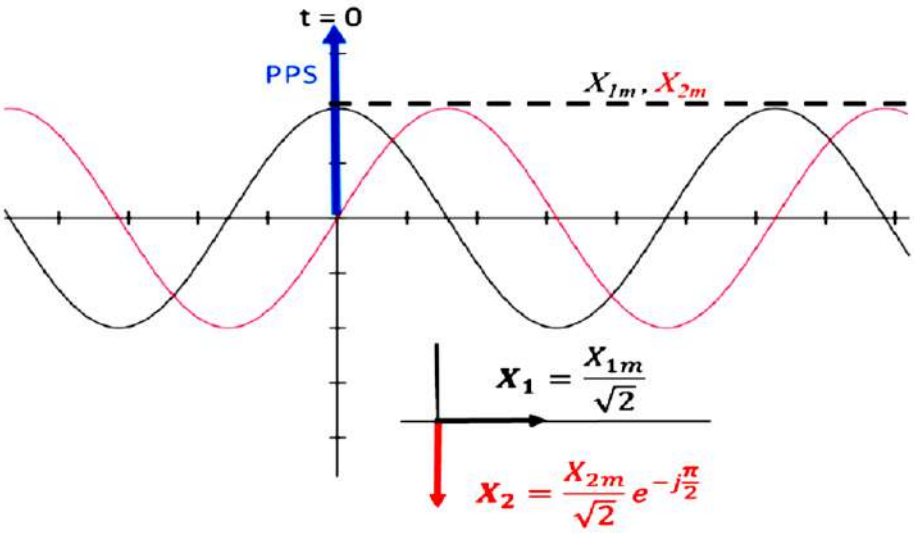


Figure I.3 Convention for synchrophasor representation.

PPS: is a pulse train of positive pulses at a rate of one pulse per second (1 PPS). The rising edge of the pulses coincides with the seconds change in the clock and provides a very accurate time reference.

In the case where the frequency *f(t)* is a function of time, it is possible to define the function $g(t) = f(t) - f_0$ where f_0 is the nominal frequency and *g(t)* is the instantaneous frequency deviation from the nominal.

The waveform representation becomes as follows:

$$x(t) = X_m(t) * cos(2\pi * \int f(t)dt + \varphi) \ = X_m(t) * cos(2\pi f_0 t + (2\pi \int g(t)dt + \varphi)) \quad \text{(I.3)}$$

where the amplitude $X_m(t)$ is also function of time.

The dynamic synchrophasor, where magnitude and phase angle are functions of the time is represented by:

$$X(t) = \frac{X_m(t)}{\sqrt{2}} e^{j(2\pi \int g(t)dt + \varphi)} \quad \text{(I.4)}$$

A special case where Xm is constant and $g = \Delta f = f - f_o$ is a constant offset from the nominal frequency f_0, is:

$$X(t) = \frac{X_m(t)}{\sqrt{2}} e^{j(2\pi \Delta f + \varphi)} \quad \text{(I.5)}$$

where the phasor rotates at the uniform rate Δf, the difference between the actual frequency and system nominal frequency, that produces the effect in Figure 04

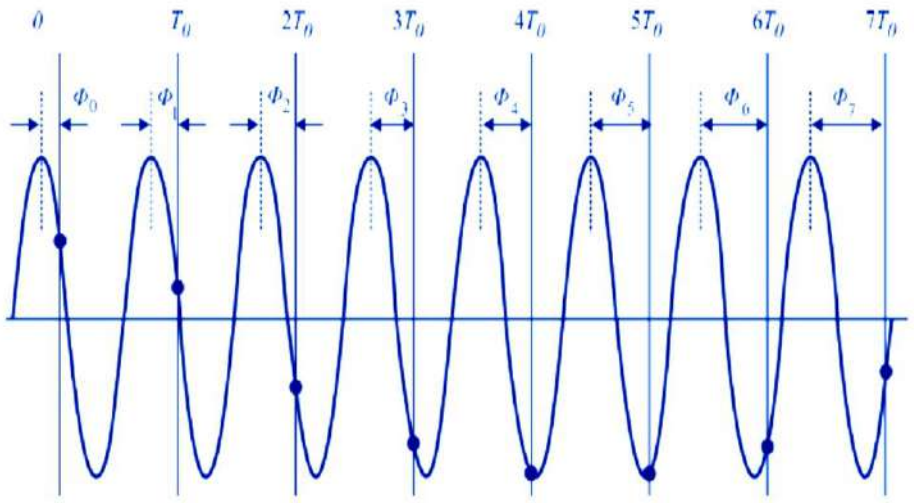


Figure I.4 Sinusoid with a frequency f>fo observed at instants that are multiples of T0.

If the sinusoid frequency f if different from f_0 but $f < 2f_0$, the phasor calculated from the waveform will have a constant magnitude, but the phase angles of the sequence of phasors calculated every T_0 will change uniformly at a rate $2\pi(f - f_0)\ T_0$

I.3-2- Frequency and ROCOF definitions

The standard also defines a way to measure the frequency and ROCOF, with a sinusoidal signal given by the formula:

$$x(t) = X_m * cos(\theta(t)) \quad \text{(I.6)}$$

the frequency is defined as:

$$f(t) = \frac{1}{2\pi} * \frac{d\theta(t)}{dt} \quad \text{(I.7)}$$

and the ROCOF:

$$ROCOF(t) = \frac{d(\frac{1}{2\pi} * \frac{d\theta(t)}{dt})}{dt} = \frac{df(t)}{dt} \quad \text{(I.8)}$$

If the argument of the cosine in the (I.6) is represented as:

$$\theta(t) = 2\pi f_0 + \varphi(t) = 2\pi \cdot [f0t + \frac{\varphi(t)}{2\pi}] \quad \text{(I.9)}$$

The formula of the frequency becomes:

$$f(t) = f_0 + \frac{d(\frac{\varphi(t)}{2\pi})}{dt} = f_0 + \Delta f(t) \quad \text{(I.10)}$$

with $\Delta f(t)$ as the deviation from the nominal system frequency and the ROCOF becomes:

$$ROCOF(t) = \frac{d^2\left(\frac{\varphi(t)}{2\pi}\right)}{d^2t} = \frac{d\Delta f(t)}{dt} \quad \text{(I.11)}$$

I.3.3 Total Vector Error (TVE)

The TVE describes the error between the actual and the measured values of the input signal. The Synchrophasor Standard IEEE 37.118, Up to these limiting values is shown in Figure 5, the TVE of 1 % must not be exceeded for stationary signals the TVE is defined as follows:

$$TVE = \sqrt{\frac{(X_{r(n)} - X_r)^2 + (X_{i(n)} - X_i)^2}{X_r^2 + X_i^2}} \quad \text{(I.12)}$$

where:

- $X_{r(n)}$ = Real part of measured signal
- $X_{i(n)}$ = Imaginary part of measured signal
- X_r = Real part of input signal
- X_i = Imaginary part of input signal

Variables that influence the TVE are: Amplitude errors and Phase errors and Synchronization accuracy (deviation from the UTC).

Synchronization accuracy is affected by a GPS timer and the precise correction of the time delay within the GPS receiver module, as well as by the optimal setup of the GPS antenna.

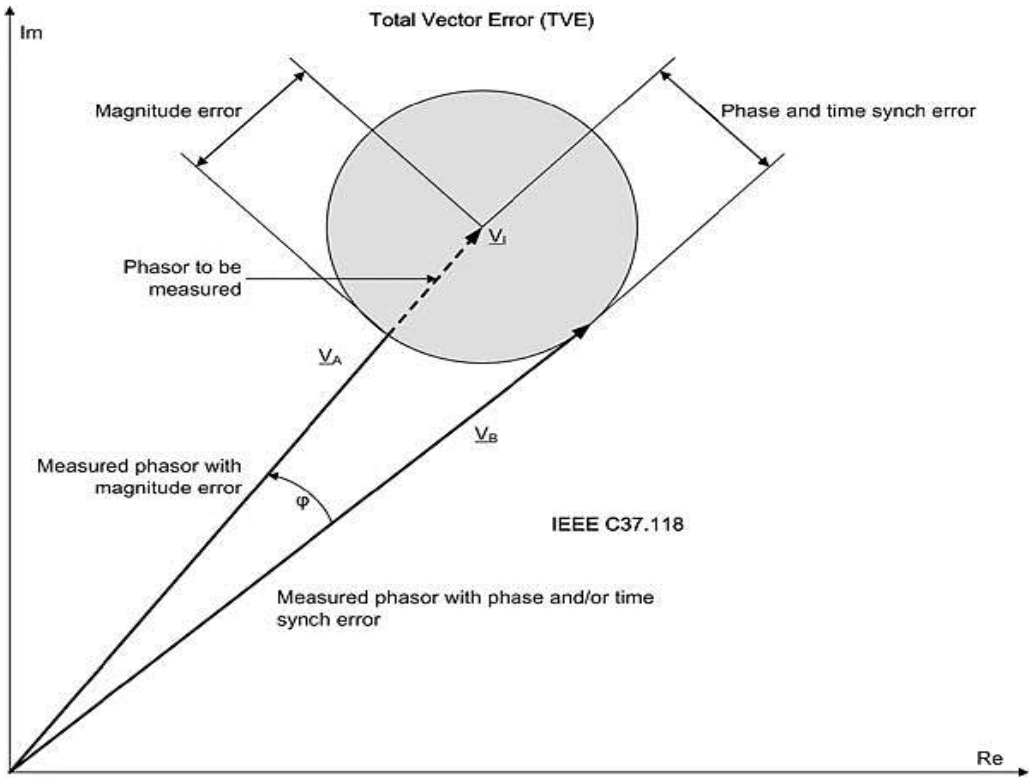


Figure I.5 Representation of the Total Vector Error.

I.4- Synchrophasor measurement unit:

The PMU is a function or logical device that provides synchrophasor with a time-synchronized measurement of a quantity described by a phasor. Like a vector, a phasor has magnitude and phase information. A PMU measures the phasor values of current and voltage. These values get a high precision timestamp and together with the values of power frequency,

power frequency change rate and optional binary data that are also time stamped are transmitted to a central analysis station. The standardized transmission protocol IEEE C 37.118 is used to do this. Data reporting rates are typically 30 to 60 records per second, the device of phasor measurement unit is shown in Figure 6.



Figure I.6 Phasor Measurement Unit (PMU) device

The GPS receiver provides the one pulse-per-second (pps) signal, and a time tag consisting of the year, day, hour, minute, and second. This helps engineers in analyzing dynamic events withinthe grid that isn't attainable with ancient SCADA measurings that generate one measurement each a pair of or four seconds.

Therefore, PMUs equip utilities with increased observation and management capability and are thought-about to be one among the foremost vital activity devices within the way forward for power systems. [1]

APMU can be a dedicated device, or the PMU function can be incorporated into a protective relay or other devices. [2] A typical hardware structure of PMU is shown in figure 7

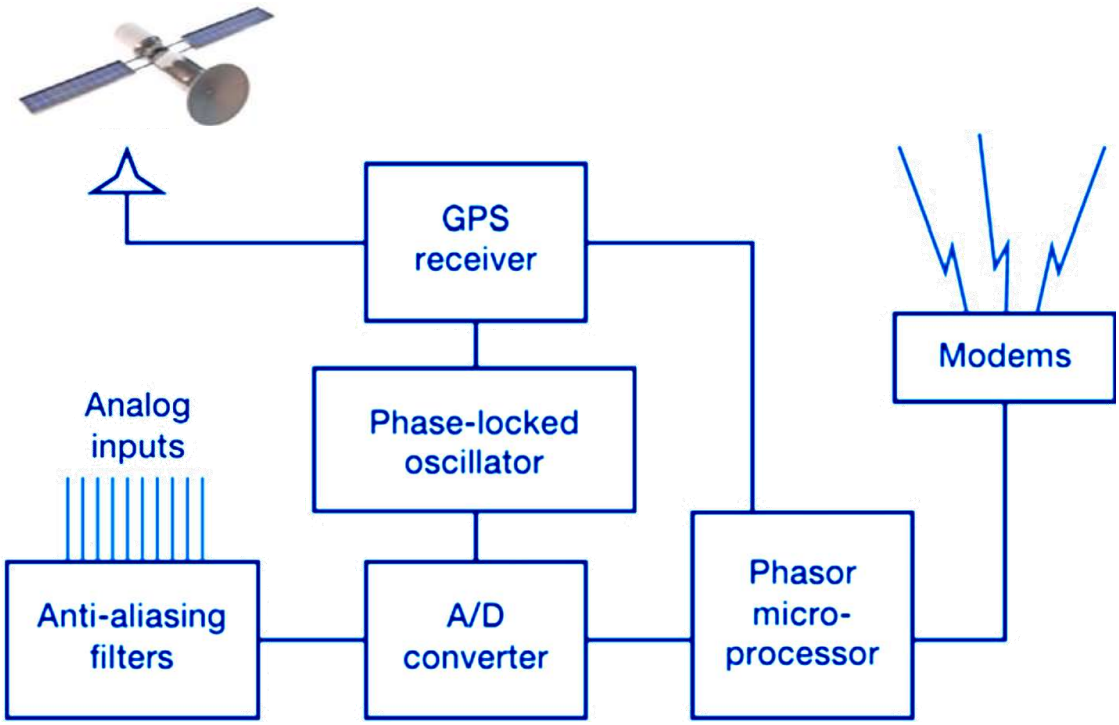


Figure I.7 Functional block diagram of a typical PMU

The PMU device is the most complicated component of the measurement system and contains the most complex measurement degradation mechanisms. A discussion of the detailed end-to-end PMU measurement system or data process path is helpful the internal mechanisms of the PMU device affect data quality in the steps:

Step 01: the analog inputs are current and voltage signals obtained from the current and voltage transformers. In most cases, magnetic core Voltage and Current Transformers (VTs and CTs) are connected to the PMU. To minimize the section errors introduced by instrument transformers, compensation routines are generally implemented in commercial PMUs.

Step 02: The PMU device contains mathematical band-pass and anti-aliasing filters that aid within the choice of the basic frequency element that's desired for mensuration. These could introduce non-negligible degradation to the activity.

Step 03: The PMU device contains an Analog to digital converter for digitally sampling point-on-wave values that can be used by the signal processor for estimating the RCF and PACF values square measure simplifications of the transformation that takes place among the noble metal. The relationship between input and output would be higher delineated with a transfer perform representing these shifts across the frequency spectrum of the conductor signal. phasor values of the

signal. The terrible nature of A/D conversion represents a degradation of activity data as a result of it truncates and, therefore, quantizes measurement values. In most cases, however, the precision of the A/D converter is designed to introduce negligible error to the measurement relative to the errors of the other system components.

Step 04: The PMU device depends on a high-precision time synchronization mechanism such as that provided by a Global Positioning System (GPS); signal and receiver and a local crystal oscillator. Time synchronization allows activity timestamping and also the accuracy of the phasor price itself. PMU standards specify the specified accuracy and exactitude of your time signals and time synchronization.

Timestamps among the PMU square measure tormented by errors like misconfiguration and also the loss of satellite signal (if GPS-originated) or network-delivered time. However, temporal arrangement accuracy is additionally subject to errors like radio interference (e.g., from poor GPS receiver placement) and GPS spoofing. A substation's GPS time supply could also be supplemented with land- or IP-based time transfer signal.

Step 05: the CPU performs the computation necessary to estimate the quantities of interest from the noninheritable signals. It estimates this and voltage phasors victimization the algorithms specific for the synchrophasor estimation. Moreover, it generates the time-stamp from the synchronization module to tag the measurements. It estimates additionally the frequency and ROCOF.

The phasor microprocessor uses the algorithmic discrete Fourier transform (DFT) algorithmic program to calculate the native positive sequence, fundamental frequency and voltage and current phasors from the sampled information. The resultant time-tagged phasors area unit forthwith out there for native or remote applications via the quality communications port. By operatively interconnected software system package of the PMU, the user's area unit capable of observance the phasors across the complete transmission network for any abnormal events. The phasor knowledge provides data concerning pre-fault or post-fault conditions. Therefore, the operators within the central room will consecutive and endlessly acquire and calculate the values of the phasor. The construct of phasor mensuration and so the basics of PMUs area unit introduced throughout this section. Figure 8 shows the sinusoidal voltage waveforms at both the sending and receiving ends of a transmission line and their phasor representations $\overrightarrow{V_1}$ and $\overrightarrow{V_2}$. (DFT), these two phasors can becalculated using Discrete Fourier transform. Most importantly, these two phasor representations sharing the same time reference from

GPS satellites, sharing the same time reference from GPS satellites, which are time-stamped and sent to the control room respectively from two different locations.

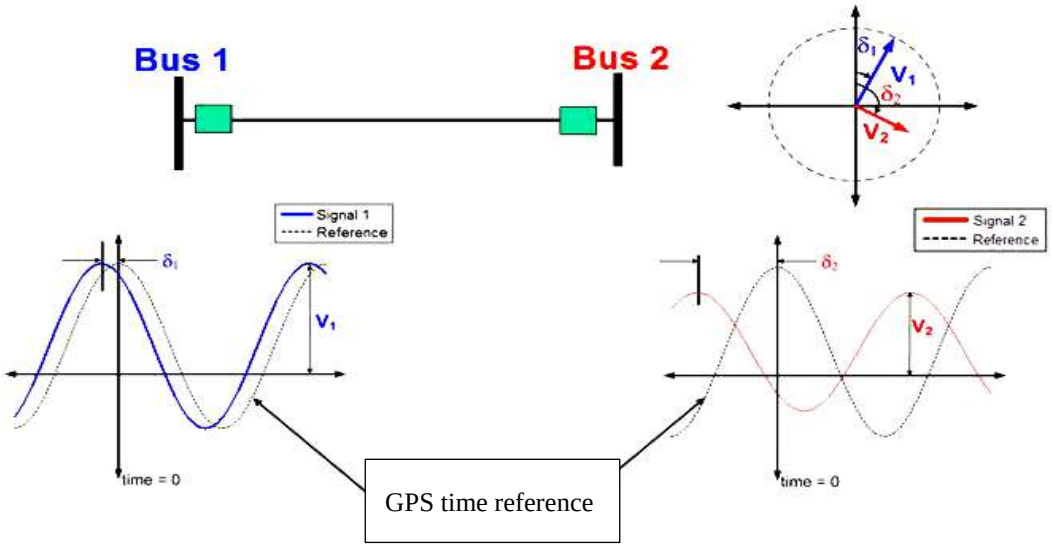


Figure I.8 Synchronized phasor representations of sinusoid waveforms

Therefore, though measurements may not arrive simultaneously due to communication delays, they can be aligned and compared using same GPS time reference at the data center.

PMUs are mainly installed at the high-voltage side requiring three phases current and voltage input signals. A diagram of the typical PMU installation on one phase at a substation is shown in Figure 09. The CT and PT scale down the current and voltage of the high voltage buses to fit the input ranges of the A/D converters in the PMU. The burdens in Figure 9 represent the VA rating of the electronic instruments connected to the PT/CT secondary circuits and the attenuators are used for adjusting the output amplitudes further. Due to the high installation and manufactory costs of PTs and CTs, PMUs are installed only at the most important nodes of the power system at the current state.

We explain in simplified terms the meaning of both the conductor and PTs, CTs in the following:

***The conductor**:* it is the physical transport medium for the electrical energy on the system. The characteristics of the electrical energy being carried contain much more information than is desired. Therefore, the measurement system must be able to differentiate between the desired and undesired information (i.e., noise and other power system phenomena). The potential energy level of the conductor makes direct measurement costly and dangerous. Therefore, these energy levels must be transformed to lower energy levels with instrument transformers (i.e., PTs and CTs).

The potential transformer (PT)*:* The PT steps down the conductor potential to a low enough value that it can be read safely and affordably by a PMU. Each PT has a defined step-down ratio for the voltage that defines the relationship between the input and the output. This ratio is an approximation. The PT introduces a complex bias to the measurement that includes a shift in magnitude of the conductor signal and a shift in phase of the conductor signal. With respect to the resultant phasor measurement, these values are called ratio correction factor (RCF) and phase angle correction factor (PACF), respectively. Changes in RCF and PACF can be created by changes in ambient and seasonal conditions as well as changes in the metering equipment condition over its operating lifetime.

The current transformer (CT)*:* The CT plays the same role as the PT in the measurement system and in the degradation of measurement quality. ACT measures the ampere flow of the conductor while the PT measures its potential flow.

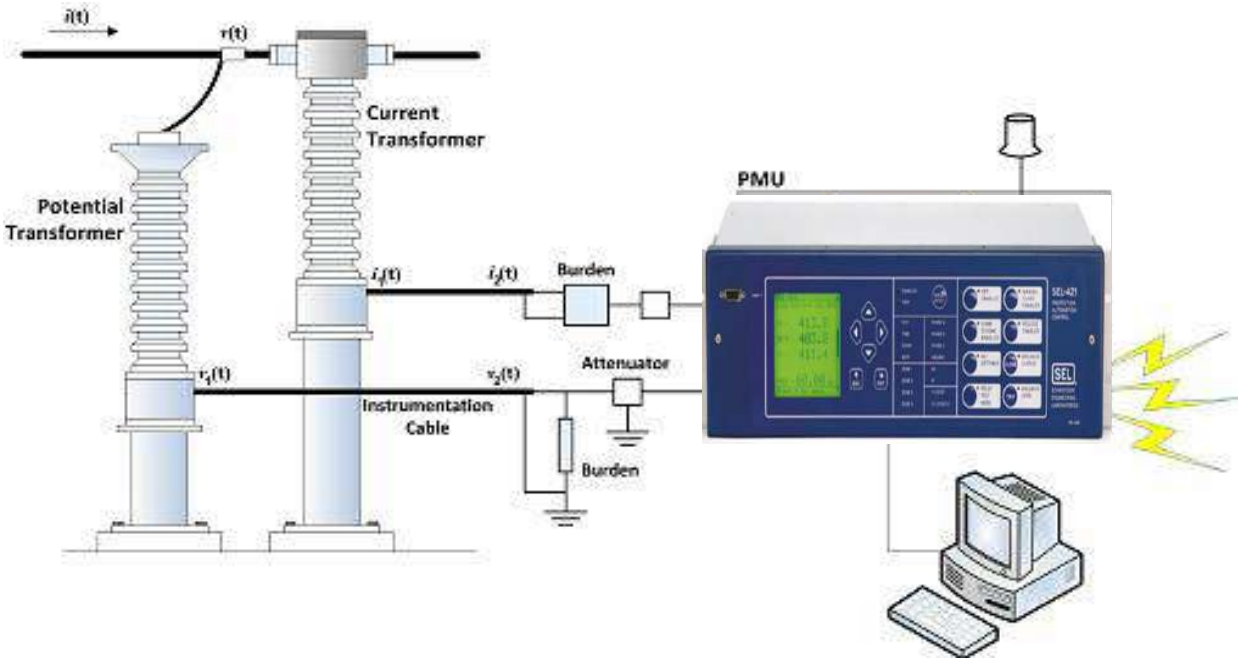


Figure I.9 PMU installation and connection diagram

I.5. Hierarchy for PMU Systems

Generally, the phasor data generated by PMUs are used in remote locations. The architecture that is used to obtain the full benefit of synchrophasor technology includes PMUs, communication links and phasor data concentrators (PDC). The hierarchy of the system is shown in Figure 10. Similar to RTUs, PMUs are installed in power system substations and provide time-stamped positive sequence voltage and current measurements of all the monitored buses and feeders. PMU data is stored in a

limited local manner which can be accessed remotely for diagnostic purposes, or used by local applications. Typically, the phasor data is sent to a PDC. PDC functionality is to gather data from several PMUs reject bad data and align time-stamped data. Local storage is available at the PDC and real-time data can be utilized for local applications. PDCs can be considered to act on a regional basis. On a system-wide scale, a super data concentrator is one level higher but has similar functions to regional PDCs, in terms of aligning time-stamps and rejecting bad data, receiving and accumulation measurements from the entire system. The communication links are bidirectional so that downstream components can be configured remotely. Intuitively the upstream channel capacity is far greater than the downstream channel capacity. In the USA and Europe, the generation of electricity is deregulated. Therefore, each utility is assigned a regional PDC to aggregate and align data from various PMUs in the covered region. The regional PDC will be located at a utility control center and will send its data to a demarcated national PDC (super PDC) in order to synchronize the data across utilities [10].

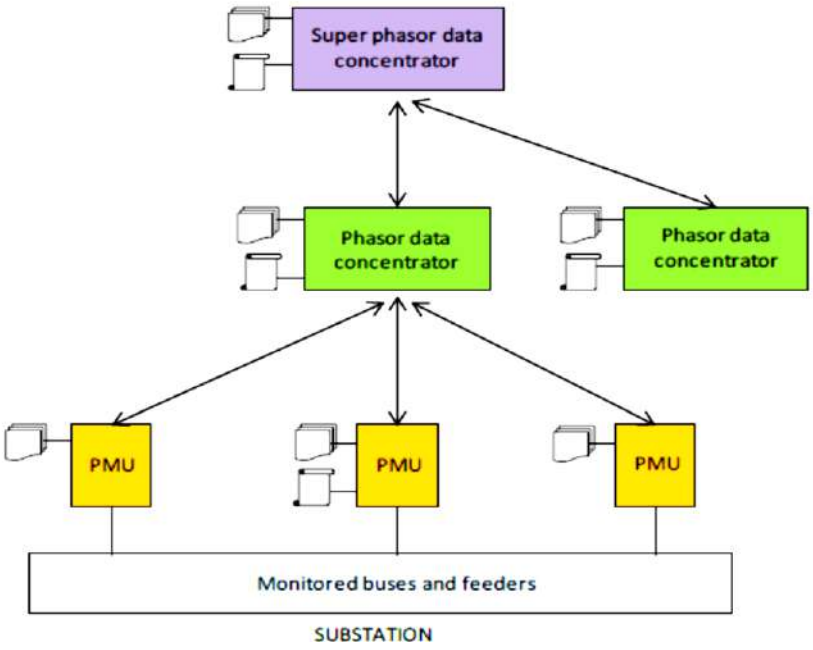


Figure I.10 The hierarchy for PMU systems

I.6. PMU Equipped System Compared to SCADA Equipped System

In [8] a combined funding task force was created to assess the benefits of integrating PMU technology in to an EMS. It consisted of two phases: Phase I consisted of an off-line preliminary study case and phase II consisted of on-line state estimation using a hybrid SCADA/PMU data set. Table 1 highlights some differences between PMU and SCADA measurement sets.

