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DOCTORAL THESIS

3rd Cycle Doctoral (D-LMD)

Presented by

Abdelkader Azzeddine LAOUID

With a view to obtaining the doctoral diploma in 3rd Cycle Doctoral (D-LMD)

Branch: Electrical Engineering

Specialty: Power electronics and the Quality of Electrical Power

Topic

Optimal location of phasor measurement units (PMUs) in power system networks based on meta-heuristic approach

Supported, on 06 /07/ 2020, before the jury composed of:

Last and first name	Grade	Institution of affiliation	Designation
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Mr Aissa AMEUR	Professeur	Université de Laghouat	Invited

Djelfa University, FST - 2020

ملخص

الغرض من المذكرة هو العثور على موضع استراتيجي لوحدات قياس الطور (PMUs) التي يمكن أن تحافظ على إمكانية ملاحظة نظام الطاقة باستخدام خوارزمية بحث جاذبية. على مدى السنوات القليلة الماضية ، كانت طريقة التحسين الأكثر استخدامًا لحل هذه المشكلة هي البرمجة الخطية الصحيحة .(ILP) على الرغم من ذلك ، أظهرت الدراسات الحديثة أن الأساليب الحتمية مثل ILP لا تزال تفشل في العثور على الوضع الأمثل لوحدات .PMU نظرًا لطبيعتها القائمة على البحث ، لا يزال من الممكن إجراء المزيد من البحث باستخدام خوارزمية الكشف عن مجريات الأمور. من المهم تحديد الموقع الأكثر استراتيجية لوحدات إدارة المشروع لضمان استخدامها بالكامل بسبب ارتفاع سعرها. تتمثل صعوبة استخدام الخوارزمية الإرشادية في ضعفها عند التعامل مع المشكلات الكبيرة ، حيث تميل إلى الوقوع في البصمة المحلية ، كما هو موضح في الدراسات السابقة حيث طبق معظمهم نهجهم المقترح على أنظمة الحافلات الصغيرة. تم تصميم الطريقة المقترحة لتحسين البحث المحلي للخوارزمية حول أفضل حل حالي للمساعدة في منع التصاق الجسيمات في البصمة المحلية وبالتالي إيجاد حل أفضل. تظهر النتائج العددية التي تم الحصول عليها أن هذه الطريقة حاسمة لأنها تتفوق على جميع الطرق الأخرى لجميع أنظمة الحافلات التي تم اختبارها ، بما في ذلك نظام الحافلات الجزائري 114 ، من حيث تكرار القياس وعدد وحدات الجسيمات. تتناول هذه الدراسة أيضًا قيود المشاكل الأخرى مثل ناقل الحقن الصفري ، وفقدان PMU المفرد ، وانقطاع الخط الواحد ، وكذلك PMU المفرد أو فشل الخط.

الكلمات المفتاحية : برمجة خطية صحيحة، وحدات قياس الطور، ناقل حقن صفر، تكرار في القياس ، خوارزمية بحث الجاذبية.

Abstract

The purpose of this thesis is to find a strategic placement of phasor measurement units (PMUs) that can maintain the observability of the power system using a gravitational search algorithm. Over the last few years, the most widely used optimization method to solve this problem has been integer linear programming (ILP). Despite this, recent studies have shown that deterministic methods such as ILP still fail to find the most optimal placement of PMUs. Due to its search-based nature, it is therefore still possible to further investigate using a heuristic algorithm. It is important to determine the strategic location of PMUs to ensure that they are fully utilized due to their high price. The difficulty in using the heuristic algorithm is its weakness when dealing with large problems, as it tends to get stuck in local optima, as shown in previous studies where most of them applied their proposed approach to small bus systems. The proposed method is designed to enhance the local search of the algorithm around the current best solution in order to help prevent particles from being stuck in the local optima and thus find a better solution. The numerical results obtained show that this method is crucial as it outperforms all other methods for all bus systems tested, including the Algerian 114 bus system, in terms of measurement redundancy and number of particle units. This study also considers other problem constraints such as zero-injection bus, single PMU loss, single line outage, and also single PMU or line failure.

Keywords: Integer linear programming (ILP), Phasor measurement units (PMUs), Zero injection bus (ZIB), measurement redundancy, gravitational search algorithm (GSA).

Abstract

L'objectif de cette thèse est de trouver un placement stratégique des unités de mesure de phase (PMUs) qui peuvent assurer l'observabilité du système électrique en utilisant un algorithme de recherche gravitationnelle. Durant ces dernières années, la méthode d'optimisation la plus utilisée pour résoudre ce problème a été la programmation linéaire en nombres entiers (ILP). Malgré cela, des études récentes ont montré que les méthodes déterministes telles que l'ILP ne réussissent toujours pas à trouver le placement le plus optimal des PMUs. En raison de sa nature basée sur la recherche, il est donc encore possible d'approfondir les recherches en utilisant un algorithme heuristique. Il est important de déterminer l'emplacement le plus stratégique des PMU afin de s'assurer qu'elles sont pleinement utilisées en raison de leur coût élevé. La difficulté d'utilisation de l'algorithme heuristique est sa faiblesse lorsqu'il s'agit de traiter des problèmes de grande taille, car il a tendance à se bloquer dans les optima locaux, comme l'ont montré des études antérieures où la plupart d'entre elles ont appliqué l'approche qu'elles proposaient aux systèmes de petits bus. La méthode proposée est conçue pour améliorer la recherche locale de l'algorithme autour de la meilleure solution actuelle afin d'éviter que les particules ne soient bloquées dans l'optima local et de trouver ainsi une meilleure solution. Selon les résultats obtenus, cette méthode est cruciale car elle surpasse toutes les autres méthodes pour tous les systèmes de bus testés, y compris le système de bus 114 algérien, en termes de redondance des mesures et de nombre d'unités de particules. Cette étude prend également en compte d'autres contraintes liées au problème, telles que le bus à injection zéro, la perte d'une seule unité de particules, l'interruption d'une seule ligne, et également la défaillance d'une seule unité de particules ou d'une seule ligne.

Mots-clés: Programmation linéaire en nombres entiers (ILP), unités de mesure de phase (PMUs), bus d'injection zéro (ZIB), redondance des mesures, algorithme de recherche gravitationnelle (GSA).

Dedication

To my mother and my father…

To all members of my family…

To all my friends…

To all teachers who have contributed to my education since I was 4 years old until today...

And for all persons who contribute to this work.

Acknowledgement

Foremost, I would like to express my sincere gratitude to my advisors **Prof. Kouzou Abdellah** and **Dr. Rezaoui Mohamed Mounir** for the continuous support of my Ph.D study and research, for their patience, motivation, enthusiasm, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I could not have imagined having two better advisors and mentors for my Ph.D study.

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Last but not the least, I would like to thank my family: my parents for giving birth to me at the first place and supporting me spiritually throughout my life.

Table of Contents

List of Tables

List of Figures

List of Acronyms and Symbols

PMU	Phasor Measurement unit
GPS	Global Positioning System
KCL	Kirchhoff's Law
KVL	Kirchhoff's Voltage Law
ILP	Integer Linear Programming
SA	Simulated Annealing
ES	Exhaustive Search
GA	Genetic Algorithm
DE	Differential Evolution
BPSO	Binary Particle Swarm Optimisation
GSA	Gravitational Search Algorithm
OPP	Optimal PMUs Placement
US	United States
SCADA	Supervisory Control and Data Acquisition
IEEE	Institute of Electrical and Electronics Engineers
NASPI	North American Synchrophasor Initiative
HMI	Human Machine Interface
RTUs	Remote Terminal Units
PLC	Programmable Logic Controller
EMS	Energy Management System
SE	State Estimation
WAMS	Wide Area Measurement system
VSC	Variable Series Capacitor
UPFC	Universal Power Flow Controllers
CT	Current transformer
VT	Voltage transformer
PLL	Phase-Locked Loop
UTC	Coordinated Universal Time
ROCOF	Rate of Change of Frequency

RMS	Root Mean Square
TVE	Total Vector Error
FE	Frequency Error
PDC	Phasor Data Concentrator
ZIB	Zero Injection Bus
$\boldsymbol{min\{N_{PMU}\}}$	Minimum Number of PMU
[A]	Connectivity Matrix
$\boldsymbol{a_{ij}}$	Binary Connectivity Parameter
$\boldsymbol{Z_j}$	Zero Injection Bus at Bus j
$\boldsymbol{f_i}$	Observability function of Bus i
$\boldsymbol{f_i^k}$	Observability function of Bus i When Line k Outage
$\boldsymbol{a_{ij}^k}$	Binary Connectivity Parameter When Line k outage
$\boldsymbol{BR_i}$	The number of branch combinations for bus i
$\boldsymbol{BC_i}$	The number of possible combinations of L out of BI_i
$\boldsymbol{BI_i}$	The number of neighboring buses to bus i
$\boldsymbol{L}$	The channels limit
N	The number of agents
N	The number of control variables
BGSA	Binary gravitational search algorithm
BOI	Bus Observability Index

General Introduction

Motivation of the research

In this modern era where nearly everything has been modernized for greater efficiency, reliability and independent control, traditional power grids are also in the process of transition to the modernized power grid, or widely known as the smart grid. The goal of the smart grid is to monitor and manage the power grid as effectively as possible while offering greater reliability and stability. It is desirable to replace older infrastructure with a smart grid that uses advanced technologies to achieve this goal. Among the advanced technologies used is the Phasor Measurement Unit (PMU). The PMU is a measuring device that can measure the bus voltage phasor on the bus where it is installed and the branch current phasor next to it. The PMU is equipped also with a Global Positioning System (GPS), which allows the measurement data provided by the PMU to be calculated in real-time through time stamping and synchronization. This is vital knowledge for power utilities, particularly for operating engineers, as it enables them to identify, anticipate, and correct problems in the event of irregular conditions in the system. It aligns with smart grid visions for better and more reliable power grid monitoring. Nevertheless, the PMU's implementation has progressed very slowly due to the significant investments required for the investment sites.

The PMU's places of placement must have communication facilities in order for the PMU to function properly and the limited number of places of placement that have them hinders its implementation. In addition, the cost of the PMU itself is very high, although the price is expected to decrease as demand increases in the future. Research in recent years has shown that using the attributes of PMUs and the use of current Kirchhoff’s Law (KCL) and Ohm's Law, the number of PMUs needed to achieve full observability of an electric system can be reduced if PMUs are strategically placed in an electric system.

Many optimisation methods have been used in recent years to determine the strategic placement of PMUs in a power system such as integer linear programming (ILP), simulated annealing (SA), exhaustive search (ES), genetic algorithm (GA), differential evolution (DE), and also binary particle swarm optimisation (BPSO). Among these optimisation methods, the ILP is the most dominant method used in solving this problem.

However, recent studies have shown that the PMUs placement obtained using the ILP method is not an optimal solution. Since the optimal PMUs placement problem does not have a unique solution, there is a possibility that meta-heuristic algorithms can be used to deal with the optimal PMUs placement problem. This is because meta-heuristic algorithms use randomisation in their algorithm formulation, hence, different results are expected from these algorithms which might improve the current solution.

Aim of the research

The main goal of the research is to find the minimum number of PMUs needed in the different IEEE bus systems using the gravitational search algorithm (GSA). Some factors such as the zero injection bus, measurement redundancy, and the limit of the number of PMU channels are taken into account in this thesis. Like other optimization methods, the GSA algorithm also has disadvantages that may affect its overall performance in achieving the main research objective. Various methods have been proposed by the existing studies. However, the effectiveness of the proposed methods from the existing studies is rarely tested on larger systems, where the particle diversity is the most important. Thus, the second aim of this thesis is to propose a method that can overcome issues concerning particle diversity and to ensure that it can be applied in larger systems. To illustrate the effectiveness of the proposed method, it will then be validated using MATLAB software. The results obtained by the proposed method will also be further evaluated by comparing it to the results of previous studies. The proposed method is expected to improve the particle diversity to avoid trapping particles in local optima and should result in a high-quality solution in all systems tested.

To summarise, the objectives of the research are listed as follows:

1. To determine the minimum number of PMUs required across different IEEE bus systems using the GSA algorithm while considering a normal operation, zero injection bus, measurement redundancy, single PMU loss, single line outage, and both single line or PMU outage.
2. To propose a method that can overcome the issue concerning lack of diversity which will be able to give quality solutions in larger systems.
3. To evaluate the proposed method efficiency, the proposed method is validated using MATLAB software and the results obtained are compared with the existing studies to evaluate their superiority.

Thesis layout

The organization of this thesis out of chapter 1 is as follows:

- Chapter 2 elaborates on the optimal PMUs placement (OPP) problem including the PMU's observability rules used to determine the observability of the power system. It also features a concise review of relevant literature to solve the optimal PMU placement problem.
- Chapter 3 presents the conventional gravitational search algorithm method and how it is implemented in general. This chapter also explains the parameters used and other variants of the gravitational search algorithm method introduced in recent years to overcome its drawbacks.
- Chapter 4 applies the proposed method into different IEEE bus systems and the simulation results for each case considered are presented. The obtained results are also compared with the existing studies to validate their effectiveness in solving the OPP problem.
- Chapter 5 concludes the thesis by explaining the contributions of the thesis. Future work is also discussed.

List of publications

- **International Conferences**

1) **LAOUID A. A**. Mohammedi RD. Kouzou A. Rezaoui MM «Optimal PMU Placement in Power System Based on Multi-objective Particle Swarm Optimization» the 15th International Multi Conference on Systems, Signals & Devices (SSD). 2018. IEEE, Hammamet, Tunisia.
2) Teta. A, Rezaoui. MM, Kouzou. A, **LAOUID. A A**, Bensaoucha. S «Analysis of reference current identification strategies for shunt active filter under distorted load conditions» The International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM 2018), 28-31 October, 2018, Algiers, Algeria.
3) **LAOUID A. A**, REZAOUI MM, KOUZOU A, Mohammedi RD «Minimizing the number of phasor measurement units using GA and PSO Algorithm» Second International Conference on Electrical Engineering (ICEEB 2018), 2-3 December, 2018, Biskra, Algeria.
4) **LAOUID A. A**, REZAOUI MM, KOUZOU A, Mohammedi RD « Optimal PMUs Placement Using Hybrid PSO-GSA Algorithm» The 4th International Conference on Power Electronics and their Applications (ICPEA), 2019, Turkey.

- **International publications**

1) **A. A. LAOUID**, R. D. MOHAMMEDI, M. M. REZAOUI,A. KOUZOU. Optimal PMUs Placement to ensure Power System Observability under Various Contingencies. Electrotehnica, Electronica, Automatica. Vol 68, pp., 2020

Chapter 1

Background Study and Literature Review

1.1 Introduction

A new concept of the next-generation electric power system, called smart grid, has been touted as the saviour in the mission of having a modern power grid infrastructure that offers improved efficiency, reliability, and safety through automated control and modern communication technologies, replacing the current electrical grid that has been ageing. It correlates with the increased demand for electricity which has gradually increased over the years as reported by the US Department of Energy report [1]. Current infrastructure's incapability of handling an automated analysis and lack of situational awareness were the two major factors that led to the major blackout in US history. The blackout that happened in 2003, which lasted for two days, affected 55 million people and caused a massive economic loss which was reported to be approximately between 4 and 10 USD billion [2]. In today's world, where everything is moving rapidly, the impact would be massive, and thus, it is crucial that preventive measures need to be taken quickly and seriously.

The lack of situational awareness of the current infrastructure is generally due to the way metering data is monitored. The smart grid aims to improve the way data is monitored by incorporating the phasor measurement unit (PMU) in its infrastructure. Currently, the supervisory control and data acquisition (SCADA) system collects one data point every 1 to 2 seconds, whereas PMUs collect 30 to 60 data points per second [3]. Additionally, a common time reference is supplied by a global positioning system (GPS) for all acquired data to satisfy the need for real-time control, thereby, allowing a more accurate assessment of the current conditions of the power systems [4]. This benefit has led to the installations of over 1,000 PMUs across North America as reported by the North American Synchrophasor Initiative (NASPI) as of March 2014 [5].

1.2 Literature review

During a long period of time, several techniques have been proposed using different types of optimization methods to solve the OPP problem to make the power system observable. The optimization methods used can be divided into two main categories: mathematical and heuristic algorithms [6].

1.2.1 Mathematical algorithms

Few among the popular mathematical algorithms for solving the OPP problems are:

1.2.1.1 Integer Programming (IP):

Integer programming (IP) is a mathematical optimization algorithm in which some or all of the optimization variables are restricted to be integers. The objective function and the constraints can be linear, nonlinear, or quadratic, and they, respectively, produce integer linear programming (ILP), integer nonlinear programming (INLP), and integer quadratic programming (IQP) algorithms [7].

The work in [8] presents the description of a simple modified ILP-based model for optimal PMU placement. The authors noted that optimal placement should consider critical contingencies in the network, and went on to carry out a voltage stability-based contingency ranking to select few contingencies to be considered with the optimal placement problem. The target of the method is to ensure complete topological observability of the system under intact and critical contingency cases. The method presented in [9] employs ILP to accomplish the task of placing PMU at strategic buses that make the entire system observable. The authors also discussed the existence of constraints in PMU measurements such as the presence of conventional measurements and bus injections.

The work in [10] proposed an IP formulation of the OPP problem, with the aim to improve the capability of the state estimator in bad data detection and processing. The model assumes that with the help of redundant measurements, the appearance of a single bad data in a set of measurements could be detectable. The model transforms the critical measurements into redundant, depending on the measurement configuration and the system topology. The model is extended to incorporate conventional measurement locations as candidates for placement and can be used to determine optimal locations when the desired level of local redundancy is considered in the system. The study in [11] while applying ILP, proposes separately or simultaneously considering additional contingency conditions such as line outages and loss of measurements. In Addition to the contingency conditions, the model also considered communication constraints of power networks as measurement limitations and included in the model to restrict the number of PMUs. In [12], the authors employed ILP to model and solve the optimal redundant PMU placement formulation for full and incomplete observability. The model also considered situations with and without zero injection measurements. Similarly, the formulation in [13] proposed considering or not the regular power flow and injection measurements.

Reference [14] presents the description of an optimal placement strategy for a fully observable network using only “branch” PMUs. The study also takes into account the PMU failures and network contingencies that involve topology changes as well as bad data detection capability of PMU measurements. The work in [15] presents a unified approach considering the impacts of both existences of conventional measurements in the OPP problem, which is formulated as a binary integer linear programming (BILP) problem. It also considered the possibility of single or multiple PMU loss, into the decision strategy. A BILP formulation is proposed in [16] takes into account the channel limits of PMUs while solving for optimal PMU placement. The method also accounts for any existing zero injection measurements. The work in [17] also used a BILP to solve an optimal solution to the PMU placement problem for network observability, given a specified number of available channels for the candidate PMUs.

1.2.1.2 Exhaustive Search (ES):

Exhaustive search is a general optimization technique, which systematically enumerates all possible candidates for the solution and selects the candidate that satisfies the objective function and the constraints. It is also known as direct search, or the "brute force" method. It has an advantage of a guaranteed global optimal solution. However, it is impractical to use exhaustive search on problems with huge search spaces. The exhaustive binary search algorithm is implemented in [18] to solve the OPP problem allowing for single branch outages with or without the existence of zero injections. An algorithm is proposed to select a preferable set based on measurement redundancy in case of multiple solutions.

1.2.2 Heuristic Algorithms

Heuristic algorithms researchers have used in solving the OPP problem include:

1.2.2.1 Genetic Algorithm (GA):

A genetic algorithm (GA) is an optimization method based on a natural selection process that mimics the biological evolution and *survival of the fittest*. GA operates on a population of binary coded individuals, known as "chromosomes," which are potential solutions to a given problem and are combined, based on their fitness, to breed new individuals [19]. Reference [20] proposes a combinatorial method of a graph theoretic procedure that estimates individual optimal solutions of objectives, and a simple non-dominated sorting GA NSGA) that finds the best trade-offs between conflicting objectives. The work in [21] used an adaptive clonal algorithm (CLONALG) to find the globally and the approximately optimal solutions, which ensures the system observability.

1.2.2.2 Tabu Search (TS):

Is a global optimization algorithm for solving optimization problems, designed to control other embedded heuristics to escape the trap of local optimality. The key objective of the Tabu Search algorithm is to constrain an embedded heuristic from returning to recently visited areas of the search space, referred to as cycling [22]. Optimal PMU Placement problem is solved [23, 24] by the Tabu Search algorithm and a fast observability analysis method based on augmented incidence matrix that only manipulates integer numbers and with the capability for fast, convenient and quantitative assessment of the network observability with regards to PMU placement schemes.

1.2.2.3 Particle Swarm Optimization (PSO):

Is a population-based optimization method, inspired by the flocking and schooling patterns of birds and fish, in which each potential solution (called a particle) is assigned a randomized velocity and made to flow through the problem hyperspace. PSO has been found in [19] to be extremely effective in solving a broad range of engineering optimization problems.

The work in [25] proposed a binary PSO for solving OPP problems, which satisfies the constraints of PMU loss or branch outage effect, with a comparatively good result. A similar methodology is proposed in [7], which takes into account any available data from existing conventional measurements, the number, and locations of zero injection buses, the number, and locations of installed PMUs, and the system topology.

1.3 Supervisory Control and Data Acquisition System (SCADA)

The Supervisory Control and Data Acquisition (SCADA) system is a type of industrial control system. It is usually a centralized system that supervises and controls processes and systems that extend over large areas. Generally, this system consists of sensors and actuators distributed over a wide area, interconnected by telecommunications links and controlled via control logics located in the control centre. The SCADA system collects information on the state of a system, transfers it to the control station, analyses and processes it, and then sends out control signals which are then executed by the actuators [26]. The SCADA system collects data from various devices in any installation and then transfers this data to a central computer or server, either near or far, which then controls and supervises the installation, the latter being subordinated by other operator stations that provide a graphical interface representing the installations and related information. SCADA systems are used to monitor or control chemical or process transport, in municipal water supply systems, to control electrical power generation, transmission and distribution, oil and gas pipelines, and other industrial protocols.

