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Optimal Placement of Phasor Measurement Unit on Integrated Nepal Power System Ensuring Power System Observability

by

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A THESIS

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled " **Optimal Placement of Phasor Measurement Unit on Integrated Nepal Power System Ensuring Power System Observability**" submitted by **Bishal Rimal** in partial fulfillment of the requirements for the degree of Masters of Science in Renewable Energy Engineering.

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ABSTRACT

For better state estimation of power system, phasor measurement unit (PMU) are superior to supervisory control and data acquisition system. Optimal PMU placement is the strategic placement of a minimum number of PMUs to ensure power system observability. Optimal PMU placement is essential to overcome the economic burden during the deployment of PMU on every bus. A strategy integrated with a modified Simulated Annealing algorithm is proposed in this thesis with the consideration of the effect of a radial bus during optimal PMU placement problems. In addition to the normal case, cases for single PMU outage and zero injection bus have been implemented in MATLAB. The simulation result of the proposed modified simulated annealing algorithm is compared and validated with modified simulated annealing algorithm for IEEE 14-bus, 30-bus, 57-bus, and 118-bus system. To recognize the superior placement set from diverse solutions given by meta-heuristic algorithm, placement set with least number of PMU and higher system observability redundancy index is used. The proposed strategy on modified Simulated Annealing algorithm has improved the result in terms of an optimal number of PMU, probability of finding an optimal number of PMU, and system observability redundancy index. For normal case, the number of PMUs required for complete power system observability of 90 bus Integrated Nepal Power System is found to be 28. Similarly, with the consideration of single PMU outage and zero injection bus, the number of PMU required is found to be 62 and 26 respectively.

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LIST OF ABBREVIATIONS

BSPO	Binary Particle Swarm Optimization
FPA	Flower Pollination Algorithm
GA	Genetic Algorithm
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IGA	Immune Genetic Algorithm
ILP	Integer linear Programming
INPS	Integrated Nepal Power System
kV	Kilo Volt
LDC	Load Dispatch Centre
OPP	Optimal PMU Placement
PSO	Particle Swarm Optimization
SCADA	Supervisory Control and Data Acquisition
RSN	Recursive Security N
RTU	Remote Terminal Unit
SA	Simulated Annealing
MTU	Master Terminal Unit
NEA	Nepal Electricity Authority
ZIB	Zero Injection Bus

CHAPTER ONE: INTRODUCTION

1.1 Background

The evolution of modern era has modernized nearly every system to become more effective, reliable, and autonomous. The conventional power grid is also within the transitional process to end up as a modernized power grid, or broadly known as the smart grid. The vision for the smart grid is to screen and oversee the power grid as efficiently as conceivable whereas giving better reliability and stability. The traditional state estimation of power system is based upon the data collected from supervisory control and data acquisition (SCADA). SCADA is not capable to measure fast and dynamic response of the network. They can measure the magnitude of bus voltage and current only. Due to the slower response of SCADA, there might be cascaded faults and eventually blackouts. On August 14, 2003, United State faced the biggest blackout in history, which cleared out over 50 million people without electricity in eight U.S. states and a portion of Canada with the loss of 7 to 10 million USD (Joo, et al., 2007). After that blackout a task force had studied and indicated the use of synchrophasor for enhancing situational awareness to prevent future blackouts. (U.S.-Canada Power System Outage Task Force, 2004). After the 2012 blackout in India, Power Grid Corporation of India Ltd. had also started to deploy synchrophasors in their power system Network.

Aged infrastructure should be replaced or upgraded with advanced technology for the realization of a smart grid. One of the advanced innovations used is the phasor measurement unit (PMU). PMU is a measurement device that can accurately measure bus voltage phasor at the bus it is installed and also the branch current phasor that is adjacent to it PMU is also equipped with Global Positioning System (GPS), thus, the measurement data provided by the PMU can be calculated in real-time due to time-stamping and synchronization. A common time reference provided by a GPS for all acquired data, fulfils the need for real-time control, thereby, allowing more exact assessment of the current condition of power system.

Integrated Nepal Power System Network (INPS) is also facing frequent system collapse as the system is not fully observable with time synchronization. Nepal Electricity Authority (NEA) is also planning to install the PMU in Integrated Nepal Power System Network (INPS). Installation of PMU in every bus is restricted with factors like compatibility of PMU in the existing system, PMU cost, available communication facility, security, and associated labour cost. The number of PMUs required realizing full observability of a power system can be diminished if the PMUs are strategically placed in a power system. Numerous optimization strategies have been used in recent years to decide the suitable placement of PMUs in a power system such as integer linear programming (ILP), genetic algorithm (GA), simulated annealing (SA), exhaustive search, differential evolution, binary particle swarm optimization (BPSO), etc. ILP can generate a single optimal solution. But usages of meta-heuristic algorithms have different expectations of results which might improve the current optimal solution.

1.2 Problem Statement

Conventional methods and SCADA systems are insufficient for accurate control of complex interconnected power system networks. In order to overcome the issue, a faster, time-stamped PMU technology was introduced which is capable to measure voltage phasor at a bus and current phasor of its incident branches. The faster responses of PMUs have enhanced the system to become capable to react on major faults thereby preventing the cascaded faults.

In Nepal, due to the lack of a proper energy management system, only analog values from instrument transformers are obtained in Load Dispatch Centre (LDC). The problem of system collapse of power networks has been frequently observed. Also, the complexity of INPS has been increased due to the injection of renewable energy, distributed generation, cross-border transmission, and electric vehicle charging station. Higher penetration of intermittent renewable energy is expected to introduce additional technical challenges not foreseen at the initial stage (Chua, 2017).

The introduction of PMU in power system network has solved the issues to some extent. GPS based synchronized signal data from PMU has been proved to be more accurate and beneficial for power system protection and control assessment. The higher cost of PMU installation bounds us to implement PMU randomly. In order to minimize the number and cost of PMU installation, optimization on the number of PMU is essential ensuring power system observability.

1.3 Objectives

1.3.1 Main Objective

The main objective of this thesis is to optimize the number of PMUs to be installed on INPS ensuring power system observability.

1.3.2 Specific Objectives

Following are the specific objectives of the thesis.

- To formulate the optimization problem for normal operation, single PMU outage and the case considering zero injection bus (ZIB) for the Optimal PMU Placement (OPP) problem.
- To implement the modified SA algorithm for IEEE 14, IEEE 30, IEEE 57, and IEEE 118 bus system considering normal operation as a base case.
- To implement the modified SA algorithm for IEEE 14, IEEE 30, IEEE 57, and IEEE 118 bus system considering single PMU outage in addition to the base case.
- To implement the modified SA algorithm for IEEE 14, IEEE 30, IEEE 57, and IEEE 118 bus system considering ZIB in addition to the base case.
- To implement validated modified SA algorithm in INPS for the determination of optimal number and location of PMU.

1.4 Limitation

This thesis will have the following limitations.

- An outage of any critical branch/ line will make some part of power system unobservable. Possible line outage is not considered on this thesis.
- The channel limit of the PMU is not considered on the thesis. PMUs are assumed to have infinite channels.
- In INPS, transmission lines of 66 kV and above are only considered.
- All substations in INPS are assumed to be able to install the PMU with current existing equipment so that the cost of installation of PMU in every bus is assumed to be equal.

CHAPTER TWO: LITERATURE REVIEW

2.1 Power System Network

The entire power system network includes generation, transmission, and distribution of electric power from generation unit to end-user. The power demand on the network continuously changes and should be matched with the power generation at every instant. Due to its dynamic nature, effective monitoring and control of the network are very essential. In these recent years, several blackouts have been recorded throughout the globe. The major reason for the deviation of operating point of network is the disturbances on the network. Disturbances might be due to the loss of line or a generating unit, sudden change in load, faults, or surges. These disturbances can be distinguished timely with the help of power system network parameters (Nagrath & D.P, 2014).

The penetration of new technology raises concern about system operation. These concerns can be addressed by deployment of synchrophasors (Jamil, et al., 2014). With the increment of penetration of intermittent renewable resources, there occurs impact on power system transient stability, small-signal stability, and frequency stability (Impram, et al., 2020).

2.2 Conventional Measurement System

For any power system network, typically active power, reactive power, node voltage, and frequency are measured continuously. The conventional measurement systems that are generally employed in the power system network are SCADA. SCADA refers to the combination of data acquisition and telemetry. SCADA system consists of a number of Remote Terminal Unit (RTU) collecting field data and sending that field data to Master Terminal Unit (MTU) with the help of a communication channel (Bailey & Wright, 2003).

The main component in SCADA system is RTU. RTU has a direct connection with different sensors, meters, and actuators that are associated with a control environment. RTU converts the information of remote station to digital form for the modem to transmit the data. MTU/ SCADA centre sends signals to several RTUs to control the process equipment through actuators and switch boxes. Data is communicated among central host computer servers and the field data interface devices and control units through communication network. The transfer medium of communication network might be either cable, radio, telephone, satellite, or any of their combination. The operator workstation consists of standard human machine interface (HMI) software which is finally connected in a network with a central host computer. The operator working from those workstations send and request the information to the host client computer in order to monitor and control the parameters of remote field. The general block diagram of SCADA is shown in Figure 2.1.

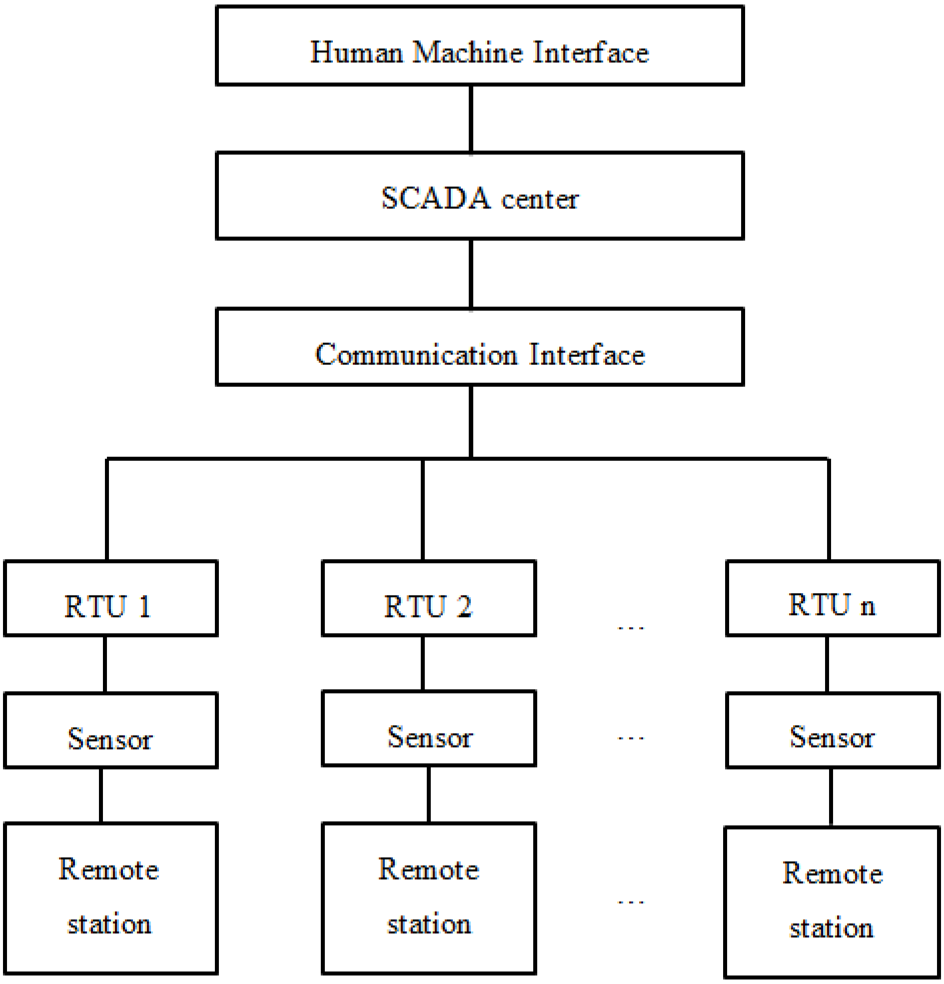

Figure 2.1: General block diagram of SCADA

SCADA allows a utility operator to monitor and control distributed processes of various remote sites. The monitoring and controlling of that complete grid and power generation plants have been done by SCADA System (Kumar, et al., 2010).

2.3 Phasor Measurement Unit

The technology of synchronized phasor measurements or synchrophasor was first proposed in the 1980s. One of the novel features of the synchrophasor measurements was their high-precision time stamping. This property means that communication delays are not a critical issue for applications that use synchrophasor data, as the data can be time-aligned using timestamps (Phadke, et al., 1983). In 1990s, PMUs were developed and then deployed on an experimental basis in actual power system. Commercial PMUs then become available and many major utilities started installation of PMUs in their power systems (Huang, et al., 2008). The emergence of the phasor measurement technology with time synchronization opens new perspectives to design advanced power system monitoring schemes (Padke & Thorpe, 2008).

As synchrophasors are time-synchronized and updated at a fast rate, they are superior to traditional SCADA measurements in capturing power system dynamic behaviors (Huang, et al., 2008). The applications of synchrophasors can generally categorize into offline applications, online monitoring applications, and real-time control/protection applications. Disturbance analysis and power system dynamic model tuning and validation are the example of offline application. Enhanced power system state estimation, monitoring of frequency and phase angle, line thermal loading, voltage instability, and oscillation are the example of application under online monitoring. The real-time control applications of synchrophasors include power flow control, oscillation and damping control, emergency control against voltage, rotor angle and frequency instability (Terzija, et al., 2011). Synchrophasor applications demand acceptable accuracy and consistency in both steady-state and transient conditions to ensure that measurements accurately reflect the behavior of the monitored system. With a growing number of commercial PMU vendors, the need for accuracy standards and interoperability between different PMUs was recognized (Terzija, et al., 2011).

PMUs extract the GPS based time stamped phasor (magnitude and phase angle) of the electrical signals in a power system, with all phase angles. In addition to the phasor values, a PMU can also estimate the frequency of measured signal and its rate of change. (Phadke, 1993). Figure 2.2 shows the major components as a block diagram of PMU.

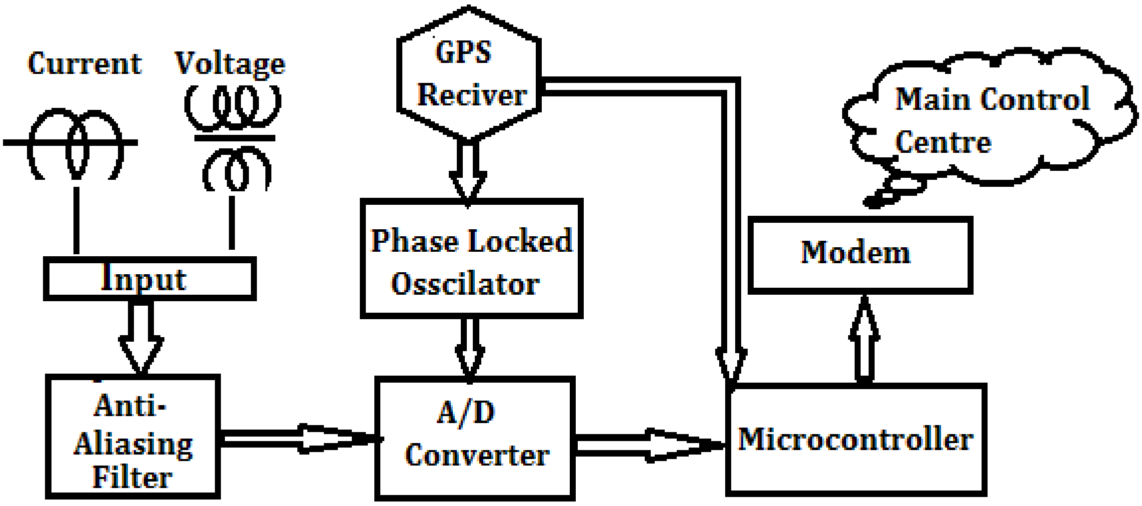

Figure 2.2: Block diagram of PMU

The major components of PMU are described below.

i. Input: The voltage and current signals are taken as input. With the help of current and potential transformer, the current and voltage are stepped down to an appropriate level.

ii. Anti-Aliasing filter: The stepped-down signals from the input are passed through the frontend anti-aliasing filters. The filter eliminates the high frequency interference signals before sampling.

iii. Analog to digital converter (ADC): The fixed frequency sampling of ADC is synchronized to a GPS clock. The high level of accuracy is achieved by correcting the errors of instrument transformer using proprietary algorithms.

iv. GPS receiver: The high accuracy synchronized time is obtained with the help of GPS satellite. Satellites transmit one pulse per second. On receiving the pulse, PMU starts to sample the data.

v. Phase locked oscillator: It generated the sampling signal with reference to synchronized time and gives sampling signal to ADC.

vi. Microcontroller: It is the central brain of PMU. It received the sampled data and computes the positive sequence estimate of the signal. It also computes the phasor using the universal reference. Along with the time stamp, it relays the computed phasor through communication media. It is also capable of measuring frequency and its rate of change.

vii. Modem: It converts the output of the microcontroller in suitable form to transmit it to main control center.

In comparison to SCADA, PMUs have several advantages. Table 2.1 shows the comparison of PMU and SCADA in terms of their basic features.

Table 2.1: Comparison of SCADA and PMU

Features	**SCADA**	**PMU**
Resolution	1 sample every 2-4 sec	10-60 samples per second
Observability	Steady State	Transient state
Time	Not synchronized	Synchronized
Phase angle	No	Yes
Focus	Local monitoring and control	Wide area monitoring and control
Total input and output channel	Approx. 100+ analog and digital (variable)	Approx. 10 phasor, 16+analog, 16+ digital

Figure 2.3 shows a comparison on observability of PMU and SCADA measurements during transients. PMU can measure transient data which could be useful for the analysis of the performance of power system network.