ELEMENT	SCADA	PMU
Estimation	Analog	**numerical**
outcome	2-5 samples per sec	**60 to 60 samples per sec**
comply with	Steady State	**Dynamic/Transient**
Monitoring	Local	**Wide Area**
Phase Angle Measurement	No	**Yes**
Measured Quantity	Magnitude – (RMS) – MW, MVAR	Magnitude (RMS) and phase offset from common reference – MW, MVAR, and Angle Difference

Table 1 indicates that the refresh rate per second for PMU/PDC setup is significantly faster than SCADA. As previously mentioned, the PMU data is time tagged, eliminating latency and skew effects that are associated with the SCADA system. PMU/PDC use newer communications technology than the SCADA architecture.

I.7.Illustration of PMU Application

Since phasor technology and so the PMU device was brought into trendy wattage networks, performances just like the responsibility, stability and controllability of power networks have reached a much better level. In the following sections, varied examples and therefore the main edges of implementing PMUs in power networks are depicted.

I.7.1 State Estimation

In the power network, the classification of state estimation in real-time management functions includes: scheduling generation and interchange; observation outages and programming alternatives; supervising regular outages; programming frequency and time corrections; coordinating bias settings and emergency restoration of the system [4]. Basically, all of the state estimation considerations higher than area unit operated by running an outsized range of load flow analyses and results are calculated over a long execution period. By using the Phasor measure Units that bring home the bacon high performance in time synchronization with wondrous truth, the state estimation

measurement is ready to be enforced supported advanced bus voltages [10]; this approach is used in preference to 1 supported early state estimation algorithms [11], that utilize the measurement of line flows, involving each real and reactive power, to estimate the bus voltage magnitudes and angles. By exploitation, the state estimator, measuring errors are often detected, known and corrected victimization the dangerous processing technique [12,13]. This procedure can be treated as a part of the state estimation method and will even be a post-estimation procedure. In a given installation, a measuring is assessed as either crucial or redundant. Redundant measurements are often far from the measuring system while not inflicting the system to become unobservable.

When a redundant measuring is erroneous, this will be detected by statistical tests based on measurement residuals. Removal of critical measurements, however, will result in an unperceivable system, and errors in these forms of measurements can't be detected. during a well-designed measuring system, the unhealthy data processing is accomplished if any crucial measuring is observed by multiple measuring devices. In principle, adding any type of measurement will improve redundancy. It is easy to include synchronal phasor measurements into state estimators alongside typical measurements, and this will be shown to enhance state estimation performance [14]. Given a power system that's absolutely evident by existing measurements, many further PMUs are often wont to convert any existing crucial measurements into redundant ones, thereby creating all bad data in the system detectable.

I.7.2 Static state estimation

After suffering large losses among the Northeast blackout in 1965 [4], the U.S.A. power utilities began to utilize analog activity technology and communication systems, just like the superordinate management and knowledge acquisition (SCADA) system that consists of terminal units (RTUs) to measure phasors. the standard methodology, like elaborate error models [15], integrates the system dynamic equation by using the magnitude and angle of bus voltages because the states and afterward measures real and reactive power flows. This ancient technique could confirm problems that were directly or indirectly moving the operation of the flexibility network. However, in terms of the huge dimension of the matrix, the process time and memory were not possible to execute in a period of time. to beat the challenges, researchers and network operators introduced a replacement plan known as the ‘static’ state estimation. Static-state estimation is associate approximation methodology that is accustomed predict the longer-term behaviour of a power network supported its gift condition. as an example, the thought of oscillation during a power network will be analyzed using info from the generators and loads that are measured by the PMUs. so as to predict associate oscillation which will occur among the longer term (e.g. one-minute period), the

knowledge collected by PMUs are transferred to a network model and conjointly the static and dynamic behaviors is calculated. Assume that the system does not change throughout the observation period; once the network operator receives a report on the prospect of losing the static stability, the operator might follow the planned procedures to upset the problem.

I.7.3 Fault Detection

In recent years, major efforts are dedicated to the exploration and development of recent methodologies that notice faults that occur within the overhead conductor [16, 17]. In power systems, the sort of fault may be classified as either a permanent fault or a short-lived fault. A permanent fault caused by events, sort of a broken cable or the malfunction of a power generator, are often situated simply because the detection devices receive vast variations in signal characteristics throughout the pre-fault and post-fault moment. In contrast, the temporary fault that is normally caused by insulator flashover would not cause the supply of the overhead transmission to collapse immediately. However, arc on nonconductors has the potential to steer to a full breakdown of the insulator once those transient phenomena occur often. Therefore, it's important to safeguard and analyze the full network and localize the fault ahead the PMU-based fault location technique [18-20] is in a position to see the fault location through synchronized fault voltages that area unit monitored by neighboring PMU put in nodes. Based on these fault node voltages, that area unit measured by PMUs, line currents between these nodes can be calculated. Then, node injection currents at 2 terminals of the faulted line area unit fashioned from the road currents. Based on the calculated fault node injection currents, fault nodes may be deduced or fault locations in transmission lines may be calculated accurately.

I.7.4 Wide Area Monitoring System

The wide area monitoring system (WAMS) [21] is a new concept for maintaining dynamic stability within the overhead line network, based on the PMU. Recently, several countries are proactively implementing WAMS in their power grid networks. Unlike previous monitoring systems, WAMS is built supported the time-synchronized measure, novel computing technology, and communication technology to achieve the synchronization of data acquisition and real-time recording from equipment and systems in distributed locations, the real-time data will be delivered to the central control station where the network operator will be able to measure and analyze the data at any point of the power network. WAMS has additional useful benefits over standard systems and would eventually replace the standard supervisory control and data acquisition (SCADA) system for the steady-state observance. Furthermore, WAMS has the ability to analyze the network oscillation, monitor and estimate the network static stability, perform the time-stamp for fault localization and see the network voltage instability. It is to this point deemed the foremost advanced technique to

sight and avoid a pervasive blackout. By optimally placing PMUs in the power network, the controllers can recognize unusual activities within the power network through the interface in the power control center.

I.8. The PMUs Application in Worldwide

Worldwide several utilities from North America, Europe, China, Russia and Brazil have started using/developing the new PMU applications to harness the potential edges of this rising technology operative very big electrical grids. In 2006, China's Wide house observation Systems (WAMS) for its six (6) grids had three hundred PMUs place among the most at 500kV and 330kV substations and power plants. Presently China has a place in over one thousand PMUs in their Grid. By 2012, China plans to possess PMUs in any respect 500kV substations and every one power plants of 300MW and on high of, In U.S their area unit 10 synchrophasor comes current involving 57 utilities and grid operators across the country and fixing concerning 850 networked PMUs. By 2013, the devices area unit operative in nearly all regions of the country. the Japanese Interconnect Phasor Project (EIPP) (now referred to as the North yank Synchrophasor Initiative or NASPI), has over forty connected phasor measure unit's aggregation information into a "Super Phasor knowledge Concentrator" system focused at Tennessee depression Authority (TVA).

Southern CA artificer is successfully exploitation Report on URTDSM synchrophasors these days to trigger some automatic grid protection functions on their system Oklahoma Gas Co. (OG&E), the USA uses synchrophasor technology as a wise tool to search out and solve real-world operative problems. The utility has supplemental quite a hundred PMUs to the system, that provided observation nearly unit of time of its transmission grid. From the synchrophasor info, OG&E can verify if a disturbance is cleared by high-speed or step-distance (delayed) tripping. the data is getting acquainted with finding the availability of event disturbance associated proceed with associate degree investigation. Another valuable use of synchrophasor knowledge is that the detection of the kit failure, most of that won't detectable by the SCADA system. System stability assessment is being distributed pattern synchrophasor information considerably capturing the intricacies of associate degree associate interconnected system like low-frequency oscillations due to generation management drawback or various reasons. the good issue concerning PMU measurements at the aim of powerhouse interconnection facilitates the patron to receive clean power (in terms of voltage fluctuation/flicker) whereas maintaining the number of system stability necessary for reliable power grid operation.

Apart from more than nations, various countries like state, Brazil, USSR, Western Electricity Coordinating Council (WECC) whose service territory extends from North American country to Mexico and some European countries have deployed/ near to deploy, a large no. of PMUs in their system.

I.9. Conclusion

In this chapter I have provided a detailed and detailed overview of the evolution and development of a device of PMUs. A historical overview of PMU Technology is introduced, and the application of the PMU, for both state estimation and fault detection, is discussed in detail. The outlines of the thesis are also presented in this chapter.

CHAPTER II

PMU'S PLACEMENT TECHNIQUES

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II.1. Introduction

As of late, due the development and development of PMUs and WAMS advances and their potential applications in power framework for guaranteeing the observing, the activity, the security, and the control, on the opposite side because of the real need for the best estimation of the power framework express, the PMUs are perceived to be a vital component in improving the exhibitions of the entire power framework and its flexibility even with disastrous disappointments. To be sure, phasor estimation innovation has increased extraordinary consideration and quick advancement everywhere throughout the world [61].

Today, PMU brings more attention to both utilities and research institutions. They are searching for the best solutions of OPP problem.

The usual total prices for apiece PMU (cost of procurement, installation, and commissioning) range among 40,000$then 180,000$. PMU distribution on every bus of network is not feasible as it leads to cost influence. Cost factor and repetitive estimations are considered as imperatives to decide ideal PMU position in power framework [91].

This advancement of PMUs relies upon accomplishing the perceptibility of the entire power framework, where they ought to guarantee the security of the entire power framework amid sporadic settings additionally distinguishing and recognizing gross blunders, which can be recognized progressively dependent on the flag exchanged from the PMUs estimation set. this procedure depends on PMU totally discernible of the network.

The OPP issue does not have an extraordinary arrangement. The ideal number of PMUs and their areas will contrast dependent on their goals and imperatives. The negligible number of PMUs and their ideal areas are chosen by utilizing any great improvement procedure. In this part, we clarify strategies of ideal position of PMUs.

II.2. The Techniques of Optimal Placement of PMUs

Since it's not economical to position PMUs at every and each bus to diagnose/detect there were problems, so we need a placement technique which can offer a whole observability of the system.

Placement techniques can depend on the PMUs application, installation restriction and the system characteristics because it isn't even necessary also to put it in each bus [88].

Numerous topological and numerical ways can be utilized to decide the best area of PMUs. Be that as it may, we have a propensity expecting to discover the one method or the blend of strategies, which will not solely minimize the installation price but can offer full observability using a minimum set of phasor measurements.

In this chapter we will introduce some acquainted techniques in installing phasor measurement unit's in the electrical networks designated in figure 01 following as:

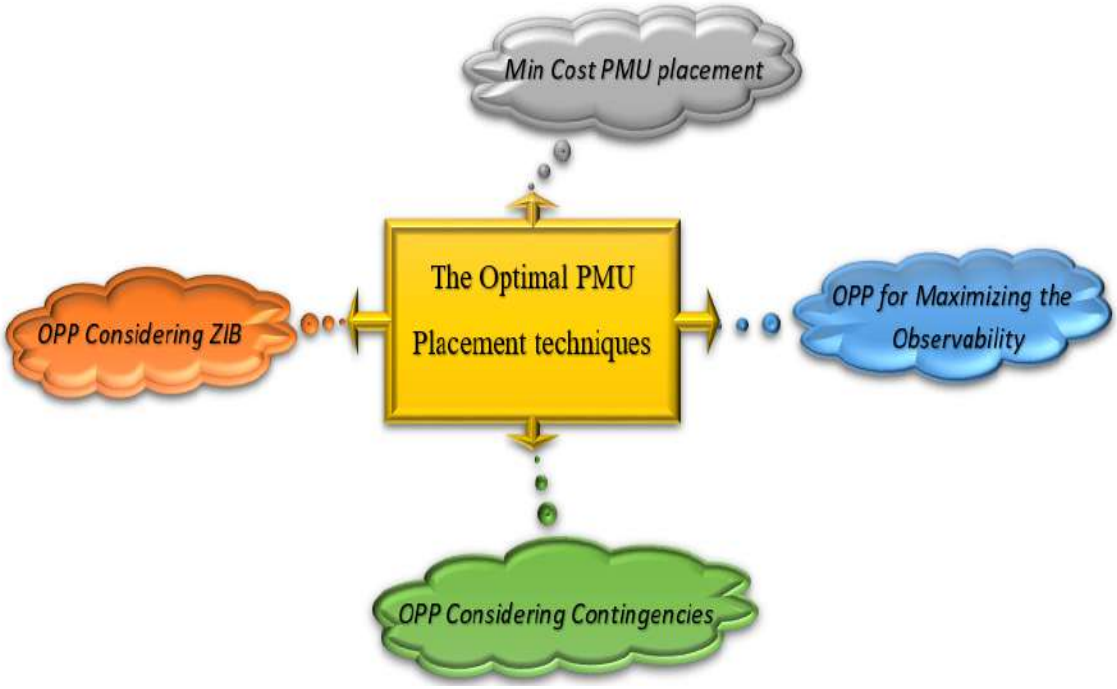


Figure II.1 The Techniques of Optimal Placement of PMUs

II.3. literature review on Previous Works

In this section, we address the work of some authors around the world in finding solutions to reduce the number of project management units installed in electrical networks [77].

Most researchers used standard IEEE networks to refute their studies. Numerous mathematical methods, including heuristic and metaheuristic methods, have been used to reduce the number of confirmed measurement units and also to select the best links in the network in order to provide the best views.

We begin with the author B. SARKAR, who has meted out in his research paper in [78] associate degree best approach of choosing the locations of PMUs using the improved technique of the genetic

algorithm (GA). The authors EBERHART and KENNEDY conjointly contributed to an analysis involving the utilization particle swarm optimization (PSO) technique for the best allocation of phasor measurement units (PMUs) for the complete observability of connected power network [81].

Farsadi et al in [79] have introduced many graph theory approaches to the OPP problem to work out the improvement resolution exploitation the Depth-First strategies.

In Reference [80], processes were effectively introduced to reduce process efforts and to resolve the minimum number of project management units needed to achieve full management potential using the greedy algorithm.

The work provided in Reference [83] was used to determine the minimum number of PMUs required using the binary search algorithm.

The researchers developed a unique model for the optimal placement of PMUs in the power system through the implementation of Integer Linear Programming (ILP) detailed in reference [82].

II.4. The Optimal PMUs Placement Problem Formulation

In this chapter, the problem of optimal PMU placement in a power system under standard process with and without zero-injection bus (ZIB). The zero-injection bus can be defined generally as a bus in the power system grid deprived of a generator and load joining as publicized in Figure 03.

For an ordinary process condition of n-bus power system without ZIB effect, the PMU placement problem can be formulated as follows [84-85]:

$$min\big(g(X)\big) \tag{II.1}$$

The vector solution of equation (II.1) has to fulfil the requirements of optimized number of PMUs and their localization at the same time, where the main aim is to ensure the topological real time observability of the whole power system network. In this equation g(X) is the objective function of the formulated problem, it is defined as follows:

$$g(X) = \sum_i^n W_i \,.\, X_i \tag{II.2}$$

Subject to:

$$f(X) \geq U_1 \tag{II.3}$$

Wi is the cost of the PMU installed at the i^{th} bus, *X* is a binary decision variable, where its elements are defined as follows:

$$X_i = \begin{cases} 1 & PMU\ is\ insttaled\ in\ node\ i \\ 0 & otherise \end{cases} \quad \text{(II.4)}$$

The entries of the vector function *f(X)* are $f_i(X)$which are all none zeros. The element $f_i(X)$ presents the observability function at the i[th] bus, and U_1 is a vector with nonzero elements.

The non-linear constraints which are presented by equation (II.4), are formed on the basis of knowledge of the existing locations and types of measurements. The vector function *f(X)* is defined as:

$$f(X) = A.X \quad \text{(II.5)}$$

The matrix A is the binary connectivity matrix that represents the connectivity information between buses of a power system. Based on equation (II.5), the element function $f_i(X)$is defined as follows [84]:

$$f_i(X) = \sum_j^n A_{ij} \,.X_j \qquad \text{and} \qquad i \in [1 \quad n] \quad \text{(II.6)}$$

The elements $A_{ij}$of matrix A connecting bus I to bus j are defined as:

$$\mathrm{A}_{ij} = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if bus } i \text{ is connected to bus } j \\ 0 & \text{otherise} \end{cases} \quad \text{(II.7)}$$

Explain all that has been said in the example shown in Figure II.2 represents the IEEE-7 bus system consisting of seven nodes (shown by bold letters) and eight branches (shown by circles); if we assume that zero injection measurement is at bus 2.

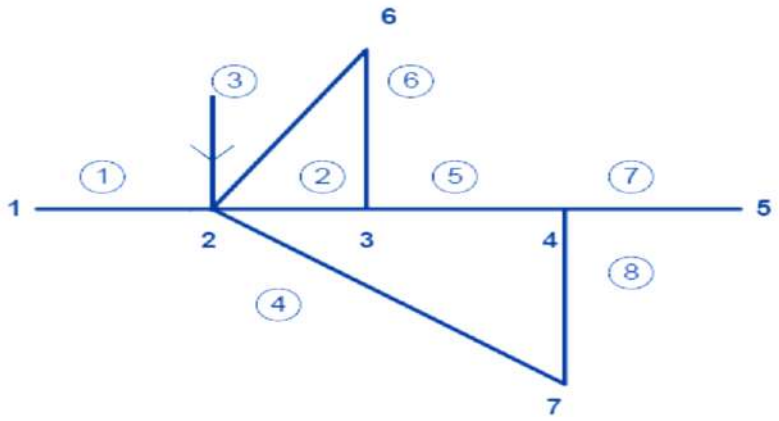


Figure II.2 The IEEE-7 bus system

Then for this system bus connectivity matrix is given as:

$$A = \begin{bmatrix} 0\,1\,0\,1\,0\,0\,1 \\ 0\,1\,1\,0\,0\,1\,0 \\ 0\,0\,0\,0\,1\,1\,0 \\ 0\,0\,1\,1\,1\,0\,1 \\ 0\,1\,1\,1\,0\,1\,0 \\ 1\,1\,1\,0\,0\,1\,1 \\ 1\,1\,0\,0\,0\,0\,0 \end{bmatrix}$$

The vector function *f(X)* is given as:

$$f(x) = \begin{bmatrix} 0\,1\,0\,1\,0\,0\,1 \\ 0\,1\,1\,0\,0\,1\,0 \\ 0\,0\,0\,0\,1\,1\,0 \\ 0\,0\,1\,1\,1\,0\,1 \\ 0\,1\,1\,1\,0\,1\,0 \\ 1\,1\,1\,0\,0\,1\,1 \\ 1\,1\,0\,0\,0\,0\,0 \end{bmatrix} * \begin{bmatrix} X1 \\ X2 \\ X3 \\ X4 \\ X5 \\ X6 \\ X7 \end{bmatrix} \geq \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

II.5. Full Topological Observability:

In the power grid, if the nodal voltage of a single bus is often measured or calculated directly by exploiting the various known voltages and branch currents, the bus is outlined as observable.

If all buses area unit observable in the grid, then the ability system will be defined like full observability [62]. There are two strategies to assess the observability of a power system:

Numerical and topological. Numerical observability would possibly involve an outsized quantity of computation and might be simply influenced by the additive error, whereas topological observability methodology is quick and sensible [63].

The minimum impact system with a minimum of one spanning measuring tree of full rank are often outlined as topologically observable [64].

As during a PMU placement problem, four rules are often coveted to analyze the topological observability of every bus among the target power system.

II.5.1. Rules for PMU Placement

Primarily based on this condition on the basic laws of branch current and node voltage in circuit theory, many rules are applied to analyze the network to ensure that the network is fully observable. The PMUs devices are able to provide the system operator with a set of synchronized phasor measurements in the system in order to make it observable. In this case, it is needed to make every existing bus

observable no matter if it has any generation/demand or not. we provide the observability concept, as following on these three cases:

***FIRST CASE*:** For PMU connected in buses, voltage phasor and current phasor of all its incident branches are known. These are known as "direct measurements" [65]. Figure II.3 shows that PMU placed within the bus-02, this process is called measured directly. Meanwhile, the branch currents connected to the node also are measured by the PMU. In first case, the well-known parameters measured by PMU are V_2, $I1_{,2}$, $I_{2,3}$ and $I_{2,4}$ and therefore the characteristic of the conductor are $R_{1,2}+ jX_{1,2}$, $R_{3,2}+ jX_{3,2}$, $R_{4,2}+ jX_{4,2.}$ The area observed by PMU on a bus is described in Figure II.3.

***SECOND CASE*:** In the event that the voltage and current phasors toward one side of a branch are far-acclaimed, the voltage phasor at the contrary end of the branch is gotten utilizing the equations (II.8) to (II.10), These are referred to as "pseudo measurements" [66]**.**

The magnitude of voltage is determined in the following formats:

$$V_1 = V_2 + I_{1.2} * (R_{1.2} + jX_{1.2}) \quad \text{(II.8)}$$

$$V_3 = V_2 - I_{3.2} * (R_{3.2} + jX_{3.2}) \quad \text{(II.9)}$$

$$V_4 = V_2 - I_{4.2} * (R_{4.2} + jX_{4.2}) \quad \text{(II.10)}$$

THIRD CASE: If voltage phasors of along blazoning of a branch are identified, the current phasor of this division container is accomplished precisely. These measurements are identified as "indirect measurements" [67].

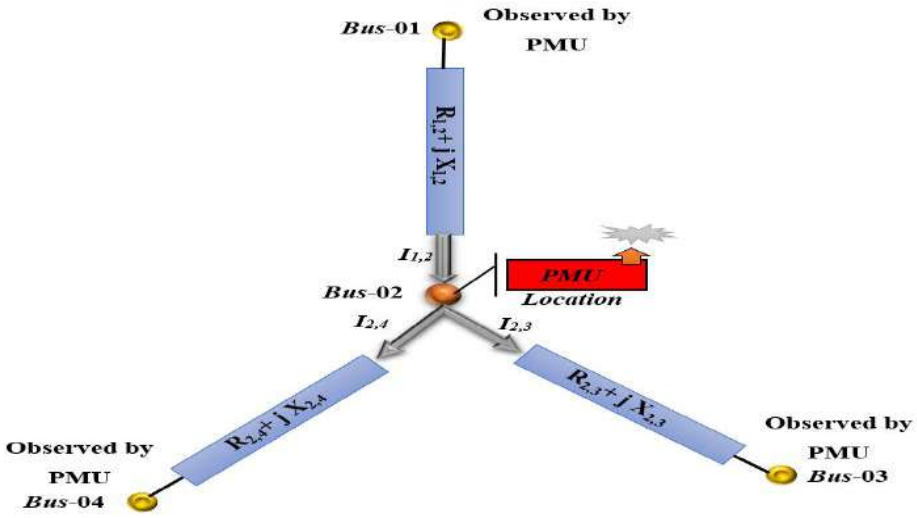


Figure II.3 The observability rules

A magnitude of voltage in Bus 01, Bus 03 and Bus 04 are observed and measured by the PMUs, the line current within the branch of 1-2;3-2 and 4-2, as well because the voltage in Bus 02, will be calculated. The equations in resolution the unidentified data are as shadows:

$$V_2 = V_1 - I_{1.2} * (R_{1.2} + jX_{1.2}) \quad \text{(II.11)}$$

$$V_2 = V_3 + I_{3.2} * (R_{3.2} + jX_{3.2}) \quad \text{(II.12)}$$

$$V_2 = V_4 + I_{4.2} * (R_{4.2} + jX_{4.2}) \quad \text{(II.13)}$$

$$I_{1.2} = I_{3.2} + I_{4.2} \quad \text{(II.14)}$$

The following example explains the direct and indirect observation of the network by the PMUs Figure II.4 shows a typical IEEE-14 bus system with PMUs placement.

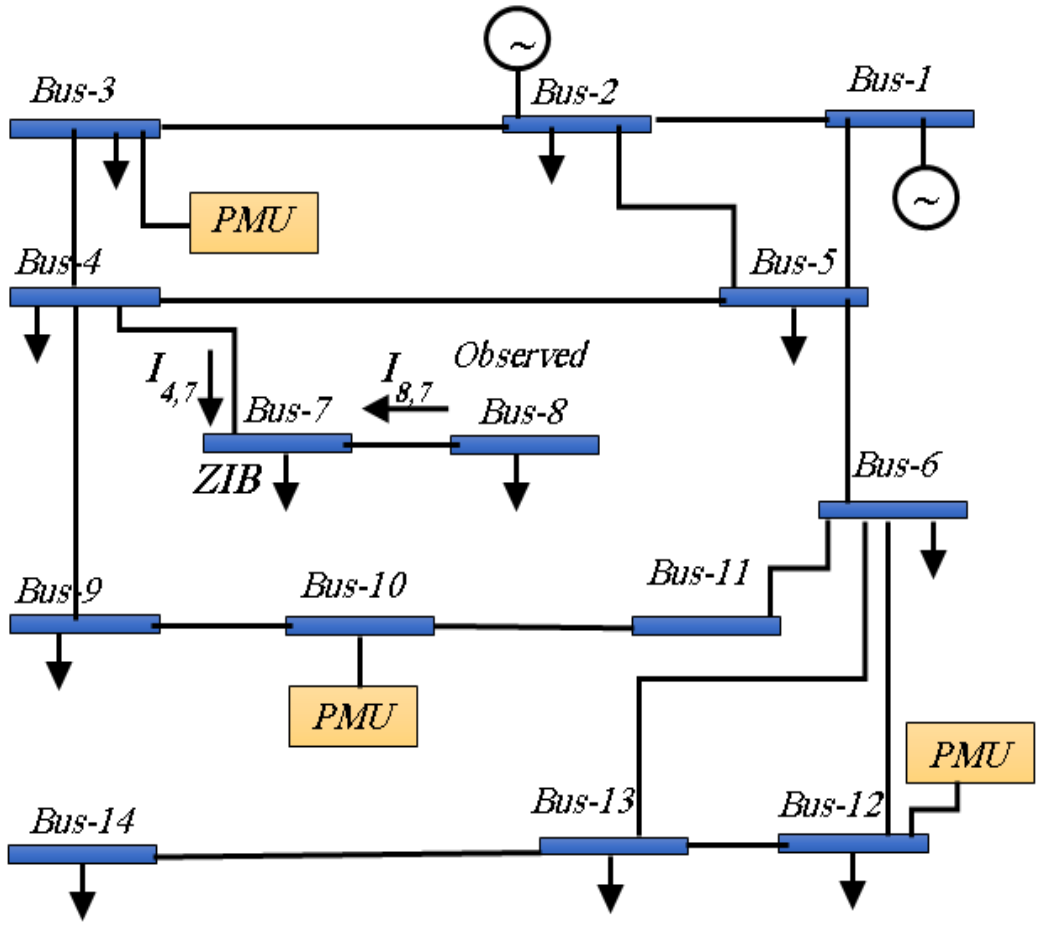


Figure II.4 IEEE-14 bus system with PMU placement.