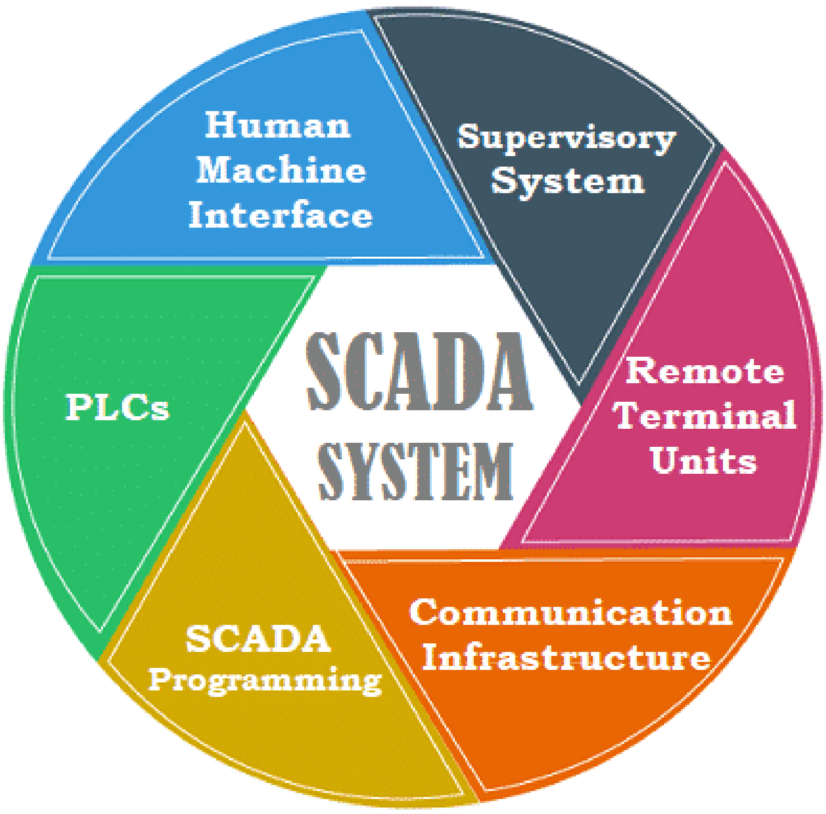

Figure 1.1: Components of SCADA System

1.3.1 Components of SCADA

A SCADA system consists mainly [27] of:

- Human Machine Interface: (HMI) is the operator window of the supervisory system. Which presents process data to a human operator, and through this, the human operator monitors and controls the process.
- Supervisory (Computer) System: this collect process data and sending commands (instructions) to the processes.
- Remote Terminal Units (RTUs): it connect to the sensors, converting the signals into digital data flow and sends the digital data to the supervision system.
- Programmable Logic Controller (PLCs): The PLC supplies both the control logic and the control processor for the SCADA system. They are as field devices because they are more economical, versatile, flexible, and configurable than special-purpose RTUs.
- Communication Infrastructure: it connects the supervision and control system to the terminal elements. As a result, it assures a continuous flow of data between the controller and the process being controlled.
- SCADA Programming: C language or derived programming language is generally used for such programming

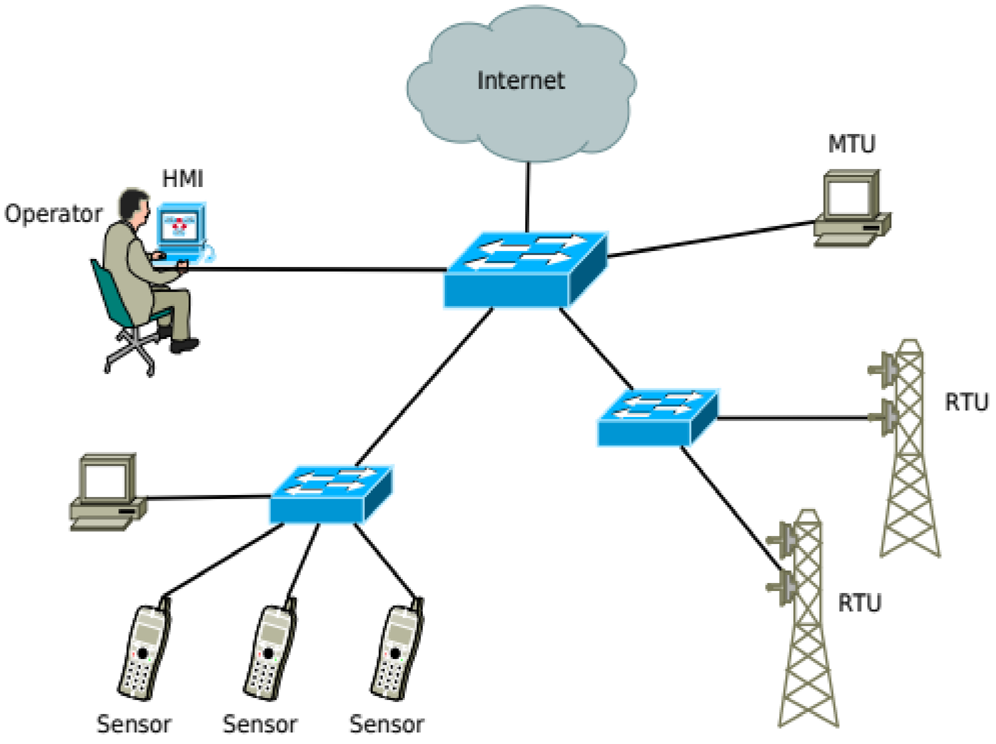

Figure 1.2: Typical SCADA System Components

1.3.2 Advantages of SCADA systems

SCADA is designed specifically to function in computers for monitoring, supervision and control of distant installations.

Among the benefits of SCADA which are recorded in [28], as follows:

- Improves reliability through system automation;
- Eliminates the need to collect data manually;
- System-wide alerts and monitoring allow operators to identify and address problems quickly;
- The automation process provides protection to workers by automatically detecting and addressing problems;
- The operators can use powerful trending analysis capabilities to detect future problems, ensure better routines;
- Maintenance of equipment and spot areas for improvement;
- Historians provides the ability to view data in various ways to improve efficiency.

1.3.3 SCADA System Limitations

The limitations of SCADA systems can be briefly summarized as follows:

- Time resolution: SCADA systems send data to the control room at intervals of 4 to 10 seconds. This rate of data exchange is quite low for an information-controlled power grid;
- Measured quantities: The SCADA systems only measure quantities, but not directions;
- Time synchronization: As there is no common time reference in SCADA measurements, it is difficult to achieve synchronization;
- Coverage area: The coverage area of the SCADA system is limited due to data processing and transmission capabilities;
- Cyber security: the traditional SCADA system is not equipped, in its basic design, with the security features needed for securing an information-controlled power grid;

1.3.4 Advantages of synchrophasor over SCADA system

The comparative advantages of the synchrophasor system over the conventional SCADA system in the operation and management of the power system are as follows:

- The sampling rate of PMU measurements is 30 to 60 data points per second, whereas the supervisory control and data acquisition (SCADA) system collects one data point every 1 to 2 seconds [29]. This higher sampling rate is important to enhance the monitoring and analysis of the dynamic behavior of power systems;
- PMUs provide synchronous measurements via a common time reference (global synchronous timestamps), for all acquired data to satisfy the need of a real-time control, thereby, allowing more accurate assessment of the current conditions of the power systems;
- A PMU can measure directly the voltage phasor of the bus, where it is installed, as well as the current phasor of the branches connected to this bus. Thus, it is possible to use a simple linear state estimation, which allows a higher accuracy and faster calculation, compared to classical non-linear state estimation methods [26];
- The measurement accuracy of a PMU is much higher compared to the SCADA system. Assuming all buses in the power grid are equipped with a PMU, the EMS can operate directly based on the measurements obtained, without the need for an SE.

Table 1.1: Comparison of Attributes of SCADA and Synchrophasor

Attribut	**SCADA**	**PMU**
Measurement	Analog	Digital
Resolution	2-4 samples per sec	Up to 60 samples per sec
Observability	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

1.4 Application of WAMS

Based on the operational characteristics of PMUs, the WAMS offers great potential for improving reliability and stability. There are a large number of WAMS applications in the literature; however, they can be classified into three principal groups of monitoring, protection and control applications.

1.4.1 Power System Monitoring

PMU based monitoring systems provide various types of functions, such as wide area visualization, model validation, status estimation, near real-time event replay, post-event analysis, early warning of potential problems, etc. These functionalities will considerably improve situational awareness. When the power grid operates under normal conditions, it is sufficient to provide applications with reduced resolution synchrophasor measurements. In contrast, for near real-time event replay mode and post-event analysis, full resolution measurements are necessary.

1.4.2 Power System Protection

Synchronized phasor measurements offer a solution to many complex protection problems and enhance the performance of protection applications. These measurements are very effective in improving the protection functions of power systems that require a slow response time. Among the protection systems that could benefit from PMUs are: adaptive dependability and security, back-up protection of distance relays, adaptive out-of-step, the stability of the grid angular voltage, etc.

1.4.3 Power System Control

Before the emergence of real-time phasor measurements, the majority of control systems were processed locally due to the short delay. Some sub-systems such as machines were controlled only by local signals [30]. Controllers such as the Variable Series Capacitor (VSC), Universal Power Flow Controllers (UPFC), and Power System Stabilizers ensure network regulation based on local feedback. While phasor measurements, in addition to remote control of the power systems, could provide direct feedback to these controllers and allow dynamic control of the power systems. The use of PMUs to damp low frequency inter-zone oscillations is one of the effective applications of WAMS [31].

1.5 Phasor Measurement Unit

1.5.1 General Structure of Phasor Measurement Unit

A PMU device is composed by different elements, as shown in Figure 2.3 :

- **Analog inputs:** are the current and voltage signals obtained from current and voltage transformers. In most cases, the current and voltage transformers (CTs and VTs) are connected to the PMU. To limit the phase errors introduced by instrument transformers, there are usually compensation routines in commercial PMUs.

- **A/D converter:** the analog to digital converter is a circuit that permits to adapt the acquired signals to the microprocessor. The conversion is disciplined by the time synchronization module, usually using the phase-locked loop (PLL) control circuit. Currently, the majority of devices on the market use sampling frequencies of the order of a few tens of kilos of samples per second.
- **Time Synchronization:** this unit is able to keep the UTC time required from the standard to synchronize the measurements. There are different suitable sources of synchronization: GPS is currently the most common solution for the synchronization of PMUs. A device may have an integrated GPS receiver or may receive the synchronization signal from an external receiver.
- **Microprocessor:** the microprocessor performs the computation necessary to estimate the quantities of interest from the acquired signals. It estimates the current and voltage phasors using the algorithms specific for the synchrophasor estimation. Moreover, it generates the time-stamp from the synchronization module to tag the measurements. It estimates also the frequency and ROCOF.
- **Data Communication:** the data communication system is used to transmit the measurements from a PMU through the network, either to/from Phasor Data Concentrator, a device specially designed to receive input data from different PMUs and to make their time alignment, or to/from Monitor Station. The data communication system must be compliant with the standard for the communication of the synchrophasor IEEE C37.118.2.

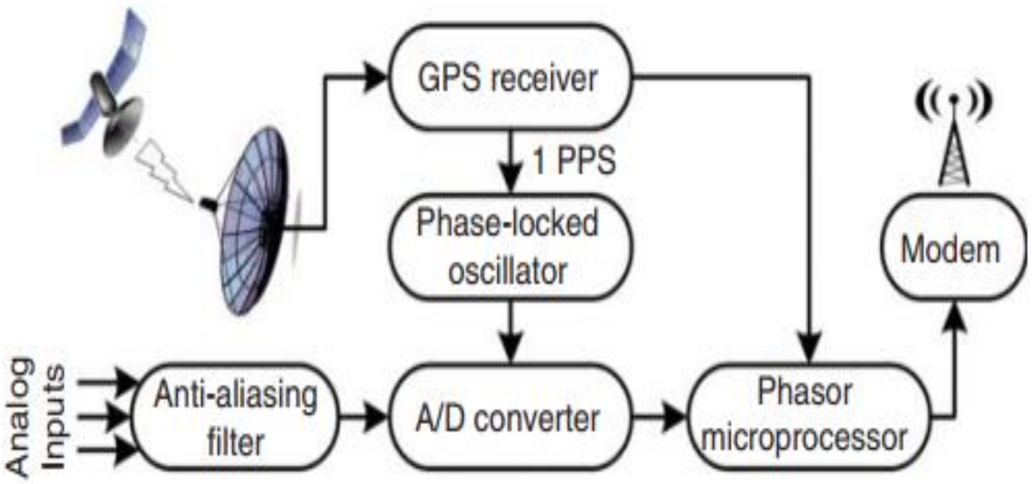

Figure 1.3: PMU basic structure

1.6 Synchrophasor Time Synchronization

Synchrophasor measurements are synchronized to UTC for sufficient accuracy in line with the accuracy requirements of the IEEE Synchrophasor Standard C37.118.1. The maximum allowable steady-state error according to the synchrophasor standard is 1% TVE, which can be caused by a phase error of 0.01 radians, corresponding to a time error of 31µs for a 50Hz system and 26µs for a 60Hz system. The most common methods for the local time dissemination are:

- 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.
- IEEE1588 standard: defines the Precision Time Protocol (PTP), which provides for an accurate synchronization mechanism (well below the microsecond) based on a master-slave architecture. The synchronization mechanism is similar to other protocol-based synchronization techniques, like NTP. However the IEEE1588 allows obtaining more accurate synchronization since the synchronization messages are timestamped usually at the hardware level, reducing the contribution due to software stack.

1.7 PMU installation process

The PMUs are nowadays installed in high-voltage substations or in large power plants. Since there are three phases, every PMU requires three connections that measure the three phases for both current and voltage. Figure 2.4 illustrates the typical installation of a PMU on one phase at a substation. Both the current transformer (CT) and the potential transformer (PT) reduce the current and voltage of the high-voltage buses to adapt to the input ranges of the A/D converters in the PMU. The burdens in Figure 2.4 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 relatively high installation costs of PTs and CTs, PMUs are currently installed only at the most important nodes of the power grid [32].

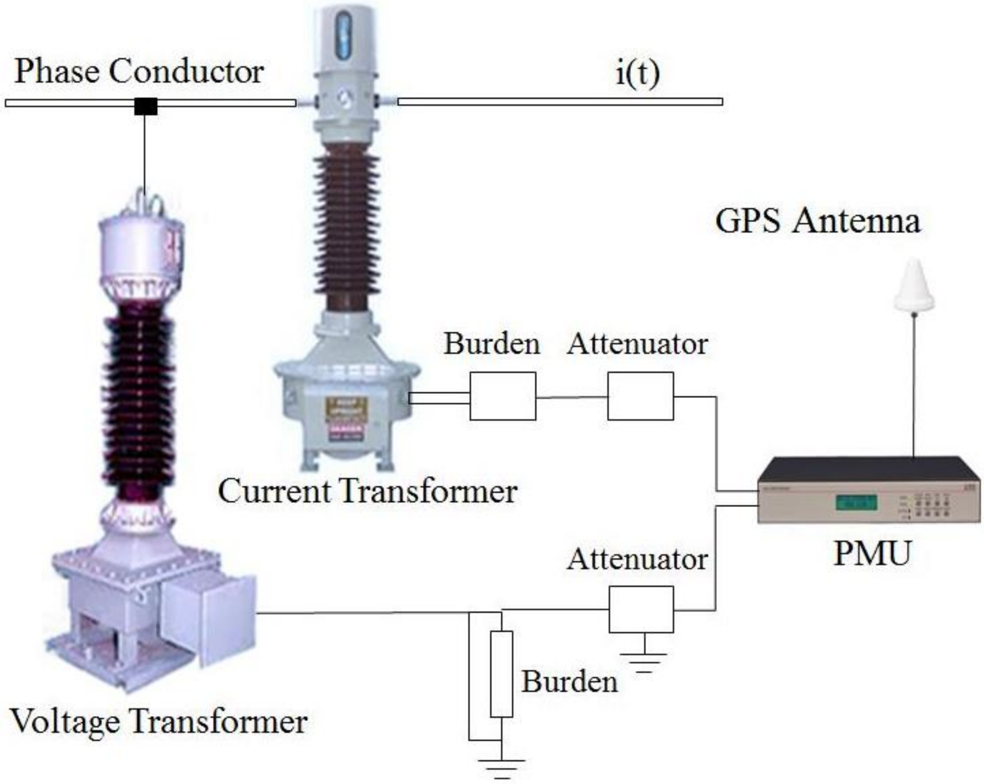

Figure 1.4 Typical PMU installation and interconnection in substation.

1.8 Synchrophasor fundamentals

Charles Proteus Steinmetz first presented a simplified mathematical description of the waveforms of alternating current electricity in the form of a phasor in 1893. In Steinmetz's technique, the time representation of steady-state alternating current (AC) quantities can be better represented by means of phasors. A sinusoidal function $x(t)$, which represents a voltage or current waveform, can be expressed mathematically as follows

$$x(t) = X_m \cos(\omega t + \delta) \tag{1.1}$$

Where,

X_m = Magnitude of the sinusoidal waveform.

ω = Angular frequency ($2\pi f$), and f is the instantaneous frequency.

δ = The angular starting point of the waveform (phase angle).

The effective value (the root mean square value (RMS)) of this sinusoid is:

$$X = \frac{X_m}{\sqrt{2}} \tag{1.2}$$

Generally, this signal is represented as the complex phasor :

$$X = \left(\frac{X_m}{\sqrt{2}}\right) e^{j\delta} \tag{1.3}$$

Euler's identity can be used to express the sinusoidal signal in terms of a further phasor as

$$X = \left(\frac{X_m}{\sqrt{2}}\right)(cos\delta + jsin\delta) = X_r + jX_i \tag{1.4}$$

Here X_r and X_i represent the real and imaginary components of the complex value in rectangular coordinates, respectively. δ is the instantaneous phase angle of the signal $x(t)$ relative to a cosine function at nominal system frequency synchronized to UTC. This angle is defined to be 0° when the maximum of $x(t)$ occurs at the UTC second rollover [1 pulse per second (PPS) time signal], and $-90°$when the positive zero crossing occurs at the UTC second rollover [33]. When the absolute time mark is added, a synchrophasor is defined as the magnitude and angle of a cosine signal as referenced to an absolute point in time as shown in Figure 2.5

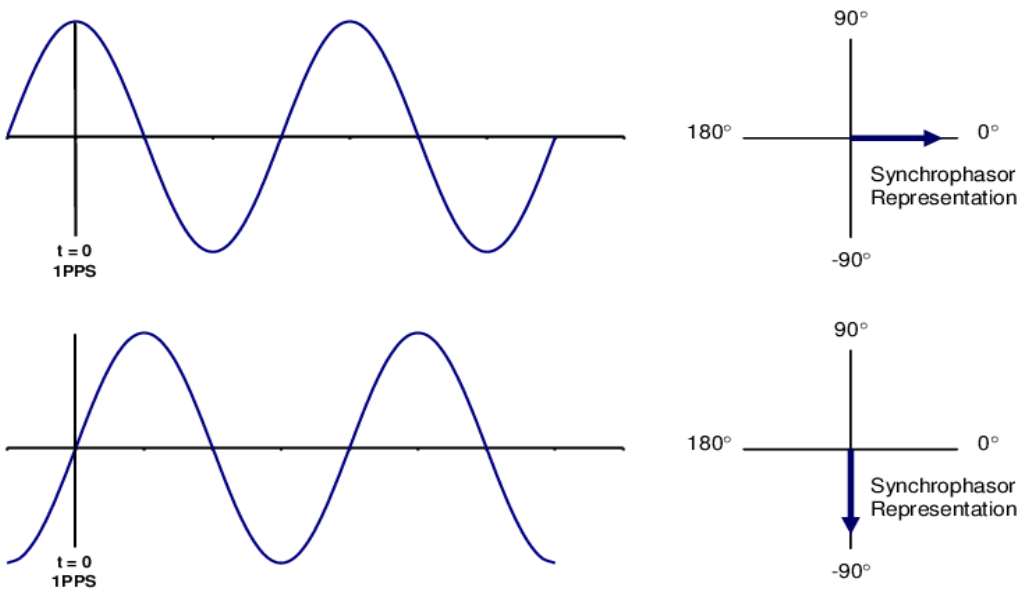

Figure 1.5: Synchrophasor representation [33]

Conventional power system measurements and analysis are made on steady-state signals (signals with constant waveform frequency over the period of measurements), but real-world power systems seldom operate at a constant frequency. For this reason, the calculations of phase angles need to consider the actual frequency of the system at the time of measurement. The phasor representation of a sinusoid is independent of its frequency.

A sinusoid $x(t) = X_m\cos(\omega t + \delta)$ has a phasor representation $X = (\frac{X_m}{\sqrt{2}})e^{j\delta}$

The phase angle δ of the phasor is determined by the starting time $t = 0$ of the sinusoid.

The sinusoid and its corresponding phasor representation are given in Figure 2.6. It is worth noting that the signal frequency w is not explicitly stated in the phasor representation. The angle δ is used to specify the value of $x(t)$ at the reference time $t = 0$.

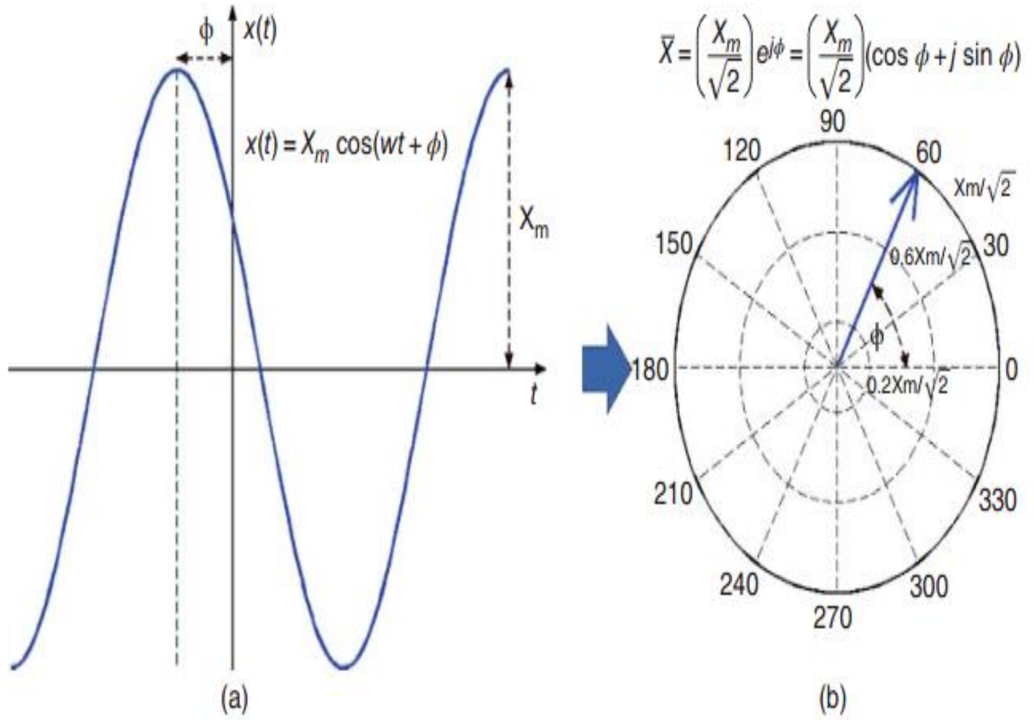

Figure 1.6: Sinusoid and its corresponding phasor representation a) sinusoidal function, (b) phasor representation.

The above illustration is equivalent to having the time reference for observation initialized at the beginning of each interval. Consider that such a sinusoid is observed at intervals $(0, T_0, 2T_0, 3T_0, \dots, nT_0)$ leading to corresponding phasor representations $(X_0, X_1, X_2,\ X_3, \dots)$ If the observation interval T0 is equal to an integer multiple of the period of the sinusoid $T = {}^{1}/_{f}$ constant phasor is obtained at each observation. Conversely, if the observation interval T_0, is not an integer multiple of T, the observed phasor will have a constant magnitude, but the phase angles of the phasor sequence $(X_0, X_1, X_2, X_3, \dots)$ will change uniformly at a rate of $2\pi(f - f_0)T_0$, where $f_0 = {}^{1}/_{T_0}$. In the course of time, the values of the observed phasor increase continuously until they reach $180°$, then they wrap around $-180°$ and continue to increase as shown in the figure 2.7 [33].