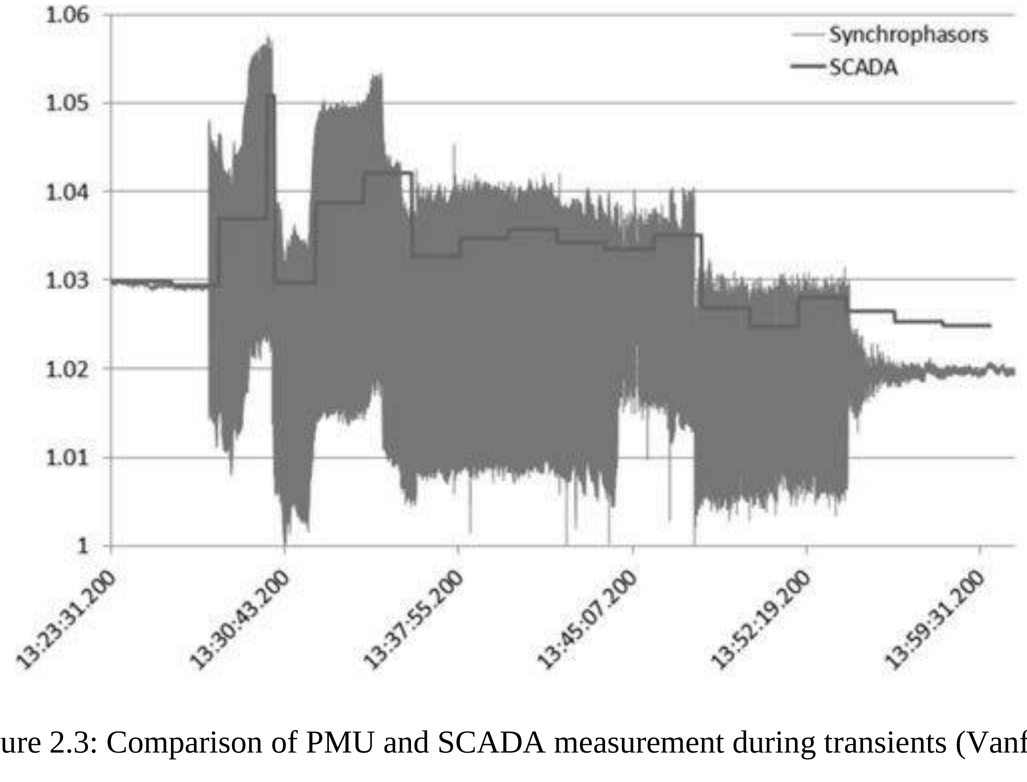

Figure 2.3: Comparison of PMU and SCADA measurement during transients (Vanfretti, et al., 2015)

2.4 PMU across the Globe

2.4.1 North America

In early 1980s first prototype of PMU was developed at Virginia Tech. Northeast USA and Canada blackout happened in 2003, which lasted for two days, affected 55 million people and caused a massive economic loss. After the blackout synchronized measurement emerged rapidly. The benefit of time synchronization has led to the installations of over 1,000 PMUs across North America as reported by the North American Synchrophasor Initiative as of March 2014 (Initiative, 2014). Mexico has been using PMU since the 1990s. Mexico is now directing its study towards implementing PMU offline in order to ascertain risks related to instability.

2.4.2 Europe

Europe has PMU installed in almost every country. The PMU installed there have characteristics like high time resolution ranging from 20 ms to 100 ms, 0.2 accuracy classes of voltage, and current and precise time synchronization.

2.4.3 Asia

In China, the entire 500 kV substations, number of important power plants, and 220/110 kV substations are provided with PMU. Till 2013 approximately 2,400 PMU sets had been deployed in their power grids (Lu, et al., 2015). After 2012 India’s blackout, Power Grid Corporation of India Ltd. had deployed 1950 PMUs in 351 substations till 2016. The 29 regional control centers, 5 state control centers, and 2 national control centers are capable to handle up to 3000 PMUs. (Harding & LLoyd, 2016). (Harding & LLoyd, 2016) has identified that the PMU technology has become a necessary component of a wide-area monitoring system for effective increment in transmission capacity of the congested corridors.

2.5 PMU Installation Cost

(Department of Energy, 2014) has studied the cost for infrastructure, procurement, installation and commission of PMU on synchrophasor projects. The hardware cost of PMU device weights for only 5% of total installation cost of project. The major cost driver includes cost for communication, security, labour and equipment. The cost of installation of communication network and PDC is more than the cost of

PMU. The cost of equipment is related to replacement of existing digital relay or digital fault recorder with PMU compatible equipment. Features of PMUs like power backup, type of display and number of CT/PT channel are the major factor that determines the cost of PMU (Department of Energy, 2014).

2.6 Power System Observability and PMU Placement Rules

A power system is said to be fully observable only if the measurements taken in the system are enough in number and location**,** to allow the grid operators to evaluate the state vector of the whole system. If the measurements made on power system network determine the bus voltage and angle at every bus, then those systems can be considered as observable (Krumpholz, et al., 1980). Full power system observability is an essential requirement for state estimation. Only when a power system is guaranteed to be observable, state estimation of the system is accurate and comprehensive (Krumpholz, et al., 1980). The two major algorithms for power system observability analysis are topology based algorithms and numerical methods (Ivatloo, 2009).

2.6.1 Numerical Observability Analysis

Numerical observability analysis is defined as the ability of the system model to be solved for a state estimate. In space estimation, the measurement model can be described as Equation 2.1.

$$\bar{z} = h(\bar{x}) + \bar{e} \qquad \text{Equation 2.1}$$

where $\bar{z}$ is the measurement vector, x is the system state vector that contains all bus voltage phasor, $\bar{e}$ is the noise or measurement error, and h(x) is a vector function corresponding to measurement vector and state vector. Equation 2.1 may be non-linear for conventional state estimation problems but while solving problems receiving from PMU data, it is a linear equation (Baldwin, et al., 1993).

Considering the accuracy of the data provided by PMUs, $\bar{e}$ is very small and thus is neglected in general. If PMU is used as measurements in power system, then the state estimator for this system is linear, which can be described as Equation 2.2.

$$\bar{z} = H\,x \qquad \text{Equation 2.2}$$

where H is the measurement function matrix and also a coefficient matrix related to the system state vector x.

For a power system with n buses and m PMUs, x is a vector with 2n - 1 dimension and H is a matrix with m*(2n-1) dimensions. If the system is fully observable, z provided by the Equation 2.2 should have (2n-1) valid elements. This means that a power system with n buses is observable if Rank (H) = 2n -1

(Baldwin, et al., 1993) thus defined numerical observability analysis as the ability of the system model to be solved for a state estimate. The system is numerically observable, if the matrix H has full rank and well-conditioned. During numerical observability analysis either fully coupled or decoupled measurement models are used. These analysis methods are based on numerical factorization of the measurement information gain or Jacobean matrix. If any of these matrices is full rank, the system is said to be observable (Abdelaziz, et al., 2013).

2.6.2 Topological Observability Analysis

Topological observability algorithms can be classified into conventional observability algorithms and PMU based observability algorithms. Conventional observability algorithms use real and reactive power injections and bus voltage and branch currents magnitudes for system observability. PMU based observability algorithm uses Kirchhoff's law and Ohm's law for virtual measurement (Chunhua & Xuesong, 2008).

At first, in order to identify the observability of power system, the voltages (magnitude as well as phasor) for all buses must be known. With the help of PMU, the voltage and branch current of a bus can be measured directly if it is installed at the bus or can be indirectly measured using other's bus voltage and branch current. For indirect measurements, using the Kirchhoff's law and Ohm's law, buses that are neighbors to the PMU installed bus can have their voltages and branch currents known through calculation. Therefore, every bus can be made observable if the PMUs are strategically placed in a power system. The following statement describes the network observability rules of a power system (Rahman & Ahmed, 2016):

Rule A: A PMU installed bus will have a direct measurement of its voltage phasor and all branch current phasor adjacent to it. Figure 2.4 demonstrates rule

A. Hence according to rule A, when PMU is installed on bus 1 then V_1, $I_{13,}$ $I_{14,}$ and I_{12} are directly measurable.

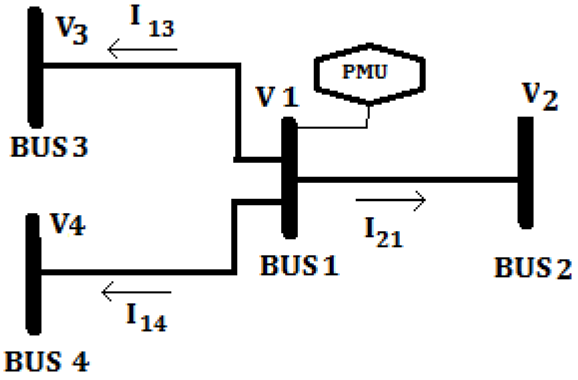

Figure 2.4: Demonstration of observability for rule A

Rule B: Using Ohm's law, if the voltage at one bus and its branch current are known, the voltage at the other bus can be calculated. Hence in Figure 2.4, if PMU is placed at bus 1, voltage V_1 and branch current $I_{13,}$ I_{14} and I_{12} are directly measurable then the voltage at bus 2, bus 3, and bus 4 can be calculated using Kirchhoff's law and Ohm's law.

Rule C: In the situation where the voltages at both ends are known, the branch currents between the two buses can be calculated according to Ohm's law. Figure 2.5 demonstrates rule C. If V_1 and V_2 are measurable then, I_{21} can be known.

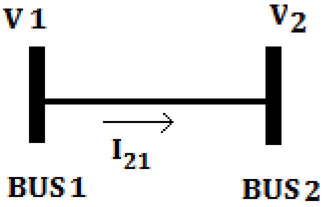

Figure 2.5: Demonstration of observability for rule C

Rule D: When the data of all branch current of a bus are known except one, then the current data of unknown branch can be virtually measured using Kirchhoff's law. In Figure 2.4 if branch current data I_{13} and I_{14} are known, I_{21} can be calculated using Kirchhoff's current law and if V_1 is known, from rule B, V_2 can also be calculated.

ZIB is the bus with neither load nor generator for current injection. Consideration of ZIB will increase the complexity but can significantly reduce the number of PMU installed on the large system. Thus, in order to minimize the number of PMUs, it is very essential to consider the ZIB (Rahman & Ahmed, 2016). Hence the following statement can be concluded.

i. If a PMU is placed at a bus, this bus and all of its neighbor buses can be observed. In Figure 2.4, if PMU is placed in bus1 then bus 2, bus 3, and bus 4 are observable.

ii. For an observable ZIB, if all of its connected nodes are observable except one, then that unobserved node can be observed.

iii. If all the nodes connected to a ZIB are observable, then that ZIB can be observed too.

2.7 Optimization Problem Formulation for PMU Placement

It is uneconomical to install PMUs at each bus so strategic placement of PMU is essential. It is thus necessary to find the most promising location of PMU to attain complete observability. Researchers have formulated various optimization problems depending upon their optimization algorithm. The major concern of the optimum location of PMU optimization function is to minimize the number of PMU installed or to minimize the cost of installation of PMU.

(Dua, et al., 2008) has categorized the optimal PMU placement problem in two categories namely: without PMU loss and with PMU loss. Each category is further divided into subcategories. The sub-category includes the consideration ZIB and without considering ZIB. If a much reliable system is required, placement should be made with consideration of a single PMU loss. Considering a single PMU loss, the placement of PMU should be made so that each bus must be observable from two different sets of PMU.

(Miljanić, et al., 2012) has considered the availability of number of measuring channels on PMU, and possible system contingencies like single measurement or branch outage using GA. In practice, there are various PMU manufacturers with a different number of channels available in the market that may be employed on power system networks. Therefore, channel availability should be considered when designing the optimal PMU metering configuration (Rahman & Zobaa, 2017).

In case of the existence of ZIB, the bus merging topology method is another popular method. The bus merging method involves a merging process between ZIB and one of its neighbors. Hence, in the merging process, the constraints for the two buses will be merged into a single constraint, thereby, reducing the number of constraints that need to be satisfied to ensure every bus is observable by the PMUs placement set. (Rahman & Ahmed, 2016) has proposed three rules for the merging of ZIB with its neighbor. The rules are mentioned below.

Rule A: Merge ZIB with its adjacent bus that is radial bus.

Rule B: If the number of bus connected to adjacent bus of ZIB is most and if one of its neighbor buses is connected to the same ZIB, this adjacent bus will be selected to merge with the ZIB.

Rule C: Merge ZIB with its neighbour bus which is connected to the most number of buses.

(Rahman, et al., 2016) has also incorporated power flow measurement to find optimal PMU location. While considering power flow measurements, if one of the voltage buses is observable, the value of the voltage at the other end can also be computed. When considering the existence of ZIB and power flow measurements, it is first necessary to solve the power flow measurement followed by ZIB. If it is not done, it might lead us to an unfeasible solution. Hence consideration of power flow measurement merges the constraints related to the measured branch into a single constraint (Rahman & Ahmed, 2016).

Although merging technique helps to reduce the candidate buses, it might increase complexity while dealing with a larger system. Also if PMU is required to be placed at a merged bus, then it will require an additional observability test to verify which of the two buses must be installed with the PMU.

(Bei, 2008) have used binary integer linear programming for optimal placement of PMU. For n bus system, without conventional measurement, (Bei, 2008) has formulated objective function so as:

$$\text{Minimize } \sum_{K=1}^{n} x_k$$

$$\text{Subjected to } T_{PMU}X \geq b_{PMU}$$

Equation 2.3

where $b_{PMU} = [1\ 1\ldots 1]^{T}_{n*1}$ and $X = [x_1\ x_2\ x_3\ \ldots x_n]^{T}$, x_i is the PMU placement variable. T_{PMU} is defined as matrix **A** in (Kumar & Sydulu, 2014).

2.8 Optimization Algorithm for PMU Placement

Strategies for solving optimal PMU placement problems have become a topic of research interest. Among the variety of algorithms, many authors have selected their best performing algorithms. (Marzieh & Mohd, 2019) has discussed optimization solving techniques under mathematical programming methods and Heuristic algorithms. This paper has included Integer linear programming, Binary semi-definite programming, Integer quadratic programming, and exhaustive search under mathematical programming methods. Under heuristics algorithm, this paper has reviewed GA, tabu search, pollination algorithm, SA, differential evolution, particle swamp optimization (PSO), immune genetic algorithm (IGA), spanning tree search, greedy algorithm, recursive security N (RSN) algorithm, teaching-learning based optimization techniques, improved binary PSO, best-fit search algorithm, mixed heuristic method and modified binary cuckoo optimization algorithms. (Marzieh & Mohd, 2019) has concluded that the combination of two or three algorithms can increase the efficiency of the optimization techniques.

(W. Yuill, 2011) has reviewed optimization techniques and categorized it into two groups namely meta-heuristic method and conventional deterministic method. Meta-heuristic methods are related to intelligent search processes. These processes can deal with discrete variables and non-continuous cost functions. Similarly, deterministic techniques use integer programming and numerical based methods extensively. Integer programming requires all unknown variables to take on integer values (W. Yuill, 2011). Under the meta-heuristic method, it has reviewed GA, PSO, and tree search topology. Under conventional deterministic technique, integer programming and binary search have been reviewed.

The integer programming formulation to unravel the OPP problem was first introduced by (Xu & Abur, 2004), where linear constraints are shaped based on network connectivity matrix which makes the evaluation of network observability much easier.

(Abbasy & Ismail, 2009) introduced a merging method known as the augmented bus merging which was formulated as a binary ILP. The ILP approach can only produce a single solution set, even when there are multiple solutions available. Often, the solution generated by the ILP method might not be the optimal solution.

GA is an optimization based approach that imitates the process of natural evolution. A non-dominated sorting genetic algorithm was proposed in (Milosevic & Begovic, 2003) to solve OPP based on two competing objectives, which are minimization of PMUs and maximization of measurement redundancy. The non-dominating sorting genetic algorithm first utilized graph theory procedure and then simple GA to estimate individual optimal solutions. Then, the non-dominated sorting GA was utilized to discover the non-dominated solution that generally signifies the best trade-off between competing objectives. (Aminifar, et al., 2009) proposed an immunity genetic algorithm (IGA) to determine the least number of PMUs required to ensure the power system observability. The IGA approach was developed to overcome the visual impairment of the crossover and mutation operators. The outcome of the proposed method indicates that it converged quicker compared to the classic GA approach.

Differential evolution (DE) is an optimization strategy that depends on the initial population generation, selection, cross-over, and mutation, similar to that of GA. DE algorithm adopted in (Al-Mohammed, et al., n.d.) tried to solve OPP considering zero-injection bus and measurement redundancy. In addition to that, the set of buses in a power system where a PMU must be installed and restricted from being installed are also considered. (Rahman, et al., 2015) has proposed improved Binary Particle Swarm Optimization (BPSO) technique. This method is applied to the IEEE test bus system for the case of consideration of zero-injection bus. The effectiveness of the method is verified by the simulation results using MATLAB software. The convergence of improved PSO method is faster and in comparison to the existing BPSO method, this method also manages to maximize the measurement redundancy.

Simulated Annealing algorithm is a stochastic method where the algorithm keeps on searching any adjacent solution better than the current solution. If the algorithm finds any better solution, it accepts the new found solution. (Kerdchuen & Weerakorn, 2008) proposes stochastic simulated annealing for solving optimal PMU placement in the power system for state estimation. (Al-Odienat, et al., 2020) has compared Depth-first search, graphical theoretic procedure using merging method, graphical theoretic procedure using nonlinear constraints method, SA and recursive security N method. This paper concluded that the simulation time for recursive security N algorithm and SA is higher but gives an optimal solution set. The name of the algorithm Simulated Algorithm comes from annealing in metallurgy. Annealing is a technique which involves heating and controlled cooling of a material. It increases the size of its crystals and hence reduces their defects. For very hard computational optimization problems where exact algorithms fail, SA can be used. Even though it usually results an approximate solution to the global minimum, it could be enough for solving many practical problems.

A simulated annealing search can be considered as a king of stochastic or local search. SA algorithm can be defined as a probabilistic meta-heuristic algorithm. (Al-Odienat, et al., 2020). SA algorithm is a stochastic method where the algorithm keeps on searching any adjacent solution better than the current solution. If the algorithm finds any better solution, it accepts the new found solution. It can be realized from the Hill-Climbing approach of searching. The problem of hill-climbing search is that it will be stuck at the local optimal solution and thus may miss the global optimal solution. As shown in Figure 2.6, the hill-climbing search starts searching at Point A and will stop at Point B. Since all of B's adjacent points have lower values than B has, the hill-climbing approach might get stuck on optimal solution as point B. However, Point B is just the local optimal point but not the global optimal point, which should be Point C.