As it is shown in this figure, the PMUs are installed in buses 3, 10 and 12, which means that the voltage phasors at these buses can be measured and also the currents circulating through the lines connected to these buses. Thus, these buses are considered as directly observable.

Where, voltage phasors at buses 1, 2, 4, 5, 6, 7, 9, 11, 13 and 14 can be estimated based on the measurements obtained at the directly observable buses.

These last buses are called the indirectly observable buses. However, the voltage phasor at bus 8 cannot be measured nor estimated, so this bus is called unobservable. If all neighboring buses of an unobservable bus are observable, so it is called depth of one Un- Observability [69].

On the other side, a power system is said to be completely observable, if all the buses in this system are directly or indirectly observable. A power system is said to be incompletely observable, if some buses are not observable.

II.5.2. Studied Networks and Incomplete Observability

Indeed, most PMU placement algorithms are designed to ensure the gadget's observability. However, complete observability will not be obtained immediately due to time regulations or various alternative problems. Topology transformation method involves the merging process of ZIB and one of its neighbours. This means that for each available ZIB, the number of buses in a power system will be reduced by one. In addition, the merging process causes a power system's network topology to be modified and network equations need to be redefined to reflect the changes. The proposed method considered the existence of ZIB and radial bus in a power system. Radial bus refers to bus which is connected to only one adjacent bus. Placing a PMU on a radial bus will ensure that no more than two radial buses and their neighbors are observed. In the meantime, placing a PMU on a bus adjacent to the radial bus will make it possible to observe more than two buses. [70] A PMU will therefore be pre-assigned to a bus adjacent to the radial bus to ensure better network coverage. The proposed method consists of three rules for sequentially evaluating each candidate bus. The rules follow:

II.5.2.1 Depth of Unobservability

the authors in [68], have proved that the intensity of unobservability refers back to the number of unobserved busses between 2 found busses. we explain this situation inside the example shown in figures II.5 and 6.

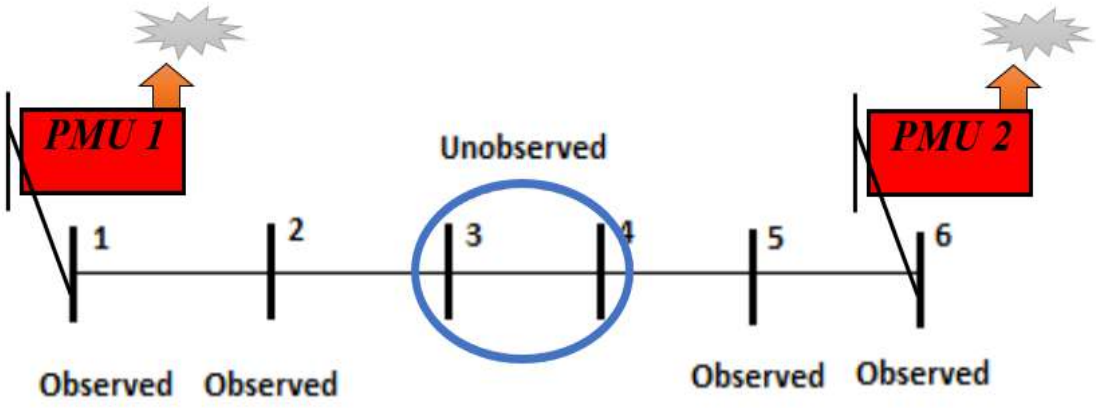


Figure II.5 First case of Depth of Unobservability

Suppose in figure 6 for the given six bus system, we can have at most 2 PMU's installed. nowadays, PMU'S connected at buses 1 and six might result in that the busses 3 and four are remaining unobserved.

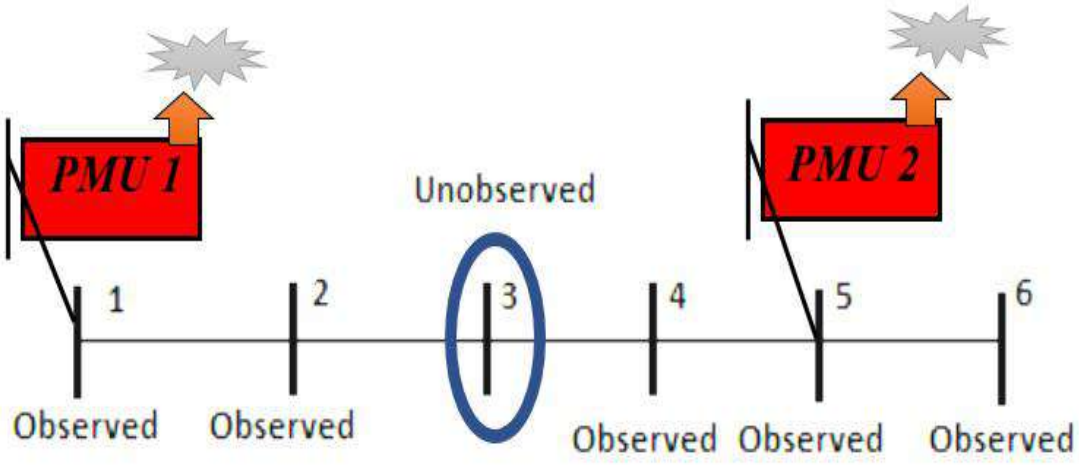


Figure II.6 Second case of Depth of Unobservability

if we exchange the vicinity of the PMU from bus 1 to 2, it might bring about best 1 bus i.e. bus three being unobserved and as a result, the latter placement set is better than the preceding one [74].

II.5.3. Zero Injection Bus Outcome

The second condition describes the zero-injection bus effect on the observability process of the power system network can be categorized following the two cases [71]:

Case 1: For the buses which are incident to an observable zero-injection bus, are all observable except one. In this case the unobservable bus can be also considered as observable bus based on the application of the Kirchhoff's current law (KCL) at ZIB.

Case 2: For the bus accident to a non-observable zero-injection bus, all of them can be observed. In this case the zero-injection bus will also be identified as observable bus by the application of the KCL at ZIB bus.

These two conditions can be combined into one by indicating that among a zero-injection bus and its incident buses, one bus may be created observable by making the others observable. Thus, topological observability analysis based on network graph is accomplished by using the above-mentioned rules [72].

II.5.4. Combining the Zero injection bus

If there are unobservable zero injection buses and acknowledged voltage phasors of its incident buses, then the voltage phasor of the zero-injection buses can come to be observable by way of making use of KCL at them. however, any other rule may be brought which enhances the observability analysis. it is a generalization of rule two. [73] it is able to be explained with one instance, as shown in in Figure 07. The buses 1 and 2 are unknown zero injection buses, and other buses are known. By using KCL law at zero injection bus1 (i.e. node1):

$$Y_{1,2} * (V_1 - V_2) + Y_{1,6} * (V_1 - V_6) + Y_{1,7} * (V_1 - V_7) + Y_{1,8} * (V_1 - V_8) = 0 \quad \text{(II.15)}$$

By using KCL law at zero injection bus 2 (i.e. node 2),

$$Y_{2,1} * (V_2 - V_1) + Y_{2,3} * (V_2 - V_3) + Y_{2,4} * (V_2 - V_4) + Y_{2,5} * (V_2 - V_5) = 0 \quad \text{(II.16)}$$

Through solving the Equations (II.15) and (II.16), unidentified variables ***V1*** and ***V2*** are calculated. Thus, unidentified ZIBs voltage phasor can be calculated by applying KCL at zero injection bus. In figure II.7 the bus 1, 2 Unknown zero injection buses, Bus 3 to 8 Known adjacent buses.

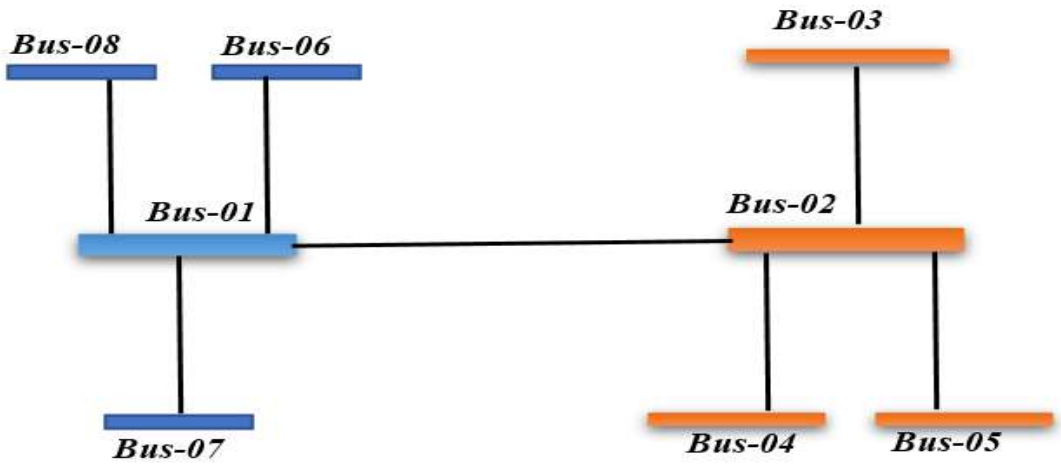


Figure II.7 Observability with considering the ZIB.

II.5.5. Zero injection bus effect in OPP problem

The whole lot approximately the zero injection buses has been explained within the preceding sections and how they can be found inside the grid. it is considered to decrease the quantity of the PMUs added and assumed in equations (II.17) to (II.20):

$$J * P \geq M \tag{II.17}$$

$$M_j = 1 \; \forall j \notin \{B_1 \cup B_2 \cup \ldots \cup B_{NZ}\} \tag{II.18}$$

$$\sum_{q \in B_z} M_q \geq |A_z| \;\; \forall z \in S_z \tag{II.19}$$

$$B_z = A_z \;\; \cup \{z\} \tag{II.20}$$

where *z* is a zero-injection bus, $\boldsymbol{A_z}$ is a set of buses adjacent to z, $\boldsymbol{B_z}$ is a set of adjacent buses to **z** and itself, ***NZ*** is the number of zero injection buses, $\boldsymbol{S_z}$ is a set of zero-injection buses in a system, ***M*** is the observability vector with a size of *N*1*, when zero injection bus effect is considered.

the constraint of equation (II.18) ensures that the buses, which aren't adjacent to zero injection buses are truly created observability. while all buses for the duration of a zero-injection bus set $\boldsymbol{B_z}$ are observable besides one bus, then the unobservable bus is observed with the aid of applying the KCL regulation at 0 injection bus. consequently, it's no longer necessary to observe all zero-injection buses or one in all the adjacent buses.

II.5.5. No PMU At Radial Buses

Additional condition used in order to minimize the number of PMUs and eliminate the computational burden in solving the OPP problem, to get rid or delete Radial buses are not preferred for PMUs placement. When a PMU is placed at a radial bus, it will measure voltage phasor of the bus itself and its just one adjacent bus. To exclude the radial buses from candidate locations of PMU placement, the subsequent constraints can be a side with OPP problem. this is applicable just for radial buses.

$$R_j * P_j = 0 \quad , j \in S \tag{II.21}$$

If a bus is a radial bus (R_j= 1), there is no PMU placement on that bus (P_j = 0) as per the constraint equation (II.17), *S* is the total number of buses in a system. Aimed at case, IEEE 14-bus organization takes a bus 8 is radial bus. Certainly, bus 8 is observed through its adjacent bus 7 (zero injection bus). This is a small system with only one radial bus.

Though, large and practical systems are having a lot of radial buses. By removing approximately useless buses for observability, the constraint equation (II.21) can increase the computation speed. This is the main advantage of not using the PMU radial bus. So, it is measured in all cases.

II.5.6. Maximizing Redundancy in Observability

The benefit of maximizing the measurement redundancy in PMU Placement observability to avoid emergencies such as damage to one of the PMU's devices to ensure comprehensive network observation. To understand the concept of measurement redundancy and its benefit, a simple six bus system is considered, as shown in Figure 07, In two cases, two PMUs are required to monitor the system completely.

II.5.6.1. Loss of A Single PMU

When determining the best location of the phasor unit in the electrical grid, this condition is often used to provide greater reliability in order to ensure the best possible observation of the electrical grid in the event of damage to one of the phasors measurements units. Despite the high reliability of PMUs.

In order to guard against such unexpected failure of PMUs, the above placement strategy is extended to account for single PMU loss. This objective is achieved by choosing two independents PMU sets, a primary set and a backup set, each of which can make the system observable on its own. If any PMU is lost, the other set of PMUs will guarantee the observability of the system.

II.5.6.2. System Observability Redundancy Index

The minimum PMUs location problematic can take occasionally many resolutions [75]. Thus, the advantage is created among the numerous obtainable dual presentation indicators that are discussed such as the Bus Observability Index (BOI) and the System Observability Redundancy Index (SORI) [76] to determine. As a concert pointer on optimization value, we can study BOI. In bus-v (Bv), we explain the BOI as the sum of PMUs that can provide us with the bus-v data. The maximum likely cost of bus observability is therefore equivalent to a bus's all-out bus connectivity (Lv) plus one:

$$B_v \leq L_v + 1 \tag{II.22}$$

To obtain the most advantageous results between the variability of the best resolutions found through entirely different ways of improvement, the System Observability Redundancy Index (SORI) is, in principle, a measure of the ad of bus coverage for all the enforced buses (*v*=1 to n) in an active system. Higher SORI price indicates that the PMU-based observation system is additional reliable. Therefore, the simplest improvement methodology is going to be designated supported the SORI. The SORI can be calculated by eq (II.23), wherever M_{SORI} represents System Observability Redundancy Index [86-87].

$$M_{SORI} = \sum_{i=1}^{n} BOI_i \tag{II.23}$$

Figure II.8 shows the study of a six bus. It is seen that it is essential to determine system observability to have the lowest PMUs.

In Figure 08, reproduce two such best solutions. The results published in Figure08(A) can be observed by two PMUs placed on buses 2 and 5. The values of $\boldsymbol{BOI_i}$ Calculated from bus 1 to 6 is 1,2,1,1,2 and 1, respectively. the $\boldsymbol{BOI_i}$ =1 in Bus 1, It means that it is monitored by one unit of PMU.

The $\boldsymbol{BOI_i}$ =2 in Bus 2, It means that it is monitored by two unit of PMUs. The calculated $\boldsymbol{M_{SORI}}$ for Figure 07(A) system is as follows:

$\boldsymbol{M}_{SORI}$= 1+2+1+1+2+1 = 8.

The system shown in Figure II.8 (B) is observable by dual PMUs placed at buses 3 and 4. *BOI* for bus-01 to bus-06 are all 1. All the buses are observed by one PMU.

M_{SORI} = 1+1+1+1+1+1 = 6.

When comparing the position of PMUs in the two Figures II.8 (A) and (B), we find that the value of M_{SORI} =8 in the figure 7(A) and M_{SORI} =6 in figure II.8 (B), therefore as best locations for PMU placement problem, we can choose bus-02 and bus-05.

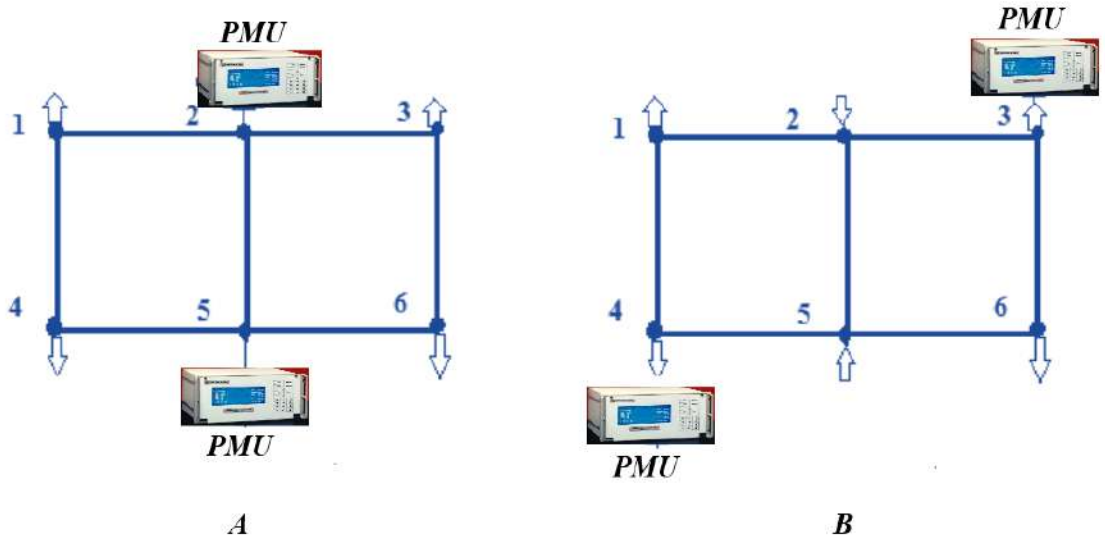


Figure II.8 Outline of 06-Bus grid

II.5. Conclusion

OPP techniques are formulated as a single objective function with a minimum number of PMUs, i.e. complete system observability. In this study, the measurement is maximized redundancy to avoid emergencies such as damage to one of the PMU's devices to ensure comprehensive observation of the power system and to reach an affordable rate at the lowest cost of PMUs. In this framework, it is necessary to use the application of certain algorithms to achieve this main goal.

CHAPTER III

LITERATURE REVIEW OF META-HEURISTIC ALGORITHMS

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III.1-Introduction

Modern industry and engineering have a constant need to design smaller and faster technologies or products that are fast and reliable and within a certain budget. These constraints give rise to optimization problems; we define a certain objective function or cost function that we seek to minimize or maximize with respect to all the parameters concerned, the initial goal being to find the optimal solution.

Optimization problems currently occupy an important place in the scientific community. Problems can be combinatorial (discrete) or continuous variable, with one or more objectives (multi-objective optimization), static or dynamic. This list is not exhaustive and a problem can be both continuous and dynamic.

For some of these problems, finding the "optimal" solution would require millions of years of computation for the fastest machines (some discrete optimization problems for which we do not know the exact polynomial algorithm. -difficile, and some optimization problems with continuous variables for which we do not know the algorithm to identify a global optimum for sure and in a finite number of calculations).

The mathematician comes to realize of the wishes by modeling the problems of life under cost functions using different types of optimization. Nowadays optimization has become an indispensable area for solve many problems in the industry or other sectors [33]. Indeed, we have witnessed in recent years a very rapid growth works using optimization methods. This trend can be observed in all areas of science. Deterministic algorithms no longer help, it was necessary to find methods to approach the best solution in a reasonable time.

The meta-heuristic technique, that is an associate improvement on the Heuristic technique, involves intelligent search processes which will upset separate variables and non-continuous value functions [37]. Basically, this method combines the randomized algorithm and local optimization algorithm to solve the optimization problem.

In this chapter and in its first part we will present a general introduction on the problem of optimization in general, basic definitions are explained, the classification of optimization problems and also discussed, then we started the study of big categories of optimization algorithms is the meta heuristic methods.

III.2. What is an optimization problem

An optimization problem is defined as the search for the minimum or maximum (optimum) of a given function. We can also find optimization problems for which the variables of the function to be optimized are subject to constraints that evolve in a certain part of the search space. In this case, we have a particular form of what the we call an optimization problem under constraints [40].

III.3. Classification of optimization problems

We can classify the various optimization problems that we encounter in everyday life according to their characteristics. The figure.1 summarizes the various criteria that fall into the classification of optimization problems:

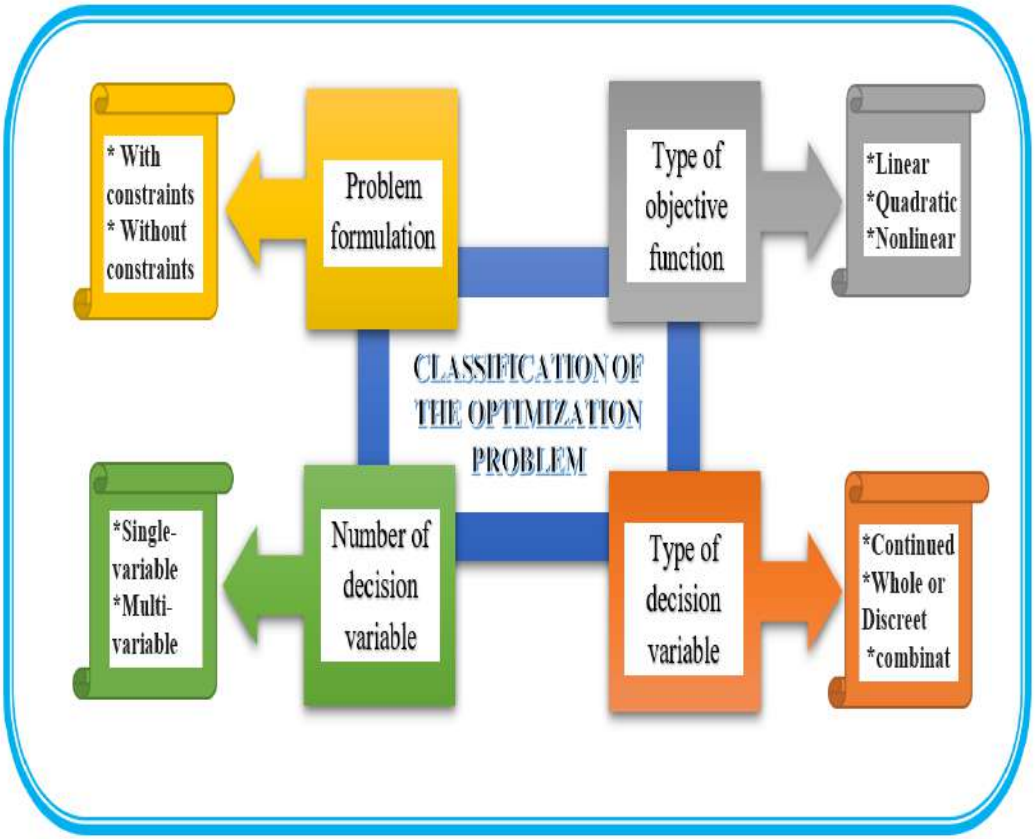


Figure III.1 Different criteria of the problem

III.4. Basic Concepts and Optimization Terminology

First, we will define the concepts common to any optimization method

A. **Objective function**: mathematical equation that represents what we want to improve in a device. It is also called optimization criterion, cost function, adaptation function, or

performance (fitness function).

- **Mono-objective problem**

A single objective optimization problem is presented in the following form:

Minimize *f (x, u)* (function to optimize).

- **Multi-objective problem**

Multi-objective optimization is a branch of combinatorial optimization whose particularity is to seek to simultaneously optimize several objectives of the same problem.

Minimize f_i *(x, u) i*=1……, N_{obj}; (N_{obj} number of functions to optimize)

B. **Parameters**: correspond to the variables of the objective function. They are adjusted during the optimization process, to obtain optimal solutions. They are also called optimization variables, design variables or project variables.

C. **Search Space**: defined by the set of combinations of parameter values. It corresponds to the solutions space. The size of the search space is defined by the number of parameters involved in the solutions. It is also called parameter space.

D. **Space of objectives**: set of search space, determined by all possible values of objective

functions;

E. **Constraints**: are defined as conditions on the state space that the variables must satisfy.

These constraints are often constraints of inequality or equality and generally allow us to limit our search space.

g (x, u) = 0 Equality constraints.

$h(x, u) \leq 0$ Constraints of inequality.

A. **Realizable domain**: area of the space (parameters and / or objectives) in which the constraints are respected. It is also called eligible space.

B. **Unrealizable**: region of the space where the constraints are violated.

Mechanisms for exploring the search space, specific to each optimization methodology, are conditioned by control parameters (number of iterations, search direction, convergence check, etc.) and by initial conditions. (initial values of parameters, limits of domains, etc.).

The following figure represents the basic principle of an optimization methodology [41,42].