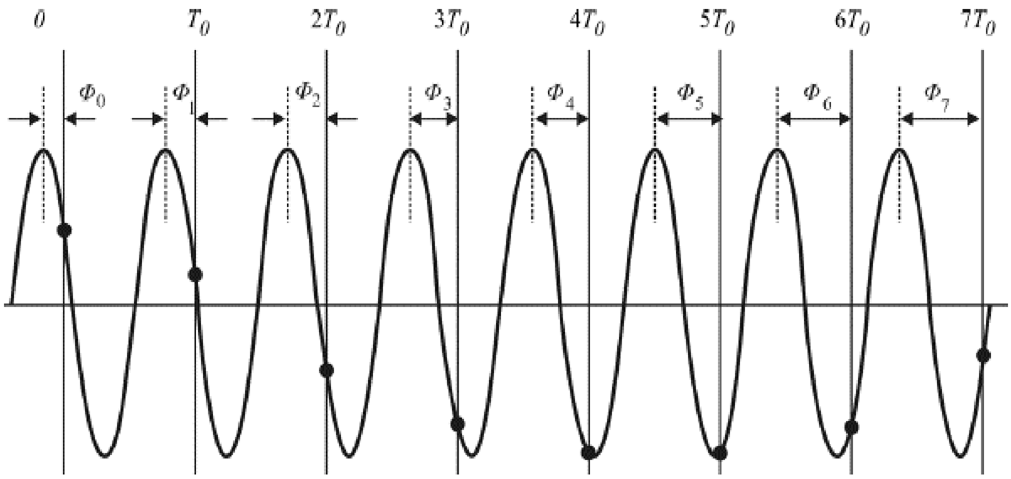

Figure 2.7: A sinusoid waveform with increasing phase angle.

1.9 Definitions of frequency and rate of change of frequency ROCOF

The phasor measurement unit can also be used to evaluate and report the frequency and rate of frequency change ROCOF, with a sinusoidal signal, in accordance with the synchrophasor standard given by the formula:

$$x(t) = X_m \cos(\theta(t)) \tag{1.5}$$

The frequency is defined as:

$$f(t) = \frac{1}{2\pi} . \frac{d\theta(t)}{dt} \tag{1.6}$$

Moreover, the ROCOF:

$$ROCOF(t) = \frac{df(t)}{dt} = \frac{d\left(\frac{1}{2\pi} . \frac{d\theta(t)}{dt}\right)}{dt} \tag{1.7}$$

If the argument of the cosine in the equation (2.5) is represented by:

$$\theta(t) = 2\pi f_0 t + \varphi(t) = 2\pi \left[f_0 + \frac{\varphi(t)}{2\pi}\right] \tag{1.8}$$

The formula for the frequency becomes:

$$f(t) = f_0 + \frac{d\left(\frac{\varphi(t)}{2\pi}\right)}{dt} = f_0 + \Delta f(t) \tag{1.9}$$

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

$$ROCOF(t) = \frac{d^2\left(\frac{\varphi(t)}{2\pi}\right)}{d^2} = \frac{d\Delta f(t)}{dt} \quad (1.10)$$

1.10 Main Synchrophaser Evaluation Criteria

According to the C37.118-2005 standard, the only index to assess PMU performance was the TVE, but numerous studies have demonstrated that the aggregated information of the TVE is not sufficient to describe the measurement performance completely. With the new standard, additional indices are being introduced in 2011 to evaluate the performance of synchrophasor, frequency, and ROCOF measurements under specific conditions, such as in the presence of step tests.

1.11 Total Vector Error (TVE)

If one compares the values obtained by the PMU estimation against the theoretical values of a synchrophasor representation of a sinusoid, differences in amplitude and phase can be observed. Although they can be specified separately, the differences in amplitude and phase are taken into account together to evaluate measurement errors.

The PMU's synchrophasor measurements need to maintain a certain level of phase and amplitude accuracy in different operating conditions. The accuracy of synchrophasor measurements is evaluated using a quantity called Total Vector Error (TVE). TVE is defined as the difference between a perfect sample of a theoretical synchrophasor and the measurement given by the unit under test at the same instant in time. This value is expressed in per unit of the theoretical phasor, as shown in the equation 2.11

$$TVE = \left(\sqrt{\frac{(\hat{X}_r(n)-X_r(n))^2+(\hat{X}_i(n)-X_i(n))^2}{(X_r(n))^2+(X_i(n))^2}}\right) \quad (1.11)$$

Where:

$\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequences of estimates given by the test PMU, and $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequences of values of the measurement at the instant of time (n).

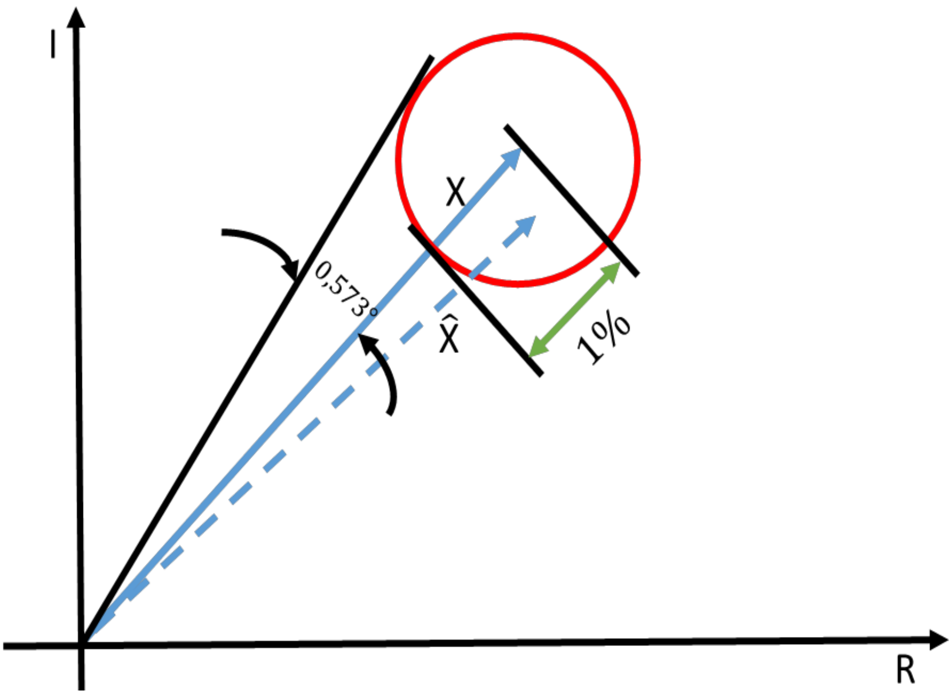

Figure 1.8: Graphical representation of the permitted TVE.

Under steady-state operation, a maximum TVE of 1% is allowable to meet the requirements of the synchrophasor standard. In general, 1% TVE can be caused by a phase error of 0.57 degrees (0.01 radians). This TVE corresponds to a time error of 26µs in a 60Hz system and 31µs in a 50Hz system. Figure 2.8 shows that 1% accuracy limit of the TVE specified in [34] corresponds to a 1% error in the phasor magnitude estimation or a 0.573 degrees error in the phasor angle estimation.

1.12 Frequency and ROCOF Error

Other measurement criteria of interest in synchrophasor evaluate are the frequency error (FE) and the rate of change of frequency (ROCOF) error (RFE). These form the index to evaluate the accuracy of the frequency measurement.

1.13 Frequency Error (FE)

The measure of error between the theoretical frequency and the measured frequency for the given instant of time is the frequency error (FE), which is defined by:

$$FE = |f_{True} - f_{Measured}| \tag{1.12}$$

The FE gives the absolute value of the difference between the theoretical frequency and the estimated one at the same time instant.

$$REF = \left| \left(\frac{df}{dt}\right)_{True} - \left(\frac{df}{dt}\right)_{Measured} \right| \tag{1.13}$$

The ROCOF measurement error (RFE) gives the absolute value of the difference between the theoretical rate of change of frequency and the estimated one at the same time instant.

1.14 Performance class of PMUs

The PMUs standard defines two performance classes of PMU, namely P-class and M-class. The P-class PMU is intended for power system applications requiring fast measurement response time and mandates no explicit filtering, such as protection applications. The M-class PMU, on the other hand, is intended for power system applications where measurement accuracy is of crucial importance, and where the presence of aliased signals can adversely affect the performances of the applications. The kinds of measurements designated for M-class are often analytical measurements that often require greater precision but do not require minimum reporting delay.

Synchrophasor Standard requires that a PMU meets all the requirements for at least one class. A network setup is aimed at providing PMU setups that can ensure performance compliance with both P and M classes so they can serve both protection and analytic measurement purposes and the required reporting rates. The major differences between the two PMU performance classes are seen in their steady-state performance and dynamic performance test conditions as specified in the standard [33].

1.15 PMU Latency

The latency is one of the most important parameters to evaluate a PMU and is defined as the time delay from when an event occurs on the power system to the time instant when it is reported in measurement data. It can include different factors as sampling windows, PMU processing, measurement filtering, etc. The limit given by the standard for this parameter is directly connected to the reporting rate and to of the class of performance. In Table 2.1, the maximum measurement reporting latency for the two performance classes is reported.

Table 1.2 Measurement Latency for Two PMU Classes.

Performance Class	Maximum Measurement Reporting Latency
P-class	$^{2}/_{F_s}$
M-class	$^{5}/_{F_s}$

1.16 Synchrophasor Components

The purpose of a synchronized phasor measurement system is to provide accurate, reliable, and high-speed (1-2 samples per cycle) phasor data to power system control centers for monitoring and analyzing the grid conditions in real-time. The phasor measurements include precise timestamps, which are synchronized to a common global positioning system (GPS) radio clock.

The components of a synchrophasor data system include:

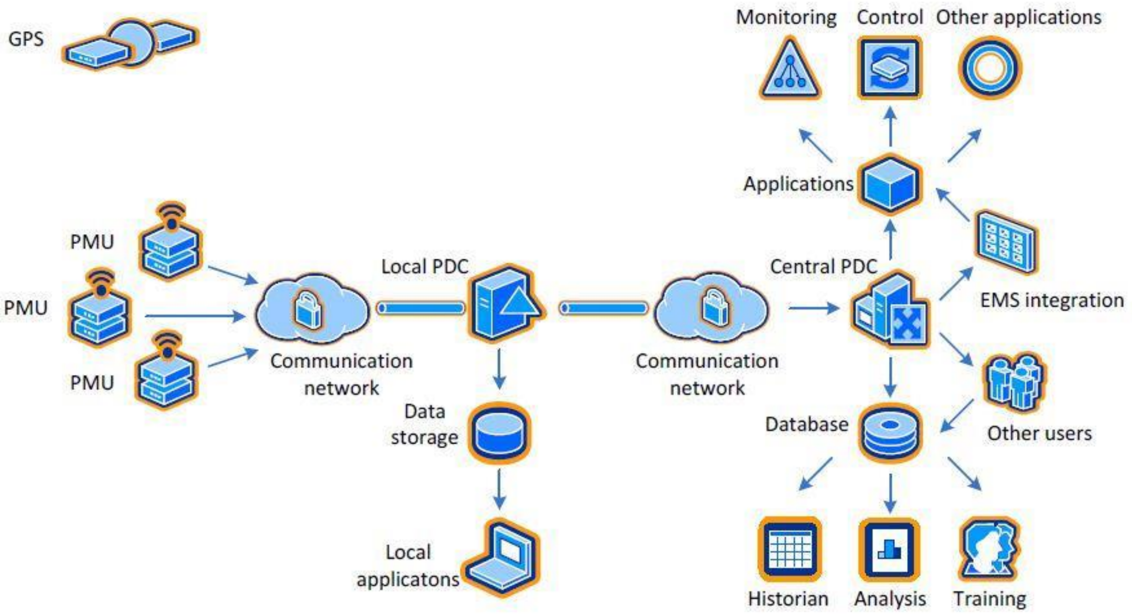

Figure 1.9: Generic Synchrophasor Architecture.

1.16.1 Phasor Measurement Unit (PMU)

In 1988, Arun G. Phadke and James S. Thorp of Virginia Tech invented phasor measurement units (PMU), which allowed the Steinmetz technology to evolve into the calculation of real-time phase-measurement measurements synchronized with an absolute time reference provided by the global positioning system.

The PMUs devices are placed in the substations of an electrical network, as shown in Figure 2.9, for measuring the voltage and current phases as they occur in the substations and stations connected to the network. These devices provide estimates of synchrophasor as well as frequency estimates. It also provides other optional information such as actual and calculated reactive power, sampled measurements.

1.16.2 Phasor Data Concentrator (PDC)

A function that collects s phasor data, and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications. PDCs may buffer d at a for a short time period, but do not store the data. The use of multiple PDCs enables the implementation of multiple layers of concentration and aggregation within an individual synchrophasor data system as shown in Figure 2.7. The hierarchical structured distributed multiple PDC systems may serve a hierarchy of systems: substation, utility, control area, reliability coordinator, and interconnection level [35].

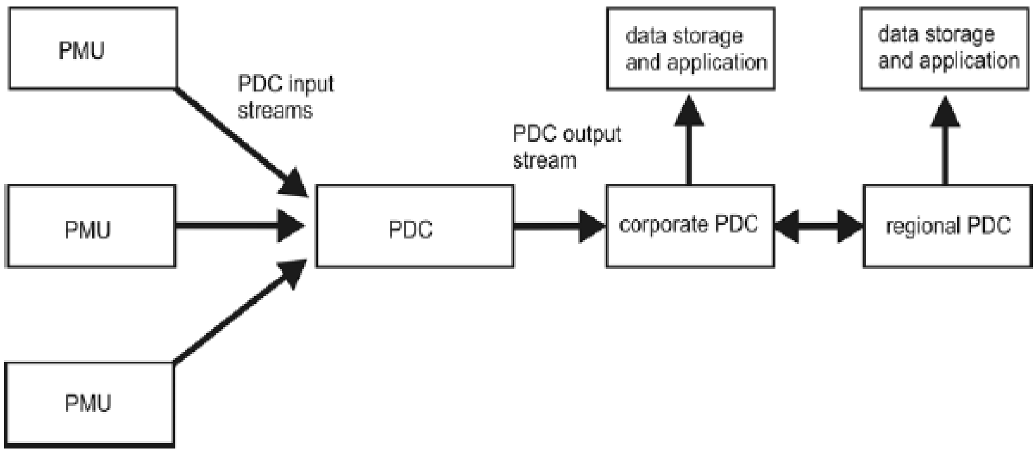

Figure 1.10: General components of PMUs

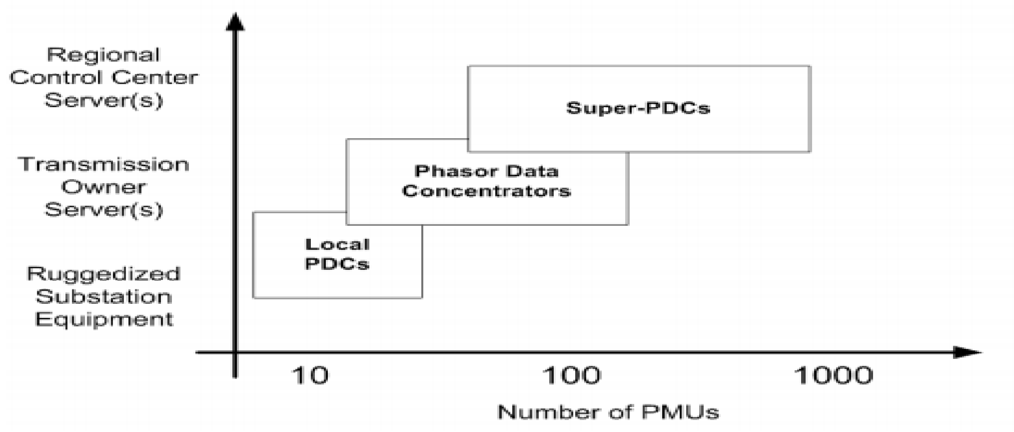

Figure 1.11: Three levels of PDC [35].

1.16.3 Super Phasor Data Concentrator (PDC)

A super phasor data concentrator (SPDC) collects information from various phasor data concentrators to afford greater use of the total amount of phasor data collected over a wide-area.

1.17 Optimal PMUs Placement

The PMU is a fundamental element in smart grids that needs several considerations when deciding to integrate it in a power system. It is essentially placed to measure the current and voltage phasors on the power grid and to send them to the control centers for the different operating and management decisions.

1.18 Criteria considered for resolving the OPP

1.18.1 Normal operating

During normal operating conditions, the problem of OPP will be solved by ignoring all of the factors listed below. The system has been assumed that not contain PMUs at the beginning. The locations of the PMUs have been determined so that the power system becomes totally observable.

1.18.2 Zero-injection bus

Zero Injection Bus (ZIB) refers to the bus that has no load or generation source attached to it. Thus, it can be modeled as a line with its own parameters. Hence, The existence of this kind of buses in a power grid can reduce the number of PMU required for complete observability of the grid.

1.18.3 No PMUs at a ZIBs

Removing PMU devices from zero-injection buses will decrease the space for research, which could improve the speed of the solution. In addition, PMUs at zero-injection buses measure current phasors of corresponding lines; thus, the KCL at zero-injection bus provides no additional information. However, the PMU placement at zero-injection buses will help find the optimal solution.

1.18.4 Single PMU loss

Despite the high reliability of PMUs, they are exposed to failures as all other measurement devices. When one of the PMUs fails, the bus that was observed via the

PMU will become unobservable if the bus is not monitored by other PMUs. Hence, this problem is addressed by ensuring that each bus is observed with two PMUs (except the radial bus). This will ensure that in case one of the PMUs fails, the observability of the power system will remain assured.

1.18.5 Single line outage

Line outage is among the contingencies that could be unsafe to observability system. An outage of a line can render the completely observable power grid unobservable, especially when the tripped-off line monitors a bus.

1.18.6 Channels limit

The PMU made by different producers does have a limited number of channels. Hence, the PMU will be limited to a certain number of branch currents and bus voltages that it can monitor at one time. Therefore, the PMUs placement set will be different for certain number of channels. It is also worthy of note that the number of analog channels available in a PMU can affect the cost of the PMU equipment.

1.19 Observability rules for PMUs

In general, the PMU placement model includes three types of components: buses, branches and injection. In this placement model, the buses are referring to substations that can be equipped with a PMU. These buses also need to be equipped with communication facilities to ensure that the PMU functions properly. Meanwhile, the branches represent transitions between two adjacent buses, where the impedance is supposed known.

Rule 1: When a bus has a PMU installed on it, its voltage phasor and all the branch currents incident to it are measured by the PMU, These measurements are called direct measurements.

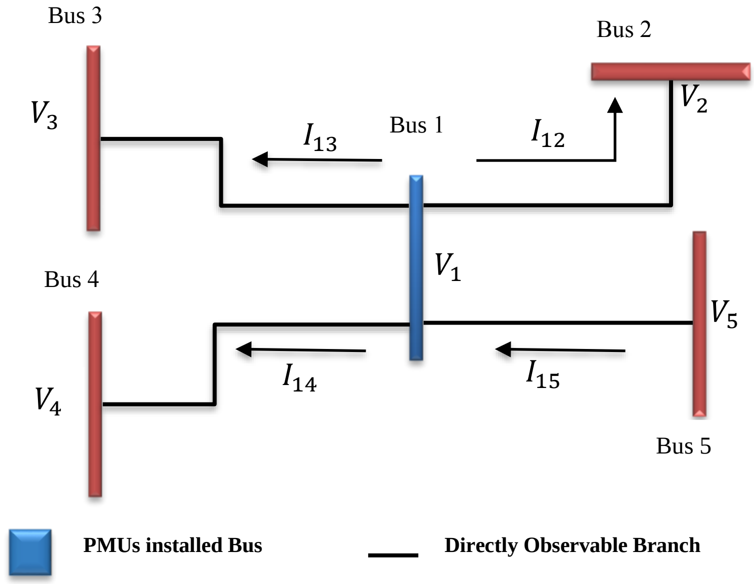

Figure 1.12: PMU Placement rule 1: observability with direct measurements.

As can be seen in Figure 2.12, Bus 1 is equipped with a PMU. Thus, the values of V_1, I_{12}, I_{13}, I_{14} and I_{51} can be directly measured by the PMU.

Rule 2: Knowing both the voltage and current phasors at one end of a line, then simply ohm's law can calculate the voltage phasor at the other end of the branch, these measurements are called pseudo-measurements.

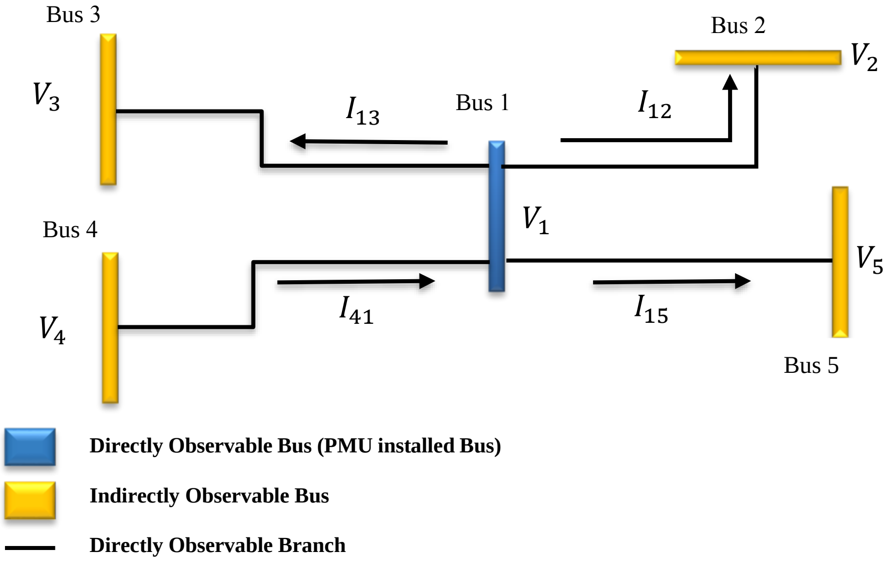

Figure 1.13: PMU placement rule 2, observability of bus voltage using pseudo measurements.

Once the values of I_{12}, I_{13}, I_{14} and I_{15} are known, it is possible to calculate the bus voltage of 2, 3, 4 and 5 using Ohm's law. The values of V_2, V_3, V_4 and V_5 are the consequences of V_1 minus the voltage drop caused by the current circulating in the branch. The following demonstrates how the V_2, V_3, V_4 and V_5 values are calculated.

For V_2:

$$I_{12} = \frac{V_1 - V_2}{R_{12} + jX_{12}} \tag{1.14}$$

$$(V_1 - V_2) = I_{12}(R_{12} + jX_{12}) \tag{1.15}$$

$$V_2 = V_1 - I_{12}(R_{12} + jX_{12}) \tag{1.16}$$

For V_3:

$$I_{13} = \frac{V_1 - V_3}{R_{13} + jX_{13}} \tag{1.17}$$

$$V_3 = V_1 - I_{13}(R_{13} + jX_{13}) \tag{1.18}$$

For V_4:

$$I_{41} = \frac{V_4 - V_1}{R_{41} + jX_{41}} \tag{1.19}$$

$$V_4 = V_1 + I_{41}(R_{41} + jX_{41}) \tag{1.20}$$

For V_5:

$$I_{15} = \frac{V_4 - V_1}{R_{41} + jX_{41}} \tag{1.21}$$

$$V_5 = V_1 - I_{15}(R_{15} + jX_{15}) \tag{1.22}$$

Rule 3: Considering a branch where the voltage phasor at both ends are known, the current of this branch can be calculated by applying ohm's law.

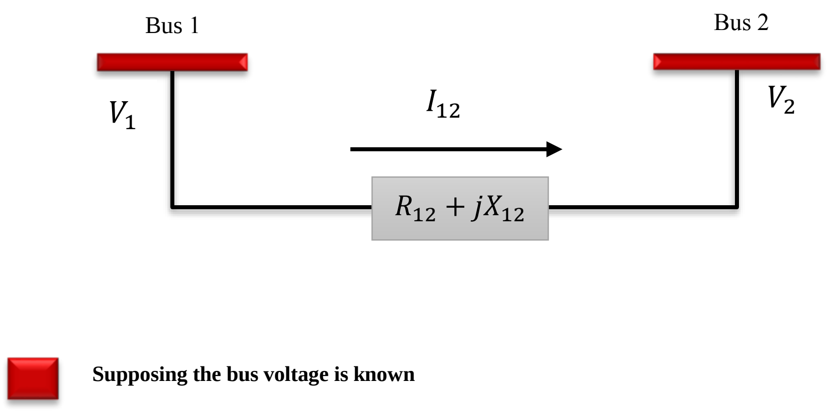

Figure 1.14: PMU placement rule 3, observability of branch current using pseudo measurements.