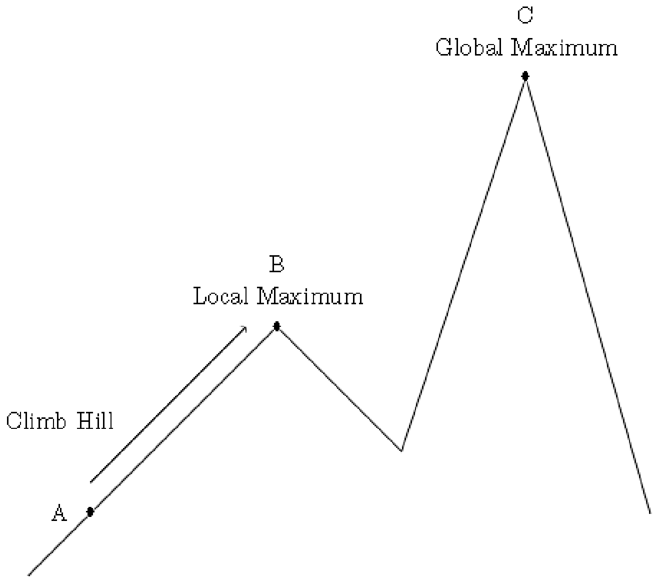

Figure 2.6: Hill climbing approach of searching optimal value

SA search simulates the motivation of atoms during the process of annealing in metallurgy. During searching, SA search will accept a worse solution in probability if there is no better solution found. SA search is expected to be able to find the global optimal solution in some probability through leaping out from the corral caused by the local optimal solution. Major strengths of SA are:

i. SA can solve non-linear problems and can handle many constraints.
ii. SA can reach the global optimum in presence of large numbers of local optimum.
iii. SA is a versatile method since it doesn't depend upon any restrictive properties of the system.

The pseudo-code for SA is mentioned below.

1. Initialization of a random initial point X_k initial temperature to T_{init} and iteration number k=0.
2. Calculation of energy function at initial assumed point X_k which is $E_1=F(X_k)$.
3. Generation of random neighborhood point X_{K+1} and calculation of the energy function as $E_2=f(X_{k+2})$ and determine $\triangle E=E_2-E_1$.
4. If $\triangle E<0$, X_k point is acceptable and go to step 6. Otherwise, generate a random value “R” between (0 1) and calculate $P = \text{Exp}^{\frac{-\Delta E}{T}}$
5. If P>R, the current point is acceptable and go to step 6 otherwise return to step 3.
6. k<N (N is the maximum number of tried within one iteration), then increase k as k=k+1 and go to step 3. Otherwise, go to step 7.
7. If T<sT (where sT is the stop temperature), algorithm stops otherwise set k=1, reduce the temperature T= (cooling rate*T) then go to step 3.

The initial temperature parameter is to be selected such that there will be ample opportunity to escape the problem from local optima. The temperature progressively decreases from an initial positive value to zero. At each time step, the algorithm randomly selects a PMU placement set close to the current placement set and measures the number of unobservable bus on placement set, and moves to it according to the temperature dependent probabilities of selecting better or worse PMU placement set.

2.9 Measurement Redundancy

For meta-heuristic algorithms, the optimal solution set might be multiple. For complete observability, a number of PMU placement sets might contain the same number of the minimum PMUs. In order to evaluate the effectiveness of each PMU placements set, the concept of measurement redundancy in terms of Bus Observability Index (BOI) and System Observability Redundancy Index (SORI) is introduced in (Dua, et al., 2008).

BOI for a bus can be defined as the number of times that bus is observed by the PMUs placement set while SORI of a system can be referred as the summation of the value of BOI for all buses of the system. The PMUs placement set with the highest number of SORI indicates that the PMUs placement set is a more effective solution and is more reliable for possible contingencies compared to other PMUs placement set with a lower value of SORI (Theodorakatos, et al., 2014). For n bus system, BOI is defined as Equation 2.4 (Dua, et al., 2008).

$$\mathrm{BOI_i} = \mathrm{A} * \mathrm{X_i} \qquad \text{Equation 2.4}$$

where A is known as binary connectivity matrix. Often the same matrixes are known as an adjacency matrix. A binary connectivity matrix indicates interconnection between different buses in a power system. The connectivity matrix can be defined as Equation 2.5.

$$\mathrm{A_{ij}} = \begin{cases} 1 \ \text{ if i = j} \\ 1 \text{ if bus i and j are connected} \\ 0 \ \text{ Otherwise} \end{cases} \qquad \text{Equation 2.5}$$

And x_i is PMU placement variable which is defined as, $\mathrm{X} = [\mathrm{x_1}\ \mathrm{x_2}\ \mathrm{x_3} \dots \mathrm{x_n}]^{\mathrm{T}}$,$\mathrm{x_i} \epsilon \{0,1\}$

$$\text{where, } \mathrm{x_i} = \begin{cases} 1, \ \text{if PMU is place at bus i} \\ 0, \ \ \text{Otherwise} \end{cases} \qquad \text{Equation 2.6}$$

Similarly, SORI is defined as Equation 2.7 (Dua, et al., 2008).

$$\text{SORI=} \ \sum_{i=1}^{n} BOI_i \qquad \text{Equation 2.7}$$

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Methodology Approach

The general methodology approach implemented in this thesis is shown in Figure 3.1. For IEEE test system, the simulation result of proposed modified SA has been compared with modified SA and other algorithms. Then the proposed method has been implemented on INPS.

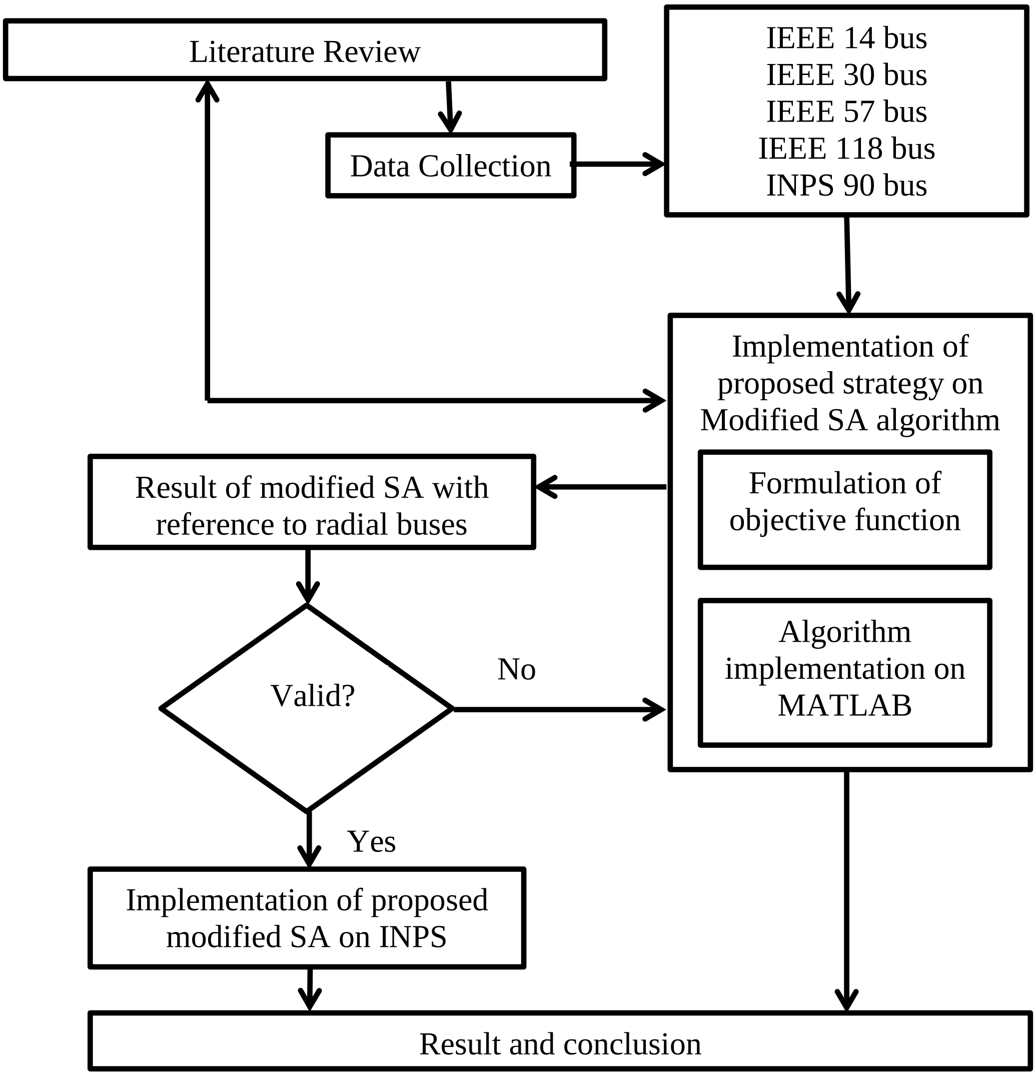

Figure 3.1: Block diagram showing the methodology framework

3.2 Data Collection

In order to validate the proposed strategy on the modified SA algorithm, IEEE test bus system with different number of bus has been used. In this thesis modified SA algorithm has been implemented on IEEE 14, IEEE 30, IEEE 57, and IEEE 118 bus system for OPP. The single line diagram for IEEE 14 bus system is shown in Appendix B. Similarly single line diagram of IEEE 30, IEEE57, and IEEE 118 bus system is shown in Appendix C, D, and E respectively. The information extracted from the single line diagram is used to construct the binary connectivity matrix. The major finding from the single line diagram is tabulated in Table 3.1.

(Subedi & Jha, 2020) has considered the voltage level of 66 kV and above while solving OPP for INPS using RSN. (Okendo, et al., 2021) has considered buses with 132kV and above for 30 buses Nairobian system. Secondary data of existing INPS 66kV and above substation have been collected from the annual report of NEA (Authority, 2020) and transmission directorate report (Authority, 2020), and LDC. The information of the existing 90 bus system is also tabulated in Table 3.1. The single line diagram of INPS is shown in Appendix E.

Table 3.1: Data of different bus system

Bus System	Number of Branches	Radial Buses	Zero Injection Buses
IEEE 14 bus	20	8	7
IEEE 30 bus	41	11, 13, 26	6, 9, 22, 25, 27, 28
IEEE 57 bus	80	33	4, 7, 11, 21, 22, 24, 26, 34, 36, 37, 39, 40, 45, 46, 48
IEEE 118 bus	179	10, 73, 87, 111, 112, 116, 117	5, 9, 30, 37, 38, 63, 64, 68, 71, 81
INPS 90 bus	104	1, 5, 12, 15, 20, 25, 35, 41, 44, 53, 63, 68, 69, 73, 79, 80, 82, 88, 90	8, 14, 15, 39, 40, 50, 55, 60, 65

3.3 Formulation of Objective Function

The OPP will have the minimization objective function to minimize the total cost of PMUs required to ensure power system observability. Since the total cost of PMU installation on each substation is nearly constant, the objective function of the OPP can be written so as to minimize the number of PMU installed ensuring power system observability.

$$\text{Minimize } \sum_{i=1}^{n} W_i x_i \qquad \text{Equation 3.1}$$

where, W_i is the total cost to install PMU in bus i.

$$\text{And, } x_i = \begin{cases} 1, & \text{if PMU is place at bus i} \\ 0, & \text{Otherwise} \end{cases} \qquad \text{Equation 3.2}$$

Here in this thesis, W_i is assumed to be equal for all buses. Hence objective function can be written as,

$$\text{Minimize } \sum_{i=1}^{n} x_i \qquad \text{Equation 3.3}$$

$$\text{Subjected to: } N_{nb}=0, \qquad \text{Equation 3.4}$$

where, N_{nb} is the number of unobservable buses. Observability of all the buses can be ensured if

$$F(\overline{X}) \geq \overline{I} \qquad \text{Equation 3.5}$$

Here $\overline{X}$ is a vector composed of x_i, x_i is PMU placement variable which is defined as,

$$\overline{X} = [x_1\ x_2\ x_3 \ldots x_n],\ x_i \in \{0,1\} \qquad \text{Equation 3.6}$$

and $F(\overline{X})$ is a vector function that represents the observability constraint functions to make n bus system fully observable.

Apart from the normal operation of the bus system, in order to increase the reliability on the observability of the bus system, a single PMU outage case is considered in the thesis. In single PMU outage consideration, each bus in the power system is ensured to be observable by a minimum two PMUs. In case of failure of any one PMU in any bus, another PMU will ensure its observability thereby increasing the reliability of the system. Also, consideration of zero injection bus reduces the total number of PMU required to ensure observability. In this thesis three separate cases are considered namely:

Case I: Normal Operation

Case II: Consideration of single PMU outage

Case III: Consideration of ZIB

3.3.1 Case I: Normal Operation

During normal operation of power system without consideration of ZIB and single power system outage, the objective function can be written to minimize the number of buses as,

$$\text{Minimize } \sum_{i=1}^{n} x_i \qquad \text{Equation 3.7}$$
$$\text{Subjected to: } F(\overline{X}) \geq \overline{I}$$

Here $\overline{X}$ is a vector composed of x_i, x_i is a PMU placement variable.$F(\overline{X})$ is a vector function that represents the observability constraint functions and $\overline{I}$ is a vector with n entries and whose all elements are 1. Constraint function vector $F(\overline{X})$ can be expressed as,

$$F(\overline{X}) = A\overline{X} \qquad \text{Equation 3.8}$$

where, A is a binary connectivity matrix. A binary connectivity matrix indicates interconnection between different buses in a power system. The connectivity matrix can be defined as Equation 3.9.

$$A_{ij} = \begin{cases} 1 \ \text{if } i = j \\ 1 \text{ if bus i and j are connected} \\ 0 \ \text{Otherwise} \end{cases} \qquad \text{Equation 3.9}$$

According to the rules of observability for the bus i in any n-bus system, the corresponding constraint function f_i can be represented as Equation 3.10.

$$f_i(\overline{X}) = \sum_{j=1}^{n} (A_{ij} x_j) \qquad \text{Equation 3.10}$$

If any $A_{ij} = 1$ and $x_j = 1$ ($j = 1,2,\ldots,n$), then $f_i(\overline{X}) \neq 0$, hence the Bus i is observable. Hence it can be concluded that if all the buses are observable then any elements of $F(\overline{X}) \neq 0$.

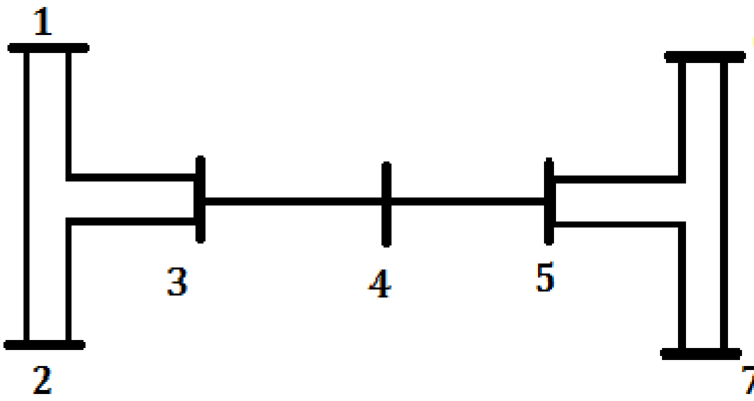

Figure 3.2: Seven bus system to demonstrate the constraint function

Figure 3.2 shows the configuration of a seven bus system to demonstrate the constraint function. The binary connectivity matrix for seven bus system can be represented as Equation 3.11.

$$A = \begin{matrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{matrix} \qquad \text{Equation 3.11}$$

The constraint function $\mathrm{f_i}(\overline{\mathrm{X}})$ for seven bus system can be expressed as Equation 3.12.

$$\begin{aligned} \mathrm{f}_1 &= x_1 + x_2 + x_3 \\ \mathrm{f}_2 &= x_2 + x_1 + x_3 \\ \mathrm{f}_3 &= x_3 + x_1 + x_2 + x_4 \\ \mathrm{f}_4 &= x_4 + x_3 + x_5 \\ \mathrm{f}_5 &= x_5 + x_4 + x_6 + x_7 \\ \mathrm{f}_6 &= x_6 + x_5 + x_7 \\ \mathrm{f}_7 &= x_7 + x_5 + x_6 \end{aligned} \qquad \text{Equation 3.12}$$

3.3.2 Case II: Consideration of Single PMU Outage

In this case, each bus must be observable by minimum of two numbers of PMUs. Some of the buses might be observable by more than two PMUs. The objective function for this case is also to minimize the number of PMU required to ensure power system observability which is similar to case I. For any n bus system, an objective function is formulated as Equation 3.13.

$$\begin{gathered} \text{Minimize,} \sum_{\mathrm{i}=1}^{\mathrm{n}} x_i, \\ \text{Subjected to: } \mathrm{F}(\overline{\mathrm{X}}) \geq \bar{\mathrm{I}} \end{gathered} \qquad \text{Equation 3.13}$$

Here $\overline{\mathrm{X}}$ is a vector composed of $\mathrm{x_i}$, $\mathrm{x_i}$ is a PMU placement variable. $\mathrm{F}(\overline{\mathrm{X}})$ is a vector function that represents the observability constraint functions as mentioned in case I. In this case II $\bar{\mathrm{I}}$ is a vector with n entries and whose all elements are 2. It signifies that each bus must be observable by at least two PMUs. The constraint function $\mathrm{F}(\bar{\mathrm{X}})$ is similar for both of the cases.

3.3.3 Case III: Consideration of ZIB

The constraint function for case I is linear. According to the rules of observability mentioned in chapter two, an indirectly observable bus can be defined as the bus that is not connected to the PMU bus but their phasor can be found out using Kirchhoff's law at ZIB. Hence with the consideration of ZIBs, the constraint function $\mathrm{F}(\bar{\mathrm{X}})$ can be modified to a non-linear constraint function. The non-linear constraint function can be expressed as Equation 3.14.

$$\mathrm{f_i}(\bar{\mathrm{X}}) = \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{ij}x_j}\right) + \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{ij}Z_j}y_{ij}\right) \qquad \text{Equation 3.14}$$

where, $\mathrm{Z_j}$ is a binary parameter whose value is 1, if bus j is ZIB, otherwise 0. Binary variable $\mathrm{y_{ij}}$ is 1 if all of bus j and its adjacent buses but not including bus i are observable or 0 otherwise. The revised part comes into existence if bus i and j are connected ($\mathrm{A_{ij}}$) and bus j is ZIB. $\mathrm{y_{ij}}$ has to be determined by using a logical operator. If, for example, there is a ZIB m, to which k normal buses composed of bus 1 to k are connected, the constraint function for bus m can be expressed as Equation 3.15.

$$\mathrm{f_1} = \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{1j}x_j}\right) + (f_2 \wedge f_3 \wedge \dots \wedge f_k \wedge f_m)$$

$$\mathrm{f_2} = \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{2j}x_j}\right) + (f_1 \wedge f_3 \wedge \dots \wedge f_k \wedge f_m)$$

$$.. \qquad \text{Equation 3.15}$$

$$\mathrm{f}_k = \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{mj}x_j}\right) + (f_1 \wedge f_2 \wedge \dots \wedge f_{k-1} \wedge f_m)$$

$$\mathrm{f}_m = \sum_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{A_{mj}x_j}\right) + (f_1 \wedge f_2 \wedge \dots \wedge f_k)$$

Here operator ∧ represents logical or. For seven bus system shown in Figure 3.3, if bus 4 is a ZIB, the nonlinear constraint function can be written as Equation 3.16.