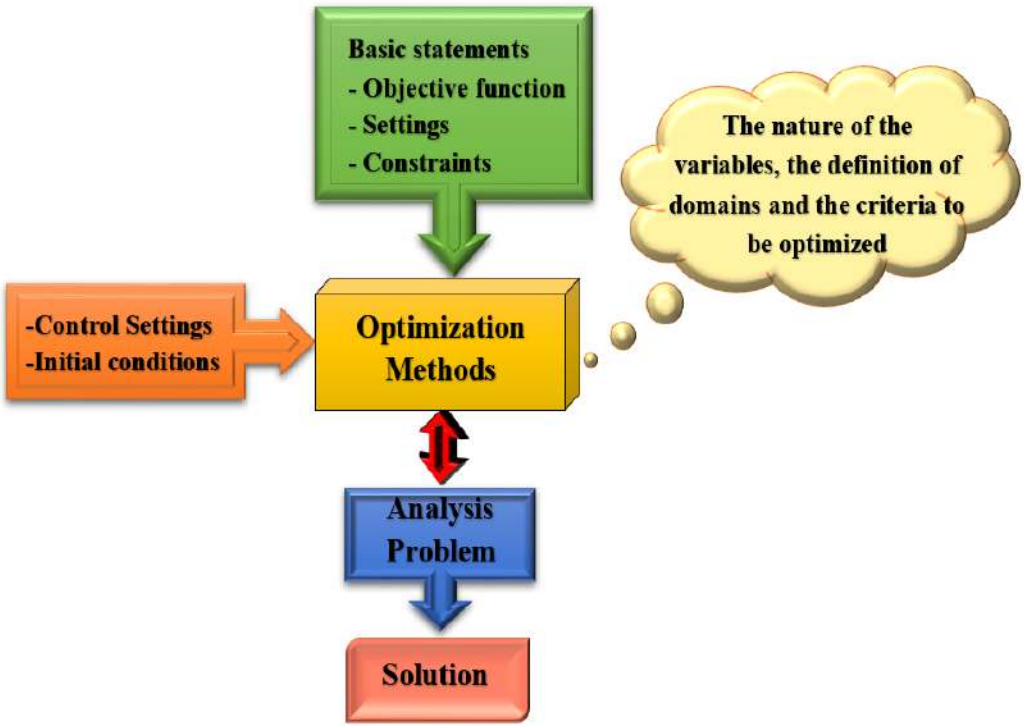


Figure III.2 Basic principle of an optimization methodology

III.5. Solving the optimization problem

The search for the optimum of a problem is carried out using optimization methods that will generally be presented in two broad categories:

Categories 01- Some of these methods are called deterministic because they lead, for a given initial solution always to the same final result. To find the optimum, they rely on a search direction that can be provided by the derivatives of the objective function. These methods have the reputation of being effective when the initial solution is close to the desired optimum. This peculiarity is a major disadvantage in the case of an objective function with several optimums, they can indeed converge towards a local optimum [43].

Categories 02- Stochastic methods, unlike most deterministic methods, do not require either a starting point or gradient knowledge of the objective function to achieve the optimal solution. They rely on probabilistic transition mechanisms and which effectively explore the research space and converge towards the global optimum. Their random nature implies that several successive executions

of these methods lead to different results for the same initialization of the optimization problem. However, they require a large number of evaluations of the objective function in comparison with deterministic methods exploiting the derivative of the objective function [44].

III.6. Deterministic optimization methods

In the literature, we find many conventional (deterministic) optimization methods. It is possible to classify these methods into two broad categories: linear programming and nonlinear programming. The first group deals with solving problems perfectly represented by a system of linear equations while nonlinear programming deals with non-linear problems. Deterministic methods are based on the calculation of the derivative of the problem, or on approximations of the latter.

They therefore require some information on the gradient vector. Many conventional optimization techniques such as linear and nonlinear programming [45], gradient method [42], Newton's method [46], quadratic programming [47, 48], and inner point method [48, 49] have been applied to solve the optimization problem related to the planning and control of electrical networks, in particular the optimization of reactive power.

These methods have the property of converging to the exact "real" mathematical solution while respecting certain conditions related to the proper functioning of the envisaged process, the latter called constraints of equalities and inequalities.

III.7. Metaheuristics: Definition and Principle

The word metaheuristic is derived from two Greek words, meta which means beyond, in a higher level, and heuristic which means the art of inventing, to make discoveries.

The decomposition etymological word allows to understand its meaning: a heuristic that allows to find other heuristics, which promotes emergence. As a reminder, heuristics are simple empirical rules that are not based on sometimes complex scientific analyzes, but on the experience and relationships accumulated over the results. These rules therefore use simply past results to optimize future research by first examining most plausible cases (Ibrahim et al., 1996, Thomas, 1998). More simply, we will say that metaheuristics form a family of optimization algorithms aimed at solving difficult optimization problems, often from the field of operational research, engineering or artificial intelligence (Faure et al., 1974).

They appeared at the beginning of 1980s with the aim of tackling difficult optimization problems for which we do not know more efficient conventional optimization methods. Metaheuristics are iterative stochastic algorithms that use alternatively phases of exploitation,

exploration and learning (memorization) to search for optimal solution. They usually start from an arbitrary solution, then progress in the search until a specified stopping criterion is reached. They aim to converge towards this the niche of the global optimum (i.e., a similar subpopulation in the neighborhood of the optimal solution), without pretending to reach the global optimum.

These algorithms therefore try to find an approximation of the best solution. The quality of the solution obtained therefore results from a compromise with the calculation time. To improve efficiency of research, deterministic methods are often used to generate base used to initialize metaheuristic algorithms.

One of the well-known benefits of metaheuristics is their ability to solve problems without a priori knowledge of mathematical formulations of these. In practice, it is sufficient to be able to associate with one or several variables the value of a given function, for example the result of a simulation. This is very different from deterministic methods (e.g., gradient method) that are essentially based on the calculation or approximation of the derivatives.

Meta-heuristics are often used for their ease of programming and manipulation. They are indeed easily adaptable to any type of optimization problem. Among the meta-heuristics most known are:

genetic algorithms (GA), Optimization algorithms by the Grey Wolf Optimizer (GWO), sine cosine algorithm (SCA) and slaps swarm algorithms (SSA)……etc.

III.7.1. Genetic algorithm optimization

Genetic algorithms (GA) are search algorithms inspired by the mechanisms of the natural evolution of living beings and the genetic. The first work was carried out by Holland in 1975 [38] in the book "Adaptation of Natural and Artificial System" which formalizes genetic algorithms in the context of mathematical optimization. The publication of David Goldberg's book in 1989 [39] describing the use of these algorithms for solving concrete problems, has made the latter more widely known in the scientific community and marked the beginning of a new interest for this optimization technique. These methods focus on simulating the selection process natural in an unfavorable environment inspired by the theory of the evolution proposed by Darwin in 1859 "Journal of Research in the Geology and Natural History. "According to these concepts, when a population is subject to the constraints of a natural environment, only individuals better adapted survive and generate offspring. Over the generations, natural selection allows the appearance of individuals better adapted to the natural environment, to the detriment of those showing notoriously unsuitable, thus ensuring the sustainability of the species. This particularity of natural evolution: the capacity of a population to

explore its environment in parallel and to recombine the best individuals between them, is borrowed by genetic algorithms.

III.7.1.1 Mechanicism of research

Recall that genetics represent an individual by a code, that is to say a set of data (called chromosomes), completely identifying the individual. Reproduction represents in this area, a random mix of chromosomes of two individuals, giving birth to individual children with a new genetic imprint, inherited from parents. The genetic mutation is then characterized in the genetic code of the child by the appearance of a new chromosome, nonexistent in the parent individuals.

This genetic phenomenon of appearance of "mutants" is rare but makes it possible to explain the changes in the morphology of the species, always in the direction of a better adaptation to the natural environment. The disappearance of certain species is explained by the laws of survival according to which only the best adapted individuals will have a sufficient longevity to generate an offspring. Unsuitable individuals will have a tendency to disappear. It is a natural selection that leads from generation to generation to a population composed of more and more adapted individuals [46]. It can be concluded that the operation of a (AG) is based on the following phases:

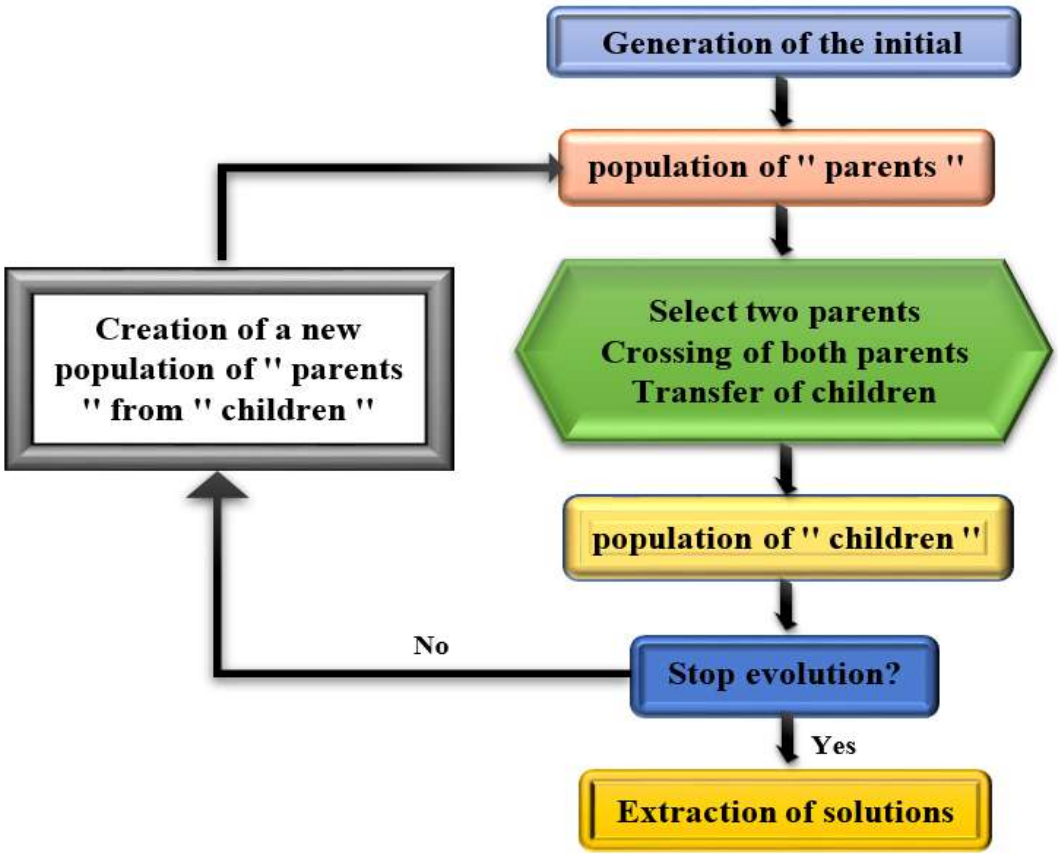


Figure III.3 Flow Chart of the Genetic Algorithm

III.7.1.1.1. Coding and initial population

First, it is necessary to represent the different possible states of the variable whose optimal value is sought in usable form for an AG: it is the coding. This makes it possible to establish a connection between the value of the variable and the individuals in the population, so as to mimic the genotype-phenotype transcription that exists in the living world. There are three main types of coding: binary coding, real coding, and n-base coding.

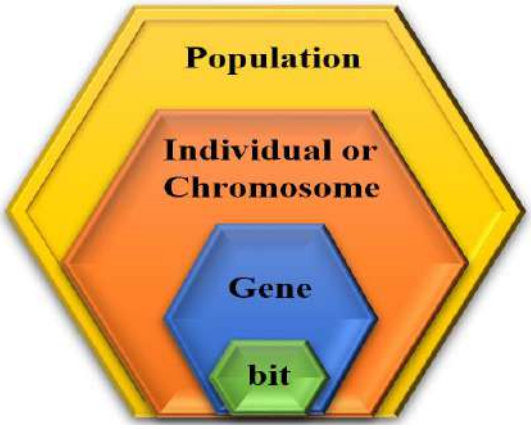


Figure III.4 The four levels of GA organization

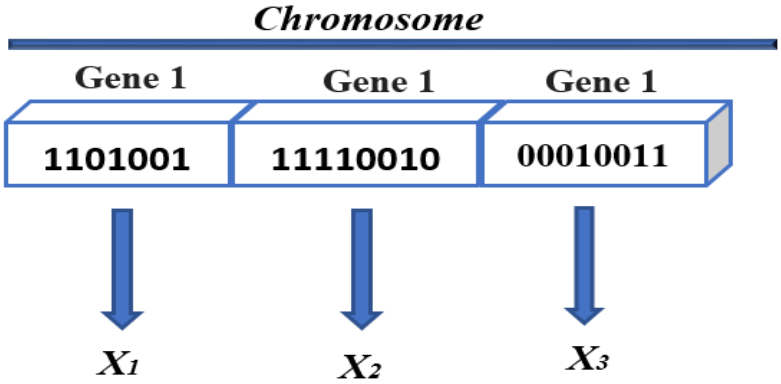


Figure III.5 Illustration of the coding of the variables

III.7.1.1.2. Binary coding

This coding was the first to be used in the field of AG. It has several advantages: minimum alphabet {0,1}, ease of development of genetic operators and existence of theoretical foundations (theory of schemas). Nevertheless, this type of coding has some disadvantages:

1. The performance of the algorithm is degraded in the face of large numerical optimization problems with high numerical accuracy. For such problems, bit-string based AGs have poor performance as shown by Michalewicz [47].

2. The Hamming distance between two neighboring numbers (number of different bits) can be quite large in the binary coding: the integer 7 corresponds to the string 0111 and the string 1000 corresponds to the integer 8. Now the Hamming distance between these two chains is 4, which often creates a convergence, not the achievement of the optimal value.

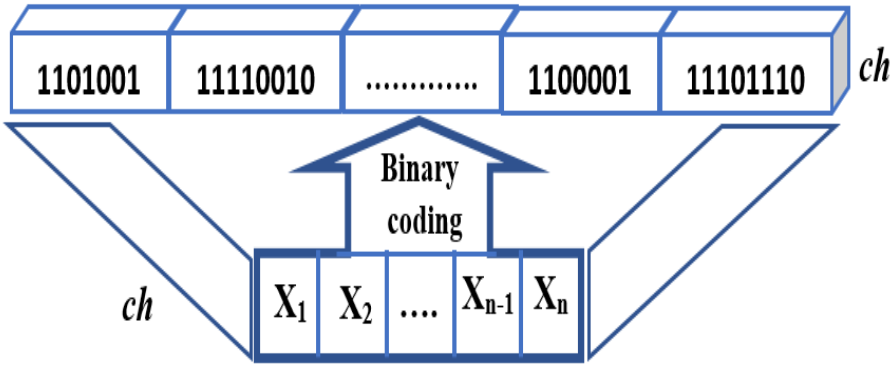


Figure III.6 Binary Coding

III.7.1.1.3. Real coding

It has the merit of being simple. Each chromosome is in fact a vector whose components are the parameters of the optimization process. For example, if we look for the optimum of a function of n variables f (x_1, x_2, ..., x_{n-1}, x_n), we can simply use a chromosome ***ch*** containing the n variables.

With this type of coding, the chromosome evaluation procedure is faster because there is no transcoding step (from binary to real). The results given by [47] show that the actual representation often leads to a better accuracy and a significant gain in terms of execution time.

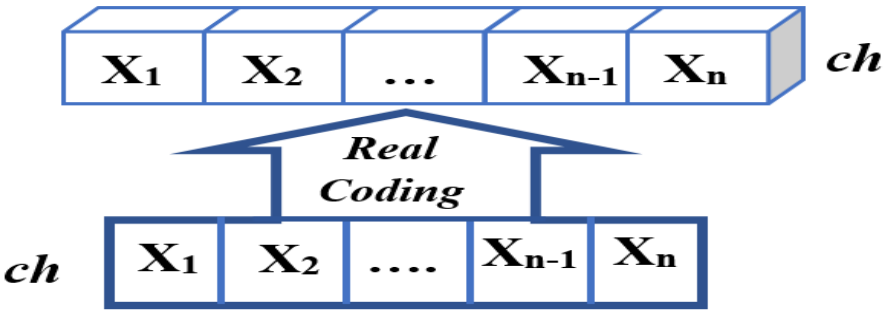


Figure III.7 Real Encoding

III.7.1.2. Operators used by GA

III.7.1.2.1. The selection

First, a population of random size is generated with a generally appropriate binary coding. Each individual (chromosome) designates a coded bit chain, which represents genes that are the variables of the cost function (V_1, V_2, V_3 ....).

Each bit is represented with two values 0 or 1 called allele. This operation is inspired by both the theory of evolution of species: individuals with better adaptation (fitness) are more likely to copy in the second generation, i.e. the strongest individuals survive with increasing probability

III.7.1.2.1.2. Crossing

First and foremost, the goal of this operation is to create diversity in our population because exploitation (copying of the best chromosome) does not lead to an optimal exploration of the entire research space, in reality we only explore part of our space if the individuals are similar the crossing operator is only a juxtaposition of the best portions of the old chromosomes whose purpose is to generate good new chromosomes and the process is repeated until the convergence towards the optimal solution (better adaptation).

There are a large number of crossover operators, the most classic in the context of stochastic optimization are (Figure 8):

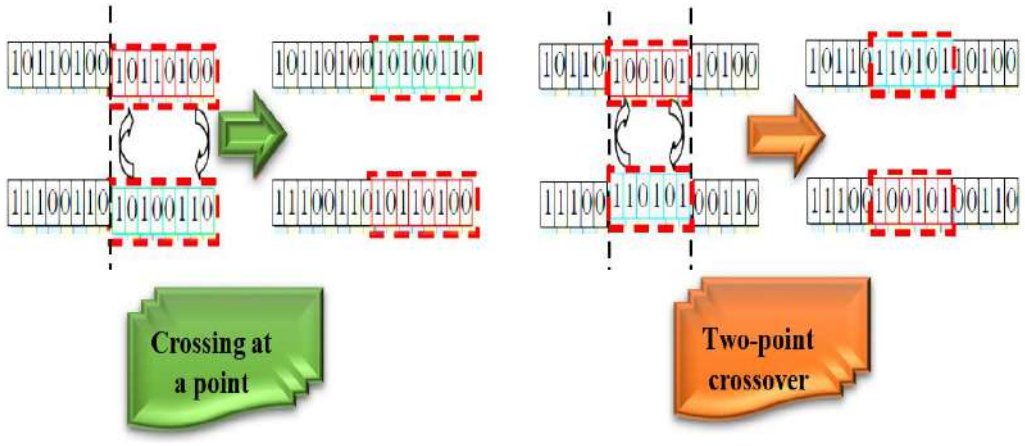


Figure III.8 Representation of the crossing operation

- **crossing at a point**, where a crossing site is chosen randomly on the chromosome, then the code chains are exchanged around this site.
- **The two-point crossing**, two crossing sites are chosen, and the code portions are exchanged alternately.

- **the uniform crossing**, where each gene of a descendant is randomly selected from the genes of the parents having the same position in the chromosome. Quite often the second descendant is built by taking the complementary choices of the first. Other types of crossings exist, such as the multipoint crossover, or specialized crosses as in the case of the commercial traveler problem or scheduling problems, which take into account the particular structure of the coding used.

III.7.1.2.1.3. The Mutation Operator

Schematically, the mutation effects a minor disruption of the chromosome of the individual, for example in the case of binary coding, a mutation site is chosen randomly, and the corresponding bit is inverted (see Figure 9).

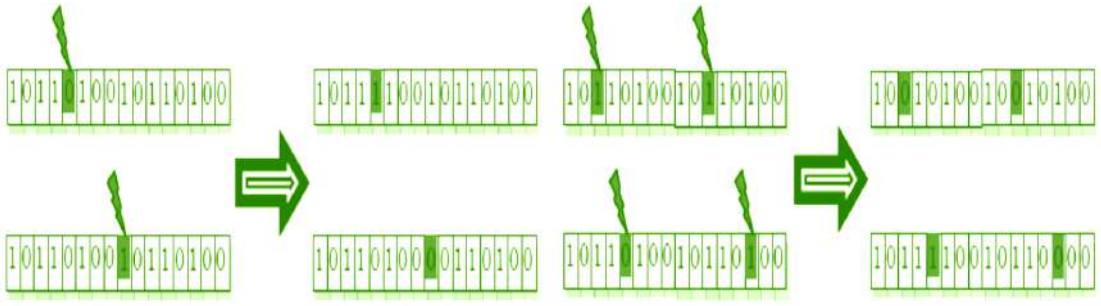


Figure III.9 Representation of the transfer operation

The effect of this operator is to "disturb" the tendency to concentration induced by selection and crossing, so as to leave the population the opportunity to "visit" other areas of the research area.

The probability of mutation usually remains very low and, very often, it is maintained at a fixed value throughout the evolution of the GA. Genetic patterns based on a variable mutation probability, which decreases as the GA evolves, are also used. From a theoretical point of view, it has been proved that such an AG converges towards the global optimum of its search space for a finite population size, if its probability of mutation pm (k) decreases with each generation while respecting the minimum bound.

III.7.2. The Grey Wolf Optimizer (GWO)

Recently, a new powerful meta-heuristic optimization algorithm called the Grey Wolf Optimizer has been introduced by S. Mirjalili et al. [53]. It has been developed mainly to solve the non-convex engineering optimization problem. It possesses some main features compared to its analytical count parts methods such as it is inspired from nature behaviors concept which can typically related

to several real physical phenomena, it has a very simple concept which allows the easy implementation, it is very flexible where it can be applied to many different problems without any special changes in the structure of the algorithm from its initial version and the important issue that it does not require any matrix or derivatives calculation which make it very competitive to complex problems and highly suitable for real problems with expensive or unknown derivative information[53].

This algorithm is inspired from the natural behaviour of the Grey Wolf which belongs to specified and elected family called "Canidae family". Indeed, the Grey Wolves are classified as highly predators which mean that they are at the top of the food provision sequence, where they prefer to live in groups of 5 to 12 maximum under a pyramidal social dominant policy as shown in Figure 10.

The dominant wolves named as alpha (α) wolves, consist of both male and females that are responsible for making decisions, hunting and other activities. They dictate orders and decisions on others but sometimes some democracy takes place where alpha wolves listen to others in the group. Although the alpha wolves are not necessarily the strongest wolves and they are followed by other wolves named as leading wolves [54].

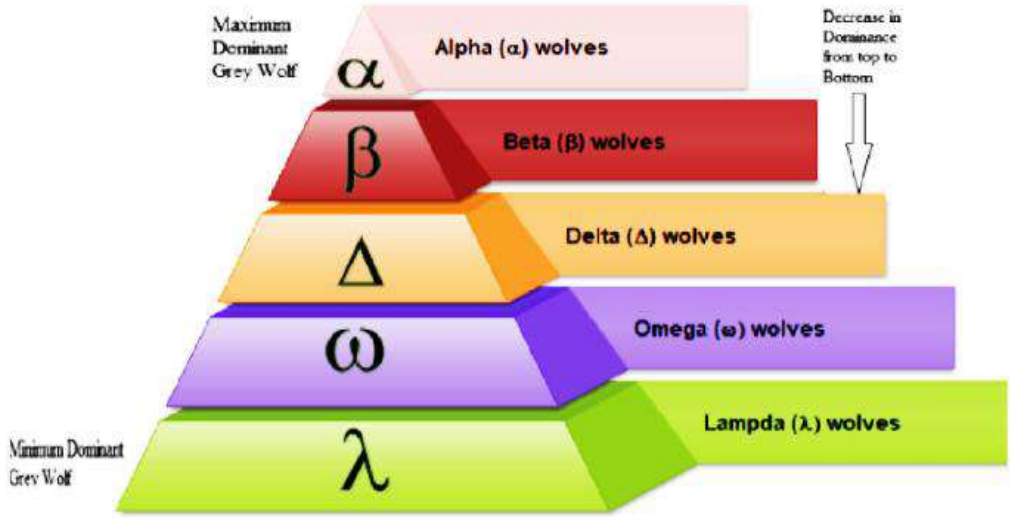


Figure III.10 The Pyramidal levels principle of the grey wolves

The second class is called beta (β) wolves. As well as alpha wolves, beta wolves may be male or female which help in supervising and support the alpha wolves and they are the best candidate to replace the dead or disappeared ones of the alphas. They obey alpha wolves but they are allowed to give orders to the wolves with low hierarchy classing.

The lowest ranking level is delta (Δ) wolves that are playing the role of scapegoat. They are just following orders and undertaking the overriding wolves. However, serious warfare would take place

if the group misses one delta wolf. Inferior wolves or omega (ω) wolves are lower rankings than alpha, beta and delta and they have to submit to them but they direct the kappa (k) wolves and lambda (λ) wolves of lowest hierarchy classes which contain the elders, scouts, hunters, caretakers, and sentinels' wolves. Sentinels protect the group.

Elder wolves are veteran wolves, who second hand to be alpha or beta. Hunters assist the alphas and betas when hunting quarry and providing food for the group. At last, the caretakers are responsible for the illness, weak and injured wolves in the group. According to Muro et al. [55], the main acts of grey wolf hunting are as follows:

1- Tracking, chasing and approaching the prey are shown in Fig. 5. (a), (b) and (c).

2- Pursuing, encircling is shown in Fig. 5 (d), (e) and (f).

3- Harassing the prey until it stops moving and attack towards the prey are shown in Figure 11 (g), (h) and (i).