In figure 1.14, the voltage phasor of bus 1 and 2 are known; so, following rule 3 the branch between bus 1 and bus 2 will be available. Supposing the current flows from bus 1 towards bus 2, by using Ohm's law, the value of I_{12} can be calculated as follows:

$$I_{12} = \frac{V_1 - V_2}{R_{12} + jX_{12}} \tag{1.23}$$

Rule 4: In the case where power flow measurement is present at some branches, when the voltage at one end of the branch is known, then the voltage at the other end of the branch will be also known.

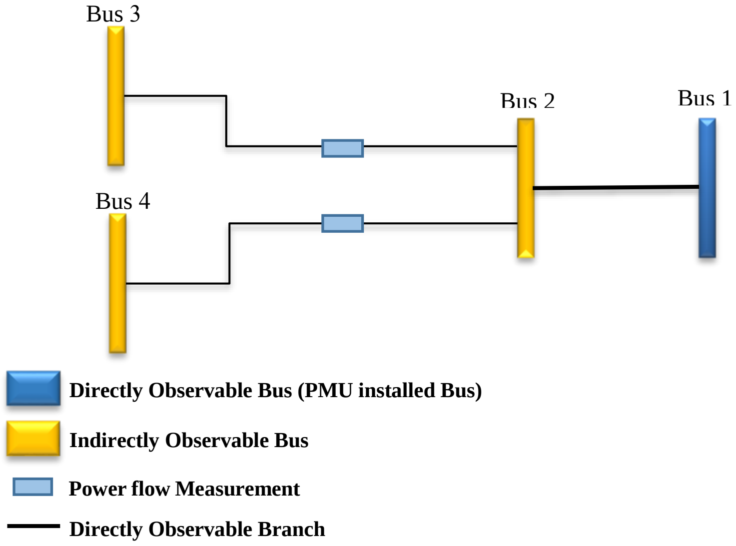

Figure 1.15: PMU placement rule 4, the observability when considering power flow measurement

Figure 1.15 illustrates the observability rules for power flow measurement. The power flow measurement is situated at branches 2-3 and 2-4 and a PMU is located at bus 1. Since the power flow measurement is present at branches 2-3 and 2-4, this means that if the voltage at bus 2 is known, it is possible to calculate the voltage at bus 3 and bus 4 by an indirect measurement because the branch currents for 2-3 and 2-4 are known. For this case, by placing the PMU at Bus 1, the voltage of Bus 2 is known, which ensures that Bus 3 and 4 are observable.

1.20 Observability rules when considering ZIB

In any power grid, zero injection buses (ZIBs) are responsible for transmitting energy through the grid transmission lines without injecting or consuming energy. In addition, knowing the value and direction of all currents flowing through a zero injection bus, excluding one, makes it possible to identify the value and direction of the unknown current. Supposing the resistance values of all connected transmission lines to the zero injection bus are known, the bus voltage connected to the zero injection bus via the transmission line with the non-measured current can be identified as well, thus allowing this bus to be observable even when the current transmitted by the zero injection bus is unknown. As a result, the number of buses to be observed is reduced by one for each available ZIB in a power system, hence reducing the number of PMUs necessary for full observability.

The following observability rules are applied to evaluate the topological observability when considering ZIB:

Rule 5: When all the buses, which are incident to an observable zero injection bus, are observable except one, it is possible to consider the non-observable bus as observable by applying the KCL at the zero injection bus.

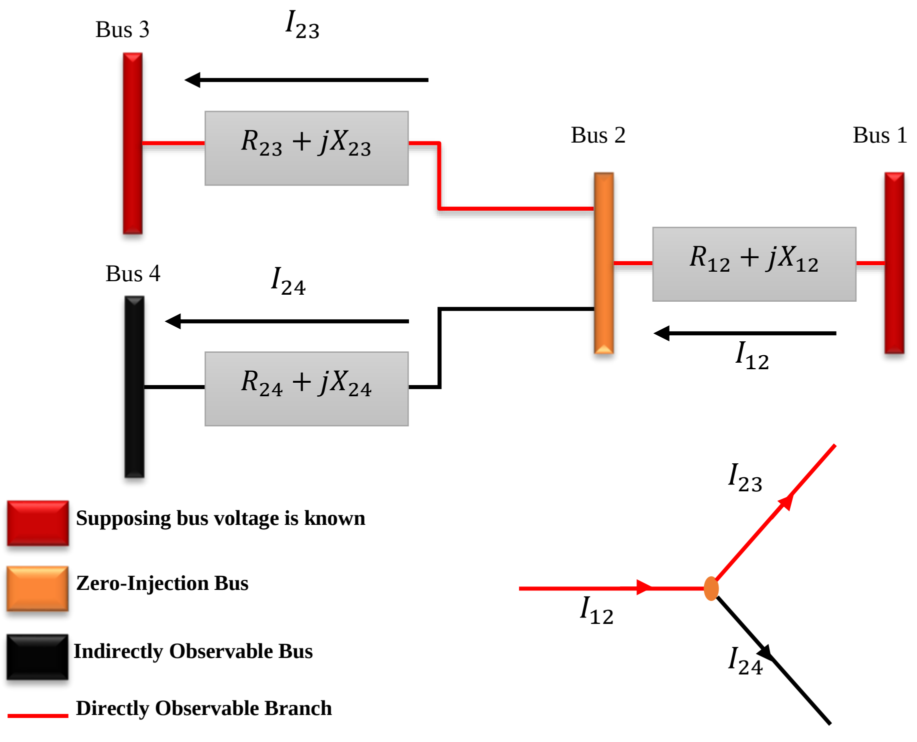

Figure 1.16: PMU placement rule 5, the observability when considering ZIB

Figure 1.16 above illustrates that the bus 2 is an observable ZIB. Supposing the value of V_1, V_2 and V_3 are known, the value of I_{12} and I_{23} can be calculated according to rule 3 previously. So, by applying the KCL at bus 2 and supposing that the current flows are as shown in Figure 1.16, the value of I_{12} is $I_{12} = I_{23} + I_{24}$. Thus, the value of I_{24} and then V_4 are both calculated as follows:

$$I_{24} = \frac{V_2 - V_4}{R_{24} + jX_{24}} \tag{1.24}$$

$$(V_2 - V_4) = I_{24}(R_{24} + jX_{24}) \tag{1.25}$$

$$V_4 = V_2 - I_{24}(R_{24} + jX_{24}) \tag{1.26}$$

Rule 6: If all incident buses to an unobservable zero injection bus are observable, then the zero injection bus will be also marked as observable by applying the KCL to the zero injection bus.

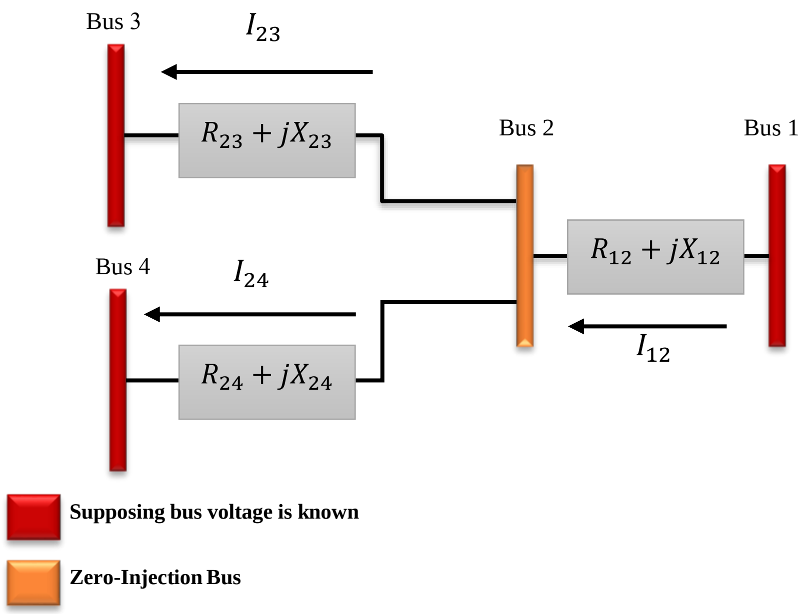

Figure 1.17: PMU placement rule 6, the observability when considering ZIB.

In figure 1.17, it is assumed that the bus 1, 3 and 4 are observable, i.e. their voltage are known. According the above rule, the voltage of the unobservable ZIB (Bus 2) can be determined as follows:

$$V_2 = V_1 - I_{12}(R_{12} + jX_{12}) \tag{1.27}$$

$$V_2 = V_3 - I_{23}(R_{23} + jX_{23}) \tag{1.28}$$

$$V_2 = V_4 - I_{24}(R_{24} + jX_{24}) \tag{1.29}$$

$$I_{12} = I_{23} + I_{24} \tag{1.30}$$

Rule 7: It' is a general case for Rule 6. Considering a group of adjacent zero injection buses whose voltage phasors are unknown and the voltage phasors of all the adjacent buses of this group are known, then the zero injection buses will be observable by using the equations KCL and KVL.

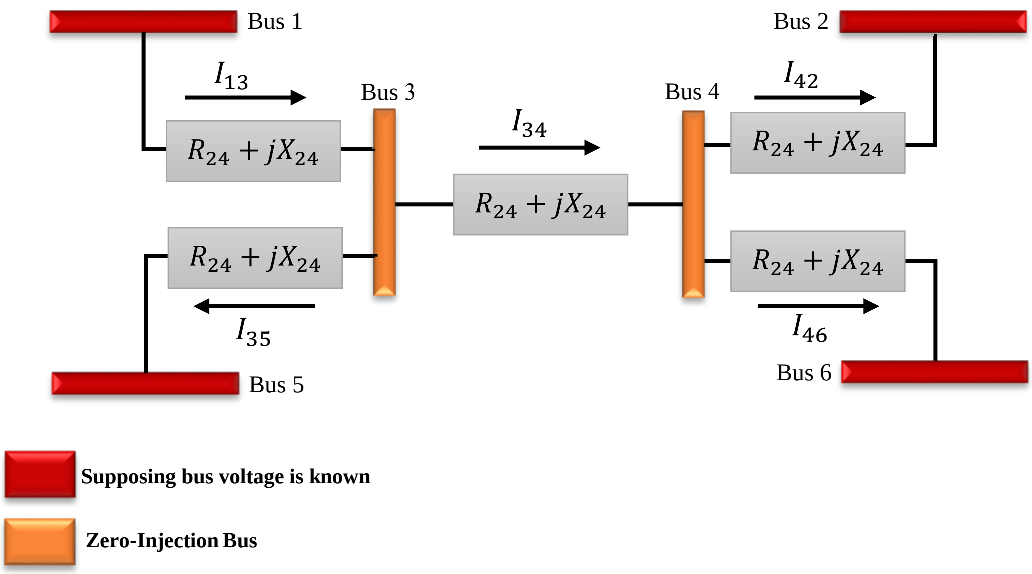

Figure 1.18: PMU placement rule 7, the observability when considering a group of ZIBs.

The figure 1.18 shows a group of zero-injection buses including bus 3 and bus 4 whose voltage phasor is unknown, whereas the voltage phasors of the buses adjacent to the mentioned group, which includes bus 1, bus 2, bus 5 and bus 6, are known. According to Rule 7, the voltage phasors of Bus 3 and Bus 4 will be determined.

1.21 OPP formulation

The principal objective of the OPP problem is to determine the minimum number of PMUs and their appropriate location to ensure complete observability of the power system. The challenge lies in accessing a fully observable power grid. Thus, the main objective function can be formulated mathematically as follows:

$$obj. = min\{N_{PMU}\} \tag{1.31}$$

$$Subject\ to\ N_{N-O} = 0 \tag{1.32}$$

Where N_{PMU} is the number of PMUs need and N_{N-O} is the number of unobservable buses. The number of non-observable buses must be equal to zero to indicate that the power system is fully observable by the PMU placement set.

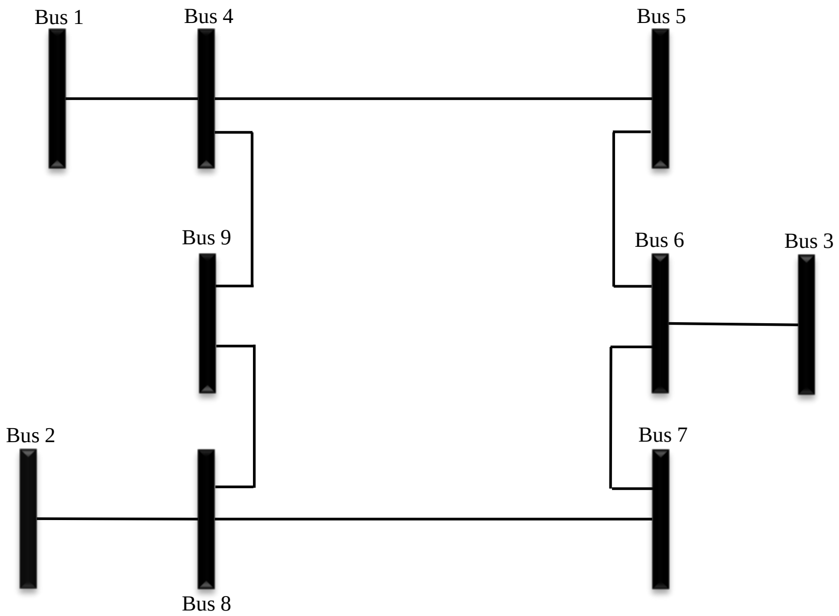

Figure 1.19: IEEE 9-bus system diagram

$$[A] = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{1.33}$$

Based on the binary connectivity matrix in equation (1.33), the constraints can be formulated as follows:

$$f(x) = \begin{array}{lll} f_1 = & x_1 + x_4 & \geq 1 \\ f_2 = & x_2 + x_8 & \geq 1 \\ f_3 = & x_3 + x_6 & \geq 1 \\ f_4 = & x_1 + x_4 + x_5 + x_9 & \geq 1 \\ f_5 = & x_4 + x_5 + x_6 & \geq 1 \\ f_6 = & x_3 + x_5 + x_6 + x_7 & \geq 1 \\ f_7 = & x_6 + x_7 + x_8 & \geq 1 \\ f_8 = & x_2 + x_7 + x_8 + x_9 & \geq 1 \\ f_9 = & x_4 + x_8 + x_9 & \geq 1 \end{array} \tag{1.34}$$

The " + " operator is used as a logical "OR" and the use of 1 in the right hand side of the constraints ensures that at least one of the variables appearing in the sum must be non-zero. For example, consider the constraints related to buses 1 and 4 as shown below:

$$f_1 = x_1 + x_4 \geq 1 \tag{1.35}$$

$$f_4 = x_1 + x_4 + x_5 + x_9 \geq 1 \tag{1.36}$$

For the first constraint $f_1 \geq 1$ implies that at least one PMU must be placed at either bus 1 or 4 (or both) in order to make bus 1 observable. similarly, the fourth constraint $f_4 \geq 1$ indicates that at least one PMU must be installed at one of the buses 1, 4, 5 or 9 (or all) in order to make bus 4 observable.

The PMU placement can be expressed as $[X]$, which acts as a binary decision variable vector, and is formulated as follows:

$$[X] = [x_1 \quad x_2 \quad x_3 \cdots x_N]^T, \text{ Where } x_i \in \{0,1\} \tag{1.37}$$

$$x_i = \begin{cases} 1 & \text{if a PMU is installed at bus i} \\ 0 & \text{otherwise} \end{cases} \tag{1.38}$$

1.21.1 Radial bus

The placement of PMUs in a strategic place will make the power system observable by means of a small number of PMUs. Supposing a PMU has an unlimited number of channels, it is obvious that setting the PMU in a bus that has many adjacent buses will provide better network coverage than a bus that has fewer adjacent buses, particularly a radial bus. The radial bus is a bus which has only one adjacent bus. Placing a PMU at a radial bus will ensure a maximum of two buses to be observed by the PMU (the radial bus and its neighbor). Conversely, a PMU placed at the bus adjacent to radial bus extends the coverage to a larger number of buses as well as the radial bus. As a result, the radical busses are excluded from the PMU candidate placement and, simultaneously, a PMU will be placed to the bus adjacent to the radial bus.

By applying this model to a network of nine buses, it is necessary to install two PMUs on buses 5 and 8.

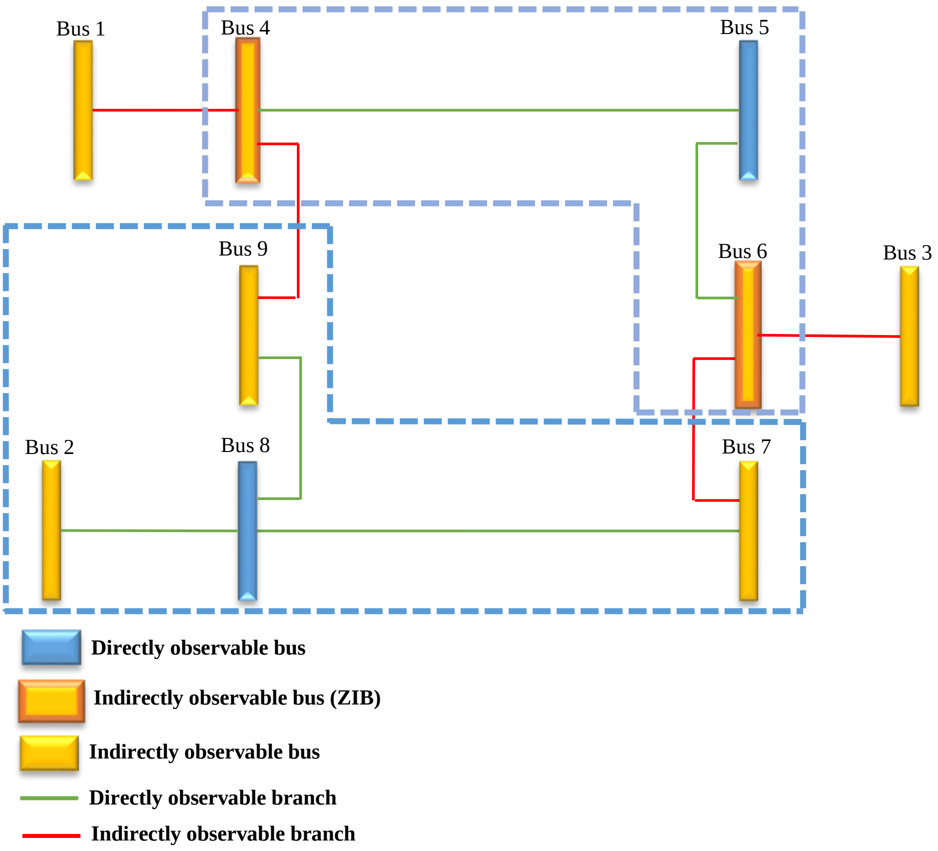

Figure 1.20: Results of IEEE 9-bus system for normal case

The proposed model has been applied to the 9-bus network and has resulted in installing two PMUs on buses 5 and 8, as shown in Figure 1. In this case, buses 4, 6 and 8 are zero injection buses and the dashed lines indicate the zone of observability of each installed PMU. Therefore, buses 4 and 6 are made observable by PMU's installation at bus 5, while buses 2, 7 and 9 are made observable by PMU's installation at bus 8. Buses 1 and 3 are rendered observable through the zero injection effect of buses 4 and 6, respectively. All buses in this case have at least one source of observability, so the network is fully observable.

1.21.2 No PMUs at Zero-Injection Buses

To reinforce the lack of PMU in zero injection buses, the following constraint is added:

$$Z_j x_j = 0, \forall\, j \in I \tag{1.39}$$

According to constraint (1.39), in zero injection buses, where Z_j is equal to one, the value of x_j would be null when no PMU is placed in these buses. In the other buses, where Z_j is zero, the value of x_j could be either zero or one.

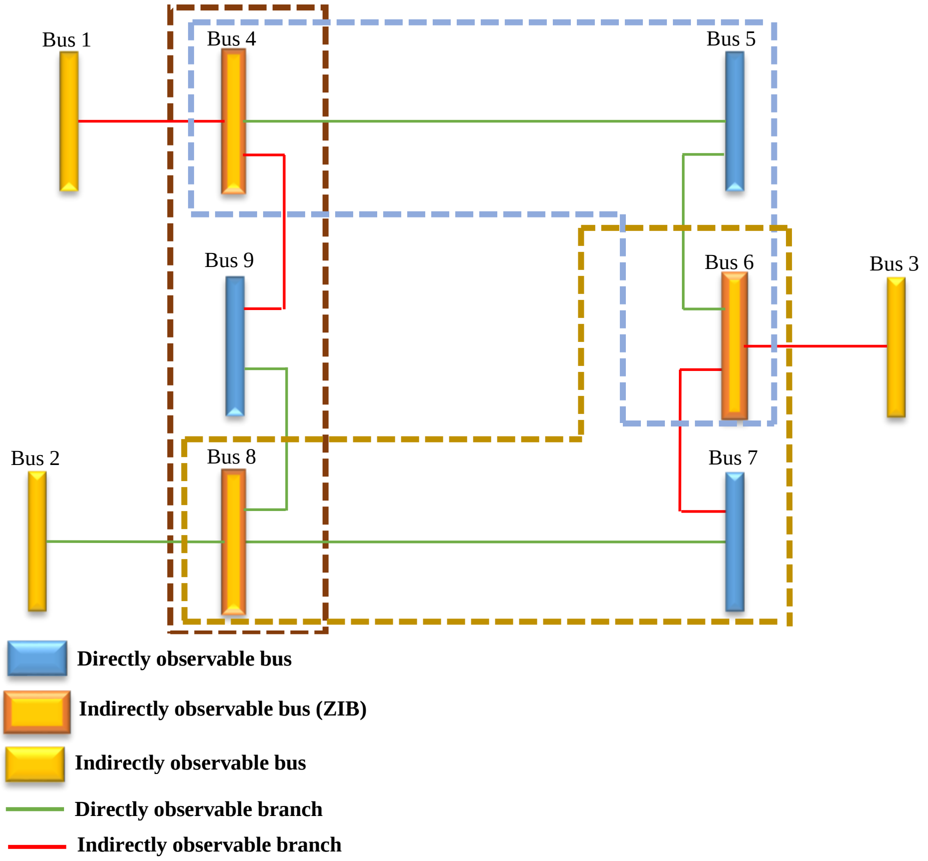

Figure 2.21: Results of IEEE 9-bus system with no PMUs at ZIBs

When applying this model in a network of nine buses, three PMUs are needed to be installed at buses 5, 7 and 9. Thus, the buses 4, 6 and 8 can be observed, and each one has a redundant measurement.

1.21.3 Single PMU loss

The purpose of this contingency is to ensure that the entire bus system will remain observable even in the case of an unexpected failure of a single PMU, caused either by device or communication link failures.

Following the proposed model, the loss of a single measurement can be modelled by modifying the inequality as follow:

$$f_i \geq 2 \tag{1.40}$$

Thus, $f_i \geq 2$ indicates that bus i needs at least two observability source.

By applying this model to a network of nine buses, it is necessary to install four PMUs on buses 4, 5, 7 and 8.