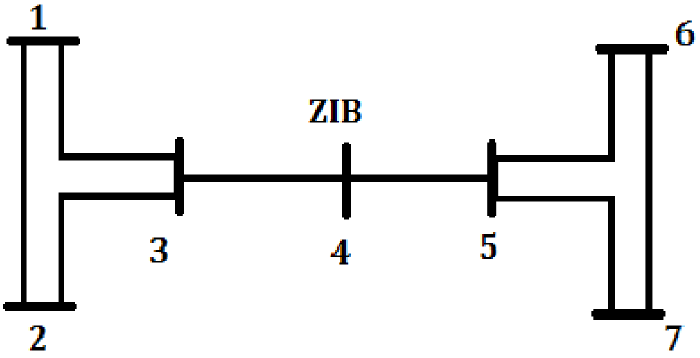

Figure 3.3: Seven bus system with ZIB to demonstrate constraint function

For any PMU placement set X, the value of f_i for all bus i should be greater than or equal to one. Some of the constraint functions are coupled with other functions so if we only calculate f_1 to f_n (where n is the total number of buses in a given system) once in a certain order, the final result may be inaccurate. Therefore, we need to repeatedly calculate f_1 to f_n and take into account their values in the last calculation, until the values of f_1 to f_n do not change after an iteration.

$$\begin{gathered}
f_1 = x_1 + x_2 + x_3 \\
f_2 = x_2 + x_1 + x_3 \\
f_3 = x_3 + x_1 + x_2 + x_4 + (f_4 \wedge f_5) \\
f_4 = x_4 + x_3 + x_5 + (f_3 \wedge f_5) \\
f_5 = x_5 + x_4 + x_6 + x_7 + (f_3 \wedge f_4) \\
f_6 = x_6 + x_5 + x_7 \\
f_7 = x_7 + x_5 + x_6
\end{gathered} \qquad \text{Equation 3.16}$$

3.3 Implementation of Algorithm

SA algorithm was originally proposed by (Baldwin, et al., 1993). (Xu & Wollenberg, 2015) proposed modified SA for OPP problem and found it to be efficient than the original SA proposed by (Baldwin, et al., 1993). Later (Al-Odienat, et al., 2020) implemented SA and modified SA algorithm for state estimation. The modified SA was originally dependent on the graph theory procedure. Generation of random neighbor solution in (Xu & Wollenberg, 2015) and (Al-Odienat, et al., 2020) incorporates only exchange and flipping of PMU without consideration of radial buses. This thesis intends to make the modified SA algorithm independent of any other algorithm thereby ensuring or restricting the PMU on radial buses for the normal case as a base case, single PMU outage case, and case with the consideration of ZIB. Initially, all buses were assumed to have PMU installed on them. The proposed strategy with modified SA algorithm has been implemented on MATLAB 2017a. The result of the proposed method is compared with modified SA mentioned in (Xu & Wollenberg, 2015) and (Al-Odienat, et al., 2020). In order to compare the simulation result of proposed strategy, the modified SA proposed by (Xu & Wollenberg, 2015) has been implemented during the thesis.

3.3.1 Pseudo-code of Simulated Annealing Algorithm

The energy function of the SA algorithm is defined to minimize the number of unobservable buses to zero. The pseudo-code of the modified SA algorithm is included Appendix F. The random placement set is determined by two strategies: (i) randomly moving a PMU to a bus without PMU and (ii) randomly adding or removing PMU from that placement set. Firstly, a random PMU from any bus is shifted to a bus without PMU in that placement set. The second strategy randomly adds or removes one PMU in that placement set. This concept of random adding and removing the PMU can be described as a random mutation. (Rahman & Zobaa, 2017) has implemented the mutation strategy in BPSO as well. This method also helps the algorithm to quickly approach the optimal solution.

During placement of PMU, randomization might place PMU on the radial bus. The placement of PMU on radial bus limits the number of observable buses to two (radial bus itself and the only bus connected to that radial bus). So, in case I and case III, PMU placement is restricted on radial buses. Similarly in case II, in order to ensure each bus to be observable by two PMU, PMU placement in the radial bus is ensured after randomization. The algorithm for Randomize(placement_best) with reference to radial bus is mentioned below.

i. Find the position of bus with and without PMU in placement_best.

ii. If either flipping of PMU placement is possible or random number > 0.5, flip a random position by adding or removing PMU in that position considering radial bus position.

iii. Else randomly exchange one position of PMU with non-PMU position considering radial buses.

The flowchart for Randomize(placement_best) with reference to radial buses is shown in Figure 3.4. The pseudo code for Randomize(placement_best) with reference to radial buses function is shown in Appendix F.

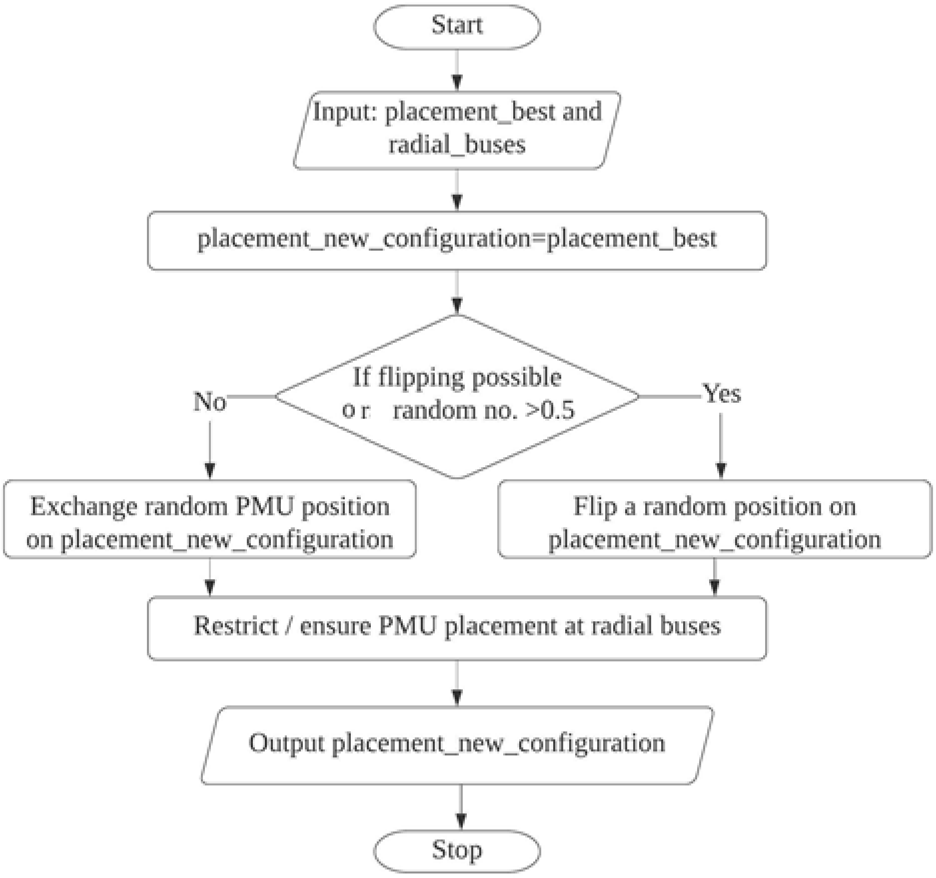

Figure 3.4: Flow chart for random generation of neighbour placement set

3.3.2 Selection of Parameter

In order to apply SA on any specific problem, one must design the algorithm by determining methods to represent solutions, generate neighborhood solutions and to reduce temperature, etc. For any optimization problem solving with SA algorithm, its performance is highly dependent on the value of the parameter selected. (Moon-Won & Yeong-Dae, 1998)

i. Energy Function: The annealing energy is defined as the total number of unobservable buses and the main objective for OPP is to minimize the total number of unobservable bus ensuring full system observability.

ii. Candidate neighbour: The candidate probable neighbour is randomly generated by defining a function ‘Randomize’ in MATLAB. The effect of PMU placement in the radial buses has been considered to ensure or restrict PMU in radial buses.

iii. Acceptance Probability: The decision for whether to accept the new PMU placement set or not, is based on the incremental change of the objective function Delta_E, and the value of controlling Temperature. The randomly generated new placement is accepted if it reduces the value of an objective function. If not the probability $p=e^{\frac{-\Delta E}{T}}$ will be evaluated. The new placement will be accepted if a random number between 0 and 1 < p, else algorithm will find another new placement randomly.

iv. Initial temperature: The value of initial temperature is assumed to be 15. Actually, it is based on the expected value of the magnitude of Delta_E. Simulation result of different test bus system shows the approximate value of Delta_E to be five. That means the average connectivity of a bus is five so the change in position of a PMU, changes the overall observability by five. (Baldwin, et al., 1993). The value of initial temperature is thus increased to three times the value of Delta_E so that there will be ample opportunity to escape the problem from local optima.

v. Search space: (Baldwin, et al., 1993) had purposed the concept of v_{test}, upper and lower boundary to limit the searching of optimal placement with the help of temperature control. (Al-Odienat, et al., 2020) introduced the modified SA where random neighborhood point is generated by randomly flipping the position of PMU and by adding or removing the PMUs at a random bus. The random addition and removal of PMUs help the algorithm for a quick approach towards an optimal solution. This action increases the search space when it approaches the optimal solution thereby increasing the probability to find the global optimal solution. (Al-Odienat, et al., 2020).

3.3.3 MATLAB

The proposed modified SA algorithm is implemented on MATLAB 2017a. A general framework of the MATLAB program is shown in Figure 3.5. Some of the major functions defined are described below.

i. The main program: 'mainv1SAlg.m' is an entrance file that asks the user to select the bus system. This program also asks the case that the user wants to simulate. It will load the data of the required bus system and run the simulation for the selected case. The optimal solution set, simulation time, BOI, and SORI are displayed as output. The MATLAB code for the main program is included on Appendix G.

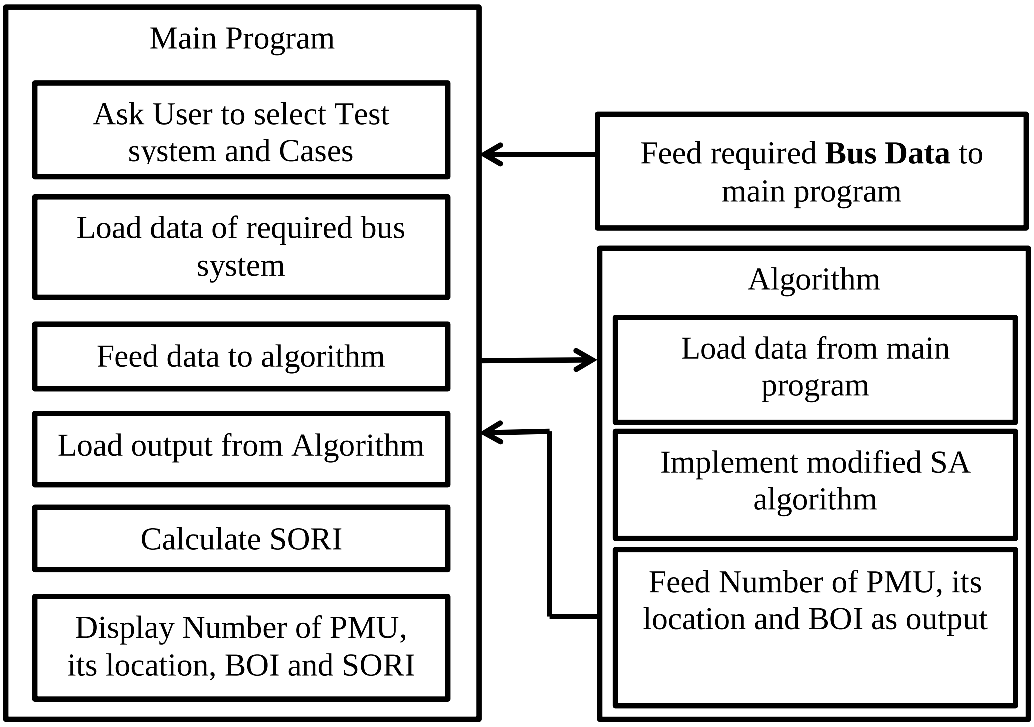

Figure 3.5: General framework of MATLAB algorithm

ii. Bus Data: The information of all bus system like connectivity matrix, information of ZIB, and radial buses is stored in .m file. Namely 'case14v1.m', 'case30v1.m', 'case57v1.m', 'case118v1.m' and 'caseinpsv1.m'.

iii. Algorithm: Modified simulated algorithm with reference to radial bus is implemented on .m file for all three cases. This algorithm will generate the constraint function and implement SA algorithm. The bus data and the required case are loaded to the respective algorithm, which in turn return the optimal placement set, simulation time, BOI, and SORI. Appendix H includes the MATLAB code for case III.

CHAPTER FOUR: RESULT AND DISCUSSION

The objective of the thesis is to obtain the minimum number of PMUs required to maintain complete power system observability. Since SA is a meta-heuristic algorithm, for the same minimum number of PMUs, multiple PMU placement sets are generated as output. In order to distinguish the quality of different PMUs placement set with the same number of PMUs, a placement set with maximum SORI is selected as an optimal solution. The proposed modified SA method has been simulated 10 times for three separate cases on four test bus system. All the simulation was carried out in MATLAB R2017a. The technical specification of the computer used to run the algorithm is Intel i7 2.13GHz with 8 GB of RAM.

4.1 Test System I: IEEE 14 Bus System

The data collected from IEEE 14 bus system is used to construct the binary connectivity matrix. The tabular form of binary connectivity matrix in vector form is tabulated in Table 4.1.

Table 4.1: Connectivity matrix for IEEE 14 bus system in vector form

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
1	[2 5]	8	[7]
2	[1 3 4 5]	9	[4 7 10 14]
3	[2 4]	10	[9 11]
4	[2 3 5 7 9]	11	[6 10]
5	[1 2 4 6]	12	[6 13]
6	[5 11 12 13]	13	[6 12 14]
7	[4 8 9]	14	[9 13]

4.1.1 Case I: Normal Operation

In case I, the OPP problem is solved without consideration of a single PMU outage and ZIB. The number of PMU required for IEEE 14 bus system to ensure power system observability is tabulated in Table 4.2 along with their location and SORI.

Table 4.2: Case I PMU placement set for IEEE 14 bus system

S.N	Number of PMU	Placement Set	SORI
1	5	1 3 7 11 13	17
2	4	2 6 7 9	19
3	5	1 4 7 11 13	20

S.N	Number of PMU	Placement Set	SORI
4	5	3 5 6 7 9	22
5	4	2 6 7 9	19
6	5	2 5 6 7 9	24
7	4	2 6 7 9	19
8	6	1 3 6 7 9 10	23
9	4	2 7 10 13	16
10	4	2 6 7 9	19

From Table 4.2, the minimum number of PMUs required is 4. The solution set of serial numbers 2, 5, 7, and 10 shows that the placement of PMUs in bus 2, bus 6, bus 7, and bus 9 has measurement redundancy SORI of 19. Also, the solution set of serial number 9 shows that the placement of PMU in buses 2, 7, 10, and 13 has a SORI value of 16. The solution set with minimum number of PMUs and maximum SORI is thus selected as an optimal solution. Hence PMU placement set on buses 2, 6, 7, and 9 are selected as an optimal solution. The value of BOI for optimal solution set [2, 6, 7, 9] is tabulated in Table 4.3.

Table 4.3: Case I value of BOI for IEEE 14 bus system

Bus Number	BOI	Bus Number	BOI
1	1	8	1
2	1	9	2
3	1	10	1
4	3	11	1
5	2	12	1
6	1	13	1
7	2	14	1

4.1.2 Case II: Consideration of Single PMU Outage

In case II, the OPP problem is solved with consideration of a single PMU outage. The simulation result in terms of the number of PMU required for IEEE 14 bus system to ensure power system observability is tabulated in Table 4.4 along with their location and SORI.

Table 4.4: Case II PMU placement set for IEEE 14 bus system

S.N	Number of PMU	Placement Set	SORI
1	9	2 3 5 6 7 8 9 11 13	36
2	9	2 4 5 6 7 8 9 10 13	39

S.N	Number of PMU	Placement Set	SORI
3	9	2 4 5 6 7 8 9 10 13	39
4	9	1 2 4 6 7 8 9 11 13	37
5	9	1 2 3 6 7 8 9 11 13	34
6	9	2 4 5 6 7 8 9 10 13	39
7	9	1 2 4 6 7 8 9 11 13	37
8	10	2 4 5 7 8 9 10 11 12 13	40
9	9	2 4 5 6 7 8 9 10 13	39
10	9	2 3 5 6 7 8 9 10 13	36

Table 4.4 shows that the minimum number of PMUs required is 9 so that the IEEE 14 bus system is fully observable. The solution set of serial numbers 2, 3, 6, and 9 shows that the placement of PMUs in buses 2, 4, 5, 6, 7, 8, 9, 10, and 13 has measurement redundancy SORI of 39. Also, the solution set of serial numbers 1, 4, 5, 7, and 10 shows the same minimum number of PMU with SORI values of 34, 36, and 37. The solution set with a minimum number of PMUs with maximum SORI is thus selected as an optimal solution. Hence PMU placement set on bus 2, 4, 5, 6, 7, 8, 9, 10, and 13 is selected as an optimal solution. The value of BOI for optimal solution set [2 4 5 6 7 8 9 10 13] is tabulated in Table 4.5.

Table 4.5: Case II value of BOI for IEEE 14 bus system

Bus Number	BOI	Bus Number	BOI
1	2	8	2
2	3	9	4
3	2	10	2
4	5	11	2
5	4	12	2
6	3	13	2
7	4	14	2

4.1.3 Case III: Consideration of ZIB

In case III, the OPP problem is solved with consideration of ZIB. Consideration of ZIB has reduced the number of PMU required to ensure power system observability. The simulation results in terms of the number of PMU required for IEEE 14 bus system to ensure power system observability is tabulated in Table 4.6 along with their location and SORI.

Table 4.6: Case III PMU placement set for IEEE 14 bus system

S.N	Number of PMU	Placement Set	SORI
1	3	2 6 9	16
2	4	2 4 6 9	22
3	3	2 6 9	16
4	4	2 9 11 13	18
5	3	2 6 9	16
6	3	2 6 9	16
7	3	2 6 9	16
8	5	3 5 9 10 12	20
9	3	2 6 9	16
10	4	2 9 10 12	17

Table 4.6 shows that the minimum number of PMUs required is 3 so that the system is fully observable. The solution set of serial numbers 1, 3, 5, 6, 7, and 9 shows that the placement of PMUs in buses 2, 6, and 9 has measurement redundancy SORI of 16. Hence PMU placement set on buses 2, 6, and 9 is selected as an optimal solution. The value of BOI for optimal solution set [2 6 9] is tabulated in Table 4.7.