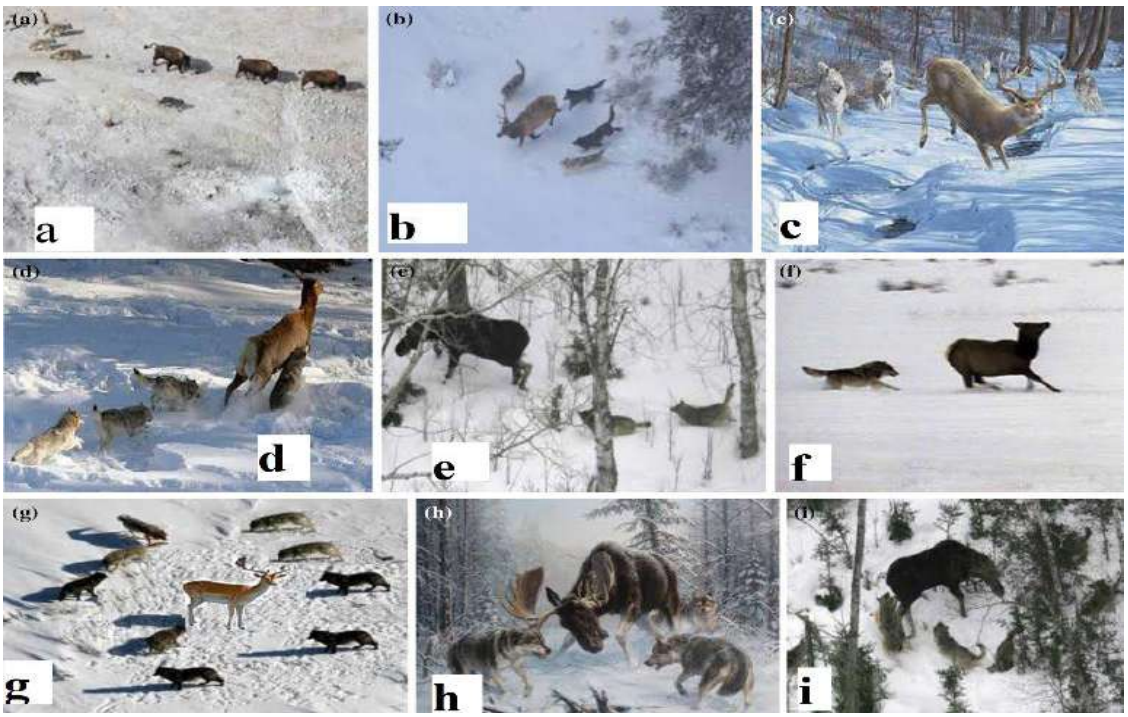


Figure III.11 The principle of the Grey Wolf hinting strategy

The GWO algorithm simulates and imitates the real hunting behaviour and the pyramid clusters of the grey wolves. In this algorithm, it is assumed that the best or fittest solution is named alpha (α). Consequently, the second and third best solutions are named beta (β) anddelta (Δ), respectively. The rest of the candidate solutions are assumed to be omega (ω), kappa (κ) and lambda

(λ). Inthe GWO algorithm, the optimization (i.e. hunting process to catch the desired prey) is guided by α, β and Δ wolves. The ω, $\lambda$and κ wolves follow these three wolves. In order to mathematically model the encircling behaviour, the following equations have been proposed [54]:

$$\vec{D} = \left|\vec{C}.\ \vec{X}_{pery}(t) - \vec{X}_{Gwolf}(t)\right| \quad \text{(III.1)}$$

$$\vec{X}_{Gwolf}(t+1) = \vec{X}_{pery}(t) - \vec{A}.\vec{D} \quad \text{(III.2)}$$

Where$t$indicates the current iteration, $\vec{A}$and $\vec{C}$are coefficient vectors,$\vec{X}_{pery}$ is the position vector of the prey, and $\vec{X}_{Gwolf}$indicates the position vector of a grey wolf. The vectors $\vec{A}$ and $\vec{C}$are calculated as follows:

$$\begin{cases} \vec{A} = 2\vec{a}.\ \vec{r}_1 - \vec{a} \\ \vec{C} = 2\ .\ \vec{r}_2 \end{cases} \quad \text{(III.3)}$$

Where the entries of $\vec{a}$ are linearly decreased from 2 to 0 over the number of iterations, and $\vec{r}_1$ and $\vec{r}_2$are random vectors who's their entries are varying within the interval of $[0,1]$. To clarify the effect of equations (III.1) and (III. 2) a 2D position vector and the possible positions of the neighbours are clarified in Figure 12 Based on the random vectors and$\vec{r}_1$ and $\vec{r}_2$ and the actual positions vectors, the grey wolves can reach any position among the possible available positions as shown in Figure 12 Therefore, A grey wolf can update its position inside the space around the prey in any random location by using equations (III.3) as shown in Figure 13.

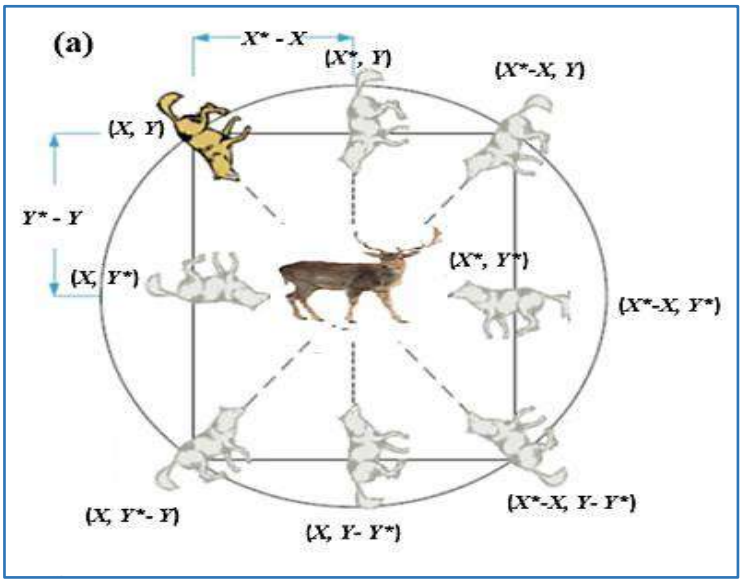


Figure III.12 Two-dimensional position vectors and possible next location w.r.t. prey [53].

Grey wolves are qualified to localize the position of a prey and then make a circle around it. The alpha wolf takes the lead in the process of hunting with the participation of beta and delta wolves. However, in a defined limited search space the exact location of the ideal prey is not known initially. Therefore, during the simulation of the mathematical model which imitates the hunting process of grey wolves, it is supposed that the alpha wolf presents the best candidate solution. Where, the beta and delta wolves have better information about the prey potential location. In this case, the three first best solutions obtained till the actual iteration are memorized and force the other search candidates including the delta, the kappa and the lambda to update their positions according to the location of the best search candidate obtained so far. The positions of the three first search candidate's alpha, beta and delta can be updated based on equations (III.4), (III.5) and (III.6), respectively.

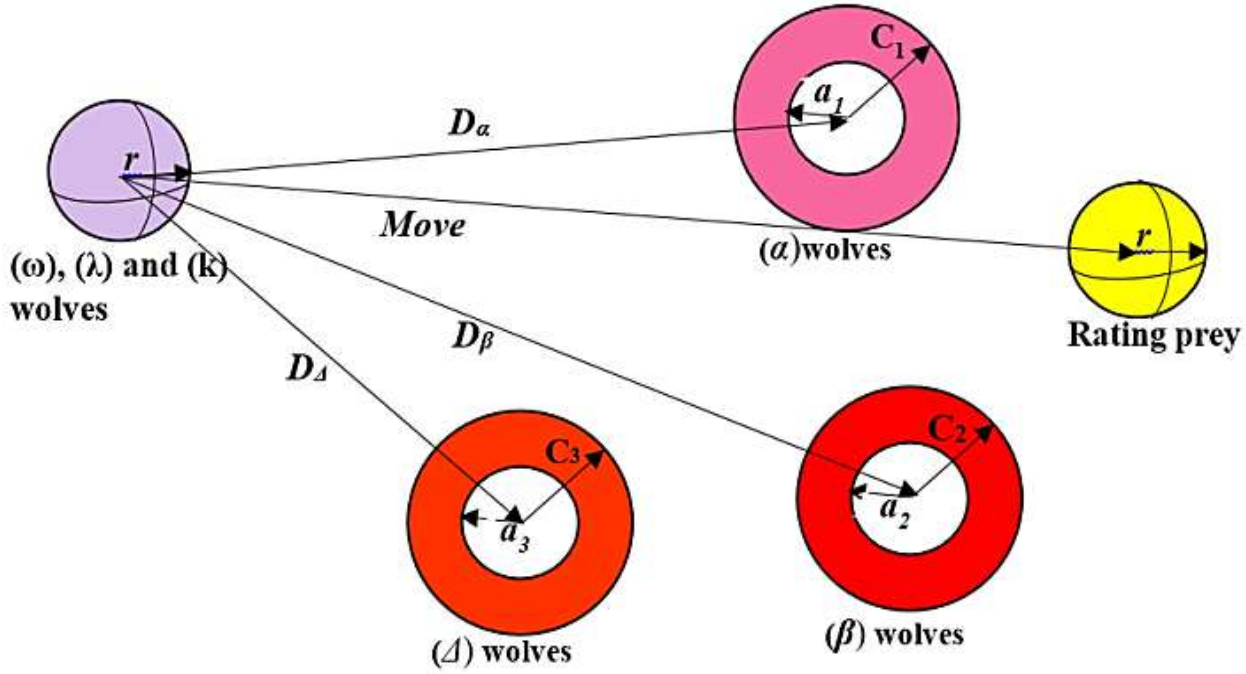


Figure III.13 The principle of the position updating

$$\vec{D}_{\alpha} = \left|\vec{C}_1 . \vec{X}_{\alpha} - \vec{X}\right| \quad \text{(III.4)}$$

$$\vec{D}_{\beta} = \left|\vec{C}_2 . \vec{X}_{\beta} - \vec{X}\right| \quad \text{(III.5)}$$

$$\vec{D}_{\Delta} = \left|\vec{C}_2 . \vec{X}_{\Delta} - \vec{X}\right| \quad \text{(III.6)}$$

The position vector of the prey with respect to alpha, beta and delta wolves can be calculated using the following mathematical formulation:

$$\vec{X}_1 = \vec{X}_{\alpha} - \vec{A}_1 . (\vec{D}_{\alpha}) \quad \text{(III.7)}$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 . (\vec{D}_\beta) \quad \text{(III.8)}$$

$$\vec{X}_3 = \vec{X}_\Delta - \vec{A}_3 . (\vec{D}_\Delta) \quad \text{(III.9)}$$

The best position can be calculated by taking and average of alpha, beta and delta wolf's positions as follows:

$$\vec{X}(t+1) = \frac{1}{3}(\vec{X}_1 + \vec{X}_2 + \vec{X}_3) \quad \text{(III.10)}$$

III.7.3 Sine Cosine Algorithm (SCA)

The SCA is another advancement method for taking care of improvement issues which makes different introductory arbitrary competitor arrangements and expects them to vacillate outwards or towards the best arrangement utilizing a numerical model dependent on sine and cosine capacities. It comprises of a few irregular and versatile factors and furthermore are coordinated to this calculation to underline investigation and abuse of the inquiry space in various points of reference of improvement. It was recently introduced by Mirjalili [56].

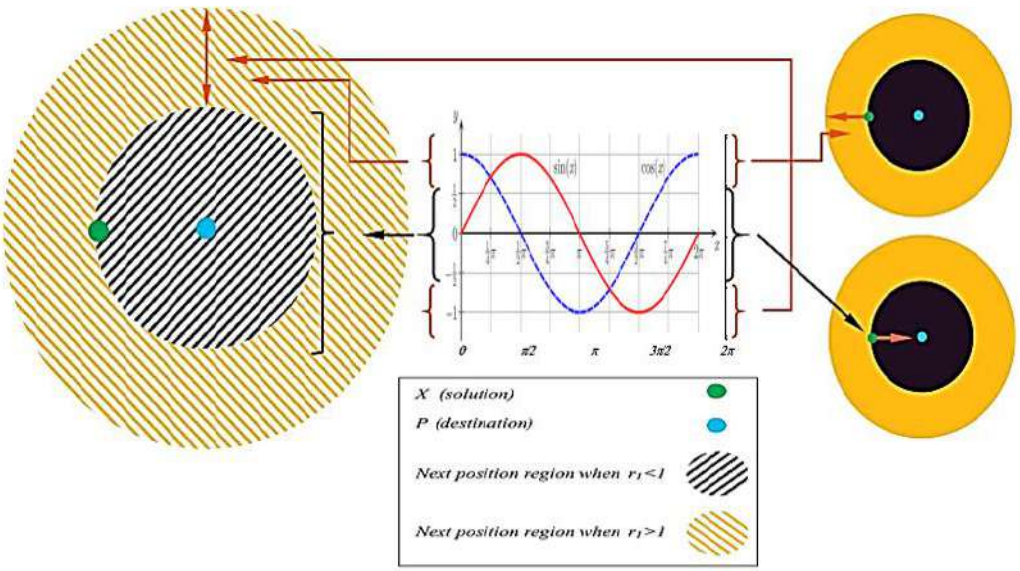


Figure III.14 Effects of Sine and Cosine on the next position.

The following equation shows the mathematical formulation of SCA:

$$M_k^{t+1} = \begin{cases} M_k^t + a_1 \times \sin(a_2) \times |a_3 W_k^t - M_k^t|, & a_4 < 0.5 \\ M_k^t + a_1 \times \cos(a_2) \times |a_3 W_k^t - M_k^t|, & a_4 \geq 0.5 \end{cases} \quad \text{(III.11)}$$

where M_k^{t+1} is the position of current solvent in kth dimension; t indicates the iteration of current, a_1 , a_2 and a_3 are arbitrary numbers, W_k is a position of the target point in kth dimension, a_4 is number of random [0, 1].

The range of sine and cosine in eqs (III.12) is redeveloped by the condition to adjust among misuse and investigation following as:

$$a_1 = x - t\frac{x}{T} \tag{III.12}$$

Where T is length of iteration and t signal the iteration of current, x is a constant.

III.7.4 Slap Swarm Algorithm (SSA)

Slaps belong to the family of Slapidae and have transparent barrel shaped body. Their tissues are highly similar to jelly fishes. They also move very similar to jelly fish, in which the water is pumped through body as propulsion to move forward [57]. The shape of a slap is shown in Figure 15.

The biological in ref [58] researches about this creature is in its early milestones mainly because their living environments are extremely difficult to access, and it is really difficult to keep them in laboratory environments. One of the most interesting behavior of slaps, which is of interest in this part, is their swarming behavior.

In deep oceans, slaps often form a swarm called slap chain. This chain is illustrated in Figure 16. The main reason of this behavior is not very clear yet, but some researchers believe that this is done for achieving better locomotion using rapid coordinated changes and foraging.

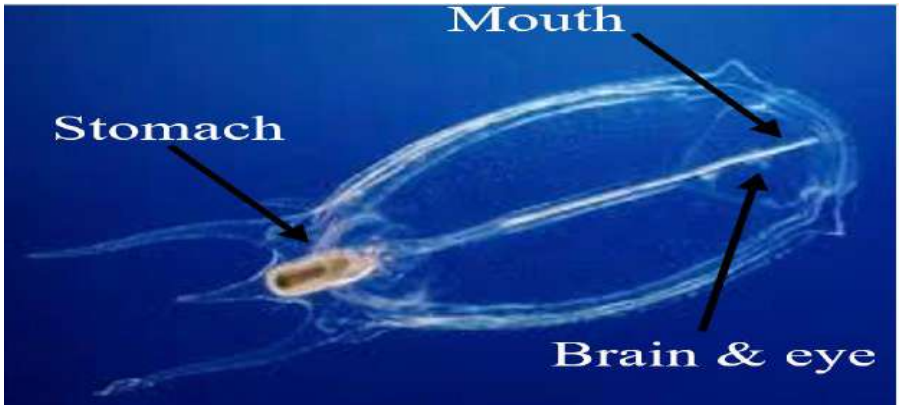


Figure III.15 Individual Slap

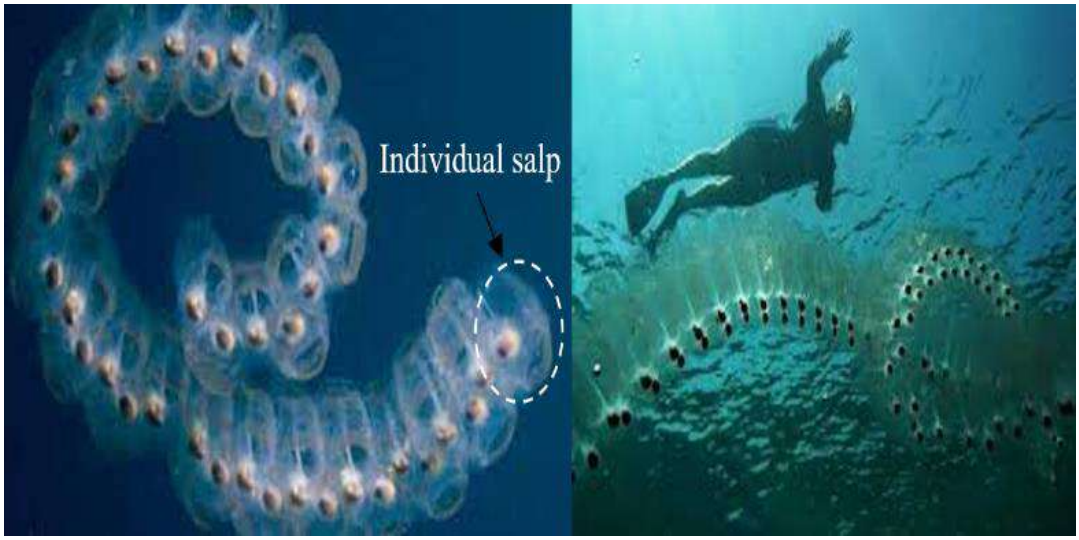


Figure III.16 Chains of Slaps

III.7.4.1. Formulation Mathematical of SAA

In ref [59,60], There is little in the literature to mathematically model the swarming behaviors and population of slaps. In addition, there is no mathematical model of slap swarms for solving optimization problems while swarms of bees, ants, and fishes have been widely modeled and used for solving optimization problems.

This subsection proposes the first model of slap chains in the literature for the purpose of solving optimization problems. Mirjalil in ref [56], To mathematically model the slap swarms, the population is first divided to two groups called leader and followers. The leader is the slap at the front of the chain (swarm), whereas the rest of slaps are considered as followers. As the name of these slaps implies, the leader guides swarm and the followers follow each other (and leader directly or indirectly). Similarly, to other swarm-based techniques, the locations of slaps is defined in an n-dimensional search space where n is the number of variables of a given problem. Therefore, the position of all slaps is stored in a two-dimensional matrix called *X*. It is also assumed that there is a food source called *F* in the search space as the swarm's target. To update the position of the leader the following equation is proposed:

$$X_j^1 = \begin{cases} F_j + c_1((Ub_j - lb_j)\, c_2 + lb_j) & c_3 \geq 0 \\ F_j - c_1((Ub_j - lb_j)\, c_2 + lb_j) & c_3 < 0 \end{cases} \quad \text{(III.13)}$$

Where X_j^1 shows the position of the first slap (leader) in the j^{th} dimension, $F_{j\,is}$ the position of the food source in the j^{th} dimension, Ub_j indicates the upper bound of j^{th} dimension, Lb_j indicates the lower bound of j^{th} dimension, c_1, c_2 and c_3 are random numbers. Eq (III.13) shows that the leader only updates its position with respect to the food source. The coefficient $c_1$is the most important

parameter in slap swarm algorithm (SSA) because it balances exploration and exploitation defined as follows:

$$c_1 = 2e^{-(\frac{4l}{L})^2} \quad \text{(III.14)}$$

where *l* is the current iteration and *L* is the maximum number of iterations. The parameter c_2 and c_3 are random numbers uniformly generated in the interval of [0,1]. In fact, they dictate if the next position in j^{th} dimension should be towards positive infinity or negative infinity as well as the step size. To update the position of the followers, the following equations is utilized (Newton's law of motion):

$$X_j^i = \frac{1}{2}at^2 + v_0 t \quad \text{(III.15)}$$

were $i \geq 2$, X_j^i shows the position of i^{th} follower slap j^{th} dimension, t is time, v_0 is the initial speed, and

$$a = \frac{v_{final}}{v_0} \quad \text{where} \quad v = \frac{x - x_0}{t}. \quad \text{(III.16)}$$

Because the time in optimization is iteration, the discrepancy between itera-tions is equal to 1, and considering $v_0 = 0$, this equation can be expressed as follows:

$$X_j^i = \frac{1}{2}\left(X_j^i + X_j^{i-1}\right) \quad \text{(III.17)}$$

where i ≥ 2 and X_j^i shows the position of i^{th} follower slap in j^{th} dimension. With eqs (III.13) and (III.17), the slap swarms can be simulated.

III.8. Conclusion

This chapter represents a general introduction to deterministic optimization methods and global optimization techniques (metaheuristics) it gives a total view on their philosophy, their implementation, their characteristics and advantages. Then we approached the study of genetic algorithms AG, Optimization algorithms by the Gray Wolf Optimizer, sine cosine algorithm slaps swarm algorithms.

CHAPTER IV

APPLICATION OF META-HEURISTIC ALGORITHMS FOR PMUS PLACEMENT

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IV.1. Introduction

In electrical network organization, some buses are not associated with any generators or compensators or stack, in such buses, the current stream is about equivalent to zero which is called as zero injection Buses. These buses are considered in advancement to limit PMUs distribution.

This chapter focuses on the application of the optimization tool, which are based on meta-heuristic algorithms for solving the problem of optimal placement PMUs for ensuring the complete system observability. The simulation was performed using PC type hp-core i3, 6th generation CPU @ 2.00 GHz, in order to better study the performances of the used algorithms and the accuracy in terms of the precision of the models we have used several distribution networks of different natures such as six IEEE standard power system networks (Institute of Electrical and Electronics Engineers) and a real Algerian power system

IV.2. Application test

In this part we have used four meta-heuristic algorithms such as the Grey Wolves Optimizer (GWO), the Slaps Swarm Optimization Algorithm (SSA), the Sine Cosine Optimization Algorithm (SCA), and the Genetic Optimization Algorithm (GA), for solving the multi-objective optimal placement of PMUs problem. All this algorithm has been applied on two study networks from the IEEE standard system and a real Algerian network.

IV.2.1. Objective function

There are two objective functions, the first to minimize the cost of the installed PMUs in the buses, this function is presented in equation (II.2) and the constraints are defined by equations (II.3 to II.5) respectively. The second objective function is used in the PMU Placement to maximize redundancy in observability, this function is presented in equation (II.22 and II.23)

IV.2.2. Parameters of optimization algorithms used in simulation

The main two parameters of the four used algorithms in the present simulation are represented in Table IV.1

Table IV.1. The parameters of the used optimization algorithms

Methods	*GWO*	*SSA*	*SCA*	*GA*
Size of the population	*30*	*40*	*30*	*100*
Max. N. of generations	*500*	*500*	*500*	*500*

IV.3. Simulation results of the studied cases

IV.3.1. Case of IEEE 9-bus

The IEEE 9-bus structure is shown in Figure. IV.1, where it contains the three synchronous machines with IEEE type-1 exciters, nine buses, six transmission lines, six transformers and three loads. It contains Zero injection buses (ZIB), which are located in three buses such as bus-4, bus-6 and bus-8. The total load connected to this power system is characterized by and active power of 315 MW and a reactive power of 115 MVAr.

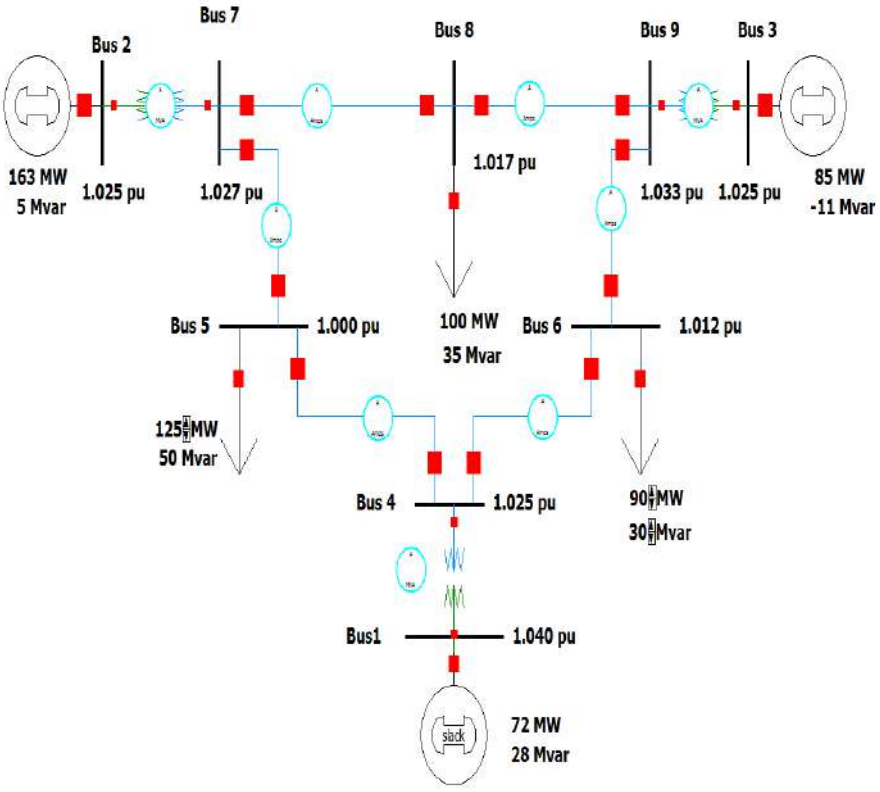


Figure IV.1. The structure if the IEEE 9-bus power system

Firstly, the first test has been performed on the IEEE 9-bus, where the problem of OPP for PMUs is solved under two cases, without and with taking into consideration the zero injection buses as shown in Figures IV.2 and IV.3 respectively. It is obvious from the obtained results that the minimum value of the fitness function is ensured in all cases and it is reached within different number of iterations depending on the used algorithm as shown in Figures. IV.2 and IV.3.