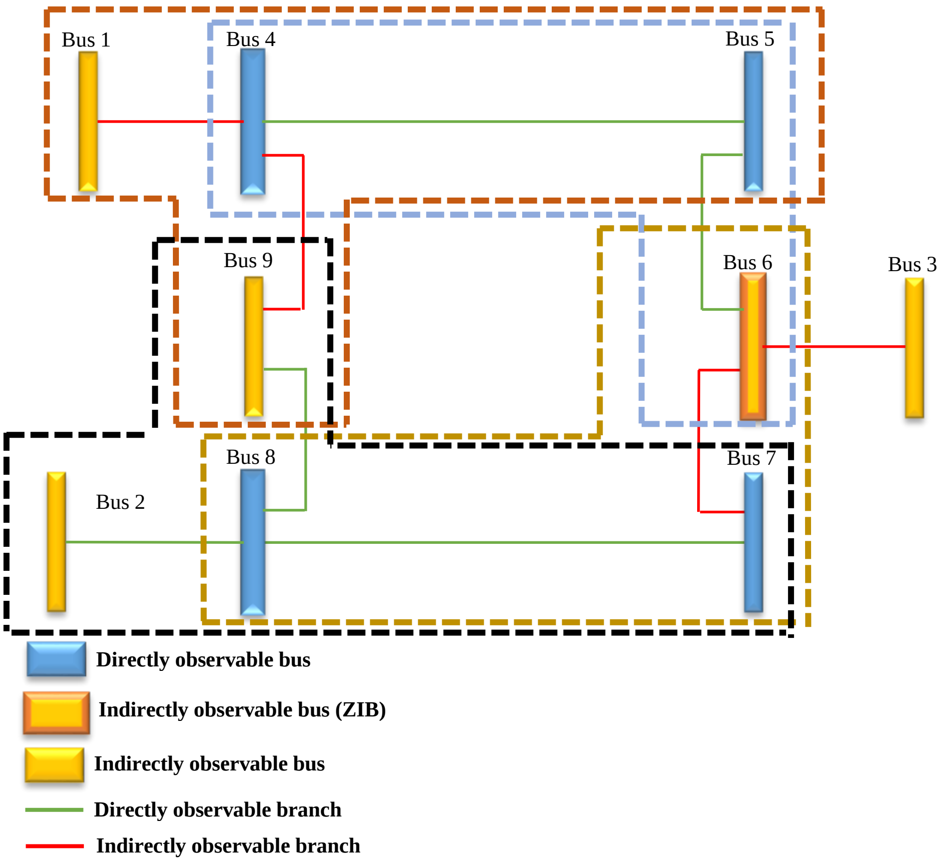

Figure 1.22: Results of IEEE 9-bus system for single PMU failure

The proposed model in Figure 3 considers four PMUs in buses 4, 5, 7 and 8 for any loss of PMUs. The buses 4,5,7,8 are observable due to their associated PMUs; moreover, buses 1, 6, 2 and 9 are observable since they are located adjacent to observable buses. Bus 3 is observable due to the zero injection effect at bus 6. As the buses (5, 6 and 7) and (4, 9 and 8) are observable during any PMU outage, the buses 3, 1 and 2 are also observable under these conditions. If one of the PMUs is lost, the buses will remain observable considering the other three PMUs.

1.21.4 Single line outage

Reliable measurements are essential to ensure that the electrical system remains observable in the possible topologies, especially in the event of credible contingencies. The branch disconnection between the i and j buses modifies the topology of the electrical system, and then, it modifies two entries of the connectivity matrix from: $a_{ij} = a_{ji} = 1$

To $a_{ij} = a_{ji} = 0$. The number of PMUs is increasing as more line failures are considered. The following are the constraints in case of an outage of single line:

$$f_i^k \geq 1 \qquad \forall\, i \in I, \forall\, k \in K \tag{1.41}$$

Where

$$f_i^k = \sum_{j \in I} a_{ij}^k\, x_j, \quad \forall\, i \in I, \forall\, k \in K \tag{1.42}$$

The binary connectivity parameter in case where line k is out, is defined as follows:

$$a_{ij}^k = \begin{cases} 0 & \text{line k is between i} - \text{j} \\ a_{ij} & \text{Otherwise} \end{cases} \tag{1.43}$$

The modelling of a single line outage for the network of nine buses has resulted in the placement of four PMUs in buses 1, 2, 3 and 6. The four PMUs ensure the observability of the network during single line failures.

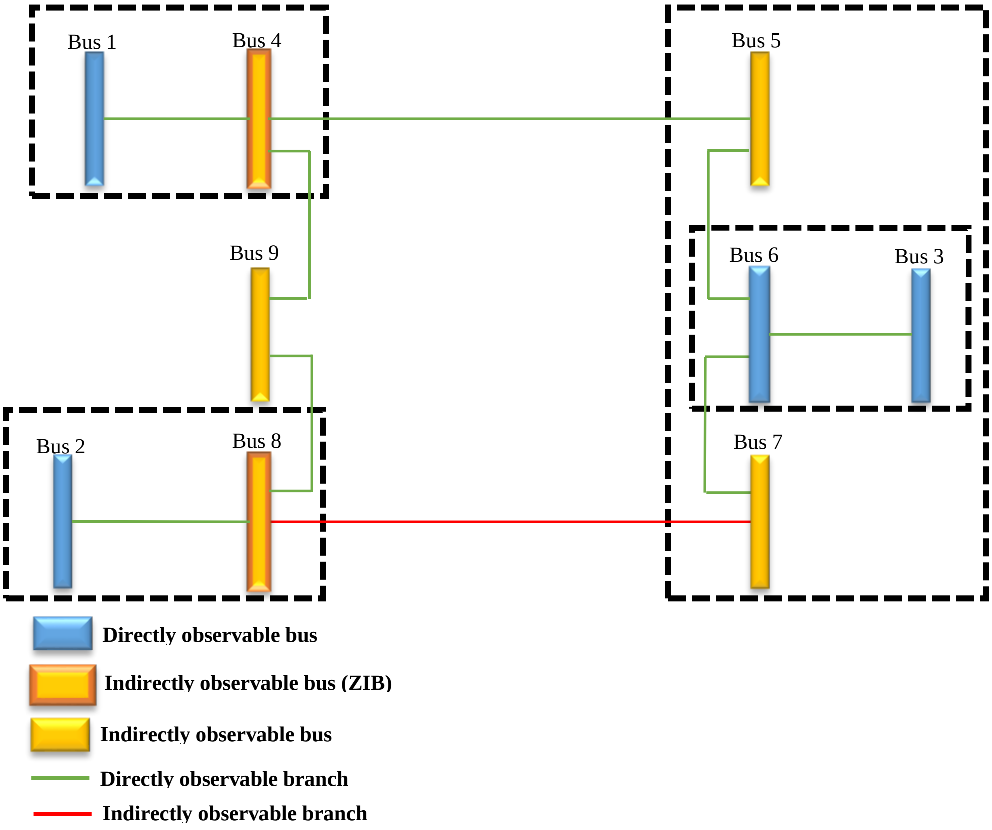

Figure 1.23: Results of IEEE 9-bus system for single line outage

The observability zone of the installed PMUs is shown in Figure 4, in which the bus observability analysis is performed as follows : The buses 1, 2, 3 and 6 are observable using their associated installed PMUs. Bus 4 is observed by the PMU installed at bus 1;

however, if line 1-4 is outage, bus 4 is also observed by the zero injection effect. Similar to bus 4, bus 5 is made observable by the PMU installed at bus 6; however, when line 5–6 is on outage, it is made observable by zero-injection of bus 4. Bus 7 is made observable by the PMU installed at bus 6, which has redundant measurements, by the zero-injection of buses 6 and 8. When line 6–7 is on outage, it is made observable by the zero-injection of bus 8. The bus 8 is made observable by the PMU located on bus 2 when the 2-8 line is operating. Furthermore, Bus 8 is made observable due to its zero injection effect. The bus 9 is made observable by the zero injection effect of buses 4 and 8. Consequently, the observability of bus 9 remains effective when either line 4-9 or line 8-9 is out of service.

1.21.5 Both of Single PMU or Single Line Outage

$$f_i^k = \geq 2 \qquad \forall\, i \in I, \forall\, k \in K \tag{1.44}$$

Where

$$f_i^k = \sum_{j \in I} a_{ij}^k\, x_j, \quad \forall\, i \in I, \forall\, k \in K \tag{1.45}$$

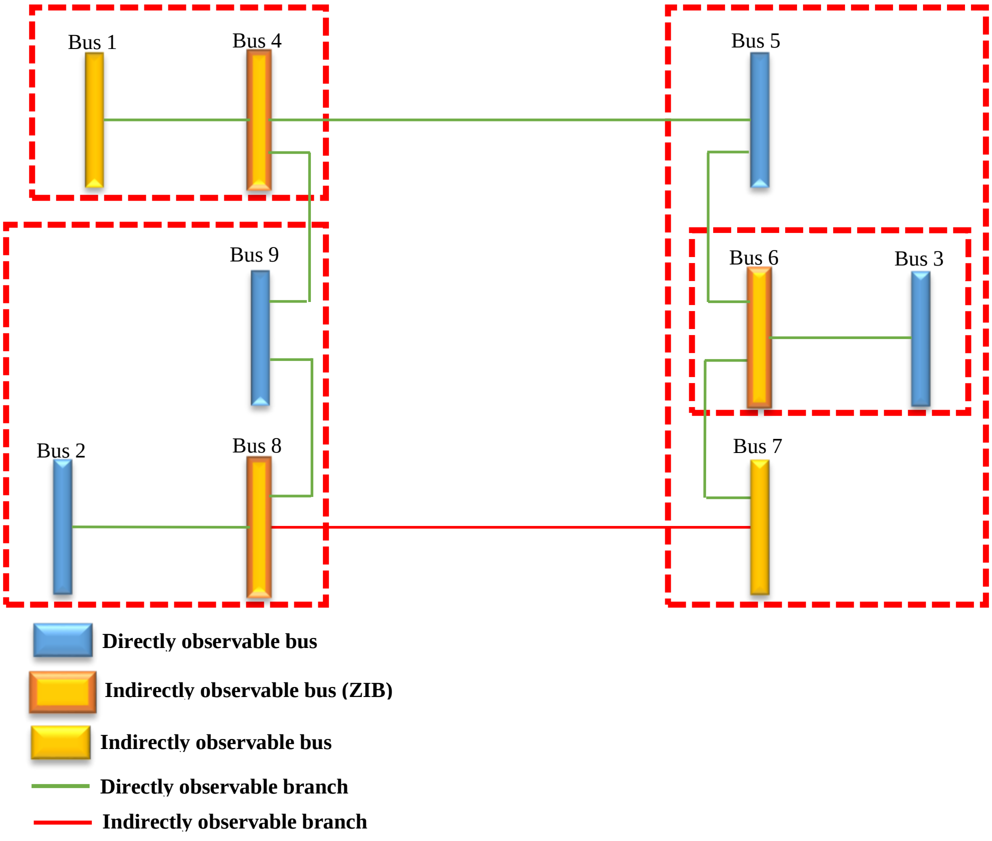

Figure 1.24: Results of IEEE 9-bus system for single line outage or single PMU outage

1.21.6 Channels limit

In most studies, the number of channels available in a PMU has been assumed to be unlimited when solving the OPP problem. However, as mentioned above, a PMU has a limited number of channels. So, to be able the PMU to be used to observe the bus voltage of the bus in which there is installed, as well as all the branch currents adjacent to it, the PMU must contain the same or higher number of channels.

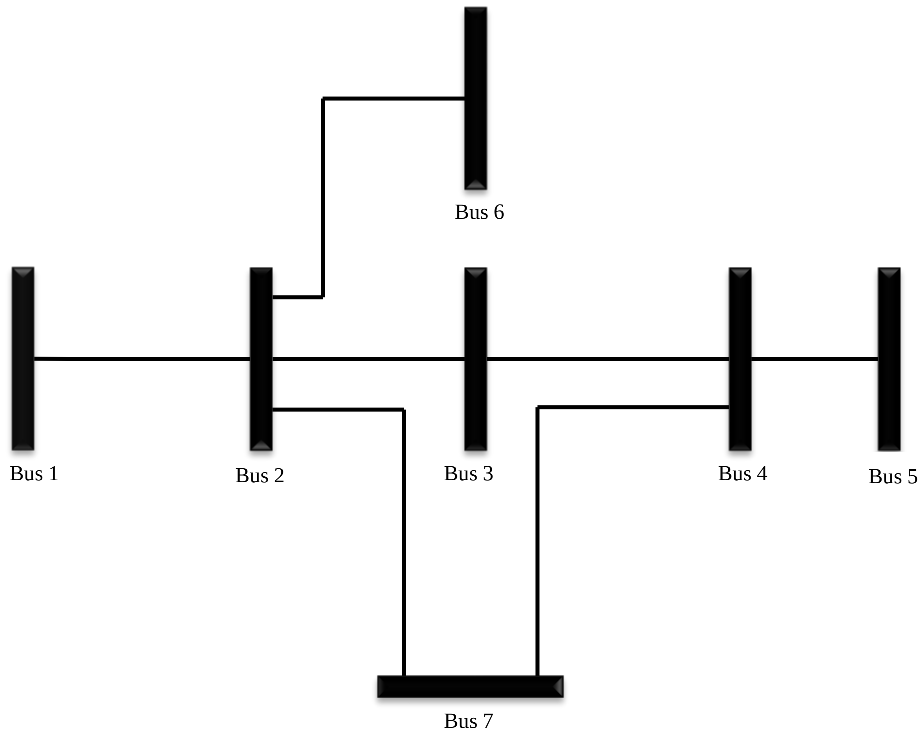

Figure 1.25: 7-bus system

For instance, a PMU is installed at bus 6 in a 7-bus system, as shown in the figure 1.25. Bus 2 is connected to four buses (buses 1, 3, 6 and 7). To monitor all the buses, even itself, it is necessary to use a PMU with a minimum of five channels - four channels for branches 2-1, 2-3, 2-6 and 2-7; and one channel for bus 2 itself. When the channels in a PMU are fewer than the number of branches connected to the bus installed by PMU, the branch combinations for each bus should be determined. consider the following equation [17]:

$$BR_i = \begin{cases} BC_i & if\ L \leq BI_i \\ 1 & if\ BI_i < L \end{cases} \tag{1.46}$$

Where BR_i is the number of branch combinations for bus i, BC_i is the number of possible combinations of L out of BI_i, BI_i is the number of neighboring buses to bus i, L is the channels limit.

In which the number of possible combinations of L out of branches BI_i can be defined as:

$$BC_i = \frac{BI_i!}{(BI_i-(L-1))!(L-1)!} \tag{1.47}$$

In order to formulate the optimization problem in case of PMU channel limitation, each row of bus-bus connectivity matrix is replaced by the combination of branches incident on the bus taking number of branches equal to channel limit at a time. a new $H_{(S \times N)}$ binary connectivity matrix has to be formed using the original connectivity matrix A that is formed in normal case. Where $S = \sum BR_i$ for each bus.

From equation, it is evident that, if the number of channels in the PMU is higher than the number of branches that are connected to the bus installed by the PMU, there is no need to identify the combinations of branches, hence $BR_i = 1$, which means a PMU is sufficient to measure all adjacent buses.

The previous approach concerning the problem of the OPP will be formulated as follows:

$$min \sum_{i=1}^{n} x_i \tag{1.48}$$

Subject to

$$H.X \geq I \tag{1.49}$$

Where $n = \sum_{i=1}^{n} BR_i$, I is an unity vector whose elements are ones,

Supposing the PMU channel limit is set as 3, since the buses 1, 5, 6 and 7 have only 2 branches or less that should be observed, the number of branch combinations as shown in the equation is: $BR_1 = BR_1 = BR_5 = BR_6 = BR_7 = 1$. On the other hand, since buses 2, 3 and 4 have at least 3 branches that must be observed, as shown in equation, the number of branch combinations can be determined using equation.

$$BR_2 \rightarrow BC_2 = \frac{4!}{(4-(3-1))!(3-1)!} = 6 \tag{1.50}$$

$$BR_3 \rightarrow BC_3 = \frac{3!}{(3-(3-1))!(3-1)!} = 3 \tag{1.51}$$

$$BR_4 \rightarrow BC_4 = \frac{3!}{(3-(3-1))!(3-1)!} = 3 \tag{1.52}$$

Therefore, the sum of the branch combinations for the 14-bus system with a 3-channel limit is: $BR_1 + BR_2 + BR_3 + BR_4 + BR_5 + BR_6 + BR_7 = 16$. Then, once the number of branch combinations for all buses has been determined, a binary connectivity matrix [H] which contains all the branch combinations for the associated bus, where bus i will have BR_i rows, can be formed as in equation. Every row represents the corresponding bus and its neighbors. As an example, suppose the Bus 2 it has six possible combinations (1-2-3, 1-2-6, 1-2-7, 2-3-6, 2-3-7, 2-6-7)

$$H = \left[\begin{array}{ccccccc} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ \hline 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ \hline 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ \hline 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ \hline 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ \hline 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ \hline 0 & 1 & 0 & 1 & 0 & 0 & 1 \end{array}\right] \tag{1.53}$$

The number of the above branch combinations can be reduced by considering the radial bus and the duplicate branch. As an example, both line 5 (R5) and line 9 (R9) have the same branch combination. Hence, it is possible to remove one of the combinations without affecting the topological observability. In the case of the radial bus, lines 1 (R1) and 14 (R14) can be eliminated since placing a PMU on buses 1 and 5 limits observability to only two buses, thus wasting the additional channel available to the PMU.

Consequently, according to equation (matrix), the optimal placement of PMUs when PMUs are limited to 3 channels for the above 7-bus system is:

$$X = [0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0] \tag{1.54}$$

The equation above indicates that 2 PMUs are needed to ensure a full observability, where one is placed at bus 2, and another one at bus 3. The PMU placed at bus 2 will observe buses 1, 2 and 7 while the other PMU which placed at bus 3 will measure buses 3, 4 and 6, since the bus 4 is a ZIB and by applying the rule 5 mentioned before the bus 5 can be assumed as observable.

The cost of a PMU with fewer channels is theoretically lower than a PMU that has more channels. For that reason, one of the objectives of this thesis is to investigate the number of PMUs required according to the different channel limits and, consequently, the possible ideal number of channels necessary to attain full observability of the power system.

1.22 Conclusion

This chapter presents the background study of the OPP problem and how the PMU is able to help in monitoring the power system. Observability rules for the PMUs are explained and explanation on how the problem constraints such as ZIB and channels limit are formulated are also presented in this chapter. Literature review of the existing studies using various methods concerning OPP problem is briefly reviewed to improve the understanding of the OPP problem.

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Chapter 2

Gravitational Search algorithm

2.1 Introduction

The Gravitational Search Algorithm (GSA) is a method of metaheuristic optimization inspired by nature. A metaheuristic optimization method consists of a generalized set of rules that can be applied for solving different optimization problems. There are many metaheuristic optimization methods that have been successfully developed based on the model of certain processes that exist in nature. Simulated annealing, for example, mimics the physical process of annealing.

The metaheuristic optimization methods are population-based stochastic search techniques. The population is defined by a set of individuals (agents) that represent potential solutions to the optimization problem. The number of agents (N) is referred to as the population size. Overall, each agent can be represented as a vector in which elements are the values of the control variables of the optimization problem. The number of control variables (n) is the dimension of the search space of the optimization problem.

Mainly, the metaheuristic methods are based on the iterative correction of the solution, in other words on the generation of a new population by applying algorithmic operators with a stochastic search mechanism on the agents of the current population. The way in which the algorithmic operators are defined is the essence of a particular metaheuristic optimization method. The success and performance of metaheuristic optimization methods depend on the right adjustment of the corresponding algorithmic parameters.

The metaheuristics are mainly focused on the rapid search for large solution spaces, the capacity to find global solutions, and the avoidance of local optimums. The main advantage of these methods compared to classical optimization methods is that they are not limited by requirements of differentiability, non-convexity, and continuity of the objective function or types of control variables. In addition, these methods are suitable for practical optimization problems by taking into account various types of objective functions and constraints.

The following are the basic elements of metaheuristic optimization methods:

- **Agent $\mathbf{x(t)}$:** It is a candidate solution represented by an n-dimensional vector, where n is the number of control variables. At iteration t, the ith agent $\mathrm{x}_i(\mathrm{t})$ can be defined like $\mathrm{x}_i(\mathrm{t}) = \left(x_i^1(t), \dots, x_i^d(t), \dots, x_i^n(t)\right)$, In which, $x_i^d(t)$ is the positioning of *i*th agent in the *d*th dimension.
- **Population $\mathbf{POP(t)}$:** It is a N-agent set at iteration t, i.e., $\mathrm{POP(t)} = [\mathrm{x}_1(\mathrm{t}), \dots, \mathrm{x}_\mathrm{N}(\mathrm{t})]^T$, Or in enlarged form:

$$POP(t) = \begin{bmatrix} x_1^1(t) & x_1^2(t) \cdots x_1^d(t) & \cdots x_1^n(t) \\ x_2^1(t) & x_2^2(t) \cdots x_2^d(t) & \cdots x_2^n(t) \\ & \vdots & \\ x_i^1(t) & x_i^2(t) \cdots x_i^d(t) & \cdots x_i^n(t) \\ & \vdots & \\ x_N^1(t) & x_N^2(t) \cdots x_N^d(t) & \cdots x_N^n(t) \end{bmatrix} \quad (2.1)$$

- **The solution space $\boldsymbol{X}$:** This is an n-dimensional solution space that is bounded by the lower and upper bounds of the control variables.

The fitness is an direct indicator of the performance of each member of the population (agent). The fitness of each agent in the population is calculated from the value of the optimized function.

The General structure of metaheuristic optimization methods:

- **Initialization**
  1. Define the objective function $F(x_i)$ and the possible solution space X.
  2. Generate initial population of N agents: $POP(1) = [x_1(1), x_2(1), \cdots, x_N(1)]^T \subseteq X$.

  The selection of the initial positions of each agent is made randomly between the minimum and maximum values of the control variables.

  Set the iteration counter: t = 1.

- **The process iterative**
  3. Calculate the fitness value $F\left(x_i(t)\right)$ for each agent $\mathrm{x}_i(\mathrm{t}), i = 1, \dots, N$ in the current population $POP(t)$.

4. Generate a new population $POP(t+1) = [x_1(t+1), x_2(t+1), \cdots, x_N(t+1)]^T \subseteq X$ via the application of algorithmic operators on the search agents of the current population $POP(t)$.
5. Repeat these steps until reaching the stop criterion.

- **End**

2.2 The original GSA description

Rashedi and his collaborators [1] successfully developed an efficient population-based metaheuristic optimization algorithm, called GSA, which is based on Newton's laws of gravity and motion for mass interaction. The literature has confirmed the high quality of GSA's performance in solving various optimization problems.