Table 4.7: Case III value of BOI for IEEE 14 bus system

Bus Number	BOI	Bus Number	BOI
1	1	8	1
2	1	9	1
3	1	10	1
4	2	11	1
5	2	12	1
6	1	13	1
7	1	14	1

4.2 Test System II: IEEE 30 Bus System

The data collected from IEEE 30 bus system is used to construct the binary connectivity matrix. The tabular form of the binary connectivity matrix is tabulated in Table 4.8.

Table 4.8: Connectivity matrix for IEEE 30 bus system in vector form

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
1	[2 3]	16	[12 17]
2	[1 4 5 6]	17	[10 16]
3	[1 4]	18	[15 19]

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
4	[2 3 6]	19	[18 20]
5	[2 7]	20	[10 19]
6	[2 4 7 8 9 10 28]	21	[10 22]
7	[5 6]	22	[10 21 24]
8	[28]	23	[15 24]
9	[6 10 11]	24	[22 23 25]
10	[6 9 17 20 21 22]	25	[24 26 27]
11	[9]	26	[25]
12	[4 13 14 15 16]	27	[25 28 29 30]
13	[12]	28	[6 8 27]
14	[12 15]	29	[27 30]
15	[12 14 18 23]	30	[27 29]

4.2.1 Case I: Normal Operation

In case I, the OPP problem is solved without consideration of a single PMU outage and without consideration of ZIB. The number of PMU required for IEEE 30 bus system to ensure power system observability is tabulated in Table 4.9 along with their location and SORI.

Table 4.9: Case I PMU placement set for IEEE 30 bus system

S.N	Number of PMU	Placement Set	SORI
1	10	2 4 6 9 10 12 15 20 25 30	50
2	10	3 5 6 9 10 12 18 23 25 30	44
3	10	1 7 9 10 12 18 23 25 27 28	42
4	10	1 5 6 9 10 12 19 23 25 30	44
5	10	1 5 9 10 12 15 19 25 28 30	42
6	11	1 7 8 9 10 12 15 17 19 25 30	44
7	10	3 5 8 9 10 12 18 24 25 29	40
8	10	2 4 6 9 10 12 15 20 25 29	50
9	10	1 6 7 9 10 12 15 20 25 30	46
10	10	3 5 8 9 10 12 19 24 25 29	40

From Table 4.9, the minimum number of PMUs required is 10 so that the system is fully observable. The maximum value of SORI for the solution set of serial numbers 1 and 8 is 50. Hence PMU placement sets [2 4 6 9 10 12 15 20 25 30] and [2 4 6 9 10 12 15 20 25 29] are considered as optimal solution. The values of BOI of both the optimal solution sets are tabulated in Table 4.10. BOI 1 represents the value of BOI for the placement set [2 4 6 9 10 12 15 20 25 30]. BOI 2 represents the value of BOI for the placement set [2 4 6 9 10 12 15 20 25 29].

Table 4.10: Case I value of BOI for IEEE 30 bus system

Bus No.	BOI 1	BOI 2	Bus No.	BOI 1	BOI 2
1	1	1	16	1	1
2	3	3	17	1	1
3	1	1	18	1	1
4	4	4	19	1	1
5	1	1	20	2	2
6	5	5	21	1	1
7	1	1	22	1	1
8	1	1	23	1	1
9	3	3	24	1	1
10	4	4	25	1	1
11	1	1	26	1	1
12	3	3	27	2	2
13	1	1	28	1	1
14	2	2	29	1	1
15	2	2	30	1	1

4.2.2 Case II: Consideration of Single PMU Outage

In case II, the OPP problem is solved with consideration of a single PMU outage. The number of PMU required for IEEE 30 bus system to ensure power system observability is tabulated in Table 4.11 along with their location and SORI.

Table 4.11: Case II PMU placement set for IEEE 30 bus system

S.N	Number of PMU	Placement Set	SORI
1	21	1 3 5 6 7 8 9 10 11 12 13 15 17 18 20 21 23 25 26 27 30	78
2	21	1 2 4 6 7 9 10 11 12 13 15 16 18 20 22 24 25 26 27 28 29	85
3	21	1 2 4 6 7 9 10 11 12 13 15 16 18 19 22 24 25 26 28 29 30	83
4	21	1 2 3 5 6 9 10 11 12 13 15 17 18 20 21 23 25 26 28 29 30	79
5	21	1 3 5 6 7 9 10 11 12 13 15 16 19 20 22 23 25 26 28 29 30	78
6	21	1 3 5 6 7 9 10 11 12 13 15 16 18 20 21 24 25 26 28 29 30	78
7	21	1 3 5 6 7 9 10 11 12 13 15 16 18 20 21 23 25 26 27 28 29	79
8	21	1 3 5 6 7 9 10 11 12 13 15 17 19 20 22 24 25 26 28 29 30	79
9	21	1 3 5 7 8 9 10 11 12 13 15 16 19 20 21 23 25 26 27 28 29	74
10	21	2 3 4 6 7 8 9 10 11 12 13 15 16 18 20 21 24 25 26 29 30	81

Table 4.11 shows that the minimum number of PMUs required is 21 so that the IEEE 30 bus system is fully observable. Solution set of serial number 2 shows that the placement of PMUs in buses 1, 2, 4, 6, 7, 9, 10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 25,

26, 27, 28, and 29 has measurement redundancy SORI of 85. Although all other solution set shows the same minimum number of PMU, their SORI value is less than 85. Hence PMU placement set in buses 1, 2, 4, 6, 7, 9, 10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 25, 26, 27, 28, and 29 are selected as optimal solution. The value of BOI for optimal solution set [1 2 4 6 7 9 10 11 12 13 15 16 18 20 22 24 25 26 27 28 29] is tabulated in Table 4.12.

Table 4.12: Case II value of BOI for IEEE 30 bus system

Bus Number	BOI	Bus Number	BOI
1	2	16	2
2	4	17	2
3	2	18	2
4	4	19	2
5	2	20	2
6	7	21	2
7	2	22	3
8	2	23	2
9	4	24	3
10	5	25	4
11	2	26	2
12	5	27	4
13	2	28	3
14	2	29	2
15	3	30	2

4.2.3 Case III: Consideration of ZIB

In case III, the OPP problem is solved with consideration of ZIB. Consideration of ZIB has reduced the number of PMU required to ensure power system observability. The number of PMU required for IEEE 30 bus system to ensure power system observability is tabulated in Table 4.13 along with their location and SORI.

Table 4.13: Case III PMU placement set for IEEE 30 bus system

S.N	Number of PMU	Placement Set	SORI
1	7	3 5 10 12 15 18 27	37
2	7	2 4 10 12 15 20 27	42
3	9	2 4 6 12 16 18 20 24 27	48
4	8	2 3 9 10 12 19 24 30	41
5	7	1 7 12 17 19 24 30	31

S.N	Number of PMU	Placement Set	SORI
6	7	2 7 12 17 19 24 30	31
7	8	1 5 10 12 18 23 25 30	37
8	7	2 4 10 12 15 18 27	42
9	8	1 5 10 12 15 18 25 29	39
10	7	2 4 10 12 19 24 30	39

Table 4.13 shows that the minimum number of PMUs required are 7 so that the system is fully observable. The solution set with a minimum number of PMU and maximum measurement redundancy SORI of 42 is [2 4 10 12 15 19 27]. Hence PMU placement set in buses 2, 4, 10, 12, 15, 19, and 27 is selected as an optimal solution. The value of BOI for optimal solution set [2 4 10 12 15 19 27] is tabulated in Table 4.14.

Table 4.14: Case III value of BOI for IEEE 30 bus system

Bus Number	BOI	Bus Number	BOI
1	1	16	1
2	2	17	1
3	1	18	1
4	3	19	1
5	1	20	2
6	3	21	1
7	1	22	1
8	1	23	1
9	1	24	1
10	2	25	1
11	1	26	1
12	3	27	1
13	1	28	1
14	2	29	1
15	2	30	2

4.3 Test System III: IEEE 57 Bus System

The data collected from IEEE 57 bus system is used to construct the binary connectivity matrix. The tabular form of binary connectivity matrix is tabulated in Table 4.15.

Table 4.15: Connectivity matrix for IEEE 57 bus system in vector form

Bus Number	Adjacent Buses	Bus Number	Adjacent Buses
1	[2 15 16 17]	30	[25 31]
2	[1 3]	31	[30 32]
3	[2 4 14]	32	[31 33 34]
4	[3 5 6 18]	33	[32]
5	[4 6]	34	[32 35]
6	[4 5 7 8]	35	[34 36]
7	[6 8 29]	36	[35 37 40]
8	[6 7 9]	37	[36 38 39]
9	[8 10 11 12 13 55]	38	[22 37 44 48 49]
10	[9 12 51]	39	[37 57]
11	[9 13 41 43]	40	[36 56]
12	[9 10 13 16 17]	41	[11 42 43 56]
13	[9 11 12 13 16 17]	42	[41 56]
14	[13 15 46]	43	[11 41]
15	[1 3 13 14 45]	44	[38 45]
16	[1 12]	45	[15 44]
17	[1 12]	46	[14 47]
18	[4 19]	47	[46 48]
19	[18 20]	48	[38 47 49]
20	[19 21]	49	[13 38 48 50]
21	[20 22]	50	[49 51]
22	[21 23 38]	51	[10 50]
23	[22 24]	52	[29 53]
24	[23 25 26]	53	[52 54]
25	[24 30]	54	[53 55]
26	[24 27]	55	[9 54]
27	[26 28]	56	[40 41 42 47]
28	[27 29]	57	[39 56]
29	[7 28 52]		

4.3.1 Case I: Normal Operation

In case I, the OPP problem is solved without consideration of a single PMU outage and without consideration of ZIB. The number of PMU required for IEEE 57 bus system to ensure power system observability is tabulated in Table 4.16 along with their location and SORI.

Table 4.16: Case I PMU placement set for IEEE 57 bus system

S.N	Number of PMU	Placement Set	SORI
1	18	1 2 6 12 19 22 25 27 29 32 36 39 41 44 46 49 50 54	69

S.N	Number of PMU	Placement Set	SORI
2	17	1 6 10 15 19 22 25 27 32 36 38 39 41 46 51 52 54	67
3	19	2 6 12 18 20 24 27 29 30 32 36 38 39 42 43 45 46 51 54	69
4	17	1 4 9 20 24 27 29 30 32 36 38 39 41 45 46 50 54	73
5	20	3 6 10 12 17 19 22 24 28 30 33 34 37 41 45 46 49 53 54 56	68
6	18	1 4 9 11 14 20 22 26 29 30 32 35 37 44 47 50 54 56	71
7	20	1 2 6 10 19 21 23 27 30 33 35 39 40 42 43 44 46 49 52 54	66
8	20	2 4 8 14 16 17 18 21 23 27 30 32 36 39 41 44 48 51 52 55	69
9	17	1 4 8 10 20 22 25 26 29 32 36 41 44 46 49 54 57	65
10	19	1 4 7 10 13 20 23 27 30 33 34 36 41 45 47 49 53 55 57	71

Table 4.16 show that the minimum number of PMUs required is 17. Although the solution set of serial numbers 2, 4, and 9 show that 17 PMUs are required, the SORI of 73 for serial number 4 placement set is maximum. Hence PMU placement set [1 4 9 20 24 27 29 30 32 36 38 39 41 45 46 50 54] are selected as optimal solution. The value of BOI for the optimal solution set is tabulated in Table 4.17.

Table 4.17: Case I value of BOI for IEEE 57 bus system

Bus Number	BOI	Bus Number	BOI	Bus Number	BOI
1	1	21	1	41	1
2	1	22	1	42	1
3	1	23	1	43	1
4	1	24	1	44	2
5	1	25	2	45	1
6	1	26	2	46	1
7	1	27	1	47	1
8	1	28	2	48	1
9	1	29	1	49	2
10	1	30	1	50	1
11	2	31	2	51	1
12	1	32	1	52	1
13	1	33	1	53	1
14	1	34	1	54	1
15	2	35	1	55	2
16	1	36	1	56	1
17	1	37	3	57	1
18	1	38	1		
19	1	39	1		
20	1	40	1		

4.3.2 Case II: Consideration of Single PMU Outage

In case II, the OPP problem is solved with consideration of a single PMU outage. The number of PMU required for IEEE 57 bus system to ensure power system observability is tabulated in Table 4.18 along with their location and SORI.

Table 4.18: Case II PMU placement set for IEEE 57 bus system

S.N	Number of PMU	Placement Set	SORI
1	38	1 2 3 5 6 7 9 12 14 18 19 21 22 23 25 26 27 29 30 32 33 34 36 39 40 41 43 44 45 46 48 49 50 51 53 54 56 57	138
2	35	1 3 4 6 9 12 15 19 20 22 24 25 26 27 29 31 32 33 34 35 37 38 40 41 43 44 46 47 50 51 52 54 55 56 57	133
3	36	1 2 4 6 8 9 12 15 18 19 21 22 24 25 27 28 30 32 33 34 36 38 39 40 41 42 43 45 46 47 50 51 52 53 55 57	133
4	33	1 3 4 6 9 11 12 15 19 20 22 24 25 26 28 29 30 32 33 34 36 37 38 41 45 46 47 50 51 53 54 56 57	130
5	37	1 3 4 5 8 9 10 11 12 14 15 19 20 22 24 26 27 29 30 31 32 33 34 36 37 38 39 41 45 47 48 49 51 52 53 54 56	146
6	36	1 3 5 6 7 10 12 15 18 19 21 22 24 26 27 29 30 31 32 33 34 36 37 41 43 44 45 46 47 49 50 52 54 55 56 57	132
7	33	1 3 4 6 9 11 12 15 19 20 22 24 26 28 29 30 31 32 33 35 36 38 39 41 44 46 47 50 51 53 54 56 57	125
8	35	1 3 4 6 9 11 12 15 18 20 21 22 24 25 26 28 29 30 32 33 35 36 38 39 40 41 42 45 46 47 50 51 53 54 57	133
9	34	1 2 4 6 7 9 11 12 15 19 20 22 24 25 27 28 31 32 33 35 36 37 38 41 45 46 47 50 51 52 53 54 56 57	132
10	35	1 2 4 6 9 11 12 14 19 20 22 24 25 27 28 29 31 32 33 34 36 37 38 39 42 43 44 45 46 48 50 51 53 54 56	132

The simulation result in Table 4.18 shows that the minimum number of PMUs required is 33. The value of SORI for the solution set is 130. Hence PMU placement sets [1 3 4 6 9 11 12 15 19 20 22 24 25 26 28 29 30 32 33 34 36 37 38 41 45 46 47 50 51 53 54 56 57] is required optimal solution. The value of BOI for the optimal solution set is tabulated in Table 4.19.

Table 4.19: Case II value of BOI for IEEE 57 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	2	21	2	41	3
2	2	22	2	42	2
3	3	23	2	43	2
4	3	24	3	44	2

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
5	2	25	3	45	2
6	2	26	2	46	2
7	2	27	2	47	2
8	2	28	2	48	2
9	3	29	2	49	2
10	3	30	2	50	2
11	3	31	2	51	2
12	2	32	3	52	2
13	4	33	2	53	2
14	2	34	2	54	2
15	4	35	2	55	2
16	2	36	2	56	3
17	2	37	3	57	2
18	2	38	3		
19	2	39	2		
20	2	40	2		

4.3.3 Case III: Consideration of ZIB

In case III, the OPP problem is solved with consideration of ZIB. Consideration of ZIB has reduced the number of PMUs required to ensure power system observability. The number of PMUs required for IEEE 57 bus system is tabulated in Table 4.20 along with their location and SORI.

Table 4.20: Case III PMU placement set for IEEE 57 bus system

S.N	Number of PMU	Placement Set	SORI
1	14	2 4 12 15 20 25 29 30 32 36 41 47 50 54	70
2	12	1 9 10 15 18 23 29 30 32 49 54 56	66
3	13	1 3 6 13 19 26 29 31 32 38 51 54 56	68
4	15	1 4 9 14 19 21 25 29 32 35 42 44 49 51 53	73
5	14	1 4 10 11 18 22 25 29 32 44 47 50 54 56	68
6	15	1 3 9 13 18 21 25 29 32 37 41 45 48 51 53	77
7	12	1 4 9 19 25 29 32 38 46 51 54 56	64
8	14	1 2 9 15 18 23 25 29 32 37 41 48 51 54	72
9	13	1 4 9 14 15 20 25 29 32 37 41 50 53	71
10	12	1 9 15 18 23 25 29 32 47 50 53 56	62

Table 4.20 show that the minimum number of PMU required is 12. The optimal solution set [1 9 10 15 18 23 29 30 32 49 54 56] has a minimum number of PMUs and

maximum SORI of 66. The value of BOI for the optimal solution set is tabulated in Table 4.21.

Table 4.21: Case III value of BOI for IEEE 14 bus system

Bus Number	BOI	Bus Number	BOI	Bus Number	BOI
1	1	21	2	41	2
2	1	22	3	42	1
3	1	23	2	43	1
4	3	24	3	44	2
5	2	25	2	45	1
6	3	26	3	46	1
7	2	27	2	47	2
8	3	28	1	48	2
9	3	29	1	49	4
10	1	30	1	50	1
11	3	31	1	51	1
12	2	32	2	52	1
13	3	33	1	53	1
14	2	34	2	54	1
15	3	35	2	55	1
16	1	36	3	56	2
17	1	37	4	57	2
18	2	38	4		
19	1	39	2		
20	1	40	3		

4.4 Test System IV: IEEE 118 Bus System

The data collected from IEEE 118 bus system is used to construct the binary connectivity matrix. The tabular form of binary connectivity matrix in vector form is tabulated in Table 4.22.