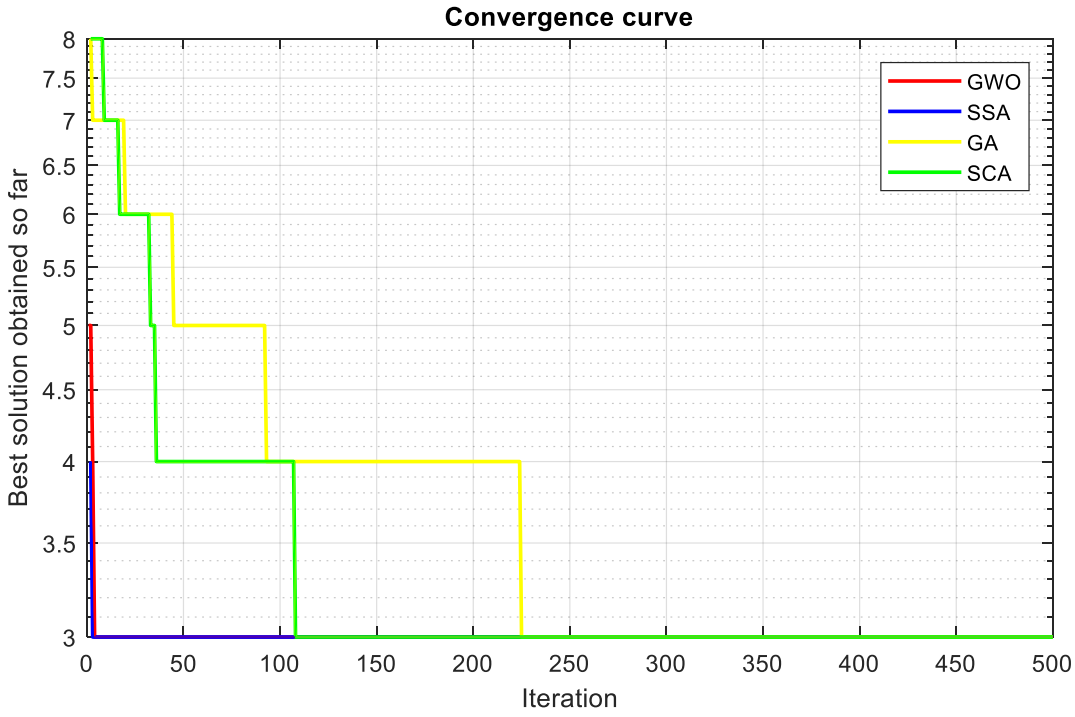


Figure IV.2. The objective function of the four used algorithms used for solving the OPP of PMUs for 9-bus without using the ZIBs

Table IV.2. The obtained results for OPP of PMUs in 9-bus without ZIBs

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	03	3, 4 and 8	10
SSA	03	1, 6 and 8	10
SCA	03	2, 4 and 6	10
GA	03	4, 6 and 8	12

In both tests the best minimum is obtained. Table. IV.1. presents the obtained OPP solution of the considered power system without considering ZIBs (the optimal number of PMUs and their optimal locations to ensure the studied power system observability). Whereas, Table.VI.2. presents the obtained OPP solution with considering ZIBs. In both cases the value of SORI is calculated to evaluate the performance of each.

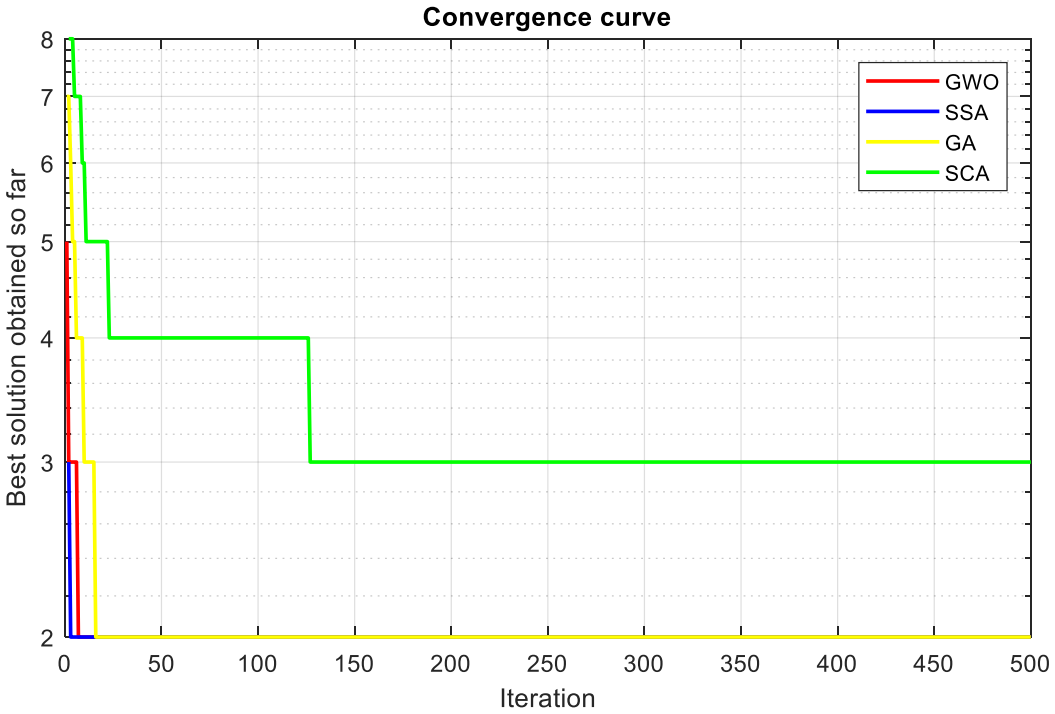


Figure. IV.3. The objective function of the four used algorithms used for solving the OPP of PMUs for 9-bus with using the ZIBs

Table IV.3. The obtained results for OPP of PMUs in 9-bus with ZIBs

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	02	6 and 8	8
SSA	03	1, 6 and 8	9
SCA	02	4 and 8	8
GA	02	6 and 8	8

It can be concluded that with the first test where there the ZIBs and not taken into account, all the algorithms give the same results to fulfill the requirement of the full observability of the studied power system. However, the obtained result for each algorithm do not give the same location within the nine buses, furthermore it is found that the AG algorithm gives the highest SORI. On the other side, in the second test when the ZIBs are considered in the OPP of PMUs, it is found that tow PMUs are sufficient to ensure the full observability of the studied power system with the algorithms GOW,

SCA and GA, and three PMUs are obtained for the SAA algorithm with lowest SORI. It can be said that almost the used algorithm gives acceptable results for ensuring the whole observability of the studied power system.

IV.3.2. Case of IEEE 14-bus

The IEEE 14-bus structure is shown in Figure. IV.4, it contains five synchronous machines with IEEE type-1 exciters where three of which are synchronous compensators used for ensuring control support sensitivity, fourteen buses, twenty transmission lines, eight transformers and eleven constant impedance loads. On the other side, this power system contains one Zero Injection Bus (ZIB) which is placed in bus seven. The full load connected to this power system is characterized by an active power of 259 MW and reactive power of 73.5 MVAr.

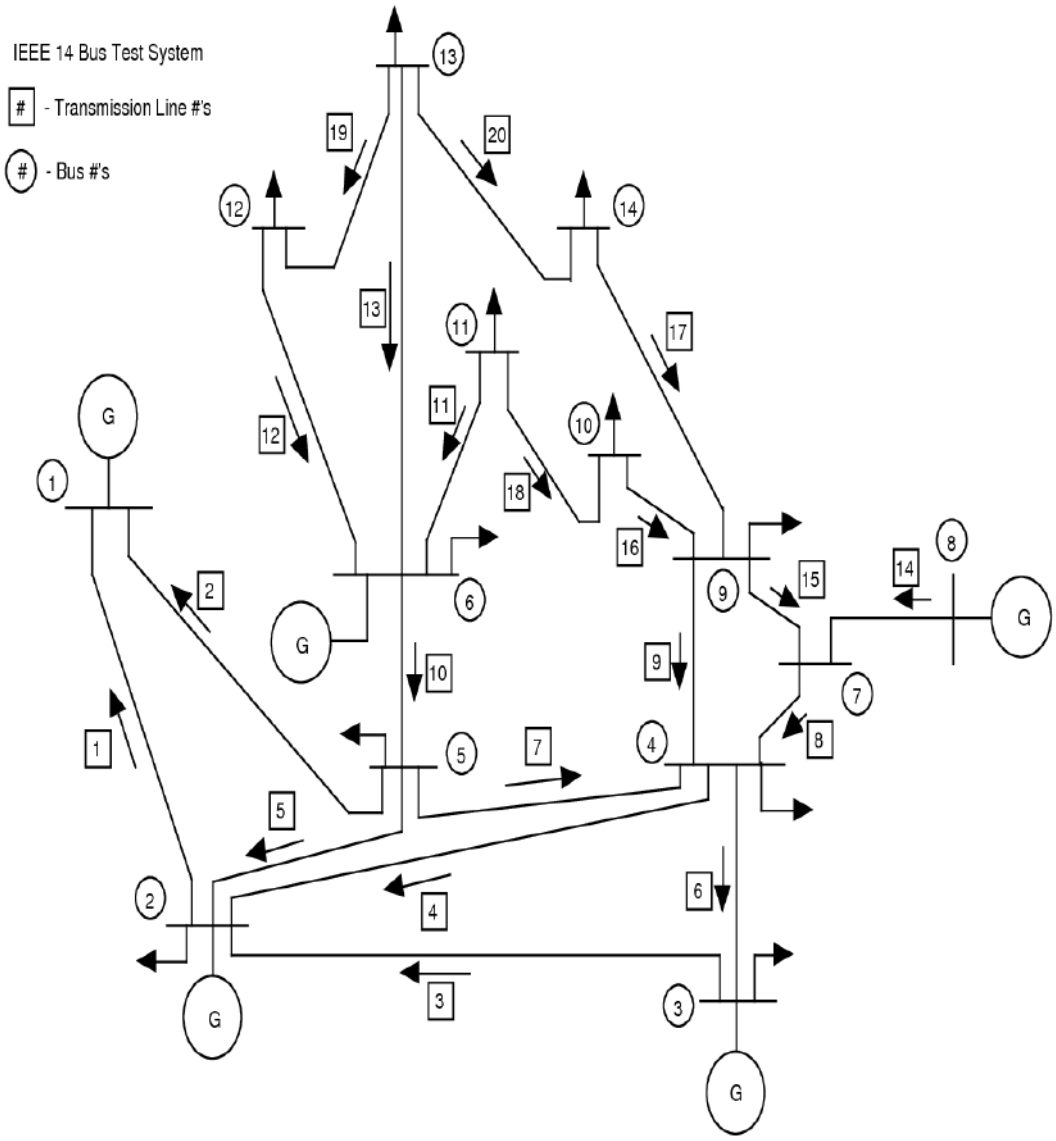


Figure IV.4. The structure if the IEEE 14-bus power system

In this case, two testes have been performed on the IEEE 14-bus power system where the OPP of PMUs has been solved under the two cases without and with taking into consideration the zero injection buses as shown in Figures. IV. 5 and IV.6 respectively. It is obvious from the obtained results that the minimum value of the fitness function for both tests is ensured in all cases and it is reached within different iterations depending on the used algorithm as shown in Figure. IV.5 and figure. IV.6 respectively.

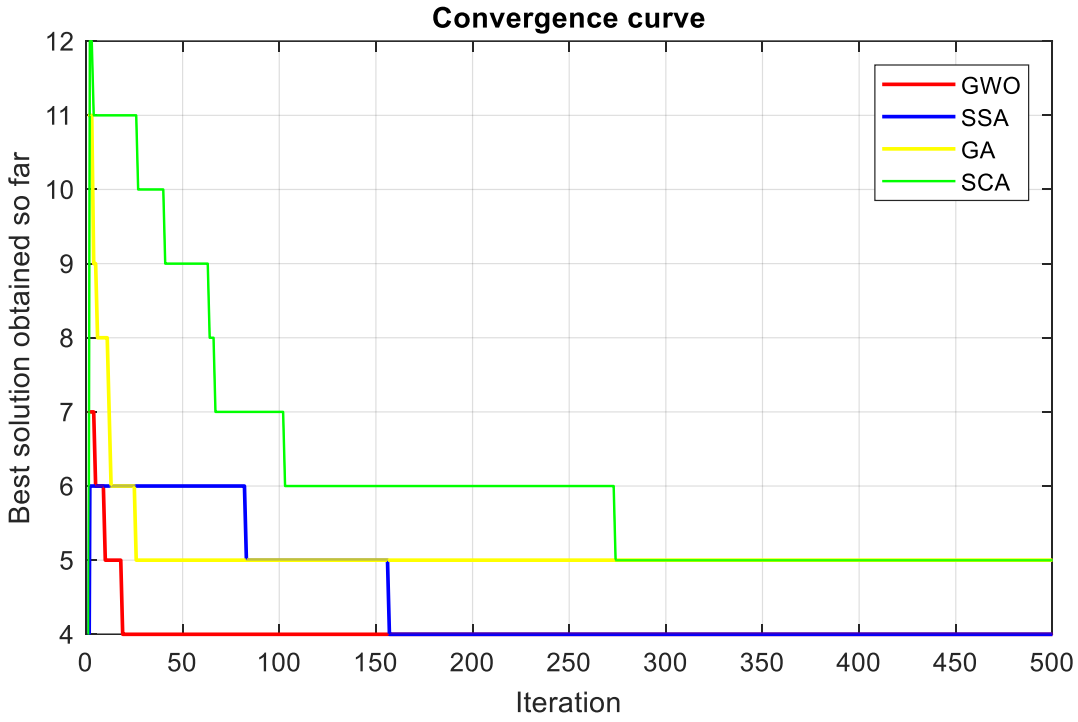


Figure IV.5. The objective function of the four used algorithms used for solving the OPP of PMUs for 14-bus without using the ZIBs

Table IV.4. The obtained results for OPP of PMUs in 14-bus without ZIBs

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	4	2, 7, 9, 11 and 12	16
SSA	4	2, 6, 8 and 9	17
SCA	5	2, 7, 9, 11 and 12	20
GA	5	3, 5, 6, 7 and 9	22

In the first test where the ZIB is not taken into account, the obtained results of the OPP of PMUs for different used algorithms are presented in Table. IV.3. It is obvious that the lowest number

of PMUs can be obtained with SSA to ensure the whole observability of the studied power system, in the same time the SORI is the lowest. While for the second test where the ZIB is taken into account the obtained results of the OPP of PMUs are presented in Table. IV.4. It can be noticed clearly that all the algorithms allow obtaining the same number of PMUs, where for the GWO, SSA and SCA they have the same location, differently from the GA, this last has the lowest SORI.

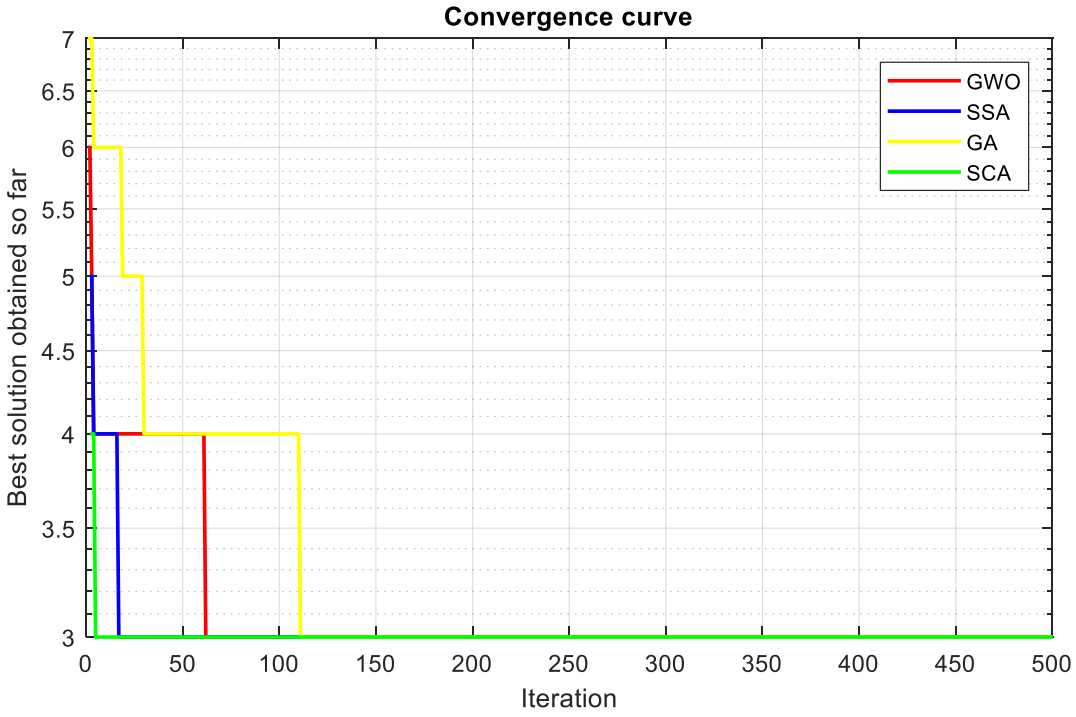


Figure IV.6. The objective function of the four used algorithms used for solving the OPP of PMUs for 14-bus with using the ZIBs

Table IV.5 The obtained results for OPP of PMUs in 14-bus with ZIBs

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	3	2, 6 and 9	16
SSA	3	2, 6 and 9	15
SCA	3	2, 6 and 9	15
GA	3	2, 10 and 13	12

IV.3.3. Case of IEEE 30-bus

The IEEE 30-bus configuration is shown in Figure. IV.7, it has six synchronous machines with IEEE type-1 exciters where four of which are synchronous compensators, 36 buses, 37 transmission lines, 10 transformers and 21 constant impedance loads. It contains six zero injection buses (ZIB), which are located at the buses 5, 6, 9, 11, 25 and 28. The total load demand in the whole studied power system is characterized by an active power of 283.4 MW and a reactive power of 126.2 MVAr.

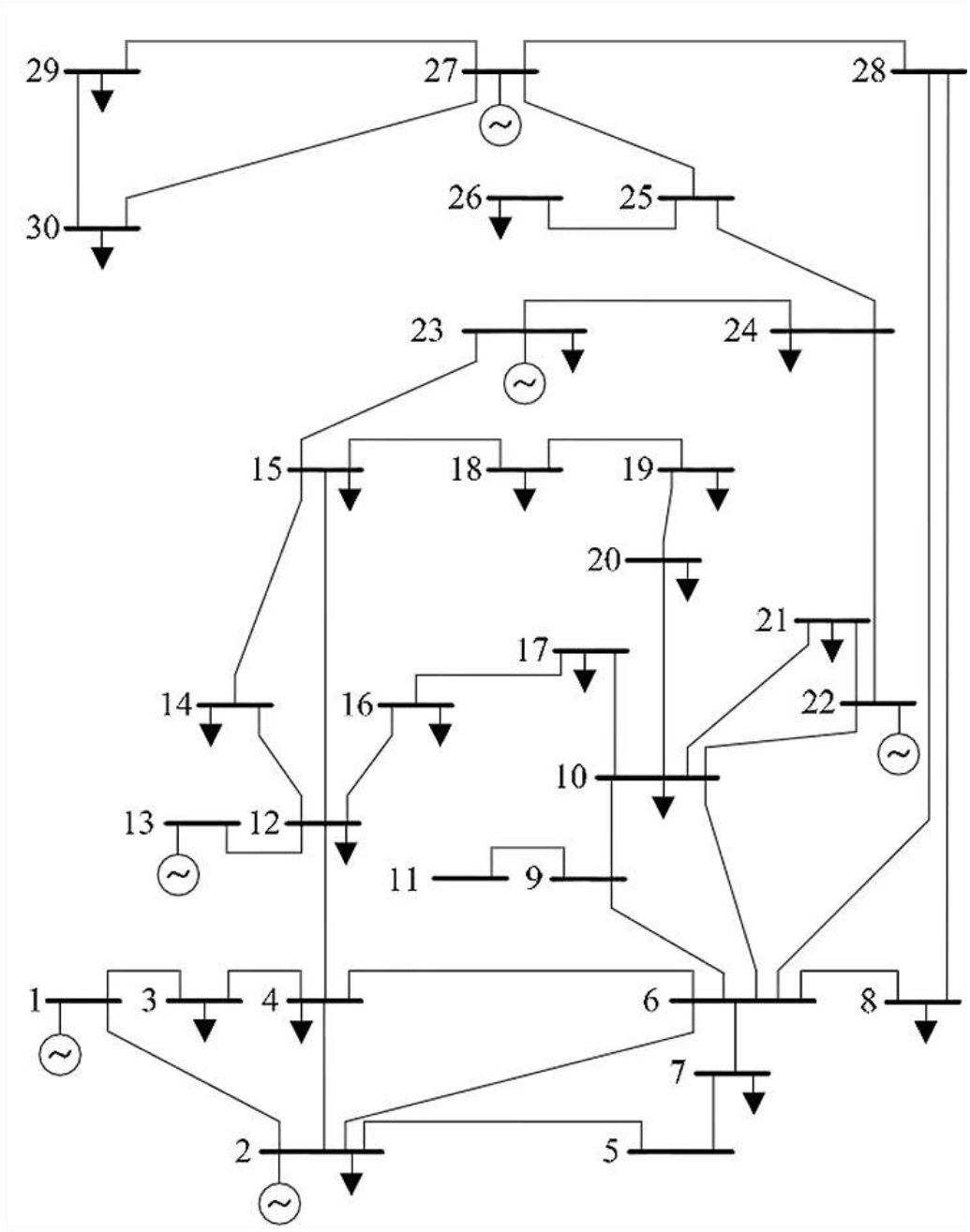


Figure IV.7. The structure if the IEEE 30-bus power system

In this case, two tests have been performed for solving the OPP of PMUs for the studied IEEE 30-bus, the two tested have been achieved with and without ZBIs respectively. The obtained results of the both tests for the minimization of the objective function are shown in Figure. IV.8 and IV.9. It is obvious that the minimum value of the fitness function is ensured in all cases and it is reached under different number of iterations depending on the used algorithm as shown clearly in Figure. IV.8 and figure IV.9.

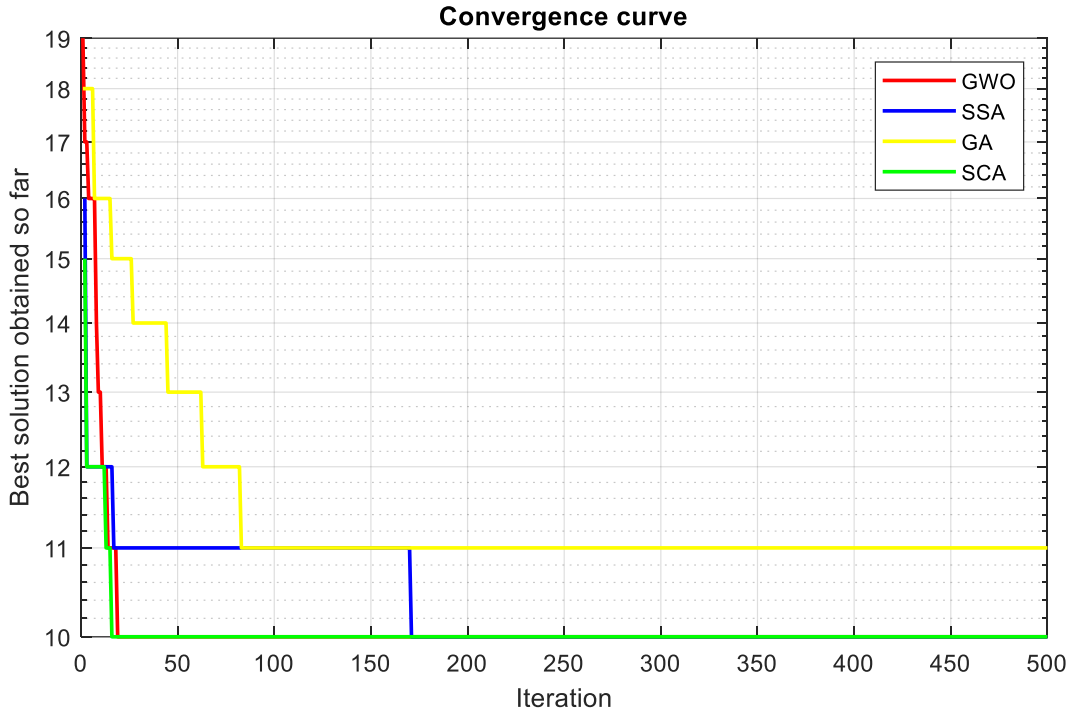


Figure IV.8. The objective function of the four used algorithms used for solving the OPP of PMUs for 30-bus without using the ZIBs

Table IV.6. The obtained results for OPP of PMUs in 30-bus without ZIBs

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	10	1, 2, 6, 9, 10, 12, 15, 19, 25 and 29	48
SSA	10	2, 4, 6, 10, 11, 12, 18, 23, 26 and 30	44
SCA	10	1, 2, 6, 9, 10, 12, 15, 20, 25 and 30	48
GA	11	2, 3, 6, 11, 13, 15, 16, 19, 22, 26 and 30	40

The results of the OPP of PMUs for the first test are presented in Table·VI.6. It is obvious that for the algorithms GOW, SSA and SCA ten PMUs can ensured the observability of the whole studied power system. Whereas, for the GA the obtained number is 11 to ensure the same task which means more costs are required.