The research agents of the GSA are a group of masses that interact with each other on the basis of Newtonian gravity and the laws of motion. According to this algorithm, the agents are considered as objects and their performance is measured by their masses. The gravity force attracts all these objects towards each other and this force causes a global movement of all objects towards the objects of greater mass. The mass position corresponds to the solution to the problem, and its gravitational and inertial masses are determined using the fitness function. In other words, each mass presents a solution. This algorithm is navigated by correctly adjusting the gravitational and inertial masses. Over time, the masses will be attracted by the heaviest mass that represents an optimal solution in the search space. The interaction of the agents in the GSA is illustrated in Figure 3.1

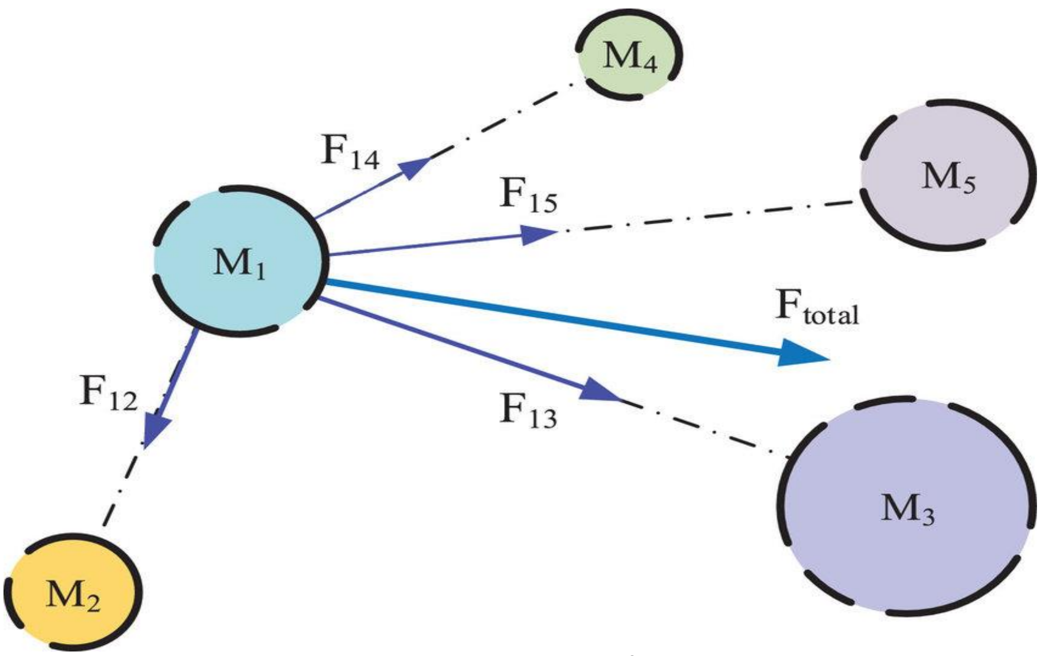

Figure 2.1: Interaction of agents in GSA

i) **The Gravity Law:** Each particle attracts all other particles, and the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the distance between them, R. According to the authors [1], R has been used instead of R^2, based on experimentation where R gives better results than R^2 in all experimental cases.

ii) **Law of Motion:** The current velocity of any mass is equal to the sum of the fraction of its previous velocity of mass and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the force acted on the system divided by the mass of inertia.

In an N-agent system, the position and velocity of the ith agent is expressed by:

$$\mathrm{x_i} = \left(x_i^1, \dots, x_i^d, \dots, x_i^n\right) \quad for\ i = 1,2, \dots N \tag{2.2}$$

$$\mathrm{v_i} = \left(v_i^1, \dots, v_i^d, \dots, v_i^n\right) \quad for\ i = 1,2, \dots N \tag{2.3}$$

In which x_i^d is the positioning of i^{th} agent in the d^{th} dimension, v_i^d is the velocity of the ith agent in the d^{th} dimension and n is the size of the space of search.

Following the evaluation of the current population fitness, the mass of each agent is calculated as follows:

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \tag{2.4}$$

$$m_i(t) = \frac{fit_i(t) - worst_i(t)}{best(t) - worst(t)} \tag{2.5}$$

Where, $fit_i(t)$represent the value of fitness of the agent i at iteration t, $best(t)$ and $worst(t)$ indicate the strongest and the weakness agent relating to their fitness value, respectively, and defined as follows (for a minimization problem):

$$best(t) = \min_{j \in \{1,2,\dots N\}} fit_j(t) \tag{2.6}$$

$$worst(t) = \max_{j \in \{1,2,\dots N\}} fit_j(t) \tag{2.7}$$

Regarding a maximization problem, the $best(t)$ and $worst(t)$ are defined as:

$$best(t) = \max_{j \in \{1,2,\dots N\}} fit_j(t) \tag{2.8}$$

$$worst(t) = \min_{j \in \{1,2,\ldots N\}} fit_j(t) \tag{2.9}$$

Newton's theory of gravitation defines the total force acting on the ith agent at iteration t as follows:

$$F_i^d(t) = \sum_{j \in Kbest, j \neq i} rand_j F_{ij}^d(t) \tag{2.10}$$

$$F_i^d(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \varepsilon} \left(x_j^d(t) - x_i^d(t) \right) \tag{2.11}$$

Where $Kbest$ is the group of first K agents with the best fitness value and biggest mass and $rand_j$ is an arbitrary number in the range [0 1]. $F_{ij}^d(t)$Is the force functioning on agent i from agent j at iteration t, $R_{ij}(t)$ is the Euclidian distance between the two agents i and j at iteration t, $G(t)$ is the gravitational constant at iteration t. ε is a small constant.

According to the law of motion, the acceleration of the ith agent, at iteration t, is given by the following equation:

$$a_i{}^d = \frac{F_i{}^d(t)}{M_i(t)} \tag{2.12}$$

Where M_i is the inertial mass of agent i.

The searching strategy on this notion can be defined to find the next velocity and position of an agent. The next velocity of an agent is defined as a function of its current velocity added to its current acceleration. Hence, the position and velocity of an agent are updated as follows:

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{2.13}$$

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \tag{2.14}$$

In which $rand_i$ is a random variable uniform in the interval [0, 1]. In GSA, this random number is used to give a random characteristic to the search.

2.3 The GSA parameters

The gravitational constant G is initialized at the beginning and will be reduced over time to control the accuracy of the search. This means that G is a function of the initial value (G_0) and time (t):

$$G(t) = G_0 e^{-(\alpha t/T)} \tag{2.15}$$

The GSA performance is controlled by the following parameters: maximum iteration T, population size N, initial gravitational constant G_0, and constant α. According to equation (3.15), the value of G is high at the beginning of the algorithm to improve the exploration capacity. In contrast, a large value of G signifies a strong attraction of power between masses, which leads to more movement and complexity. Over time, G should be decreased to find the optima around a good solution. Consequently, the G value profoundly affects the performance of the algorithm, so it must be carefully controlled. Equation (2.15) is an exponential function known as the decay curve, and the rate of decay is t/T. The decay rate specifies the rate of decrease of G and, hence, the rate and velocity of movement of the agents. The G_0 is the initial value. Thus, it is important to correctly set G_0 and alpha [2].

The $Kbest$ parameter in equation (2.11) is used to achieve a good compromise between exploration and exploitation. The algorithm must use exploration at the beginning in order to avoid trapping in a local optimum. As the iterations expire, exploration must be fade out and exploitation must fade in. The number of agents that attract others is determined by $Kbest$ and must be controlled to ensure an adequate balance between exploration and exploitation. The $Kbest$ value is calculated as a function of time. at the beginning of the iterations, it is large, but it decreases with time. Over the first iterations, almost all agents attract others to prevent the GSA from trapping in the local optima. This ensures exploration in the GSA research process. During the next iterations, the value of $Kbest$ should be reduced to focus on exploitation rather than exploration and improve the convergence rate. The large value for $Kbest$ decreases the convergence rate and gives the algorithm the chance to explore the search space more and prevent trapping in local optima. However, with increasing $Kbest$, the complexity and computational time is increased. Therefore, (2.16) is proposed in [2] to control the value of $Kbest$ during the progress of the algorithm.

$$Kbest = K_0\left[{}^{t}\!/_{T}\,(1-p)+1\right] \tag{2.16}$$

Where t is the current iteration, T is the maximum number of iterations and p is the fractional of total agents in the last iteration.

The different steps of the proposed algorithm are as follows:

1. Random initialization.

2. Evaluation of the fitness of the agents.
3. Update G (t), best (t), worst (t) and Mi (t) for i = 1,2, . . ., N.
4. Calculating the total force in different directions.
5. Calculation of acceleration and velocity.
6. Updating the position of the agents.
7. Repeat steps 3 to 7 until the stop criterion is reached.
8. End.

2.4 GSA General Remarks

The principle of GSA is shown in Figure 2.2.

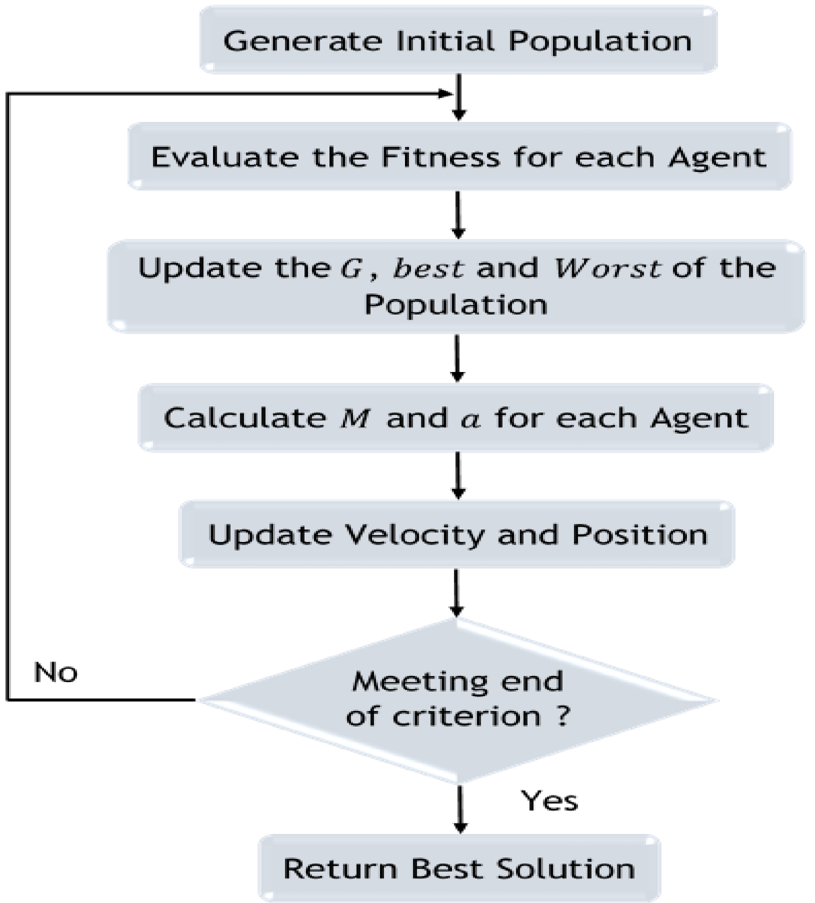

Figure 2.2 Flowchart of GSA

To highlight the effectiveness of GSA, a few remarks are noted:

- Since each agent can observe the performance of the others, the gravitational force is an information transfer tool.
- Due to the force that acts on the agent by the other agents in his neighbourhood, he can see the space around him.

- A heavy mass has a large effective radius of attraction and therefore a high intensity of attraction. Therefore, agents with higher performance have a greater gravitational mass. As a result, other agents tend to move towards the better agent.
- The gravitational constant adjusts the accuracy of the search so it decreases over time (similar to the temperature in the simulated annealing algorithm).
- The gravitational and inertial masses are assumed to be the same. However, for some applications, different values for them can be used. A bigger mass of inertia provides a slower movement of the agents in the search space and thus more precision. Conversely, a bigger gravitational mass causes a greater attraction of the agents. This leads to faster convergence.

The pseudo-code of the standard version of the gravitational search algorithm is the following:

Algorithm: The standard gravitational search algorithm

Parameters initialization
Set the initial values of gravitation constant G0, α and ξ
set the initial iteration t=0
Initial population
For i=1: i ≤N **do**
    Generate an initial population Xi (t) randomly, where $X_i = (x_i^1,...,x_i^d,...,x_i^n)$
end for
while termination criteria == 0
    Solutions evaluation
    Evaluate the fitness function f (xi (t)) for each agent in the population X (t).
    Assign the best, worst agent in the population X (t).
    Solution update
    Update the gravitational constant G as shown in equation 1.
    for i=1:i≤N **do**
        for j=i+1: j<N **do**
            Calculate the force action on agent i from agent j as shown in equation 4.
        end for
        Calculate the total force that act on agent i from agent j as shown in equation 7.
        Calculate the inertial mass Mi. as shown in equation 15, 16.
        Calculate the acceleration of the agent i as shown in equation 10.
        Update the velocity of agent i as shown in equation 11.
        Update de position of agent i as shown in equation 12.
    end
    Set t =t+1
end while
Produce the best solution
Return the best solution.

2.5 Binary gravitational search algorithm

The original GSA authors [1] introduced a binary version of the algorithm [3]. The optimization problems, which are defined in real space, can also be performed in binary space. The solution is to display real digits with a few bits in binary mode. The binary search space is considered as a hypercube in which an agent can move to closer and farer corners of the hypercube by flipping different numbers of bits.

The development of a binary version of GSA means that some of the basic concepts of GSA are modified. In a discrete binary environment, only 0 or 1 can be assigned to each dimension. To move within a dimension means that the value of the corresponding variable changes from 0 to 1 or conversely. To introduce a binary mode for the gravitational algorithm, the procedure for updating the force, acceleration, and velocity can be considered as the original (continuous) algorithm [equations. (2.11)-(2.14)]. The major difference between the binary (BGSA) and continuous gravitational search algorithm is that in the binary algorithm, updating the position means switching between the values "0" and "1". This switching has to be done as a function of the velocity of the mass. The idea of the author [3] is to update the position in a manner that the current bit value is changed with a probability that is calculated according to the mass velocity. In other words, BGSA updates the velocity based on (2.13) and considers the new position to be either 1 or 0 with the given probability.

It will be useful, prior to defining a transfer function to match the velocity to the probability of position update, to review some basic concepts of GSA [1, 3]:

- A large absolute value of the velocity shows that the current position of the mass is not proper and a great movement is required to reach the optimum position.
- A small absolute value of the velocity indicates that the current position of the mass is close to the optimum position, and there is a small distance reaching the optimum position. Then, after finding the optimal solution, the velocity becomes zero.

In accordance with the above-mentioned concepts of the GSA, in the implementation of the BGSA, the following concepts should be taken into account [3]:

- A large absolute value of velocity must provide a high probability of changing
  the position of the mass respect to its previous position (from 1 to 0 or vice versa).

- A small absolute value of the velocity must provide a small probability of changing the position. In other words, a zero value of the velocity represents
  that the mass position is good and must not be changed.

2.6 Measurement redundancy

The GSA is a meta-heuristic algorithm, so there will be a number of PMU placement sets that will have a similar number of minimum PMUs required for full observability. The quality of each PMU placement set is evaluated using the measurement redundancy concept of the Bus Observability Index (BOI) and the Redundancy Index System (SORI) which are introduced in [4]. BOI is the number of times a bus is observed by the fixed PMU placement while SORI refers to the sum of the BOI for all buses [5]. According to the PMU placement set that has the highest number of SORIs, this set has a better and more reliable solution for possible contingencies than the PMU placement set that has a low number of SORI [6]. Therefore, in this thesis, this concept will be used to evaluate and compare the PMU placement sets obtained from the proposed method and prior studies in terms of measurement redundancy. BOI and SORI are defined as follows:

$$BOI_i = AX_i \tag{2.17}$$

$$SORI = \sum_{i=1}^{B} BOI_i \tag{2.18}$$

2.7 Fitness function

All GSA particles carry possible solutions to the problem under study. The utility of each possible solution for the problem under study should be evaluated using a fitness function to ensure that the best solution is always chosen in priority over other possible solutions. The objective of this thesis is to find the minimum number of PMUs and maximizing measurement redundancy while ensuring full observability of the power system. Thus, the fitness function should be able to evaluate the three important criteria :

1. The number of PMUs to make the power system observable.
2. The measurement redundancy.
3. The power system observability.

The fitness function for solving the OPP problem can be formulated as follows:

$$F = min\{(w_1 \times N_{PMUs}) + (w_2 \times N_{obs}) + (J \times C)\} \tag{2.19}$$

Where

- w_1, w_2 C and are the weight parameter.
- N_{PMUs} is the number of PMUs.
- N_{obs} is the number of observable bus.
- J is the measurement redundancy.

As illustrated in equation (2.19), the fitness function is formed from three components - number of PMUs, observability, measurement redundancy - to assess the three criteria mentioned above. The first component determines how many bus is observed by the PMUs placement set from the particle being evaluated. It has been mentioned in section 1.18 that a power system is deemed observable if all buses in the system are observable by the PMUs.

For instance, for a 14-bus system, to determine that it is completely observable, the value of N_{obs} must equal to 14, which indicates all seven buses in the power system are observable. The value of N_{obs} can be determined as follows:

$$N_{obs} = |\{x \in BOI | x \neq 0\}|$$

Since BOI implies how many times each bus is being observed by the PMUs, the number of buses observed by the PMUs placement set can be determined based on how many nonzero elements in vector BOI for the corresponding particle. The second component determines the number of PMUs which can be determined as follows:

$$N_{PMU} = X^T X$$

For the third component, the value of J is formulated as follows:

$$J = (M - BOI)^T \times (M - BOI)$$

M is the coveted value of measurement redundancy. The vector $(M - BOI)$ calculates the difference between the coveted and current number of times the bus is observed.

2.8 Conclusion

OPP techniques are formulated as a multi-objective objective function with a minimum number of PMUs, i.e. complete system observability and maximize the factor SORI. 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.

2.9 References

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Chapter 3

Results and Discussion

3.1 Introduction

In this chapter, the proposed methods will be applied on various IEEE bus systems ranging from 14 to 57 buses and on the Algerian large-scale power test system with 114 buses in order to check the application of these methods to solve the problem of OPP. For each bus system, the data are obtained from MATPOWER [1] and [2] and are shown in the appendix.

All the simulations are carried out using MATLAB R2019a software. The technical characteristic of the computer used to perform the simulations is intel core i7 2.4 GHz and 8 GB of RAM. The values of the parameters used in equation (3.19) during the simulations are shown in Table 4.1

Table 3.1: The values of each parameter used in simulation

Parameter	Value
Number of Iterations	2000
Number of Particles	4*N
Weight value for the number of bus observed, w_1	1
Weight value for the number of PMUs, w_2	-2
Weight value for the measurement redundancy, c	0.02

The purpose of the proposed methods is to identify the minimum number of PMUs needed to ensure full observability while maximizing measurement redundancy. Since the methods proposed are meta-heuristic algorithms, it is expected to have several PMU placement sets, and to distinguish between the quality of each PMU placement set that has the same number of PMUs, the one with the highest measurement SORI value will be selected as the optimal best result. As mentioned previously, the set with the highest measurement redundancy indicates that it is better than the set that has low measurement redundancy. Furthermore, to assess the performance of the proposed methods to resolve the OPP problem, a comparison will be made between the SORI value of the PMU placement set obtained by the proposed method and existing studies. The proposed methods are implemented to solve the problem of OPP by considering various cases. The following are the cases considered for the proposed methods:

I. Normal operation case
II. Case considering ZIBs
III. No PMUs at ZIBs
IV. Case considering single PMU loss
V. Case single branch outage
VI. Case either single PMU or branch outage

The algorithm was run 20 times with random particle initialization for each case. The results of each case are presented in the following sections. The presence of a radial bus is considered for all test cases to achieve the best possible solution. The table 3.2 shows the location of the radial bus for each test system.

Table 3.2: The location of radial bus for all tested bus systems.

Test system	Number of radial bus	Location of radial bus
IEEE 14-bus	1	8
IEEE 24-bus	1	7
IEEE 30-bus	3	11, 13, 26
IEEE -39bus	9	30, 31, 32, 33, 34, 35, 36, 37, 38
IEEE 57-bus	1	33
Alg 114-bus	20	12, 14, 15, 38, 39, 45, 49, 61, 65, 69, 76, 77, 78, 79, 91, 92, 95, 104, 108, 113

For each radial bus in Table 3.2, the PMU is prevented from being placed on the radial bus. In contrast, it is recommended to place the PMU on the bus that is adjacent to the radial bus.

3.1.1 Normal operation case

In such a case, the OPP problem is resolved by ignoring ZIBs. The number of PMUs required for each test system, including their locations and the SORI value for each PMU placement set, is shown in Table 3.3.

Table 3.3 : PMU locations for normal operation

Test system	Number of PMUs	Locations of PMUs (N_{PMU})	SORI	N_{PMU}/N
IEEE 14-bus	4	2, 6, 7, 9	19	0.2857
IEEE 24-bus	7	2, 3, 8, 10, 16, 21, 23	31	0.2916
IEEE 30-bus	10	2, 4, 6, 9, 10, 12, 15, 19, 25, 27	52	0.3333
IEEE -39bus	13	2, 6, 9, 10, 13, 14, 17, 19, 20, 22, 23, 25, 29	52	0.3333
IEEE 57-bus	17	1, 4, 6 , 9, 15, 20, 24, 28, 31, 32, 36, 38, 41, 46, 51, 53, 57	72	0.2982
Alg 114-bus	33	2, 4, 13, 16, 18, 19, 20, 26, 29, 31, 34, 41, 42, 46, 47, 54, 57, 59, 63, 68, 69, 74, 82, 87, 88, 93, 96, 100, 101, 103, 105, 109, 111	159	0.2894

It is clear from the table 3.3 that the number of PMUs required to achieve full observability increases as the size of the power system increased. N_{PMU}/N is the ratio of the number of PMU's to the number of buses. Furthermore, the number of PMUs is in the range of 20% to 30% from the number of bus that needs to be observed [3].

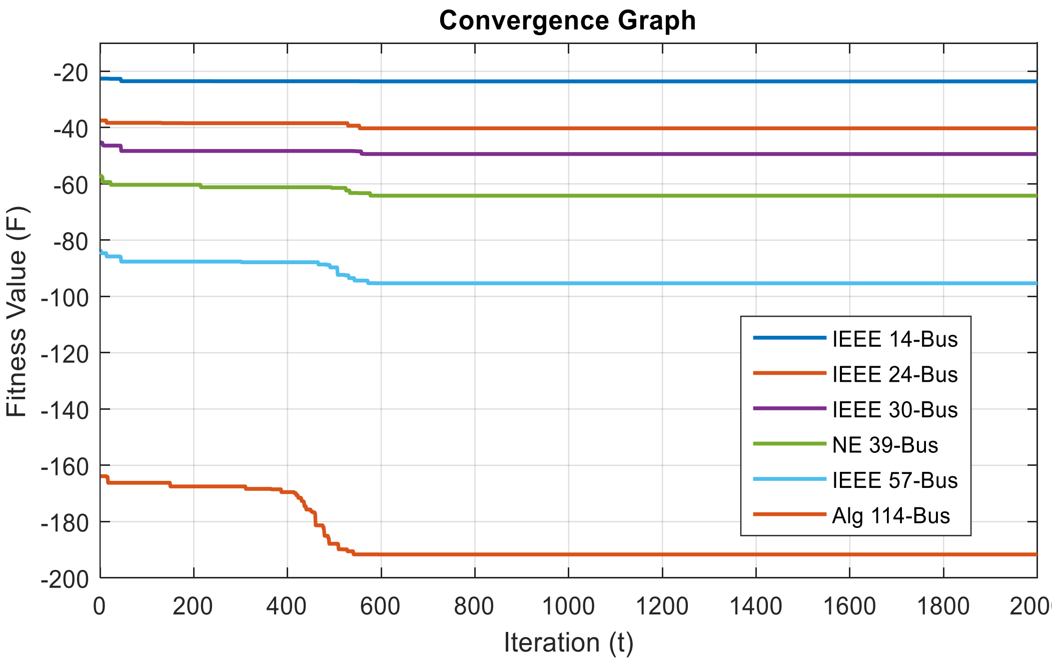

Figure 3.1: Convergence Graph for the Six Test Systems for case1

Figure 3.1 presents the convergence graph for all the test system without considering ZIBs. It can be noticed clearly that all the solution obtained managed to converge probably at t=600.