Table 4.22: Connectivity matrix for IEEE 118 bus system in vector format

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
1	[1 2 3]	41	[40 41 42]	81	[68 80 81]
2	[1 2 12]	42	[40 41 42 49]	82	[77 82 83 96]
3	[1 3 5 12]	43	[34 43 44]	83	[82 83 84 85]
4	[4 5 11]	44	[43 44 45]	84	[83 84 85]
5	[3 4 5 6 8 11]	45	[44 45 46 49]	85	[83 84 85 86 88 89]
6	[5 6 7]	46	[45 46 47 48]	86	[85 86 87]

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
7	[6 7 12]	47	[46 47 49 69]	87	[86 87]
8	[5 8 9 30]	48	[46 48 49]	88	[85 88 89]
9	[8 9 10]	49	[45 47 48 49 50 51 54 66 69]	89	[85 88 89 90 92]
10	[9 10]	50	[49 50 57]	90	[89 90 91]
11	[4 5 11 12 13]	51	[49 51 52 58]	91	[90 91 92]
12	[2 3 7 11 12 14 16 117]	52	[51 52 53]	92	[89 91 92 93 94 100 102]
13	[11 13 15]	53	[52 53 54]	93	[92 93 94]
14	[12 14 15]	54	[49 53 54 55 56 59]	94	[92 93 94 95 96 100]
15	[13 14 15 17 19 33]	55	[54 55 56 59]	95	[94 95 96]
16	[12 16 17]	56	[54 55 56 57 58 59]	96	[80 82 94 95 96 97]
17	[15 16 17 18 30 31 113]	57	[50 56 57]	97	[80 96 97]
18	[17 18 19]	58	[51 56 58]	98	[80 98 100]
19	[15 18 19 20 34]	59	[54 55 56 59 60 61 63]	99	[80 99 100]
20	[19 20 21]	60	[59 60 61 62]	100	[92 94 98 99 100 101 103 104 106]
21	[20 21 22]	61	[59 60 61 62 64]	101	[100 101 102]
22	[21 22 23]	62	[60 61 62 66 67]	102	[92 101 102]
23	[22 23 24 25 32]	63	[59 63 64]	103	[100 103 104 105 110]
24	[23 24 70 72]	64	[61 63 64 65]	104	[100 103 104 105]
25	[23 25 26 27]	65	[38 64 65 66 68]	105	[103 104 105 106 107 108]
26	[25 26 30]	66	[49 62 65 66 67]	106	[100 105 106 107]
27	[25 27 28 32 115]	67	[62 66 67]	107	[105 106 107]
28	[27 28 29]	68	[65 68 69 81 116]	108	[105 108 109]
29	[28 29 31]	69	[47 49 68 69 70 75 77]	109	[108 109 110]
30	[8 17 26 30 38]	70	[24 69 70 71 74 75]	110	[103 109 110 111 112]
31	[17 29 31 32]	71	[70 71 72 73]	111	[110 111]
32	[23 27 31 32 113 114]	72	[24 71 72]	112	[110 112]
33	[15 33 37]	73	[71 73]	113	[17 32 113]
34	[19 34 36 37 43]	74	[70 74 75]	114	[32 114 115]
35	[35 36 37]	75	[69 70 74 75 77 118]	115	[27 114 115]
36	[34 35 36]	76	[76 77 118]	116	[68 116]
37	[33 34 35 37 38 39 40]	77	[69 75 76 77 78 80 82]	117	[12 117]

Bus No.	Adjacent Buses	Bus No.	Adjacent Buses	Bus No.	Adjacent Buses
38	[30 37 38 65]	78	[77 78 79]	118	[75 76 118]
39	[37 39 40]	79	[78 79 80]		
40	[37 39 40 41 42]	80	[77 79 80 81 96 97 98 99]		

4.4.1 Case I: Normal Operation

The simulation result of modified SA with reference to radial bus for IEEE 118 bus system to ensure power system observability is tabulated in Table 4.23 along with their location and SORI.

Table 4.23: Case I PMU placement set for IEEE 118 bus system

S. N	No. of PMU	Placement Set	SORI
1	36	1 7 9 11 12 15 18 21 27 29 30 32 34 35 39 41 45 49 52 56 59 64 67 68 71 72 75 77 80 85 86 90 94 102 105 110	169
2	35	3 6 9 11 12 17 21 24 26 28 34 37 41 45 49 52 56 62 64 68 71 74 76 78 84 86 88 91 92 96 100 107 108 110 114	156
3	38	1 6 9 11 12 17 20 22 25 27 29 32 35 37 42 43 48 49 51 54 57 60 63 66 68 71 72 74 78 85 86 90 92 96 100 105 110 118	174
4	36	2 6 9 11 12 14 17 20 23 26 29 35 37 42 44 46 52 56 57 62 63 68 71 75 79 83 86 89 92 96 100 106 108 110 115 118	157
5	34	3 6 9 11 12 17 20 23 28 30 36 37 41 43 48 49 52 56 59 61 67 68 71 75 77 80 85 86 90 94 102 105 110 114	164
6	37	2 4 6 9 12 15 18 21 25 29 36 38 40 43 46 50 53 55 58 62 64 68 70 71 76 78 84 86 89 92 96 100 107 108 110 113 114	151
7	35	3 5 9 12 13 17 20 23 28 30 35 37 42 43 48 49 53 56 62 64 68 71 75 77 79 85 86 90 92 94 97 100 105 110 114	171
8	36	1 5 9 12 15 19 22 24 27 30 31 32 34 37 41 45 49 52 56 62 64 68 71 74 76 78 80 83 85 86 91 92 95 102 105 110	171
9	37	2 5 9 12 15 17 20 23 26 27 31 32 36 40 43 48 49 52 56 61 64 65 66 68 71 75 77 80 85 86 91 94 102 103 106 109 110	179
10	35	2 5 9 11 12 17 21 25 28 33 34 35 40 45 49 52 56 59 65 67 68 70 71 76 79 85 86 91 92 96 100 106 109 110 114	166

The optimal number of PMU required is found to be 34 with a SORI value of 164. The value of BOI for the optimal solution set is tabulated in Table 4.24.

Table 4.24: Case I BOI value for IEEE 118 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	1	31	1	61	2	91	1
2	1	32	2	62	2	92	2
3	2	33	1	63	1	93	1

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
4	1	34	3	64	1	94	1
5	3	35	2	65	1	95	1
6	1	36	1	66	2	96	2
7	2	37	1	67	1	97	1
8	2	38	2	68	1	98	1
9	1	39	1	69	4	99	1
10	1	40	2	70	2	100	1
11	2	41	1	71	1	101	1
12	3	42	2	72	1	102	1
13	1	43	1	73	1	103	2
14	1	44	1	74	1	104	1
15	1	45	1	75	2	105	1
16	2	46	1	76	1	106	1
17	2	47	1	77	3	107	1
18	1	48	2	78	1	108	1
19	1	49	2	79	1	109	1
20	1	50	1	80	2	110	1
21	1	51	2	81	2	111	1
22	1	52	1	82	1	112	1
23	1	53	1	83	1	113	1
24	1	54	3	84	1	114	1
25	1	55	2	85	2	115	1
26	1	56	2	86	2	116	1
27	1	57	1	87	1	117	1
28	1	58	1	88	1	118	1
29	1	59	3	89	2		
30	2	60	2	90	1		

4.4.2 Case II: Consideration of Single PMU Outage

The result of modified SA with reference to radial bus for IEEE 118 bus system to ensure power system observability is tabulated in Table 4.25 along with their location and SORI.

Table 4.25: Case II PMU placement set for IEEE 118 bus system

S.N	No. of PMU	Placement Set	SORI
1	75	1 3 5 7 9 10 11 12 13 14 17 19 20 22 23 24 25 27 29 30 31 32 33 35 36 37 40 42 43 44 46 48 50 51 52 54 55 57 58 61 62 63 64 67 68 69 71 73 74 75 77 78 80 83 85 86 87 89 90 92 93 95 96 100 101 105 107 108 110 111 112 114 116 117 118	308

S.N	No. of PMU	Placement Set	SORI
2	70	1 3 5 6 9 10 11 12 15 17 18 20 21 22 25 27 28 29 30 32 34 35 37 40 41 44 45 46 49 52 53 56 57 58 59 61 63 66 67 68 70 71 72 73 74 76 77 79 80 84 85 86 87 89 90 92 94 96 100 101 105 106 108 110 111 112 114 116 117 118	299
3	70	2 3 5 7 9 10 11 12 15 17 19 20 22 23 24 26 27 28 29 30 32 34 36 37 40 41 44 45 46 49 50 51 53 54 56 61 62 63 64 67 68 70 71 73 75 76 78 79 80 83 85 86 87 89 91 92 94 96 100 101 105 106 108 110 111 112 115 116 117 118	304
4	71	1 3 5 7 9 10 11 12 15 17 19 20 22 23 24 26 27 28 30 31 32 34 36 37 40 41 44 45 46 49 50 51 52 54 56 60 61 63 64 66 67 68 71 73 74 75 76 77 79 80 84 85 86 87 88 90 91 92 94 96 100 101 105 106 109 110 111 112 114 116 117	307
5	69	1 2 5 6 9 10 11 12 15 17 19 21 22 23 24 25 26 27 29 31 32 34 35 37 40 42 44 45 46 49 51 52 54 56 57 59 62 64 65 67 68 71 73 74 75 76 77 79 80 83 85 86 87 89 91 92 94 96 100 102 105 106 108 110 111 112 114 116 117	306
6	69	1 3 5 6 9 10 11 12 15 17 18 20 21 23 24 26 27 29 30 31 32 34 35 37 40 42 44 45 46 49 52 53 56 57 58 59 62 63 64 66 68 71 73 74 75 76 77 78 80 83 85 86 87 89 90 92 94 96 100 101 105 106 108 110 111 112 115 116 117	302
7	74	1 3 4 6 7 9 10 11 12 15 17 18 20 21 23 26 27 28 29 30 32 35 36 37 40 41 43 44 45 46 49 51 52 53 56 57 59 61 64 66 67 68 71 72 73 74 75 77 78 80 83 85 86 87 88 90 91 93 94 95 97 100 101 102 105 107 109 110 111 112 115 116 117 118	300
8	69	2 3 5 7 9 10 11 12 15 17 19 21 22 24 25 27 29 30 31 32 34 35 37 40 41 43 44 46 48 49 50 51 52 54 56 59 62 63 64 66 68 70 71 73 75 76 77 78 80 83 85 86 87 89 91 92 94 96 100 101 105 106 108 110 111 112 115 116 117	308
9	68	1 2 5 6 9 10 11 12 15 17 19 21 22 24 25 27 28 29 30 32 34 35 37 40 41 44 45 46 49 52 53 56 57 58 59 61 63 66 67 68 70 71 73 75 76 77 79 80 83 85 86 87 89 91 92 94 96 100 102 105 106 109 110 111 112 115 116 117	299
10	73	1 3 5 7 9 10 11 12 15 16 18 19 20 21 23 26 27 28 29 30 32 34 36 37 40 42 44 45 46 49 51 52 54 56 57 61 62 63 64 67 68 71 72 73 74 75 76 77 78 80 81 84 85 86 87 89 91 92 93 95 96 100 102 105 107 108 110 111 112 113 115 116 117	305

The optimal number of PMU for IEEE 118 bus system for a single PMU outage is found to be 68 with the SORI value of 299. The value of BOI for the optimal placement set is tabulated in Table 4.26.

Table 4.26: Case II value of BOI for IEEE 18 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	2	31	3	61	2	91	2
2	3	32	2	62	3	92	6
3	3	33	2	63	2	93	2

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
4	2	34	3	64	2	94	4
5	3	35	2	65	2	95	2
6	2	36	2	66	3	96	3
7	2	37	4	67	2	97	2
8	3	38	2	68	2	98	2
9	2	39	2	69	5	99	2
10	2	40	3	70	4	100	4
11	3	41	2	71	3	101	2
12	4	42	3	72	2	102	2
13	2	43	2	73	2	103	3
14	2	44	2	74	2	104	2
15	3	45	4	75	3	105	2
16	2	46	2	76	2	106	3
17	3	47	2	77	4	107	2
18	2	48	2	78	2	108	2
19	3	49	3	79	2	109	2
20	2	50	2	80	4	110	4
21	2	51	3	81	2	111	2
22	2	52	2	82	3	112	2
23	4	53	2	83	2	113	2
24	2	54	4	84	2	114	2
25	2	55	2	85	4	115	2
26	2	56	4	86	3	116	2
27	5	57	2	87	2	117	2
28	3	58	2	88	2	118	2
29	2	59	4	89	3		
30	2	60	2	90	2		

4.4.3 Case III: Consideration of ZIB

The simulation result of case III, for IEEE 118 bus system to ensure power system observability is tabulated in Table 4.27 along with their location and SORI.

Table 4.27: PMU placement set for IEEE 118 bus system

S.N	No. of PMU	Placement Set	SORI
1	32	3 8 11 12 16 19 21 24 27 29 32 36 40 44 46 50 52 56 62 65 70 75 77 80 85 86 89 92 96 101 105 110	164
2	33	2 7 8 12 15 19 21 25 29 32 34 37 41 45 49 52 56 61 67 72 75 76 79 80 85 86 90 92 96 102 105 110 114	165
3	30	3 8 11 12 19 21 27 31 32 35 40 44 48 49 53 56 59 66 72 75 77 80 83 86 89 92 96 101 105 110	162

S.N	No. of PMU	Placement Set	SORI
4	34	1 5 9 12 13 19 21 23 28 31 34 35 40 45 49 52 56 62 65 71 74 76 79 84 86 89 92 96 100 106 109 110 113 114	162
5	35	2 9 11 12 18 21 27 31 32 33 34 40 44 47 49 51 54 57 59 65 66 70 71 75 77 78 85 86 90 92 96 100 107 108 110	181
6	32	2 9 11 12 19 21 27 31 32 34 37 42 45 46 52 56 57 59 66 72 75 77 80 85 86 90 92 95 100 107 109 110	166
7	35	2 9 11 12 15 17 21 23 28 35 40 44 47 49 50 51 53 59 67 69 70 71 76 79 83 86 89 92 95 97 100 106 108 110 114	170
8	31	2 6 8 12 15 19 20 23 29 32 34 40 44 46 50 51 54 61 66 71 75 77 80 85 86 90 94 102 105 110 114	155
9	33	3 8 11 12 18 21 27 28 32 33 36 40 44 47 48 50 51 54 59 66 72 74 76 77 80 84 86 89 90 94 102 105 110	154
10	32	2 9 11 12 18 19 21 24 27 29 32 34 37 41 45 49 52 56 61 62 70 78 80 85 86 90 92 96 102 105 110 118	165

The minimum number of PMU required is found to be 30 with its SORI value of 162. The value of BOI for the optimal placement set is shown in Table 4.28.

Table 4.28: Case III value of BOI for IEEE 118 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	1	31	2	61	1	91	1
2	1	32	3	62	1	92	2
3	2	33	1	63	1	93	1
4	1	34	1	64	1	94	2
5	3	35	1	65	2	95	1
6	1	36	1	66	2	96	2
7	1	37	2	67	1	97	2
8	1	38	1	68	1	98	1
9	1	39	1	69	3	99	1
10	1	40	1	70	1	100	2
11	2	41	1	71	1	101	1
12	3	42	2	72	1	102	2
13	1	43	1	73	1	103	2
14	1	44	1	74	1	104	1
15	1	45	2	75	2	105	1
16	1	46	1	76	1	106	1
17	1	47	1	77	3	107	1
18	1	48	2	78	1	108	1
19	1	49	3	79	1	109	1
20	2	50	1	80	3	110	1
21	1	51	1	81	1	111	1

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
22	1	52	1	82	3	112	1
23	1	53	1	83	1	113	1
24	1	54	4	84	1	114	1
25	1	55	2	85	3	115	1
26	1	56	2	86	1	116	1
27	2	57	1	87	1	117	1
28	1	58	1	88	1	118	1
29	1	59	2	89	2		
30	1	60	1	90	1		

4.5 Existing INPS 90 Bus System

The data collected from the existing INPS 90 bus system is used to construct the binary connectivity matrix. The tabular form of binary connectivity matrix is tabulated in Table 4.29.

Table 4.29: Connectivity matrix for INPS 90 bus system in vector form

Bus No.	Name	Adjacent Buses	Bus No.	Name	Adjacent Buses
1	Kabeli	[1 2]	46	Suijatar66	[26 45 46 47 48 49 51]
2	Amarpur	[1 2 3]	47	Teku	[46 47 48]
3	Phidim	[2 3 4 6]	48	K-3	[46 47 48]
4	Illam	[3 4 6]	49	Patan	[46 49 61]
5	Anarmani	[5 6]	50	Balaju	[45 50 51 58]
6	Damak	[3 4 5 6 7]	51	Balaju66	[46 50 51 58]
7	Duhabi	[6 7 8 9]	52	Trishuli	[51 52 53 54]
8	Kushaha	[7 8 9]	53	Chilime	[52 53]
9	Rupri	[7 8 9 10]	54	Devighat	[52 54 55]
10	Lahan	[9 10 11]	55	Chapali66	[54 55 56 58]
11	Mirchaiya	[10 11 12 13]	56	New Chabahil	[55 56 57]
12	Tingja	[11 12]	57	Lainchaur	[51 56 57]
13	Dhalkebar	[11 13 14 16]	58	Chapali	[50 55 58 59]
14	Dhalkebar220	[13 14 15 65]	59	Bhaktapur	[58 59 60 62]
15	Dhalkebar400	[14 15]	60	Bhaktapur66	[59 60 61 66]
16	Chapur	[13 16 17]	61	Baneshwor	[49 60 61]
17	Pathalaya	[16 17 18 23 24]	62	Lamosanghu	[59 62 63 64]
18	New Parwanipur	[17 18 19]	63	Bhotekoshi	[62 63]
19	Parwanipur	[18 19 20 21]	64	Khimti	[62 64 65]

Bus No.	Name	Adjacent Buses	Bus No.	Name	Adjacent Buses
20	Birjung	[19 20]	65	New Khimti	[14 64 65]
21	Simra	[19 21 22]	66	Banepa	[60 66 67]
22	Amlekhjung	[2 22 28]	67	Panchkhal	[66 67 68 69]
23	Kamane	[17 23 24]	68	Indrawoti	[67 68]
24	Heutauda	[17 23 24 25 27 28 29]	69	Sunkoshi	[67 69]
25	Kulekhani III	[24 25]	70	Bharatpur	[29 30 32 70 71]
26	Kulekhani I	[26 28 46]	71	Kawashwoti	[70 71 72]
27	Kulekhani II	[24 27 42]	72	Bardaghat	[71 72 73 74]
28	Heutauda 66	[22 24 26 28]	73	Gandak	[72 73]
29	Purbi Chitwan	[24 29 70]	74	Butwal	[72 74 75 77]
30	Marsyangdi	[30 31 33 45 70]	75	Kaligandaki	[74 75 76]
31	Markhi Chowk	[30 31 32]	76	Syangja	[34 75 76]
32	Damauli	[31 32 33 34 70]	77	Shivapur	[74 77 78]
33	M. Marsyangdi	[30 32 33]	78	Lamahi	[77 78 79 80 81]
34	Lekhnath'	[32 34 35 36 76]	79	Jhimruk	[78 79]
35	Madi	[34 35]	80	Ghorai	[78 80]
36	Pokhara	[34 36 37]	81	Kusum	[78 81 82 83]
37	Modi	[36 37 38]	82	Hapure	[81 82]
38	Kushma	[37 38 39]	83	Kohalpur	[81 83 84]
39	Kushma220	[38 39 40]	84	Bhuragaun	[83 84 85]
40	Dana220	[39 40 41]	85	Lamki	[84 85 86]
41	Dana	[40 41]	86	Pahalmanpur	[85 86 87]
42	Matatirtha	[27 42 43 45]	87	Aatariya	[86 87 88 89]
43	Samundratar	[42 43 44]	88	Mahendranagar	[87 88]
44	Upper tirshuli 3B	[43 44]	89	Sayule	[87 89 90]
45	Suijatar	[30 42 45 46 50]	90	Balanch	[89 90]

4.5.1 Case I: Normal Operation

The simulation result for INPS 90 bus system to ensure power system observability is tabulated in Table 4.30 along with their location and SORI.