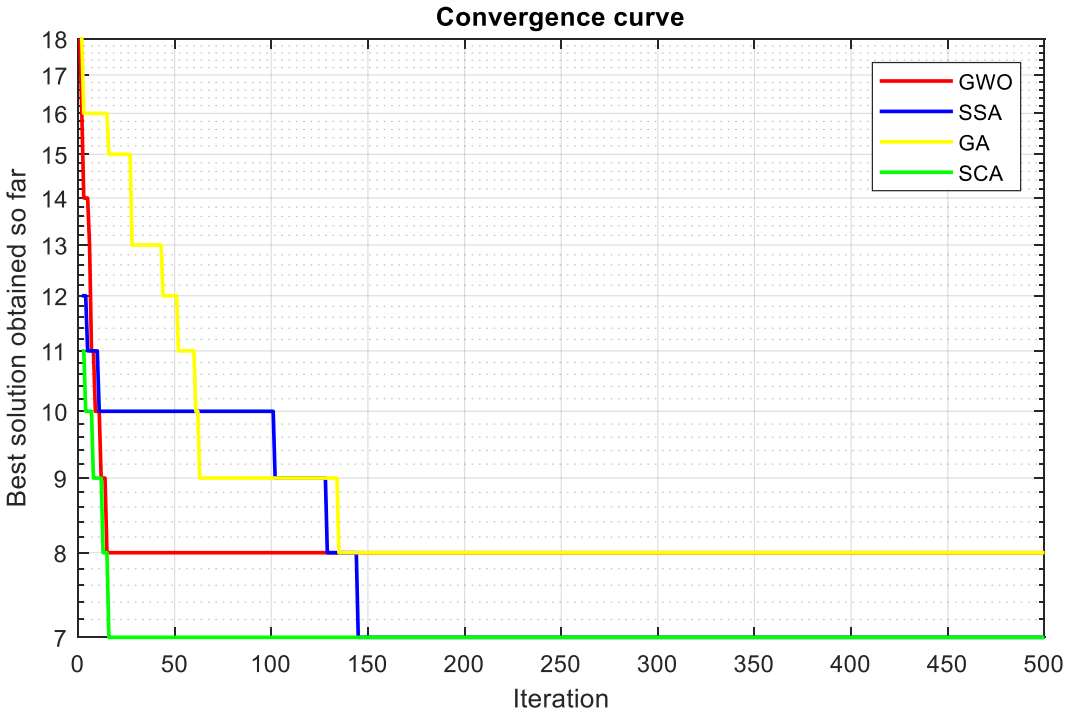


Figure IV.9. The objective function of the four used algorithms used for solving the OPP of PMUs for 30-bus with using the ZIBs

Table IV.7. The obtained results for OPP of PMUs in 30-bus with ZIBs

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	8	2, 4, 6, 10, 12, 15, 25 and 30	43
SSA	7	3, 6, 10, 12, 18, 24 and 29	34
SCA	7	3, 6, 10, 12, 18, 24 and 30	34
GA	8	3, 6, 10, 12, 15, 24, 26 and 27	40

The obtained results of OPP of PMUs for the second test are presented in Table. IV.76. It is obvious when the ZIBs are taken into account the number of the required PMUs to ensure the whole observability of the studied power system, is reduced to seven for SSA and SCA algorithms, whereas it is reduced to eight for the other two algorithms. Therefore, it can be said that taking into account the ZIBs in solving the OPP presents more benefits form point of technical and economical point of view.

IV.3.4. Case of IEEE 39-bus

The modified IEEE 39-bus test power system contains 49 buses, 32 transmission lines, 24 transformers and 10 generators as shown in Figure IV.10. It has 19 constant impedance loads under a total active power of 6097.1 MW and reactive power of 1408.9 MVAr. All the generators are equipped with an IEEE type-1 exciter and a simple turbine governor. This test power system contains ten zero injection buses (ZIB), which are located at the buses 2, 5, 6, 10, 11, 13, 14, 17, 19 and 22.

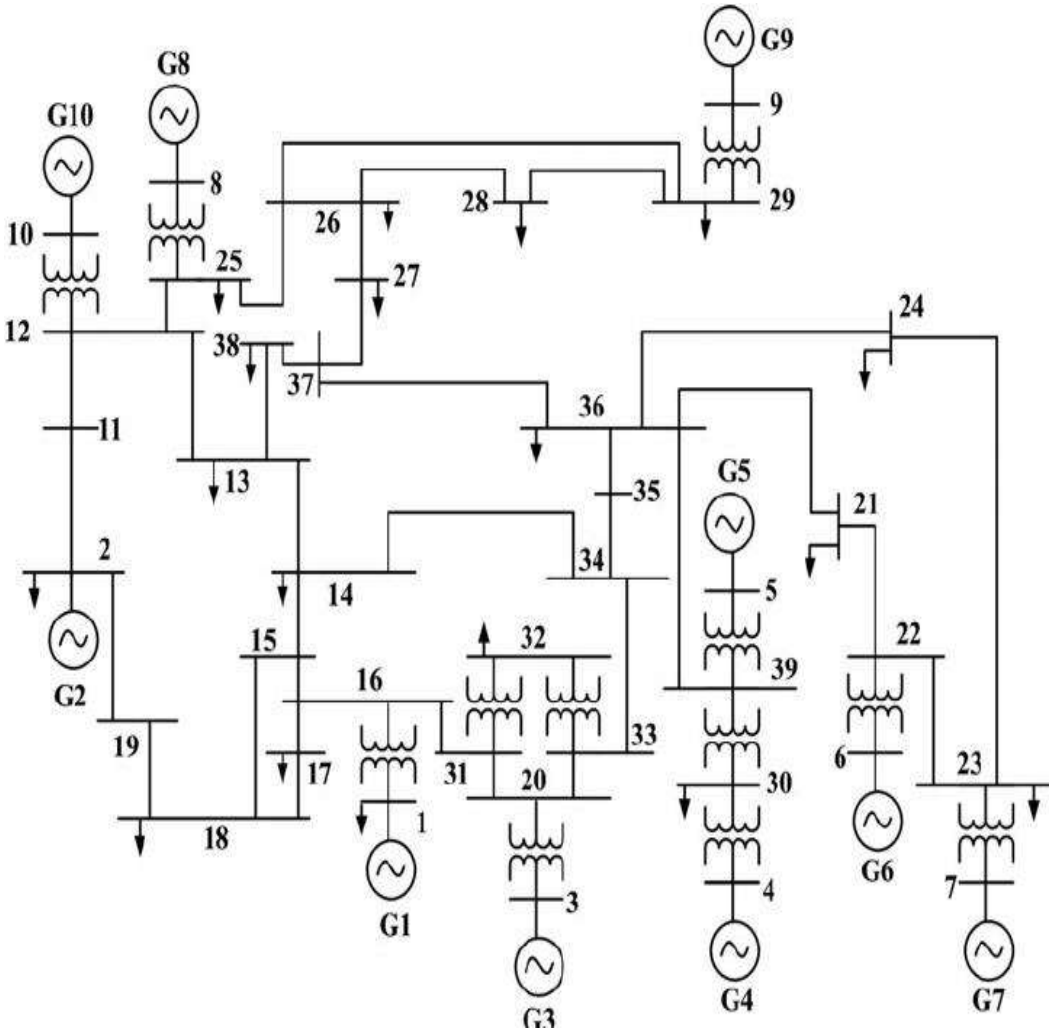


Figure. IV.10. The structure if the IEEE 39-bus power system

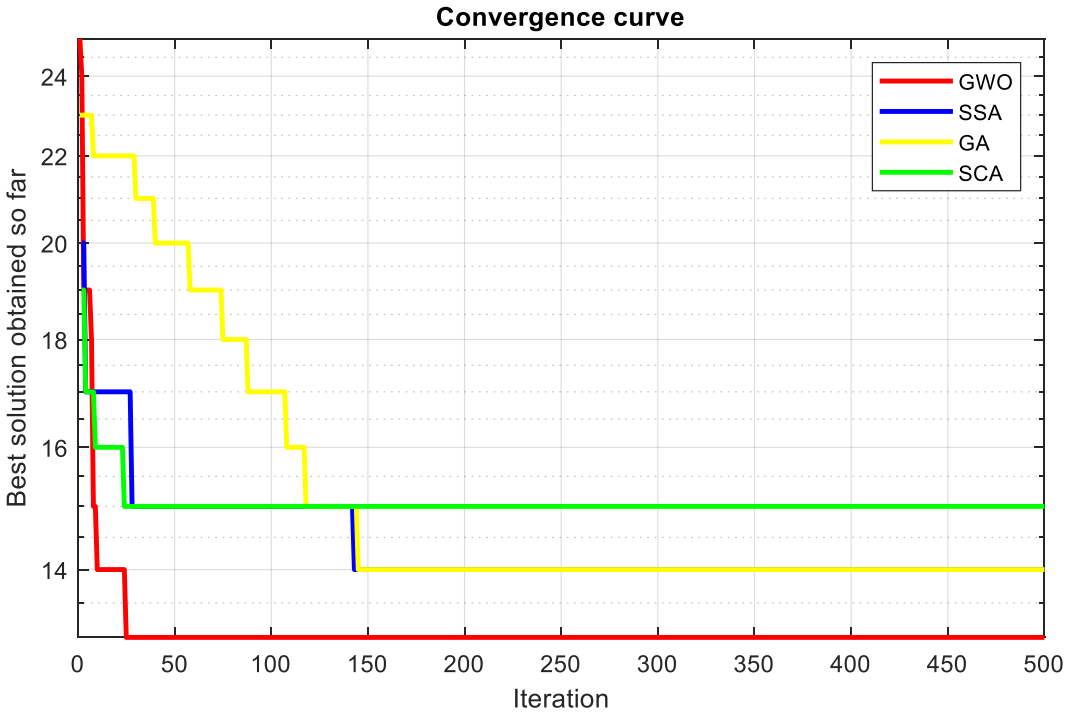


Figure IV.11. The objective function of the four used algorithms used for solving the OPP of PMUs for 30-bus without using the ZIBs

Table IV.8. The obtained results for OPP of PMUs in 39-bus without ZIBs

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	13	2, 3, 6, 9, 12, 15, 20, 22, 23, 26, 29, 32 and 37	48
SSA	14	2, 4, 6, 9, 10, 11, 15, 17, 22, 23, 26, 34, 37 and 38	51
SCA	15	1, 2, 4, 8, 10, 11, 15, 18, 19, 22, 23, 25, 26, 31 and 38	55
GA	14	1, 4, 6, 9, 12, 16, 17, 22, 25, 29, 32, 33, 34 and 36	48

Similarly, to the previous simulations, two tests have been performed for solving the OPP of PMUs in the IEEE 39-bus test power system, without and with considering the ZIBs. The obtained results of the minimization of the objective function for the first test is shown in Figures IV.11. On the other side, the number of MPUs and their corresponding locations are presented in Table IV. 8. It can be seen clearly that the best one is obtained with the GWO, where 13 PMUs are required to ensure the whole studied power system observability.

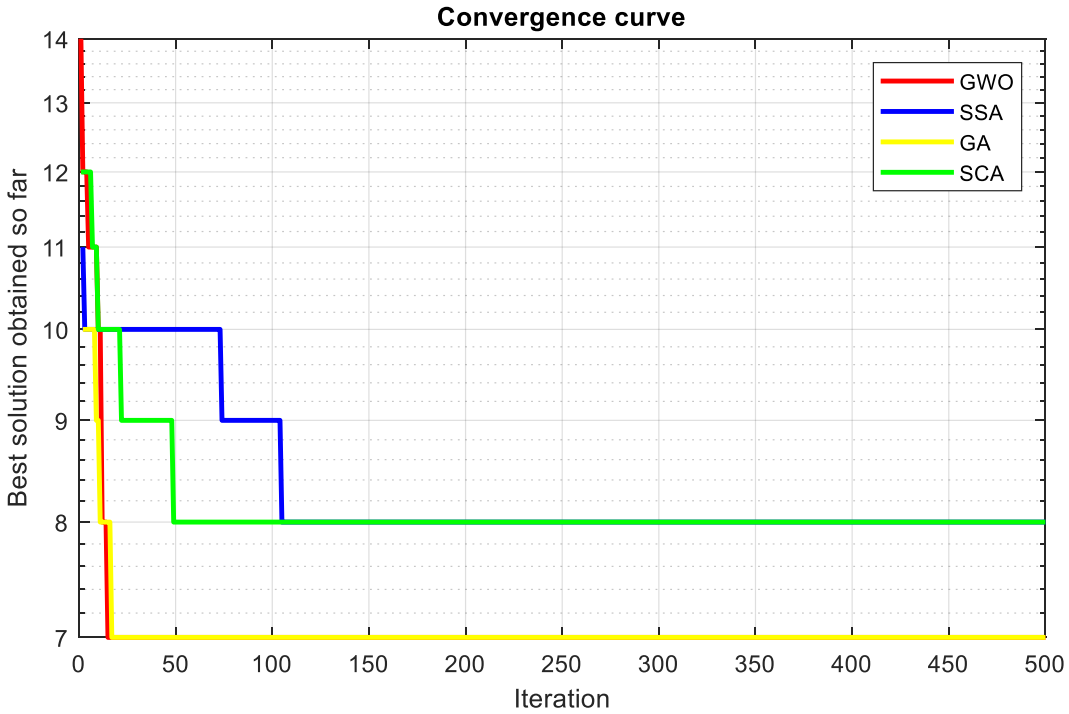


Figure IV.12. The objective function of the four used algorithms used for solving the OPP of PMUs for 39-bus with using the ZIBs

The obtained results of the objective function minimization in the second test based on considering the ZIBs are shown in Figure. IV.12, it is obvious that the obtained minimum with the GWO and GA is better and can be reached within a smaller number of iterations benefiting from less computation costs. The number of the PMUs obtained are 7, 8, 7 and 8 for GOW, SAA, SCA and GA respectively as presented in table IV.9.

Table IV.9. The obtained results for OPP of PMUs in 39-bus with ZIBs

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	7	2, 3, 6, 15, 22, 29 and 37	30
SSA	8	2, 4, 11, 17, 22, 26, 34 and 38	32
SCA	7	2, 8, 10, 16, 25, 32 and 38	30
GA	8	1, 5, 10, 15, 17, 29, 32 and 36	32

IV.3.5. Case of IEEE 57-bus

The fourth case uses the IEEE 57-bus test power system. It is composed of seven synchronous machines with IEEE type-1 exciters where three among them are used as synchronous compensators, 64 buses, 65 transmission lines, 22 transformers and 42 constant impedance loads with a total active power of 1250.8 MW and a reactive power of 336.4 MVAr. This test power system includes 13 ZIBs, which are located at buses 4, 7, 11, 21, 22, 24, 26, 34, 36, 37, 39, 34, 36, 37, 39, 40, 45, 46 and 48. shown in figure.IV.13.

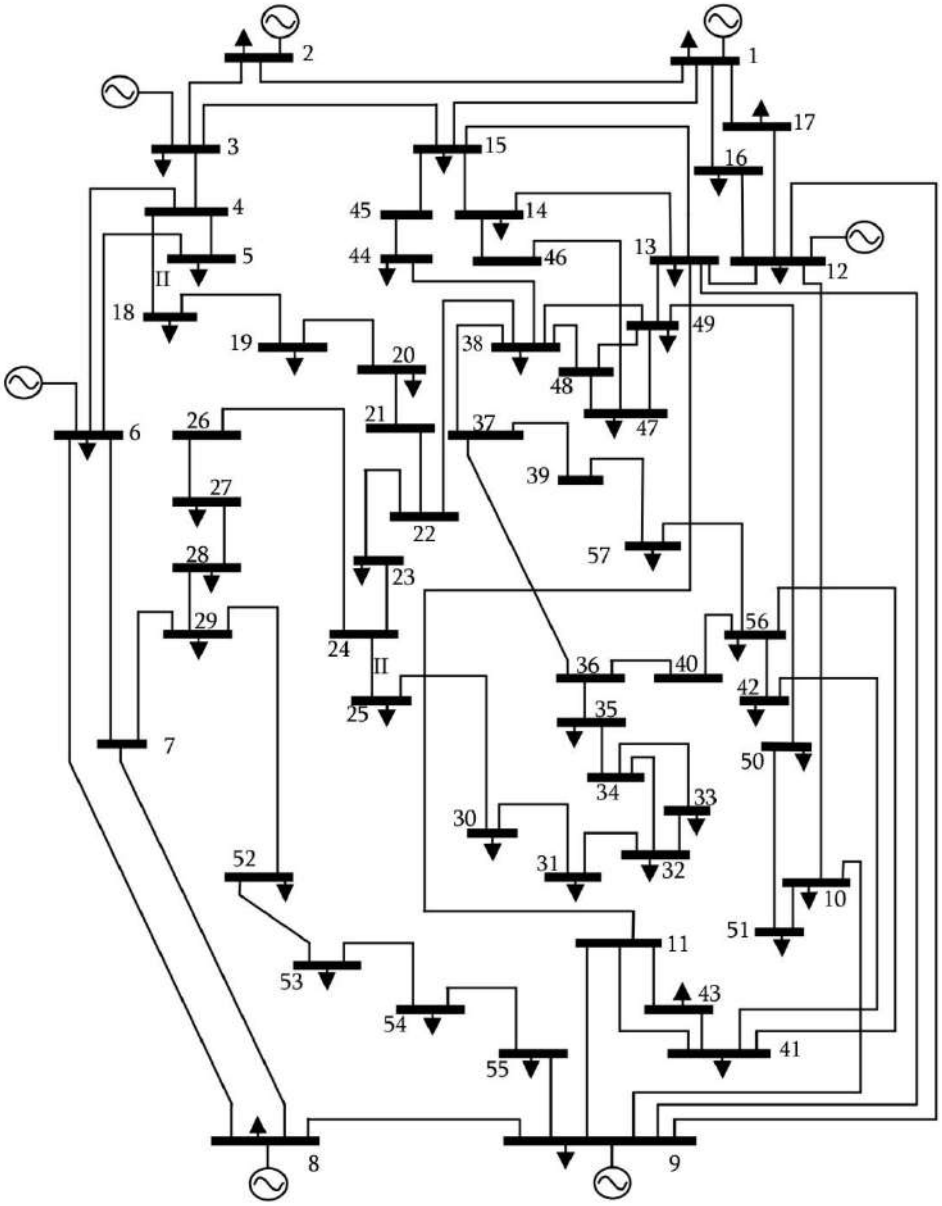


Figure IV.13. The structure if the IEEE 57-bus power system

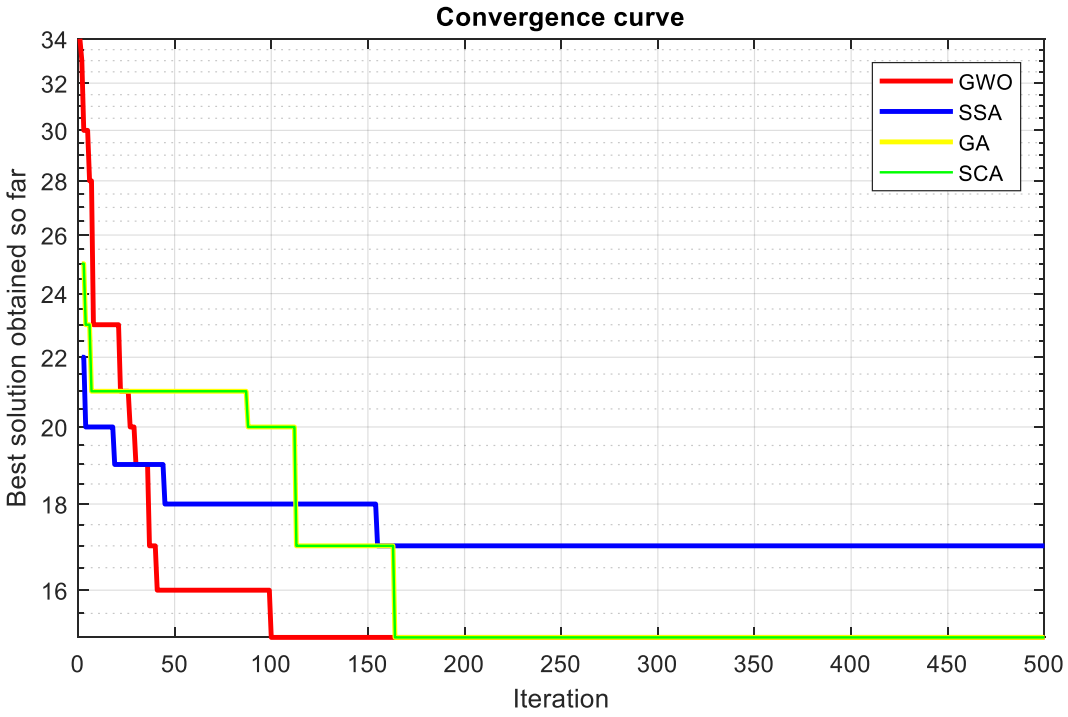


Figure IV.14. The objective function of the four used algorithms used for solving the OPP of PMUs for 57-bus without using the ZIBs

The first test has been performed without considering the ZIBs. The obtained results are presented Figures. IV.14, it is clear that the best one is obtained with the GWO algorithm in comparison with other algorithms, where a number of 100 iterations is enough to reach the minimum of the objective function. The closer results are obtained with the algorithm to GA, it reaches the same minimum in about 170 iterations. This result proves clearly that the GWO is a very competitive alternative for ensuring the optimization of the objective function.

Table IV.10. The obtained results for OPP of PMUs in 57-bus with zero injections are ignored

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	15	1, 4, 9, 19, 24, 27, 31, 35, 38, 41, 46, 50, 52, 54 and 56	61
SSA	18	1, 3, 6, 10,15, 19, 23, 25, 29, 32, 36, 40, 41, 45, 46, 49,54 and 56	67
SCA	15	1, 4, 9 ,21, 22, 25, 28, 32, 34, 43, 44, 46, 50, 53 and 56	57
GA	15	3, 4, 7, 12, 15, 22, 27, 30, 33, 43, 47, 50, 52, 54 and 56	67

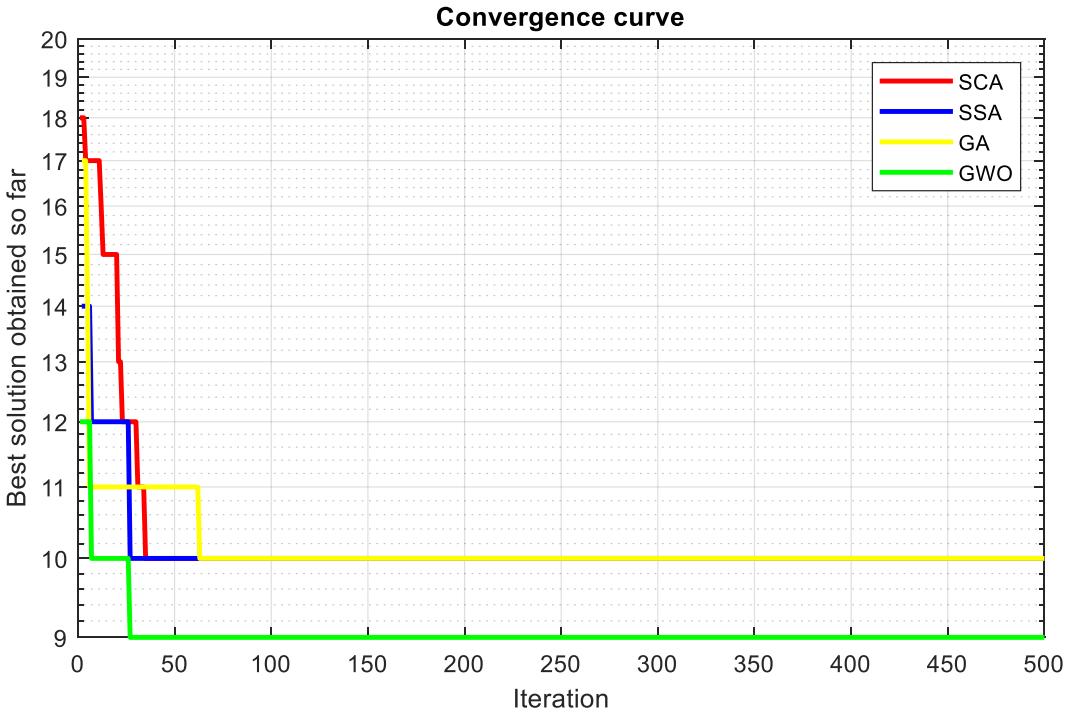


Figure IV.15. The objective function of the four used algorithms used for solving the OPP of PMUs for 57-bus with using the ZIBs

In the second test which is based in using the ZIBs, only the GWO algorithm reaches the best minimum within less than 30 iterations. Indeed, the other three used algorithms reach the minimum in less number of iterations compared to the first test, but they cannot reach the best minimum as shown in figure IV.15. On the other side, in the first test the minimum obtained number of the required PMUs for ensuring the observability of the whole studied power system is 15. This number is obtained by the GWO, SCA and GA algorithms as presented in Table IV.10. However, when the ZIBs are considered in the calculations, the number of the minimum required number of the PMUs is reduced greatly, as far the best number is 9 which can be obtained only by GWO and SCA algorithms as shown in Table IV.11. Based on these results, it can be said that the GWO algorithm in the best for the application presented in this section where less number of PMUs and the best minimum of the objective function are obtained in less computation time.

Table IV.11. The obtained results for OPP of PMUs in 57-bus with zero injections are Considered

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	9	5, 9, 19, 27, 38, 46, 50, 54 and 56	48
SSA	10	2, 6, 15, 23, 29, 32, 36,40,45 and 56	59
SCA	9	1, 4, 9, 25, 32, 34, 43, 53 and 56	45
GA	10	3, 7, 12, 27,30, 33, 47, 50, 52and 56	59

Provide us with a case with zero injections are Considered Shown in the table.VI.11The number of PMUS used in the monitoring and monitoring of the angle and phase of both the voltage and current in the network where the number in this case is limited between 9and 10 PMUs. And this situation is better than the other economically speaking I mean cost and maintenance also the number of less and less plaques also provides us with the least additional cost.

IV.3.6. Case of IEEE 118-bus

This test power system contains 54 synchronous machines with IEEE type-1 exciters where 20 among them are used as synchronous compensators to ensure the control of the voltage along the power system. This power system is composed of 172 buses, 185 transmission lines, 76 transformers and 91 constant impedance loads, which consume in total an active power of 3668 and a reactive power of MW and 1438 MVAr. On the other side, it contains 10 zero injection buses as shown in Figure IV.16.