3.1.2 Case Considering ZIB

In such a case, the presence of ZIB in the power system is considered when solving the OPP problem. The locations of the ZIBs of each test system tested are indicated in Table 3.4.

Table 3.4 : The ZIBs location for every test system

Test system	Number of ZIB	ZIBs location
IEEE 14-bus	1	7
IEEE 24-bus	4	11, 12, 17, 24
IEEE 30-bus	6	6, 9, 22, 25, 27, 28
IEEE -39bus	12	1, 2, 5, 6, 9, 10, 11, 13, 14, 17, 19, 22
IEEE 57-bus	15	4, 7, 11, 21, 22, 24, 26, 34, 36, 37, 39, 40, 45, 46, 48
Alg 114-bus	22	2, 14, 16, 18, 27, 28, 31, 42, 44, 46, 48, 58, 60, 64, 72, 74, 75, 81, 86, 93, 96, 105

Meanwhile, the results obtained for each bus system is given in Table 3.4. Notice that the number of PMUs required for all buses are reduced when the presence of ZIB in power system is considered compared to the results obtained for normal operation.

Table 3.5: The PMUs placement for case considering ZIB

Test system	Number of PMUs	Locations of PMUs (N_{PMU})	SORI	N_{PMU}/N
IEEE 14-bus	3	2, 6, 9	16	0.2857
IEEE 24-bus	6	2, 8, 10, 15, 20, 21	29	0.2916
IEEE 30-bus	7	2, 4, 10, 12, 15, 18, 27	41	0.3333
IEEE -39bus	8	3, 8, 13, 16, 20, 23, 25, 29	43	0.3333
IEEE 57-bus	11	1, 6, 13, 19, 25, 29, 32, 38, 51, 54, 56	60	0.2982
Alg 114-bus	28	2, 3, 4, 13, 18, 19, 20, 26, 29, 31, 34, 41, 47, 54, 57, 59, 63, 68, 69, 82, 88, 93, 98, 100, 102, 103, 109, 111	149	0.2894

As an example, the IEEE 30-bus system, in normal operation, requires 10 PMUs to achieve full observability, whereas, in the case considering ZIB, only 7 PMUs are sufficient. Figure 3.1 illustrates the location of PMUs placement for IEEE 39-bus system and how the PMUs placement set conforms to the observability rules that ensure the power system is observable.

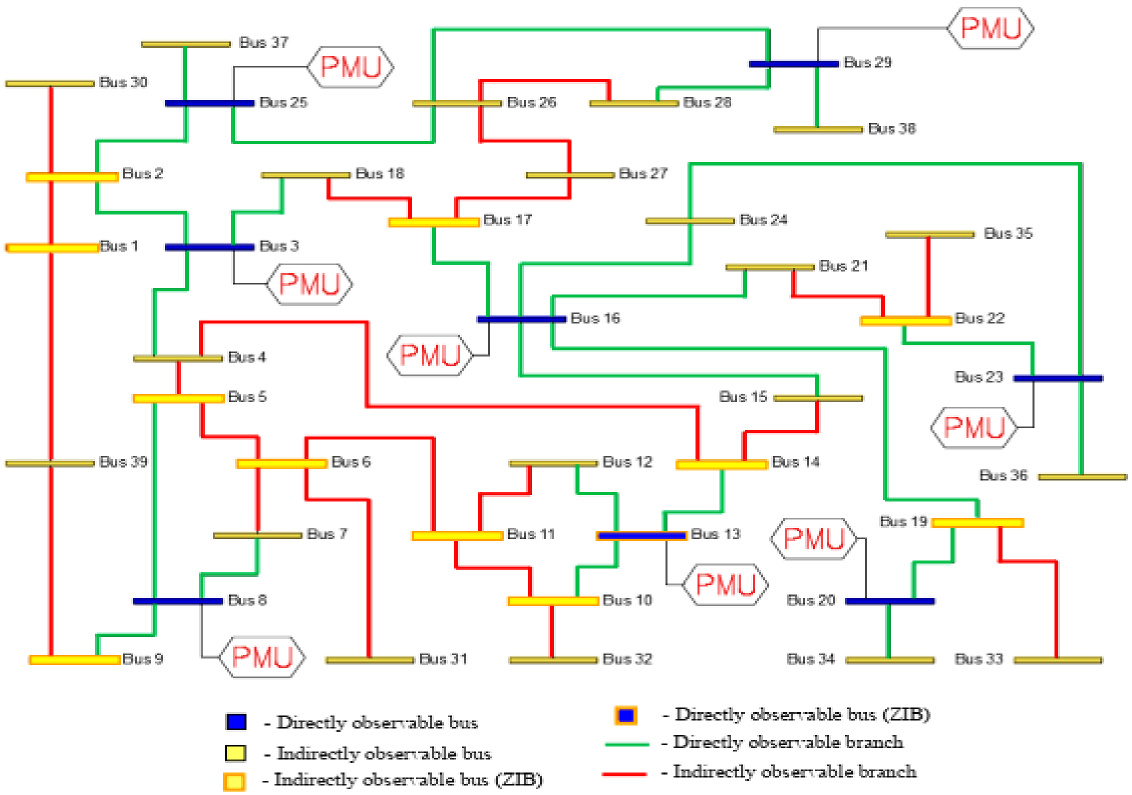

Figure 3.2 The PMUs placement and how it makes IEEE 39-bus system observable

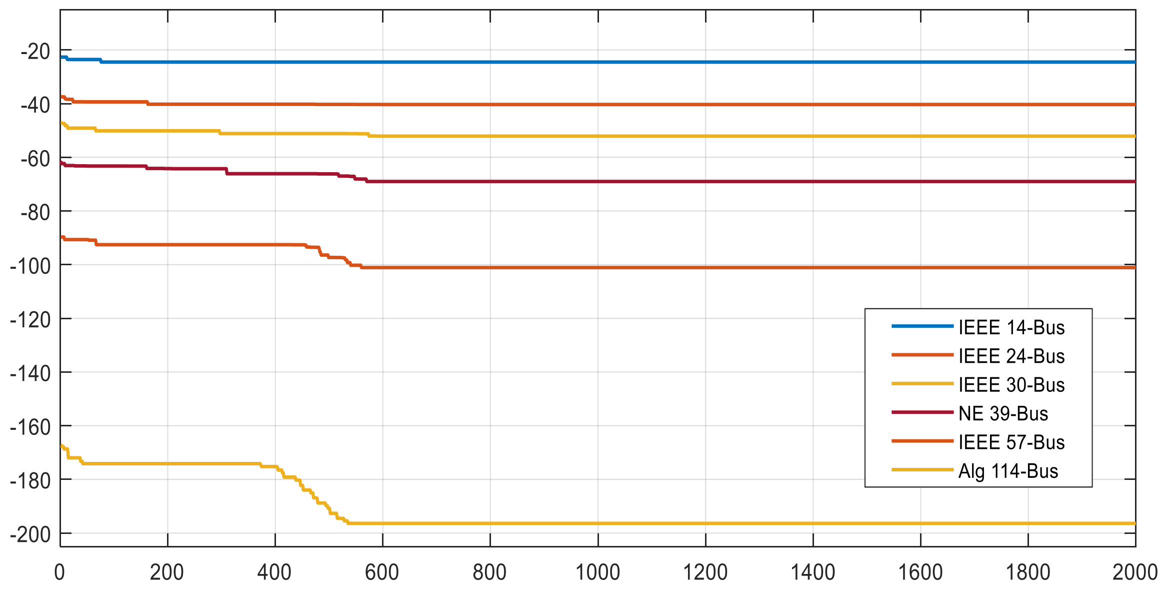

Figure 3.3: Convergence Graph for the Six Test Systems with ZIBs

In Figure 3.3 the convergence graph for all the test system without considering ZIBs are presented. For IEEE 14-Bus and 24-Bus the solution converged finally at t=200, whereas It can be noticed clearly that the rest solutions obtained managed to converge probably at t=600.

3.1.3 No PMUs at ZIBs

PMUs at zero-injection buses measure current phasors of corresponding lines; so the KCL at zero-injection bus provides no additional information but will help find the optimal solution. While removing PMUs from zero-injection buses will reduce the search space and enhance the solution speed.

Table 3.6 : The PMUs placement when considering no PMUs located at ZIBs

Test System	Number of PMUs	Positions of PMUs	SORI
IEEE 14-bus	3	2, 6, 9	16
IEEE 24-bus	6	2, 8, 10, 15, 20, 21	29
IEEE 30-bus	7	2, 4, 10, 12, 19, 24, 30	38
NE 39-bus	8	3, 8, 12, 16, 20, 23, 25, 29	43
IEEE 57-bus	12	1, 6, 9, 13, 19, 25, 29, 32, 38, 51, 53, 56	67
Alg 114-bus	29	1, 3, 4, 13, 19, 22, 25, 29, 30, 34, 41, 47, 54, 57, 59, 63, 68, 71, 73, 84, 85, 89, 91, 98, 101, 103, 108, 112, 113	140

3.1.4 Case considering single PMU loss

In this case, at least two PMUs will monitor each bus in the power system to ensure if one of the PMUs charged to monitor the corresponding bus fails, the bus will still be observable from the other PMUs. At this stage, the number of PMUs needed for this case will obviously be increased since each bus has to be observed by more than one PMU, and the results presented in the table 3.7 confirm this notion.

Table 3.7: PMUs placement for case considering single PMU loss.

Test System	Number of PMUs	Positions of PMUs	SORI
IEEE 14-bus	7	2, 4, 5, 6, 9, 11, 13	34
IEEE 24-bus	11	1, 2, 7, 8, 9, 10, 16, 18, 19, 20, 21	46
IEEE 30-bus	14	2, 3, 4, 7, 10, 12, 13, 15, 16, 18, 20, 24, 27, 30	60
NE 39-bus	17	2, 6, 8, 10, 13, 16, 18, 20, 21, 23, 25, 26, 29, 34, 36, 37, 38	66
IEEE 57-bus	23	1, 3, 6, 9, 12, 14, 15, 18, 20, 25, 27, 29, 31, 32, 33, 38, 39, 41, 50, 51, 53, 54, 56	97
Alg 114-bus	59	1, 2, 3, 4, 10, 12, 13, 16, 18, 19, 20, 22, 23, 25, 26, 29, 32, 34, 36, 38, 39, 40, 41, 43, 47, 49, 52, 54, 57, 59, 61, 63, 65, 67, 68, 69, 71, 77, 78, 79, 80, 82, 84, 87, 88, 89, 92, 93, 98, 100, 101, 102, 103, 108, 109, 110, 111, 112, 113	239

For instance, for the Algerian 114-bus system, the number of PMUs when single PMU loss is taken into account is 59 PMUs. It is more than when it is compared to the normal operation and the case considering ZIB, where the number of PMUs required is 33 and 28 PMUs, severally.

3.1.5 Case single branch outage

Concerning the situation of an outage of a single line, the places of PMUs have already been identified in a way that outage of any line does not influence the system monitoring. Similar to the previous case, the number of PMUs will be also high to ensure that the system remains observable in the event of a failure affecting one of the lines. The optimal PMUs number obtained, the observability, and their location by the suggested approach is presented in the table 3.8.

Table 3.8: Number and position of PMUs in single line outage.

Test System	Number of PMUs	Positions of PMUs	SORI
IEEE 14-bus	7	1, 3, 6, 8, 9, 11, 13	25
IEEE 24-bus	8	1, 2, 8, 9, 10, 16, 20, 21	38
IEEE 30-bus	14	2, 3, 5, 6, 10, 11, 12, 13, 15, 17, 19, 24, 26, 29	56
NE 39-bus	12	2, 3, 6, 8, 13, 16, 20, 22, 23, 25, 26, 29	55
IEEE 57-bus	21	1, 2, 6, 12, 14, 15, 19, 23, 25, 28, 31, 33, 35, 38, 41, 50, 51, 52, 53, 55, 56	84
Alg 114-bus	49	3, 4, 6, 11, 12, 13, 15, 17, 19, 22, 25, 30, 32, 35, 36, 38, 39, 40, 43, 45, 47, 49, 53, 56, 61, 65, 68, 69, 71, 73, 77, 78, 79, 80, 82, 83, 87, 89, 91, 92, 95, 98, 102, 103, 104, 107, 108, 112, 113	175

As mentioned in the case above the number of PMUs needed is high compared to the first three cases, but it is less than the fourth case for the IEEE 24, 39, 57, and Algerian 114-bus networks.

3.1.6 Case either single PMU or branch outage

Determining the location of PMUs in this case will ensure that either line outage or PMU failure does not influence the observability of the system. The results obtained via the suggested method are presented in Table 3.9.

Table 3.9: Number and position of PMUs in case either single PMU or branch outage.

Test System	Number of PMUs	Positions of PMUs	SORI
IEEE 14-bus	7	2, 4, 5, 6, 9, 11, 13	34
IEEE 24-bus	11	1, 2, 7, 8, 9, 10, 16, 19, 21, 22, 23	46
IEEE 30-bus	17	1, 2, 4, 5, 6, 10, 11, 12, 13, 15, 17, 19, 20, 24, 26, 27, 29	69
NE 39-bus	17	2, 6, 8, 12, 13, 16, 18, 20, 23, 25, 26, 29, 34, 35, 36, 37, 38	64
IEEE 57-bus	21	1, 2, 6, 12, 14, 15, 19, 23, 25, 28, 31, 33, 35, 38, 41, 50, 51, 52, 53, 55, 56	84
Alg 114-bus	62	2, 3, 5, 6, 8, 10, 12, 13, 16, 19, 20, 22, 25, 26, 29, 30, 32, 34, 36, 38, 39, 41, 43, 45, 47, 49, 50, 53, 54, 57, 59, 61, 62, 63, 65, 67, 68, 69, 71, 77, 78, 79, 80, 82, 83, 87, 89, 90, 91, 92, 95, 98, 99, 101, 103, 104, 107, 108, 109, 111, 112, 113	234

3.2 Comparison with previous studies

The results of simulations carried out by the proposed method are compared with previous studies to assess the effectiveness of the proposed method. The comparison is done between the number of PMUs and the SORI value versus the results obtained in previous studies that used different methods to solve the OPP problem and considering a normal operation case, ZIB, loss of a single PMU, single line failure, and either a single PMU or branch failure.

The comparison results between the proposed approach with existing studies are presented in Table 3.10. The comparison covers both all IEEE buses and the Algerian system of 114 buses. It should also be mentioned that the solution with the highest SORI value is the most efficient solution. As evident from Table 3.10, all studies being compared including proposed method managed to get the same number of PMUs across all IEEE bus systems tested. However, the values of measurement redundancy are different for some bus systems. For the small bus systems, the measurement redundancy obtained by the proposed method is mostly the same as existing studies. However for Algerian 114-bus the difference is more prominent. Overall, the proposed method managed to get the highest quality solution for all bus systems.

Table 3.10: The comparison results between proposed method and existing studies on the number of PMUs and measurement redundancy for normal operation

Algorithm	**Parameter**	**14-Bus**	**24-Bus**	**30-Bus**	**39-Bus**	**57-Bus**	**Alg 114-Bus**
Proposed Method	N_{PMUs}	4	7	10	13	17	33
	$SORI$	19	31	52	52	71	159
GWO [4]	N_{PMUs}	4	-	10	-	-	38
	$SORI$	19	-	48	-	-	157
MFO [4]	N_{PMUs}	4	-	10	-	-	39
	$SORI$	19	-	46	-	-	153
CS [4]	N_{PMUs}	4	-	10	-	-	37
	$SORI$	19	-	50	-	-	168
WDO [4]	N_{PMUs}	4	-	10	-	-	45
	$SORI$	19	-	44	-	-	185
VNS [5]	N_{PMUs}	4	7	10	-	17	-
	$SORI$	19	31	67	-	71	-
BPSO [6]	N_{PMUs}	4	7	10	13	-	-
	$SORI$	19	31	48	49	-	-

PSO-MFO [7]	N_{PMUs}	4	-	10	-	17	-
	$SORI$	19	-	52	-	67	-
FPA [8]	N_{PMUs}	4	-	10	13	17	-
	$SORI$	19	-	52	52	72	-
BGSA [9]	N_{PMUs}	4	-	10	-	-	-
	$SORI$	19	-	52	-	-	-
MICA [10]	N_{PMUs}	4	-	10	-	17	-
	$SORI$	17	-	48	-	67	-
BSDP [11]	N_{PMUs}	4	-	10	-	17	-
	$SORI$	16	-	50	-	66	-
SQP [12]	N_{PMUs}	4	7	10	13	17	-
	$SORI$	19	31	48	52	71	-

Table 3.11: The comparison results between proposed method and existing studies on the number of PMUs and measurement redundancy for case considering ZIB

Algorithm	**Parameter**	**14-Bus**	**24-Bus**	**30-Bus**	**39-Bus**	**57-Bus**	**Alg 114-Bus**
Proposed Method	N_{PMUs}	3	6	7	8	11	28
	$SORI$	16	29	41	43	60	149
GWO [4]	N_{PMUs}	3	-	7	-	-	35
	$SORI$	15	-	36	-	-	155
MFO [4]	N_{PMUs}	3	-	7	-	-	36

	$SORI$	15	-	36	-	-	146
CS [4]	N_{PMUs}	3	-	7	-	-	34
	$SORI$	15	-	36	-	-	142
WDO [4]	N_{PMUs}	3	-	8	-	-	49
	$SORI$	15	-	37	-	-	190
BGSA [9]	N_{PMUs}	3	-	7	-	-	-
	$SORI$	15	-	36	-	-	-
PSO-GSA [13]	N_{PMUs}	3	-	7	-	11	-
	$SORI$	16	-	41	-	60	-
BPSO [6]	N_{PMUs}	3	6	7	13	-	-
	$SORI$	15	29	36	51	-	-
BPSO [14]	N_{PMUs}	3	6	7	8	11	-
	$SORI$	16	29	41	43	60	-
ILP [15]	N_{PMUs}	3	6	7	8	11	-
	$SORI$	16	27	33	43	60	-
BSDP [11]	N_{PMUs}	3	-	7	-	11	-
	$SORI$	16	-	36	-	57	-
ILP [16]	N_{PMUs}	3	-	7	8	11	-
	$SORI$	16	-	34	43	59	-
BPSO [17]	N_{PMUs}	-	6	7	8	11	-
	$SORI$	-	28	37	40	59	-
ES [18]	N_{PMUs}	3	6	7	8	11	-
	$SORI$	16	27	36	43	60	-

The same thing can be observed in Table 3.11 for the case considering ZIB. The proposed method managed to get the best quality solution including the Algerian 114-bus.

Table 3.12: Comparison results with available methods considering single PMU loss

Test System	Proposed Method	PSO-GSA [13]	BILP [19]	GA [20]	ES [18]	HDPSO [21]	ILP [22]
IEEE 14-Bus	7	7	7	7	7	7	7
IEEE 24-Bus	11	-	-	11	13	-	-
IEEE 30-Bus	14	14	15	14	15	16	15
NE 39-Bus	17	-	17	17	18	17	18
IEEE 57-Bus	23	24	25	25	26	23	26
Alg 114-bus	59	-	-	-	-	-	-

Table 3.12 tabulated a comparison results between the suggested technique and some previous studies for the third case (loss of single PMUs). For IEEE 30 and bus, 57-bus, the suggested approach managed to get optimal number less than other methods.

Table 3.13: Comparison results with available methods considering single line outage

Test System	Proposed Method	ILP [23]	BPSO [24]	BPSO [25]	ILP [22]
IEEE 14-Bus	7	7	7	7	7
IEEE 24-Bus	8	-	-	-	-
IEEE 30-Bus	14	14	15	15	15
NE 39-Bus	12	18	17	17	18
IEEE 57-Bus	21	22	22	22	26
Alg 114-Bus	49	-	-	-	-

Table 3.13 summarizes the comparative results between the method used and some modern methods for each test system. From this table, the optimal PMU numbers are the same in the IEEE 14-bus system. In the IEEE 24-bus system the optimal PMUs number is 8 in proposed approach. In IEEE 30-bus, the numbers of PMUs is lower in the suggested technique compared to [22], [24] and [25] but similar to [23]. In NE 39-bus and IEEE 57-bus, the optimum number of PMUs is 12 and 21 respectively in the suggested method; which is less than all the compared methods. With regard to Algerian 114-bus, the number of PMUs is 49, since there are no other ways to compare with them, the only suggested method that has reached to this solution remains.

3.3 Conclusion

In this chapter, the proposed method explained in the previous chapter is applied to several IEEE bus systems namely the IEEE 14-bus, 24-bus, 30-bus, 39-bus, 57-bus, 118-bus, and Alg 114-bus. MATLAB software is used to perform the simulations and the results obtained are given in this chapter. To evaluate its effectiveness, the results obtained are compared with existing studies. The comparison results indicate the proposed method managed to outperform existing studies and it can be used to solve the OPP problem for case considering ZIB, single PMU loss.

3.4 References

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Conclusions and Future Works

4.1 Conclusions

In this thesis, optimal PMUs placement set that can guarantee full observability of the power system is investigated based on several practical constraints such as ZIB, single PMU loss, single line outage, and both single PMU or single line outage. It is investigated by using the GSA method, which uses the intelligence of the swarm to determine the best solution.

However, it is widely known that population-based methods such as GSA has the tendency to have performance issues when dealing with large problem size. As a result, the algorithm tends to converge at local optima, instead of global optima, which gives the optimal solution among all possible solutions. Recent studies in this research area indicated that the balance between exploration and exploitation must be maintained to avoid the particles from being trapped in local optima.

To validate the performance of the proposed method, the proposed method was simulated on the IEEE 14-bus, 24-bus, 30-bus, 39-bus, 57-bus, and Algerian 114-bus systems by using MATLAB software. Since there is no unique solution for the PMUs placement, in addition to the number of PMUs required to achieve complete observability of the power system, the measurement redundancy, which indicates the reliability of the PMUs placement set, is used. The results indicated that the proposed method is the most reliable method for all IEEE bus systems tested for the case considering normal operating and ZIB. Furthermore, for Alg 114-bus system, which was never considered in the existing studies that used GSA algorithm, a part of having the most reliable PMUs placement sets, the proposed method managed to reduce the number of PMUs needed for the case considering ZIB when compared to the deterministic method, namely the BSDP method. This indicated that the proposed method is applicable to large systems.