Table 4.30: Case I PMU placement set for INPS 90 bus system

S.N	No. of PMU	Placement Set	SORI
1	28	2 6 9 11 13 14 19 24 28 30 34 38 40 43 46 52 57 58 60 62 67	115

S.N	No. of PMU	Placement Set	SORI
		72 74 78 81 84 87 89	
2	29	2 6 7 11 14 16 19 24 28 30 34 37 40 43 46 51 52 56 59 60 62 67 72 74 78 81 85 87 89	119
3	28	2 6 7 11 14 17 19 22 24 30 34 37 40 43 46 50 52 56 61 62 67 72 74 78 81 84 87 89	114
4	29	2 6 8 11 14 17 19 24 28 32 34 37 40 43 45 46 49 52 56 59 62 67 72 75 78 81 85 87 89	118
5	31	2 6 8 11 14 17 19 22 24 32 34 36 39 40 43 46 52 56 58 60 62 67 70 72 76 78 81 83 86 87 89	124
6	29	2 6 7 11 13 14 19 22 24 30 34 38 40 43 46 49 50 52 56 62 66 67 72 74 78 81 85 87 89	116
7	32	2 6 9 11 14 17 19 21 24 26 32 34 38 40 43 45 47 49 50 52 56 62 64 66 67 72 75 78 81 84 87 89	123
8	30	2 6 7 11 14 17 19 21 24 26 30 34 37 40 43 47 49 51 52 56 59 62 67 72 74 78 81 84 87 89	118
9	28	2 6 8 11 14 16 19 21 24 30 34 37 40 43 46 52 56 58 61 62 67 72 75 78 81 84 87 89	110
10	28	2 6 9 11 14 16 19 22 24 30 34 38 40 43 46 50 52 56 61 62 67 72 74 78 81 84 87 89	112

The minimum number of PMU required for the case I is found to be 28 with the SORI value of 115. Hence PMU should be installed at bus 2, 6, 8, 11, 14, 16, 19, 21, 24, 30, 34, 37, 40, 43, 46, 52, 56, 58, 61, 62, 67, 72, 75, 78, 81, 84, 87 and 89. The value of BOI for the optimal placement set is tabulated in Table 4.31.

Table 4.31: Case I BOI value for INPS 90 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	1	24	2	47	1	70	1
2	1	25	1	48	1	71	1
3	2	26	2	49	1	72	2
4	1	27	1	50	1	73	1
5	1	28	2	51	3	74	2
6	1	29	1	52	1	75	1
7	2	30	1	53	1	76	1
8	1	31	1	54	1	77	2
9	1	32	1	55	1	78	2
10	2	33	1	56	1	79	1
11	2	34	1	57	1	80	1
12	1	35	1	58	1	81	2
13	3	36	1	59	3	82	1
14	2	37	1	60	1	83	2
15	1	38	1	61	1	84	1
16	1	39	2	62	1	85	1

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
17	1	40	1	63	1	86	1
18	1	41	1	64	1	87	2
19	1	42	1	65	1	88	1
20	1	43	1	66	2	89	2
21	1	44	1	67	1	90	1
22	1	45	2	68	1		
23	1	46	1	69	1		

4.5.2 Case II: Consideration of Single PMU Outage

The number of PMU required for case II on INPS 90 bus system to ensure power system observability is tabulated in Table 4.32 along with their location and SORI.

Table 4.32: Case II PMU placement set for INPS 90 bus system

S.N	No. of PMU	Placement Set	SORI
1	65	1 2 3 5 6 7 9 11 12 14 15 16 17 19 20 21 24 25 28 29 30 32 34 35 36 37 39 40 41 42 43 44 45 46 47 52 53 55 56 57 58 60 61 62 63 64 67 68 69 71 72 73 74 76 78 79 80 81 82 84 85 87 88 89 90	216
2	64	1 2 3 5 6 7 9 11 12 13 14 15 17 19 20 21 24 25 28 29 30 32 33 34 35 37 38 40 41 42 43 44 46 48 51 52 53 55 57 58 60 61 62 63 65 67 68 69 71 72 73 74 76 78 79 80 81 82 84 85 87 88 89 90	214
3	63	1 2 4 5 6 7 9 11 12 13 14 15 17 19 20 21 24 25 27 28 30 32 34 35 37 38 40 41 43 44 46 48 51 52 53 55 57 58 60 61 62 63 65 67 68 69 70 72 73 74 75 78 79 80 81 82 83 85 86 87 88 89 90	211
4	68	1 2 4 5 6 8 9 11 12 13 14 15 16 18 19 20 21 23 24 25 27 28 29 30 32 33 34 35 37 38 40 41 43 44 46 47 49 50 51 52 53 55 56 59 61 62 63 65 66 67 68 69 71 72 73 74 76 78 79 80 81 82 84 85 87 88 89 90	221
5	69	1 2 4 5 6 8 9 11 12 13 14 15 17 19 20 21 24 25 26 27 28 29 30 31 33 34 35 36 38 39 40 41 43 44 45 47 48 49 51 52 53 55 56 59 60 61 62 63 65 67 68 69 71 72 73 74 75 78 79 80 81 82 83 85 86 87 88 89 90	222
6	67	1 2 3 5 6 7 9 11 12 14 15 16 17 19 20 22 24 25 28 29 30 31 33 34 35 36 37 39 40 41 42 43 44 46 47 49 51 52 53 55 57 58 60 62 63 64 66 67 68 69 71 72 73 74 75 78 79 80 81 82 83 84 86 87 88 89 90	220
7	62	1 2 3 5 6 8 9 11 12 13 14 15 17 19 20 21 24 25 27 28 30 32 34 35 37 38 40 41 43 44 46 48 51 52 53 55 56 58 60 61 62 63 65 67 68 69 70 72 73 74 76 78 79 80 81 82 84 85 87 88 89 90	208
8	64	1 2 4 5 6 8 9 11 12 13 14 15 17 19 20 22 24 25 27 28 30 32 34 35 37 38 40 41 43 44 46 48 49 51 52 53 55 56 58 61 62 63 65 66 67 68 69 70 72 73 74 75 78 79 80 81 82 83 84 86 87 88 89	212

S.N	No. of PMU	Placement Set	SORI
		90	
9	67	1 2 4 5 6 8 9 11 12 13 14 15 17 19 20 22 24 25 28 29 30 31 33 34 35 36 37 39 40 41 42 43 44 45 46 48 52 53 55 56 57 58 60 61 62 63 64 67 68 69 71 72 73 74 75 78 79 80 81 82 83 84 86 87 88 89 90	219
10	66	1 2 3 5 6 7 8 10 11 12 14 15 16 17 19 20 21 24 25 28 31 32 33 34 35 36 38 39 40 41 42 43 44 46 47 49 50 51 52 53 55 56 60 62 63 64 66 67 68 69 70 72 73 74 75 78 79 80 81 82 84 85 87 88 89 90	218

The minimum number of PMU required is found to be 62 with the SORI value of 208. The value of BOI for optimal PMU placement set is tabulated in Table 4.33.

Table 4.33: Case II value of BOI for INPS 90 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	2	24	5	47	2	70	3
2	3	25	2	48	2	71	2
3	3	26	2	49	2	72	3
4	2	27	2	50	2	73	2
5	2	28	2	51	3	74	2
6	3	29	2	52	3	75	2
7	3	30	2	53	2	76	2
8	2	31	2	54	2	77	2
9	2	32	3	55	3	78	4
10	2	33	2	56	2	79	2
11	3	34	4	57	2	80	2
12	2	35	2	58	2	81	3
13	3	36	2	59	3	82	2
14	4	37	2	60	2	83	2
15	2	38	2	61	2	84	2
16	2	39	2	62	2	85	2
17	2	40	2	63	2	86	2
18	2	41	2	64	2	87	3
19	3	42	2	65	2	88	2
20	2	43	2	66	2	89	3
21	2	44	2	67	3	90	2
22	2	45	2	68	2		
23	2	46	3	69	2		

4.5.3 Case III: Consideration of ZIB

Consideration of ZIB has reduced the number of PMUs required to ensure power system observability. The simulation result for INPS 90 bus system is tabulated in Table 4.34 along with their location and SORI.

Table 4.34: Case III PMU placement set for INPS 90 bus system

S.N	No. of PMU	Placement Set	SORI
1	27	2 6 10 11 17 19 22 24 26 30 34 38 43 48 49 52 56 62 65 67 72 76 78 81 84 87 89	112
2	28	2 6 9 11 16 19 22 24 32 33 34 38 43 46 49 51 52 55 62 64 67 72 76 78 81 84 87 89	120
3	28	2 6 7 11 17 19 24 28 30 34 37 40 43 47 49 52 57 59 62 65 67 72 76 78 81 85 87 89	118
4	26	2 6 10 11 13 19 24 28 30 34 37 40 43 47 52 56 61 62 67 72 75 78 81 84 87 89	109
5	26	2 6 7 11 13 19 24 28 30 34 38 43 48 49 51 52 54 62 67 72 75 78 81 85 87 89	112
6	27	2 6 10 11 13 19 22 24 32 34 38 43 46 49 52 55 57 62 67 70 72 74 78 81 85 87 89	119
7	27	2 6 7 11 13 19 21 24 31 32 34 37 40 43 46 49 52 56 62 67 72 75 78 81 84 87 89	116
8	26	2 6 9 11 13 19 21 24 32 34 38 43 46 49 52 56 62 67 70 72 75 78 81 84 87 89	115
9	26	2 6 8 11 13 19 22 24 30 34 36 39 43 46 49 52 56 62 67 72 74 78 81 85 87 89	113
10	26	2 6 7 11 16 19 22 24 30 34 38 43 46 49 52 56 62 64 67 72 74 78 81 85 87 89	112

The minimum number of PMU required for INPS 90 bus system with the consideration of ZIB is found to be 26 with a SORI value of 115. The value of BOI for the optimal placement set is tabulated in Table 4.35.

Table 4.35: Case III value of BOI for INPS 90 bus system

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
1	1	24	1	47	1	70	2
2	1	25	1	48	1	71	1
3	2	26	1	49	1	72	1
4	1	27	1	50	1	73	1
5	1	28	1	51	1	74	1
6	1	29	2	52	1	75	1
7	2	30	1	53	1	76	1
8	1	31	1	54	1	77	1

Bus No.	BOI	Bus No.	BOI	Bus No.	BOI	Bus No.	BOI
9	2	32	3	55	1	78	2
10	2	33	1	56	2	79	1
11	2	34	2	57	1	80	1
12	1	35	1	58	1	81	2
13	2	36	1	59	1	82	1
14	1	37	1	60	1	83	2
15	1	38	1	61	2	84	1
16	1	39	1	62	2	85	1
17	1	40	1	63	1	86	1
18	1	41	1	64	1	87	2
19	2	42	1	65	2	88	1
20	1	43	1	66	1	89	2
21	2	44	1	67	2	90	1
22	1	45	1	68	2		
23	1	46	2	69	1		

4.6 Validation and Verification

The main objective of this thesis is to implement the modified SA algorithm on INPS thereby ensuring complete power system observability. In order to ensure the effectiveness of the algorithm, it has been implemented on IEEE 14, IEEE 30, IEEE 57, and IEEE 118 bus system. Thus to validate the result of proposed modified SA proposed in this thesis, the optimal number of PMUs (N), the value of SORI, and probability of finding the optimal number of PMU (P) for different bus system are compared with modified SA algorithm and other algorithms.

4.6.1 Case I: Normal Condition

For case I Table 4.36 shows the comparison of simulation results of the proposed method with modified SA and stochastic SA.

Table 4.36: Validation table for case I: normal condition

S.N	Bus system	Proposed Modified SA			Modified SA			Stochastic SA (Kerdchuen & Weerakorn, 2008)
		N	SORI	P	N	SORI	P	N
1	IEEE 14 bus	4	19	0.5	4	19	0.5	4
2	IEEE 30 bus	10	50	0.9	10	48	0.6	10
3	IEEE 57 bus	17	73	0.3	17	71	0.1	19
4	IEEE 118 bus	34	164	0.1	35	154	0.1	34

S.N	Bus system	Proposed Modified SA			Modified SA			Stochastic SA (Kerdchuen & Weerakorn, 2008)
		N	SORI	P	N	SORI	P	N
5	INPS 90 bus	28	115	0.5	32	119	0.5	-

The minimum number of PMU required for IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, IEEE 118 bus, and INPS 90 bus system are found as 4, 10, 17, 34, and 28 respectively. For IEEE 14, IEEE 30, and IEEE 57 bus system, although the minimum number of PMU required are same, the SORI and probability of finding the optimal number of the solution have been significantly increased. For higher bus system, the proposed strategy with modified SA results out less number of PMUs.

4.6.2 Case II: Consideration of Single PMU Outage

The simulation result of the proposed modified SA algorithm for the case with consideration of a single PMU outage is compared with modified SA and FPA. The comparison table is shown in Table 4.37.

Table 4.37: Validation table for case II: consideration of single PMU outage

S.N	Bus system	Proposed Modified SA			Modified SA			FPA (Abdelsalam, et al., 2020)	
		N	SORI	P	N	SORI	P	N	SORI
1	IEEE 14 bus	9	39	0.9	9	39	0.3	9	39
2	IEEE 30 bus	21	85	1	21	85	0.8	21	83
3	IEEE 57 bus	33	130	0.2	34	130	0.1	33	129
4	IEEE 118 bus	68	299	0.1	70	305	0.2	69	313
5	INPS 90 bus	62	208	0.1	64	214	0.3	-	-

In order to maintain the observability minimum number of PMU required for IEEE 14, bus, IEEE 30 bus, IEEE 57 bus, IEEE 118, and INPS 90 system are found as 9, 21, 33, 68, and 62 respectively. For IEEE 14 and IEEE 30 bus system, although the minimum number of PMUs required is same, the SORI and probability of finding the optimal number of solution is more. For higher bus system, the proposed strategy with modified SA results out less number of PMUs.

4.6.3 Case III: Consideration of ZIB

The simulation result of the proposed modified SA for the case with consideration of ZIB is compared with modified SA and RSN. The comparison of the result is tabulated in Table 4.38.

Table 4.38: Validation table for case III: consideration of ZIB

S.N	Bus system	Proposed Modified SA			Modified SA			RSN ((Subedi & Jha, 2020)	
		N	SORI	P	N	SORI	P	N	SORI
1	IEEE 14 bus	3	16	0.6	3	16	0.3	3	N/A
2	IEEE 30 bus	7	42	0.6	7	35	0.4	7	33
3	IEEE 57 bus	12	66	0.3	12	64	0.1	12	54
4	IEEE 118 bus	30	162	0.1	32	158	0.3	N/A	N/A
5	INPS 90 bus	26	115	0.5	28	111	0.1	-	-

In order to maintain the observability minimum number of PMU required for this case for IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, IEEE 118 bus, and INPS 90 bus system are 3, 7, 12, 30, and 26 respectively. For IEEE 14 bus, IEEE 30 bus, and IEEE 57 bus system, although the minimum number of PMUs required is same, the SORI and probability of finding the optimal number of solution is more. For higher bus system, the proposed strategy with modified SA results out less number of PMUs. The proposed modified SA result out better solution than RSN.

The proposed Modified SA with reference to radial bus has improved the result in comparison to modified SA. For the base case, the optimal number of PMUs required for the test system shows that an average PMUs on 30.33% of the total number of buses is capable to ensure the power system observability. Similarly for the case of a single PMU outage, in order to ensure observability, an average number of PMUs required is 63.72% of the total number of buses on that system. For the case with consideration of ZIB, an average PMU on 23.99% of the total number of buses is essential to ensure observability of the system.

Modified SA mentioned on (Al-Odienat, et al., 2020) was dependent on graph theory procedure for initial placement set. But the proposed modified SA with reference to radial buses has eliminated the dependency of modified SA with the graph theory method. For the case with normal operation and consideration of ZIB, placement of PMU on the neighbor bus of radial bus instead of radial bus ensures better BOI and hence higher SORI. Thus in this thesis, placement of PMU on radial bus is restricted on the case I and case III. Similarly, for case II with the consideration of a single PMU outage, placement of PMU on radial bus is ensured while implementing modified SA. The result of the proposed strategy on modified SA to find out the optimal number of PMU is less than the finding of modified SA for the higher number of bus system. In some system, although the result in terms of the number of PMU seems to be equal, the probability of finding the optimal number is more. Also, the measurement redundancy of the placement set has been significantly increased.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

The following conclusions have been drawn from the thesis.

- The optimization problem for the OPP has been formulated for three different cases considered in the thesis. The objective function for all cases is defined for the minimum number of PMUs required to ensure complete power system observability. The constraint function for normal operation and single PMU outage can be represented by linear function while it is nonlinear for consideration of ZIB.
- The optimal number of PMUs required for the normal base case in IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, and IEEE 118 bus system is 4, 10, 17, and 34 respectively. In order to ensure observability, PMU should be approximately installed at an average of 30.32% of the total number of buses.
- With the consideration of a single PMU outage, the required optimal number of PMUs for IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, and IEEE 118 bus system are 9, 21, 33, and 68 respectively. Approximately PMU should be installed at 63.72% of the total number of buses.
- For IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, and IEEE 118 bus system consideration of ZIB has reduced the number of PMUs to 3, 7, 12, and 30 respectively. In order to ensure observability, consideration of ZIB reduced the optimal number of required PMU to approximately 23.99% of the total number of buses.
- For the existing INPS 90 bus system, proposed modified SA results out 28, 62, and 26 numbers of PMUs for the case I, case II, and case III respectively.

Some of the major recommendations are listed below.