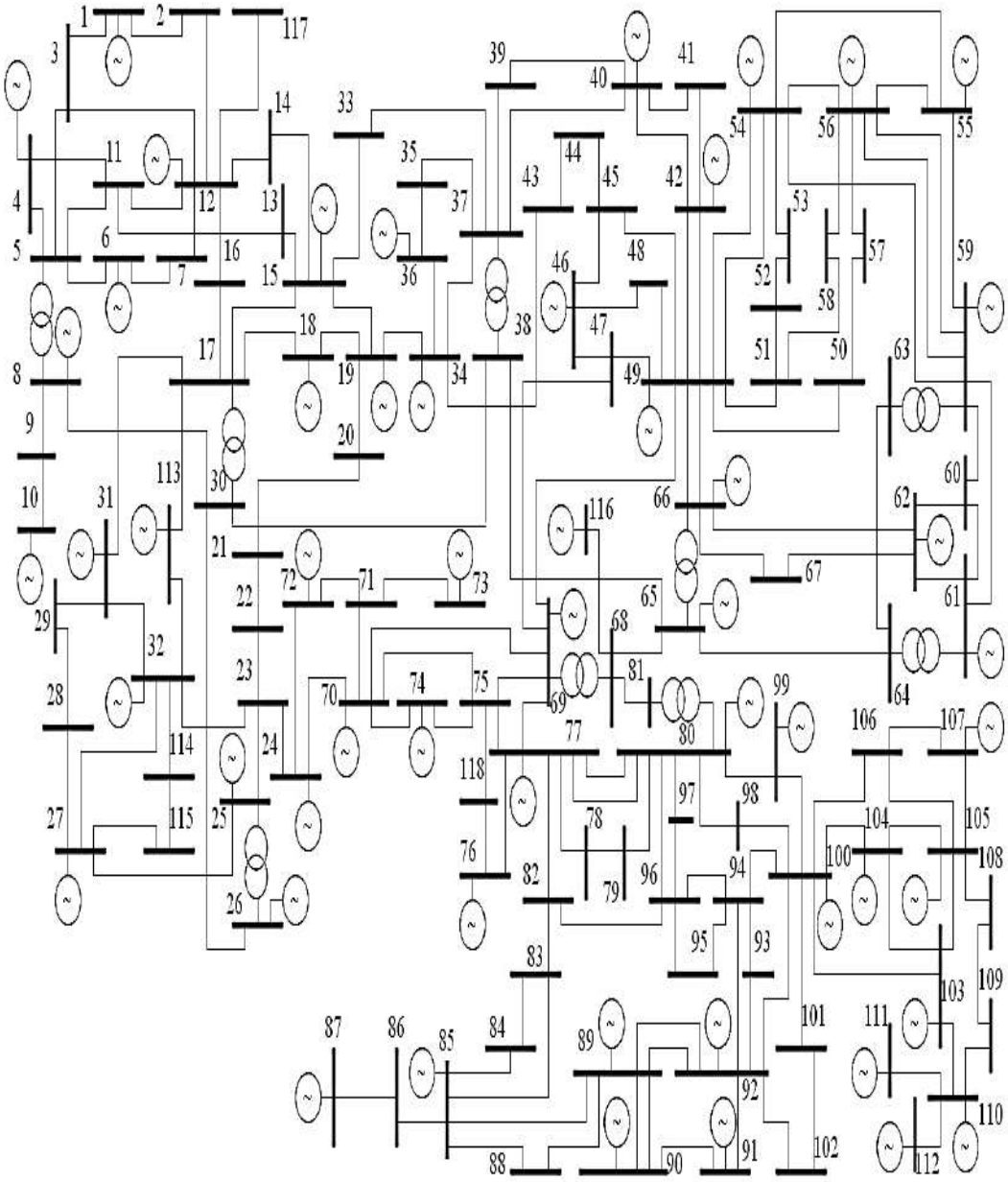


Figure IV.16. The structure if the IEEE 118-bus power system

This test power system is simulated similarly to the previous ones. The obtained result of the minimization of the objective function of the both tests, with and without taking into account the ZIBS are shown in figures IV. 17 and Iv.18 respectively. Based in these results, it is obvious tha with the GWO algorithm the best minimum in less number of iterations.

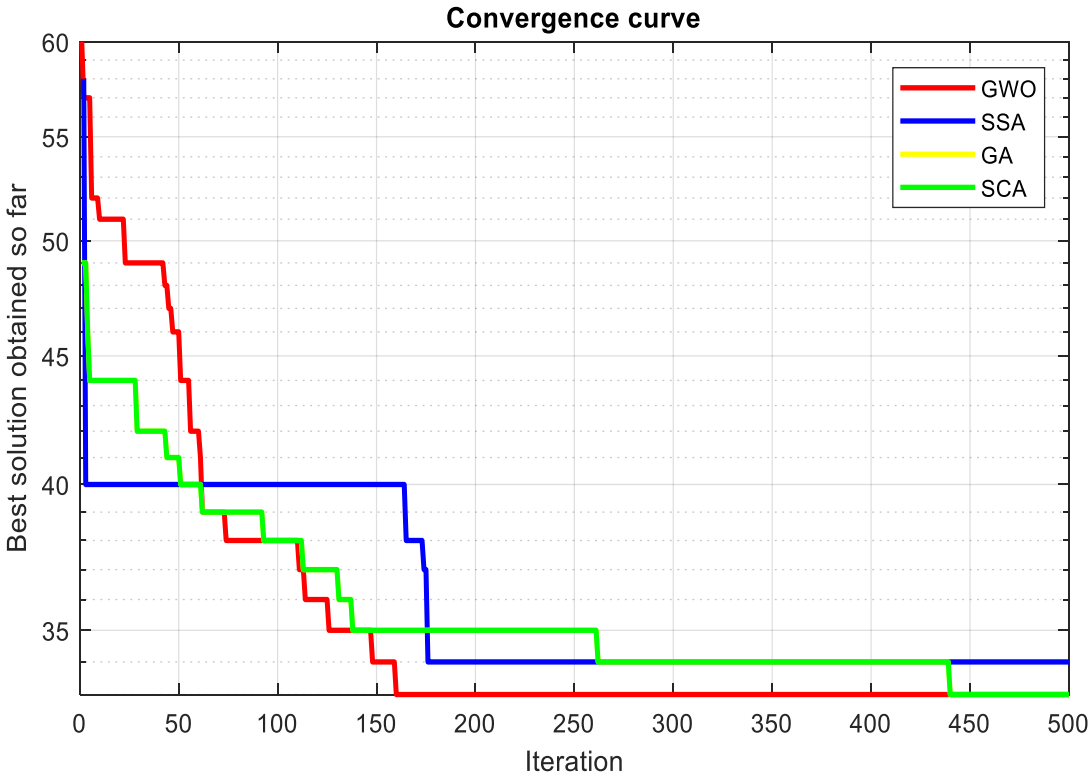


Figure IV.17. The objective function of the four used algorithms used for solving the OPP of PMUs for 118-bus without using the ZIBs

According to the obtained results, which as presented in Table IV.12 and IV.13, it is clear that the GWO algorithm allows finding the best number of the PMUs, in the second test the number of the PMUs based on GWO is 26 which is the lowest number compared to the other three algorithms, in the same time this number is very reduced compared to the one obtained in the first test. It can be conclude based on the results shown in the Figures IV.17 and IV.18 and the ounces presented in Tables IV.12 and IV.13 that the GWO algorithm is the best among the algorithm which have been used in this thesis.

Table IV.12. The obtained results for OPP of PMUs with zero injections are ignored

METHODS	NO OF PMU'S	Position of PMU in Buses	SORI
GWO	33	2, 5, 10, 12, 15, 17, 21, 24, 27, 30, 36, 40, 47, 49, 52, 54, 61, 63, 66, 68, 73, 77, 80, 85 87, 91, 93, 96, 101, 105, 110, 115 and 118	160
SSA	34	3, 5, 9, 12, 15, 19, 21, 26, 28, 32, 36, 40, 43, 47, 49, 53, 56, 60, 66, 72, 73, 75, 77, 80, 84, 86, 88, 91, 93, 101, 105, 110, 115 and 116	160
SCA	33	2, 5, 10, 15, 17, 21, 25, 27, 29, 30, 34, 36, 40, 45, 49, 50, 54, 59, 61, 67, 70, 71, 78, 84, 89, 92, 96, 100, 106, 110, 111, 115 and 118	160
GA	33	2, 5, 10, 12, 15, 17, 21, 24, 27, 30, 36, 40, 47, 49, 52, 54, 61, 63, 66, 68, 73, 77, 80, 85 ,87, 91, 93, 96, 101, 105, 110, 115 and 118	160

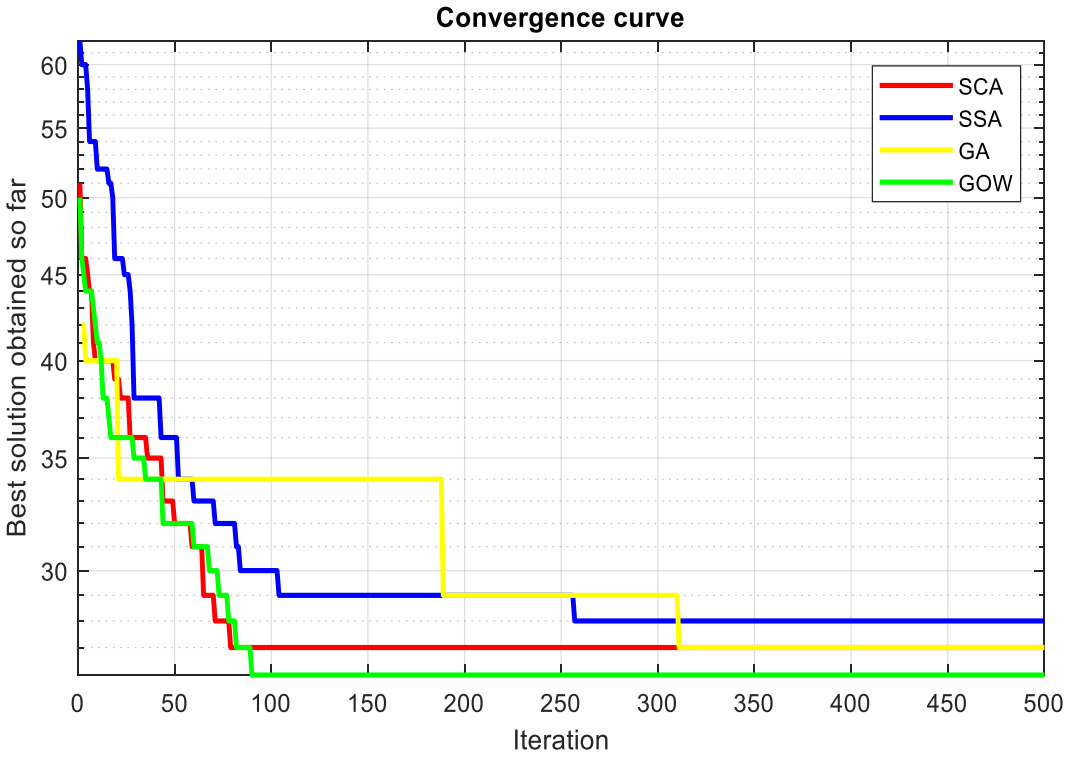


Figure IV.18. The objective function of the four used algorithms used for solving the OPP of PMUs for 118-bus with using the ZIBs

Table IV.13. The obtained results for OPP of PMUs in 118-bus with zero injections are Considered

METHODS	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
GWO	26	2, 8, 11, 15, 19, 21, 27, 32, 34, 40, 45, 49, 52, 56, 62, 65, 72, 75, 77, 80, 86, 90, 94, 101, 105 and 110	160
SSA	28	5, 8, 12, 15, 17, 20, 23, 29, 34, 40, 45, 49, 52, 56, 62, 65, 70, 75, 77, 80, 85, 89, 92, 96, 100, 105, 110 and 115	160
SCA	27	3, 8, 15, 17, 21, 27, 29, 32, 34, 40, 43, 46, 50, 54, 62, 64, 70, 75, 77, 80, 85, 86, 91, 94, 101, 105 and 110	160
GA	27	3, 7, 12, 17, 21, 24, 27, 32, 34, 38, 40, 45, 49, 52, 56, 59, 66, 75, 77, 80, 85, 86, 90, 94, 101, 105 and 110	160

At the end of the first part of the simulations, all the obtained results can be summarized in figure IV.19. In this Figure, the best obtained numbers of PMUs, which are requires to ensure the observability of all the six studied power systems under the consideration and no consideration of the ZIBs are presented. It can be concluded that in all case nearly the GWO is almost the best, as an example only in the case of the IEEE 30-bus power systems the GWO offers eight PMUs which is not the best, but as the number of the buses and the complexity of the power system increases the GWO may be considered the best algorithm to be chosen.

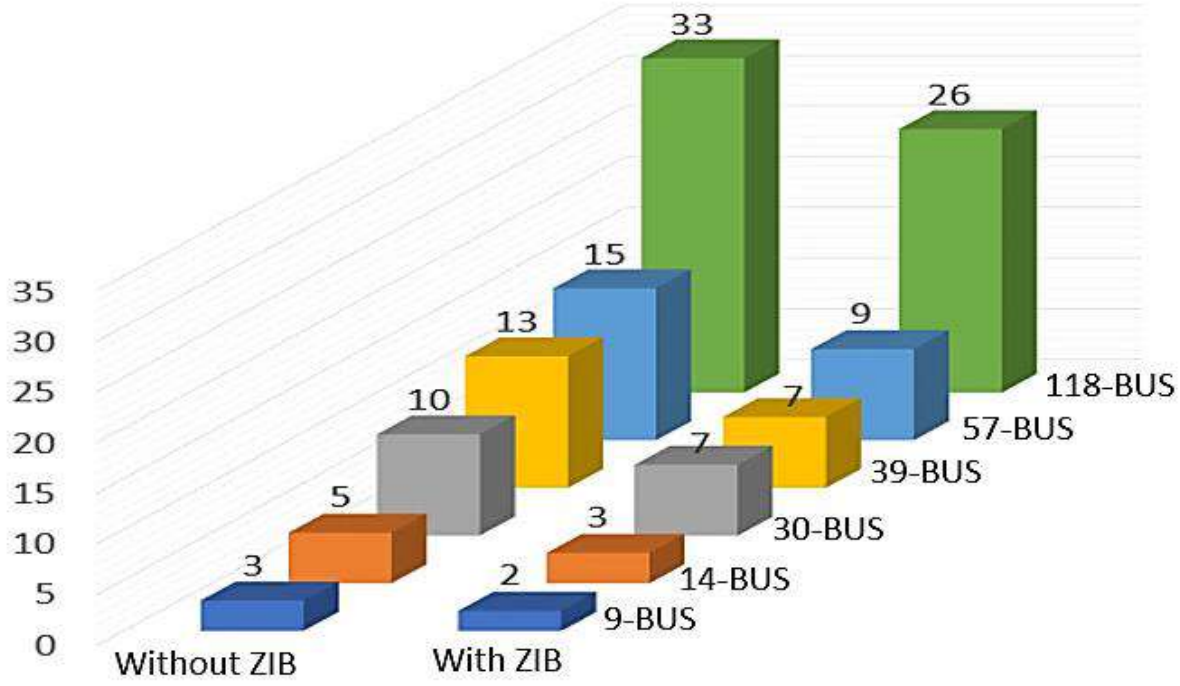


Figure IV.19. Comparison of the obtained results of the number of required PMUs in the six studied power systems with and without consideration of the ZIBs.

It is important to mention that the usual total prices of a PMU (cost of the product and installation) ranges between 40,000$ to 180,000$ depending on the quality of the product. Therefore, the installation of a PMU at every bus of the power system is not feasible as it leads to high costs.

It can be deduced from the aforementioned study that the rate of saving in the cost of installing the PMUs in the studied power systems with number of buses 9, 14, 30, 39, 57 and 118 can be between 76.66% and 88% when the ZIBs are considered. For example, in 9-bus power system the total cost is 16,200,000$ if a PMUs is installed at each bus (9 PMUs are used), But after the process of optimization studied in this, only two PMUs can be enough to ensure the whole system observability, which leads to a cost of 360,000$, in this case, we will have a saving rate in the cost of 78.78% which is very attractive and encouraging the use of the PMUs in the whole power system.

Either in case without considering the ZIBs, it can deduce from our presented study that the saving rate can reach a percentage value between 66.67 % and 72.04 %, and this also can be considered an attractive issue from point of economical view.

IV.3.7. Case of 114-bus Algerian grid

The Algerian 114-bus configuration is shown is Figure. IV.20, it consists of 114 buses, 175 branches (lines and transformers) and 15 generators. The load demand consumption is characterized by an active power of 3,727 MW and a reactive power of. This power system contains 22 zero injection buses, which are located at the buses 2, 14, 16, 18, 27, 28, 31, 42, 44, 46, 48, 58, 60, 64, 72, 74, 75, 81, 86, 93, 96 and 105.

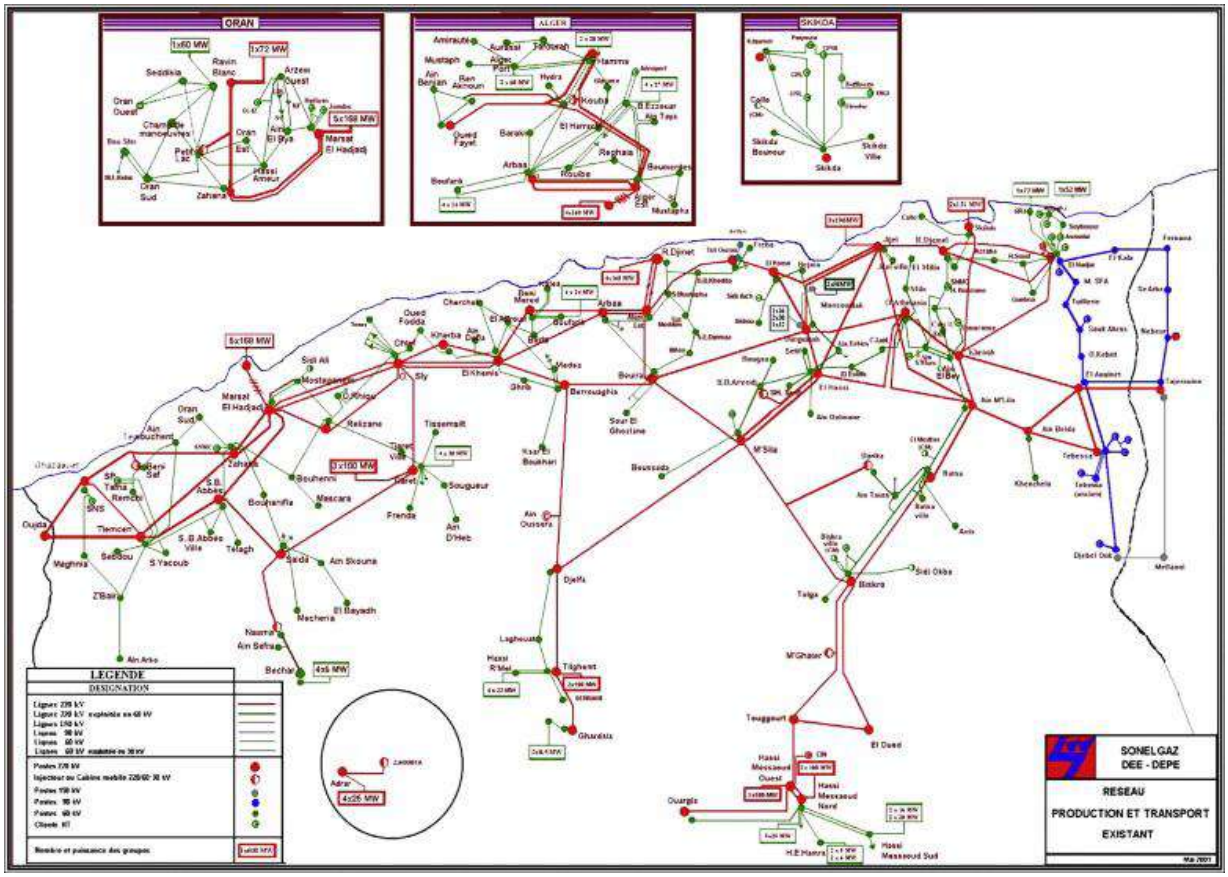


Figure IV.20. The structure if the 114-bus Algerian network

In this thesis, to show more validity of the proposed algorithm for solving the OPP problem, it is applied in this case on the existing 114-bus Algerian power system. The main objective remains the same as in the previous cases, that is, the determination of the optimal required number of PMUs and the best placements of this obtained number of PMUs to ensure the accurate observability of the whole studied power system. Furthermore, two cases are taken into account, with considering the ZIBs and without considering the ZIBs as shown in Figure.VI.21.

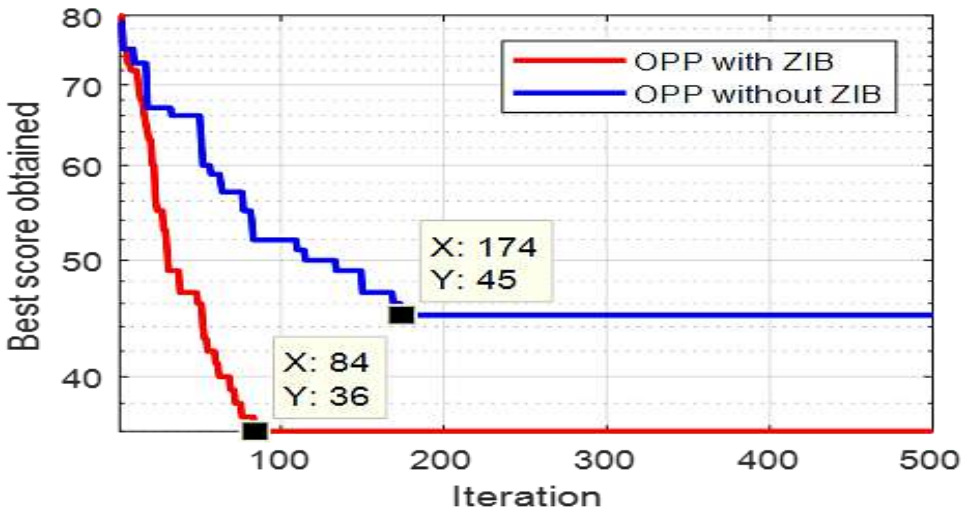


Figure IV.21. The objective function of the four used algorithms used for solving the OPP of PMUs for 114-bus Algerian network

Table IV.14. The obtained results for OPP of PMUs in 114-bus Algerian network without and with considering ZIB

***GWO* Methods**	**NO OF PMU'S**	**Position of PMU in Buses**	**SORI**
Zero Injections Are Ignored	45	5, 6, 8, 9, 11, 13, 16, 17, 18, 19, 22, 24, 28, 29, 38, 40, 41, 43, 44, 47, 53, 54, 61, 63, 70, 71, 73, 74, 77, 80, 81, 83, 89,93, 95, 98, 101, 103, 105, 106, 109, 110, 113 and 114	170
Zero Injections Are Considered	35	1, 3, 5, 11, 12, 16, 18, 19, 20, 26, 29, 30, 34, 40, 44, 46, 49, 54, 57, 59, 63, 68, 71, 74, 80, 84, 87, 90, 93, 95, 98, 99, 105, 109, 112 and 113	154

The obtained results are presented in Table.IV.14. Where, for both cases the obtained number of the required PMUS is 45 and 36 respectively, which means that if the ZIBs are taken into account in solving the OPP problem with the proposed algorithm GWO, 9 PMUs can be saved. This can be considered economically and technically a very successful task.

IV.4. Conclusion

This chapter focuses mainly on the application of the four algorithms such as GOW, SSA, SCA and GA for solving the problem of optimal placement of PMUs for ensuring the complete studied power system observability. Where, it is has been proved that the application of the four algorithms has improved efficiently the observability task and its reliability for the all studied power systems in this study. Some validation tests have been performed on the IEEE standard systems such as the 9, 14, 30, 39, 57 and 118-buses, and a final test has been performed on the Algerian 114-bus real power system. The simulated outcomes conclude the efficiency of all the proposed approaches in finding the minimized number of required PMUs and their optimal locations, however the GWO algorithm is found to be the best among the proposed algorithms. Whereas, a less cost for the installation of the PMUs is obtained and an efficient access and observability of the complete studied power system are ensured.

General Conclusion and future works

The work presented in this thesis is devoted to solving the problem of optimal placement of the Phase Measure Units, which allow ensuring the full and the accurate observability of the whole power system. To achieve this main objective, four meta-heuristic optimization algorithms have been selected for the minimization of the proposed objective function modeling the problem of the optimal placement of PMUs, such as the Grey Wolf Optimizer (GWO), slaps swarm algorithm (SSA) and sine cosine algorithm (SCA) and Genetic Algorithm (GA). The choice of these algorithms was based mainly on the computation time, the simplicity of the algorithm and the less number of parameters. On the other side, to check the validity of the proposed objective function and the chosen optimization algorithms six test IEEE power system and the Algerian 114-bus have been used for this validation through the performed simulation, where to case have been checked for each power system such as with taking into account the ZIBs and without taking into account ZIBs. After comparing the obtained results, it was found that all the algorithms can ensure the main objective of solving the OPP. However, the SSA and SCA algorithms have heavy computational burdens due to the fact that these methods are probability-based searching algorithms and they are also unable to guarantee the global optimal solution compared with the other two algorithms of GA and GWO. Indeed, the GWO algorithm is easy to understand and operate, the computation of this method is fast and it is found that the result from this method is always the best.

Two main conclusions can be considered. The first is that the consideration of the ZIBs in the objective function allows improving clearly the obtained results, where a less number of PMUs with optimized localization can be obtained. The second is that the GWO algorithm is found to be the best in term of time calculation to reach the minimum of the objective function, and therefore the optimized number of the required PMUs is less.

In future works, the multi-objective optimization method has such conflicting objective functions that give rise to a set of optimal solutions instead of single solution, since no solution can be considered better than any other, with respect to all objective functions. In future work, tow objective functions for minimizing the number of PMUs for achieving complete system observability can be performed.

1st object minimizing the error the generated by this PMUs into the electrical grid.

2ndobject maximizing the measurement redundancy of the weak buses for enhancing the voltage stability level of the system.

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