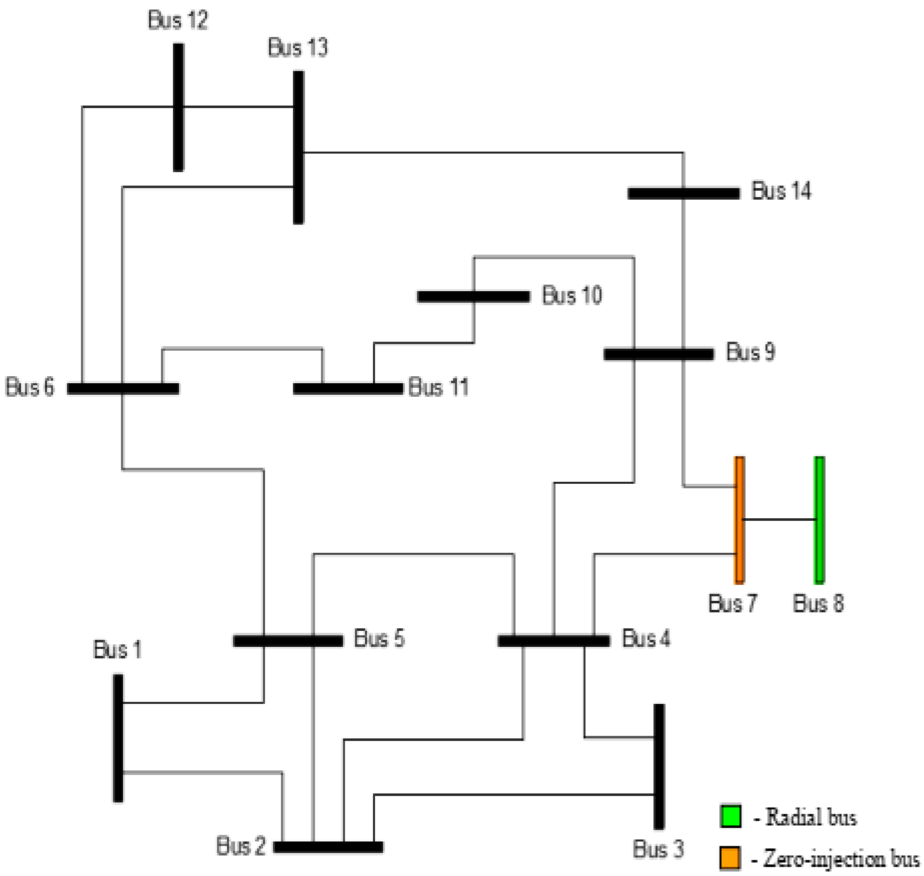
To summarise, for the GSA algorithm that tends to have performance issues when dealing with large problem size, the proposed method proved that it is applicable for larger systems when compared with the existing studies that used different optimization methods.

4.2 Future work

- The implementation of the proposed method to the GSA algorithm encourages the algorithm to find the optimal solution during the beginning of the iterations, especially in small bus systems. Consequently, the remaining iterations proved to be a waste of computational cost since it no longer able to improve the existing solution. Therefore, a proper stopping criterion that can determine if the algorithm is unable to improve the current solution might help in this regard.
- Reduce the complexity of the algorithm and the computation time by integrating all practical constraints into a single fitness function. This ensures observability validation to ensure feasibility of each PMUs placement set can be eliminate, which will help reduce the complexity of the algorithm. It also makes ease of implementation for every practical constraints in the algorithm.
- Investigate the proposed method by using numerical observability. Having the proposed method suitable for both type of observability may improve the flexibility of the proposed method should numerical observability is desired.

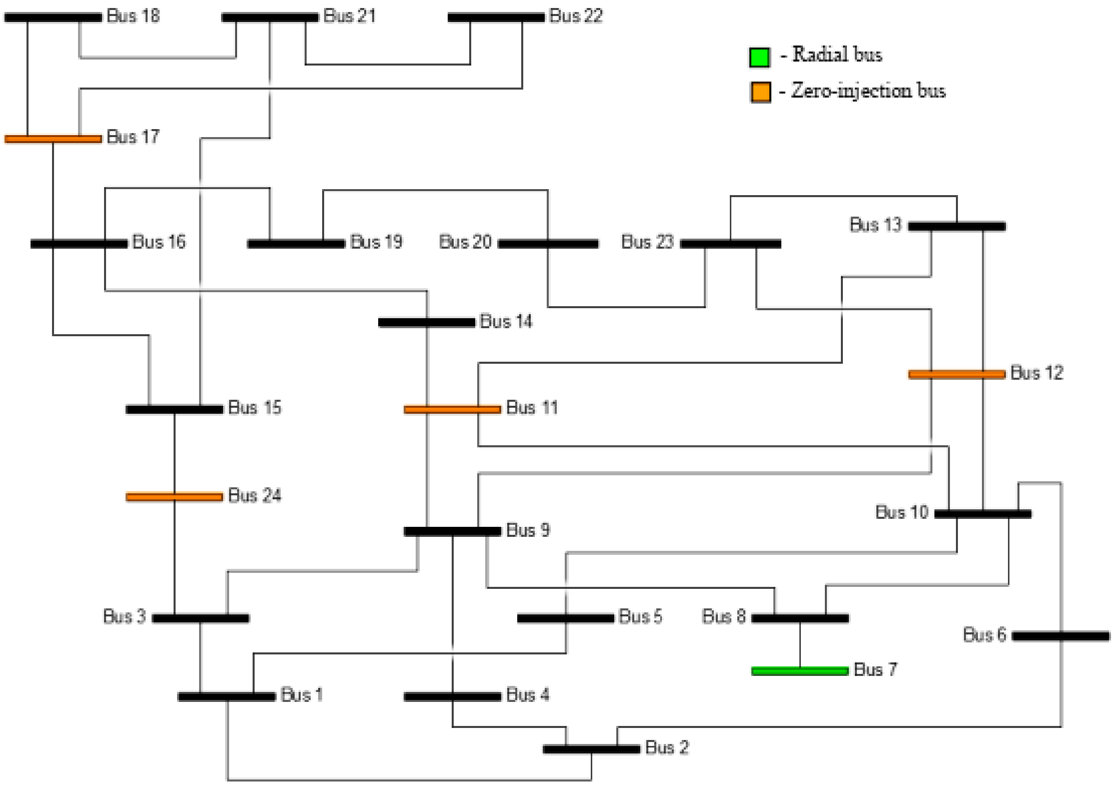
Appendix

IEEE 14-bus Data



Branch	*From Bus*	*To Bus*
1	1	2
2	1	5
3	2	3
4	2	4
5	2	5
6	3	4
7	4	5
8	4	7
9	4	9
10	5	6
11	6	11
12	6	12
13	6	13
14	7	8
15	7	9
16	9	10
17	9	14
18	10	11
19	12	13
20	13	14

IEEE 24-bus Data



Branch	From Bus	To Bus
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2	1	3
3	1	5
4	2	4
5	2	6
6	3	9
7	3	24
8	4	9
9	5	10
10	6	10
11	7	8
12	8	9
13	8	10
14	9	11
15	9	12
16	10	11
17	10	12
18	11	13
19	11	14
20	12	13
21	12	23
22	13	23
23	14	16
24	15	16
25	15	21
26	15	24
27	16	17
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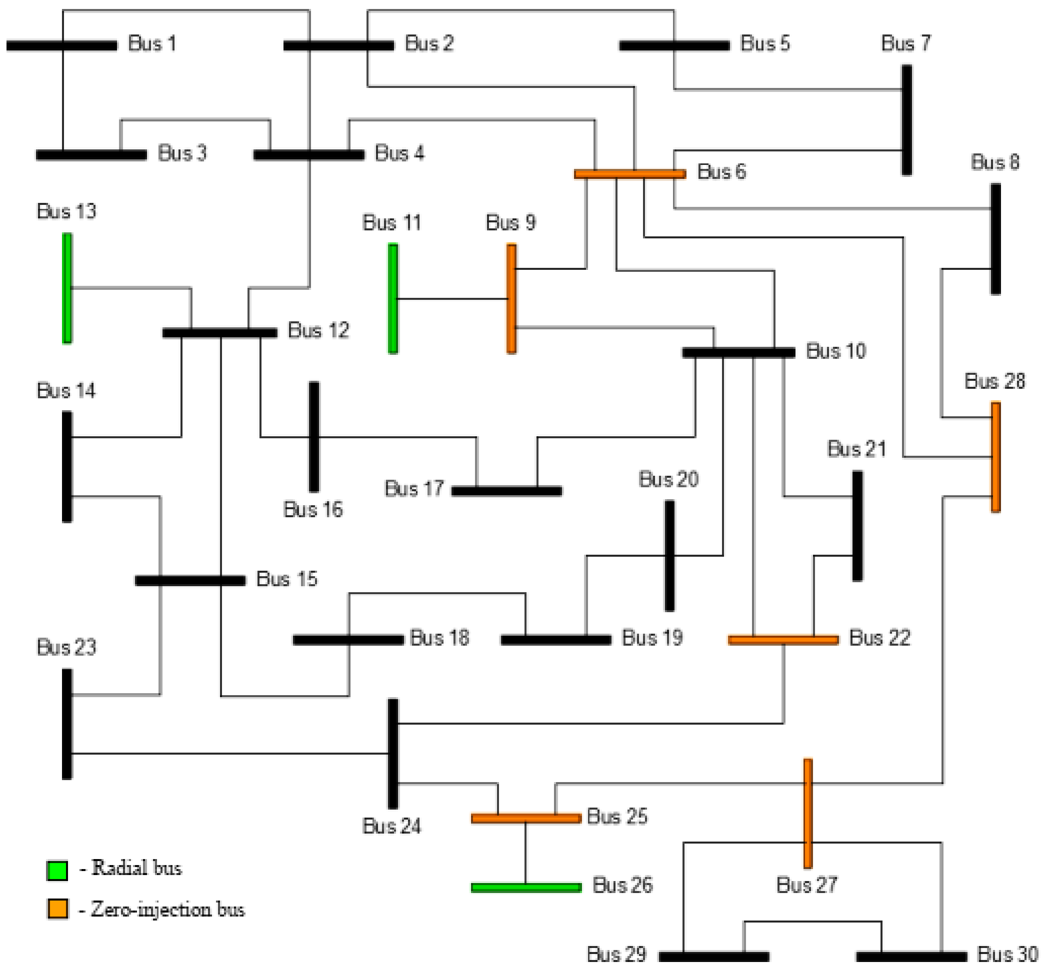
30	17	22
31	18	21
32	19	20
33	20	23
34	21	22

IEEE 30-bus Data

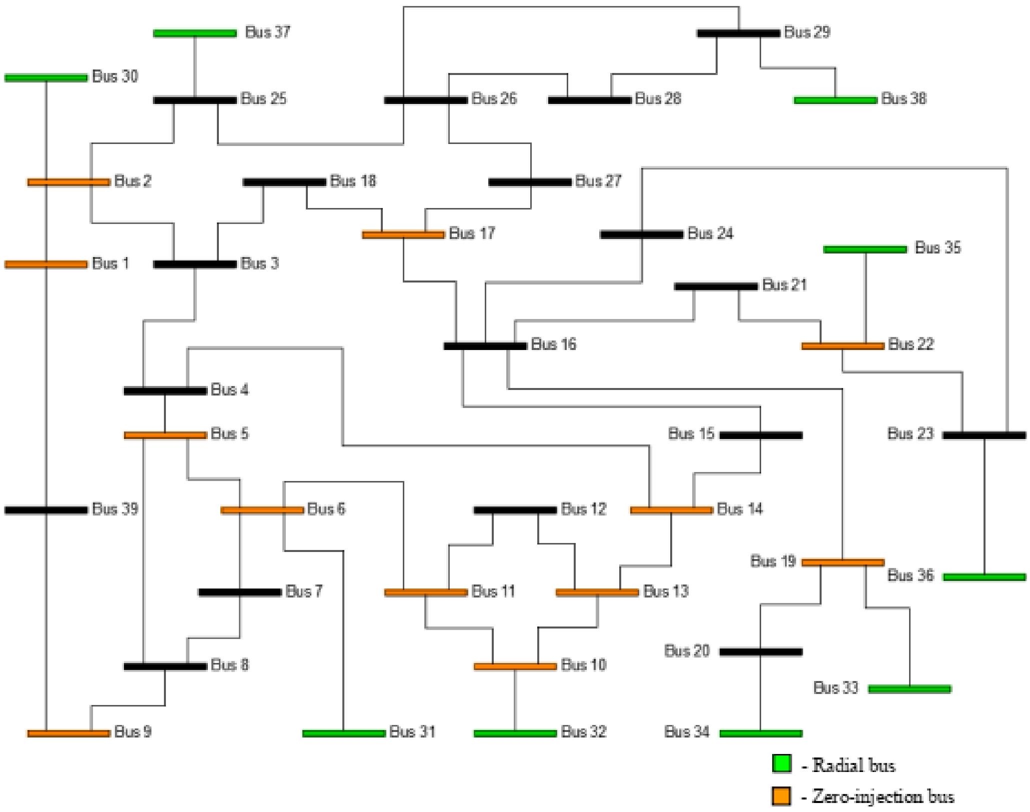


Branch	From Bus	To Bus
1	1	2
2	1	3
3	2	4
4	3	4
5	2	5
6	2	6
7	4	6
8	5	7
9	6	7
10	6	8
11	6	9
12	6	10
13	9	11
14	9	10
15	4	12
16	12	13

Branch	From Bus	To Bus
17	12	14
18	12	15
19	12	16
20	14	15
21	16	17
22	15	18
23	18	19
24	19	20
25	10	20
26	10	17
27	10	21
28	10	22
29	21	22
30	15	23
31	22	24
32	23	24

Branch	From Bus	To Bus
33	24	25
34	25	26
35	25	27
36	28	27
37	27	29
38	27	30
39	29	30
40	8	28
41	6	28

IEEE 39-bus Data



Branch	*From Bus*	*To Bus*
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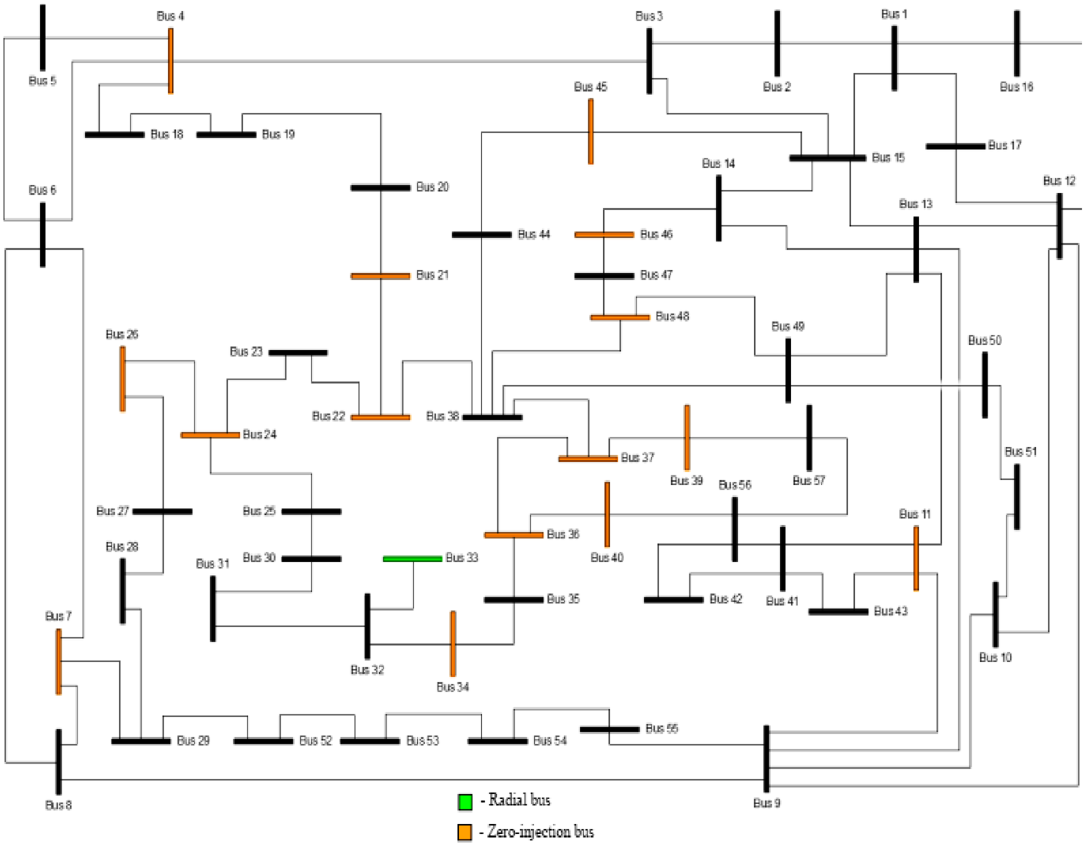
2	1	39
3	2	3
4	2	25
5	2	30
6	3	4
7	3	18
8	4	5
9	4	14
10	5	6
11	5	8
12	6	7
13	6	11
14	6	31
15	7	8
16	8	9

Branch	*From Bus*	*To Bus*
17	9	39
18	10	11
19	10	13
20	10	32
21	12	11
22	12	13
23	13	14
24	14	15
25	15	16
26	16	17
27	16	19
28	16	21
29	16	24
30	17	18
31	17	27
32	19	20

Branch	*From Bus*	*To Bus*
33	19	33
34	20	34
35	21	22
36	22	23
37	22	35
38	23	24
39	23	36
40	25	26
41	25	37
42	26	27
43	26	28
44	26	29
45	28	29
46	29	38

IEEE 57-bus Data



Branch	From Bus	To Bus
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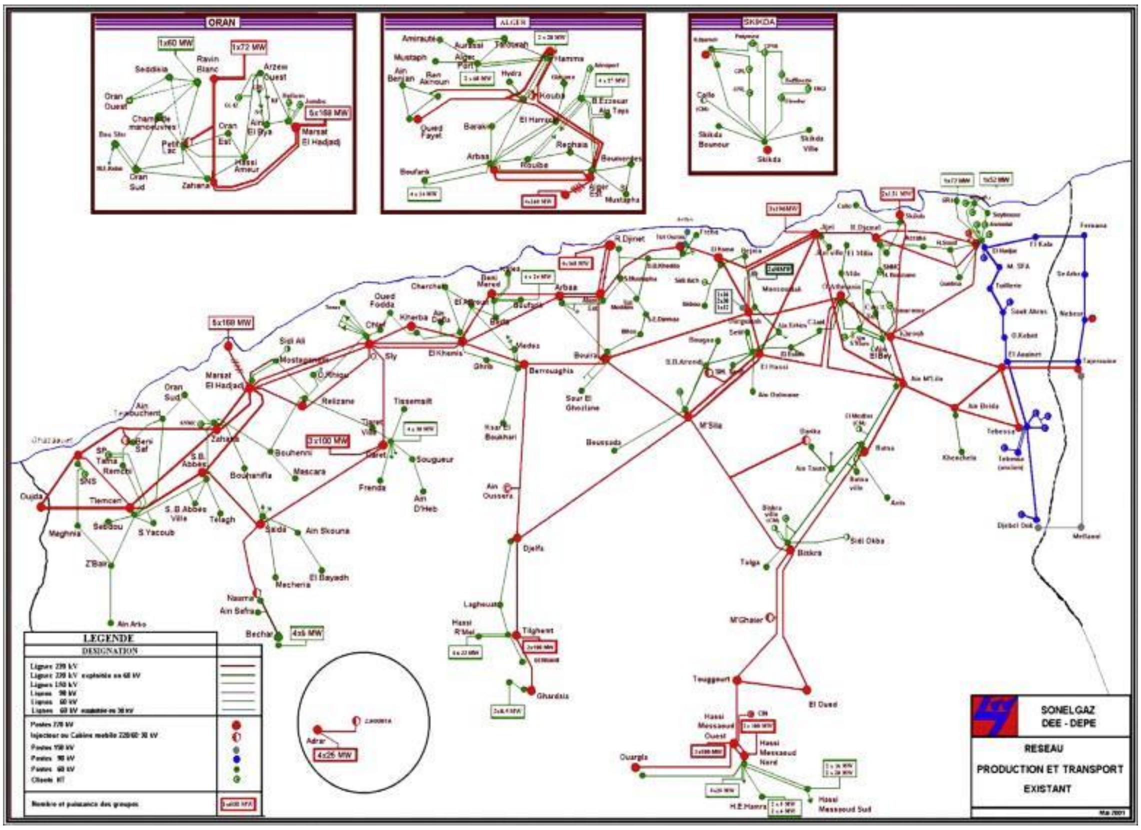
2	2	3
3	3	4
4	4	5
5	4	6
6	6	7
7	6	8
8	8	9
9	9	10
10	9	11
11	9	12
12	9	13
13	13	14
14	13	15
15	1	15
16	1	16
17	1	17
18	3	15
19	4	18
20	5	6
21	7	8
22	10	12
23	11	13
24	12	13
25	12	16
26	12	17
27	14	15

Branch	From Bus	To Bus
28	18	19
29	19	20
30	21	20
31	21	22
32	22	23
33	23	24
34	24	25
35	24	26
36	26	27
37	27	28
38	28	29
39	7	29
40	25	30
41	30	31
42	31	32
43	32	33
44	34	32
45	34	35
46	35	36
47	36	37
48	37	38
49	37	39
50	36	40
51	22	38
52	11	41
53	41	42
54	41	43

Branch	From Bus	To Bus
55	38	44
56	15	45
57	14	46
58	46	47
59	47	48
60	48	49
61	49	50
62	50	51
63	10	51
64	13	49
65	29	52
66	52	53
67	53	54
68	54	55
69	11	43
70	44	45
71	40	56
72	56	41
73	56	42
74	39	57
75	57	56
76	38	49
77	38	48
78	9	55

Algerian 114-bus Data



Branch	*From Bus*	*To Bus*
1	2	1
2	6	1
3	2	6
4	4	42
5	4	42
6	4	3
7	5	3
8	5	4
9	4	7
10	15	16
11	16	3
12	16	14
13	8	42
14	8	4
15	10	7
16	10	11
17	7	6
18	11	42
19	6	3
20	9	2
21	9	3

Branch	*From Bus*	*To Bus*
22	13	12
23	10	13
24	17	21
25	17	21
26	17	72
27	17	27
28	17	31
29	31	28
30	17	64
31	21	44
32	60	31
33	21	60
34	60	44
35	58	44
36	72	101
37	72	58
38	58	75
39	75	107
40	75	74
41	44	42
42	44	42

Branch	***From Bus***	***To Bus***
43	42	48
44	48	44
45	107	101
46	64	97
47	72	96
48	96	98
49	96	95
50	18	22
51	18	37
52	37	22
53	19	26
54	19	26
55	19	34
56	20	18
57	20	24
58	20	24
59	20	29
60	20	35
61	35	29
62	20	32
63	22	32

Branch	***From Bus***	***To Bus***
64	22	24
65	22	24
66	23	30
67	23	36
68	36	30
69	33	18
70	32	33
71	26	25
72	24	25
73	26	34
74	29	26
75	29	39
76	38	34
77	18	73
78	18	73
79	62	18
80	20	52
81	20	52
82	54	59
83	52	59
84	57	51

Branch	***From Bus***	***To Bus***
85	57	77
86	52	53
87	53	54
88	52	30
89	71	70
90	40	41
91	40	50
92	71	69
93	70	68
94	43	46
95	51	43
96	54	55
97	55	43
98	73	62
99	73	67
100	68	67
101	29	26
102	73	66
103	63	66
104	63	65
105	63	65
106	56	54
107	57	56

Branch	***From Bus***	***To Bus***
108	47	50
109	47	46
110	67	66
111	49	41
112	19	78
113	19	79
114	59	61
115	45	46
116	85	87
117	85	86
118	85	81
119	87	106
120	87	82
121	87	99
122	103	105
123	105	101
124	105	104
125	103	106
126	81	82
127	80	82
128	80	84
129	84	83
130	82	83

Branch	From Bus	To Bus
131	100	98
132	100	97
133	98	97
134	99	100
135	87	100
136	100	84
138	84	80
139	86	81
140	98	99
141	101	102
142	99	102
143	99	101
144	98	94
145	94	82
146	92	93
147	93	91
148	93	91
149	90	89
150	88	89
151	90	93
152	103	110
153	110	112
154	103	114

Branch	From Bus	To Bus
155	109	108
156	109	107
157	112	114
159	112	111
160	113	111
161	80	88
162	81	90
163	86	93
164	42	41
166	58	57
167	44	43
168	60	59
169	64	63
170	72	71
171	18	17
172	21	20
173	27	26
174	28	26
175	31	30
176	48	47
177	74	76