- The existing equipment of INPS substation might be PMU incompatible so the cost of installation of PMU on each substation might be different. Consideration of different levels of cost can ensure a better optimal solution.
- In order to achieve better reliability, critical lines, and their losses can be considered while formulating connectivity matrix and optimization problems.

- PMUs have finite channel limit which varies with manufactures. Channel limit can be considered while implementing the OPP problem.
- The OPP problem can be done with the consideration of the future expansion of INPS. NEA has already planned to install PMU on five cross-border substations (New Butwal, Hetauda, Dhalkebar, Inaruwa, and Duhabi). The OPP problem can be solved with the consideration of remaining part of INPS only.
- To find the best solution, the researcher can develop a new algorithm by using the concept of machine learning or some way of data mining to organize a new algorithm.

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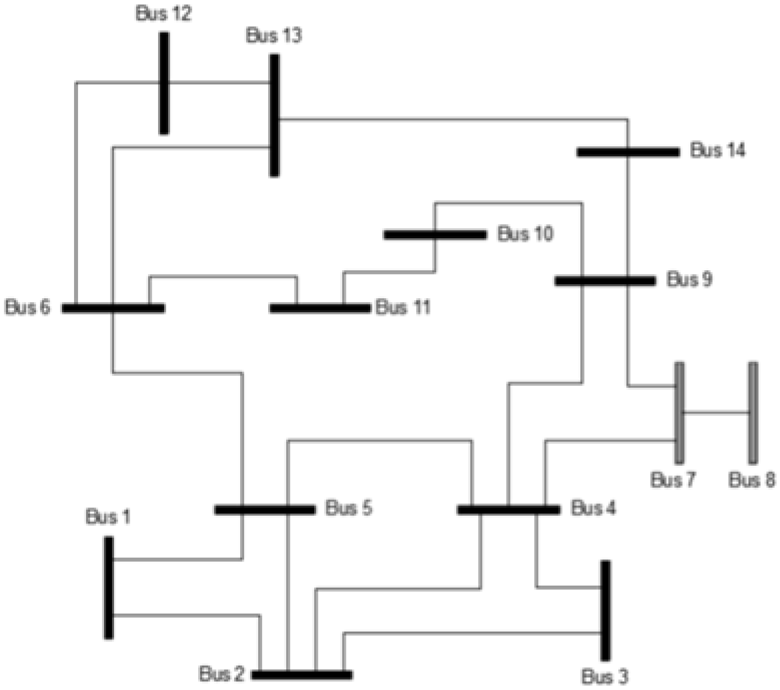
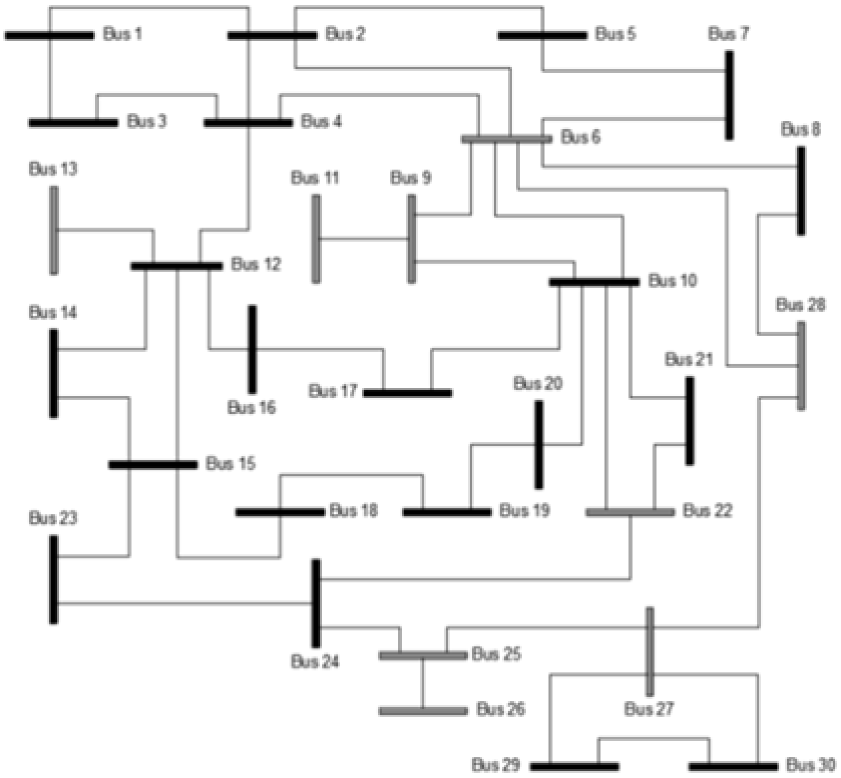
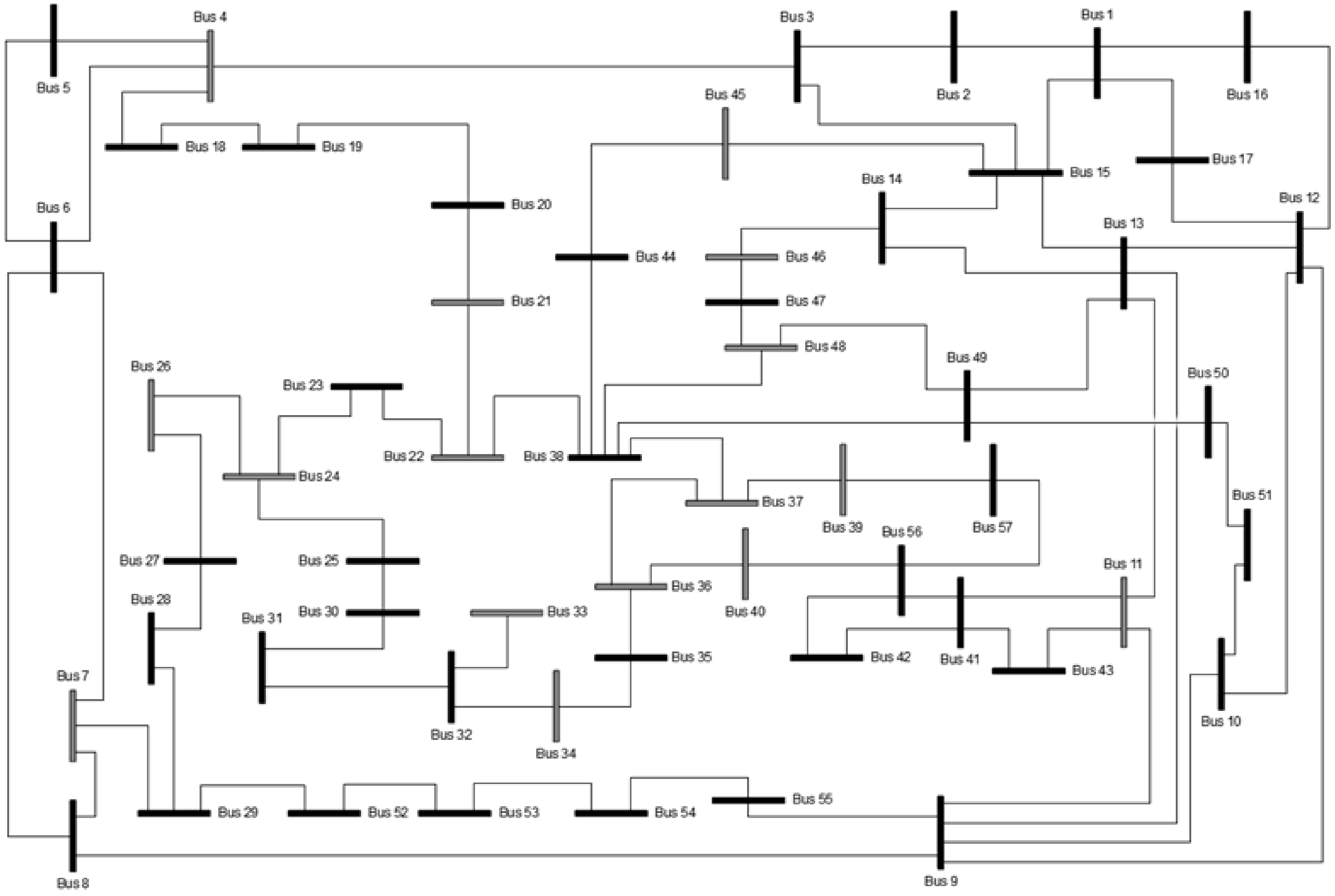
APPENDIX A: Single Line Diagram of IEEE 14 Bus System



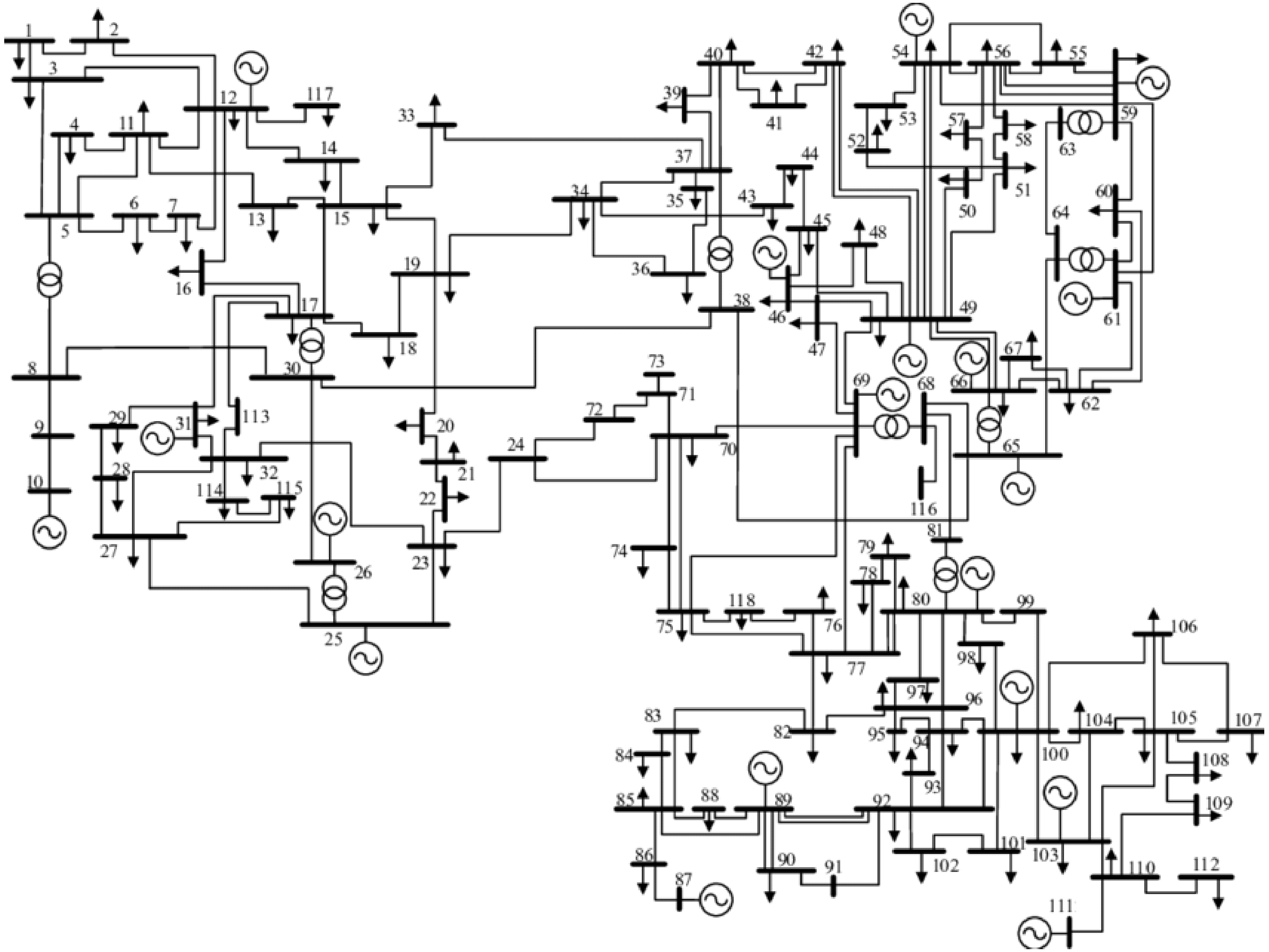
APPENDIX B: Single Line Diagram of IEEE 30 Bus System



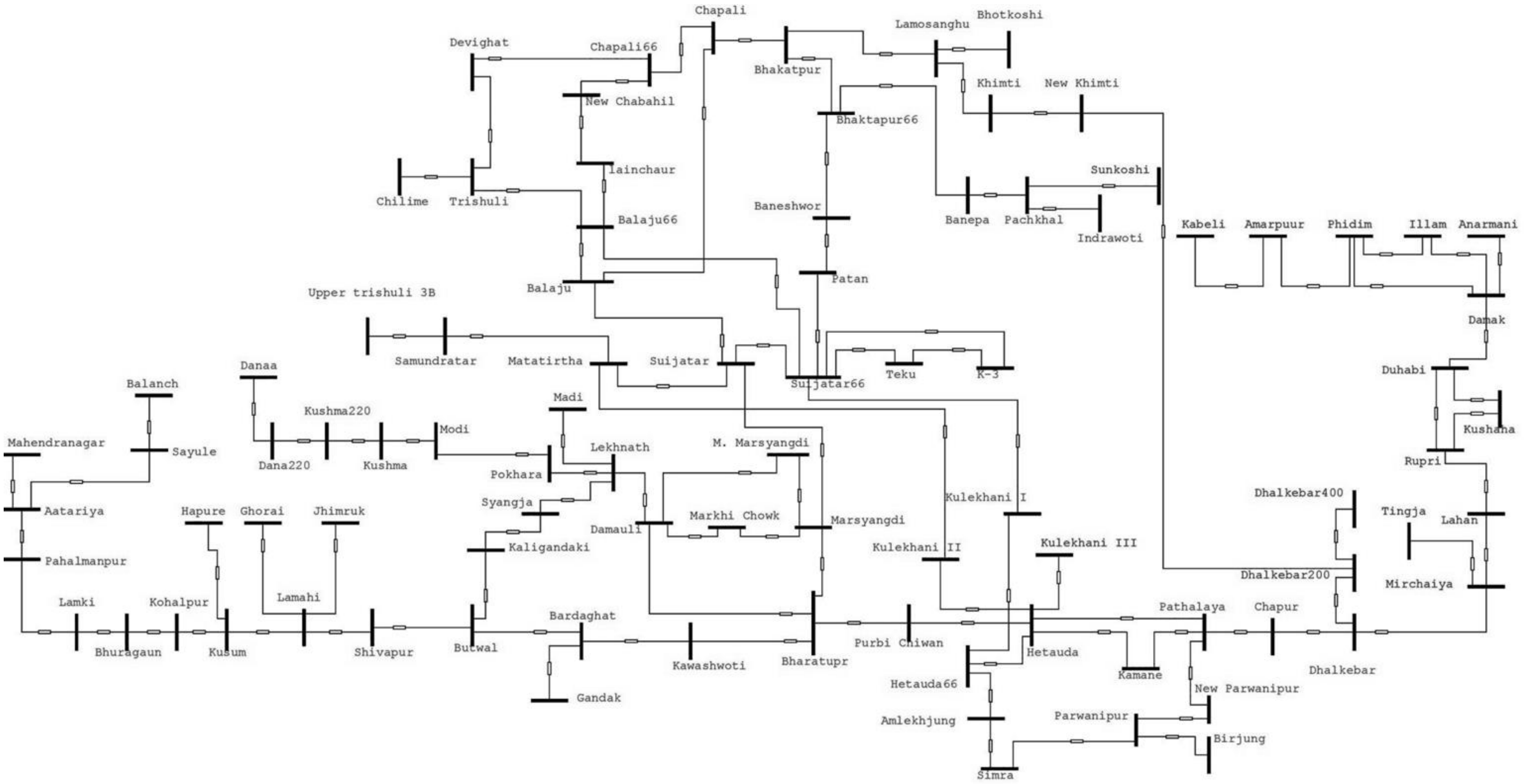
APPENDIX C: Single Line Diagram of IEEE 57 Bus System



APPENDIX D: Single Line Diagram of IEEE 118 Bus System



APPENDIX E: Single Line Diagram of INPS 90 Bus System



APPENDIX F: Pseudo-code

I: For Mofied SA Algorithm

```
Input= placement_initial, radial buses
Output= placement_best
1    Set T=15
2    Set Iteration=0
3    Placement_best=placement_initial
4    Do while Iteration < number of buses
5        placement=placement_best
6        E_best=0
7        Set i=1
8        Do for i<number of buses
9            i=i+1
10           placement_new=Randomize placement_best with reference to radial
             buses
11           E_new= number of unobservable buss for placement_new
12           If E_new=0 and new placement set don’t have more number of PMU
13               Accept new solution as best solution and set Iteration=-1
14               Goto 8
15           Delta_E= E_new-E_best
16           If Delat_E>0 and random number>exp(-Delta_E/T)
17               Reject new solution
18               Goto 8
19           Placement=placement_new
20           E_best=E_new
21           Goto 8
22       Iteration= Iteration+1
23       T=0.879*T
24       Goto 4
25   Return placement_best
```

II: For Randomize(Placement_Best) Function

```
Input = placement_best, radial_buses
Output = placement_new_configuration
        placement_new_configuration = placement_best
        If flipping possible and random number>0.5
Flip a random position on placement_new_configuration
Restrict/ensure PMU on radial buses of placement_new_configuration
        End
        Else,
Exchange random PMU position
Restrict/ensure PMU on radial buses of placement_new_configuration
        End
Return placement_new_configuration
```

APPENDIX G: MATLAB Code

I. For main program ‘mainv1SLg.m’

```
%Main file
%Run for OPP problem
%Ask User to select Test bus system
fprintf('1: IEEE 14 bus system\n2: IEEE 30 bus system\n3: IEEE 57 bus
system\n4: IEEE 118 bus system\n5: Integrated nepal power system\n ')
while true
    c = input('Pleas input 1, 2, 3, 4: ');
    if c == 1
        data = case14v1();
        test_case = 'IEEE 14-bus System';
        break;
    elseif c == 2
      data = case30v1();
      test_case = 'IEEE 30-bus System';
        break;
    elseif c == 3
       data = case57v1();
       test_case = 'IEEE 57-bus System';
         break;
    elseif c == 4
        data = case118v1();
        test_case = 'IEEE 118-bus System';
       break;
     elseif c == 5
        data = caseinpsv1();
        test_case = 'INPS bus system';
       break;
    end
end
%% Simulated annnealng method on bus name to display and continue.
fprintf('\n')
fprintf('Simulated Algorithm is being used for %s \n',test_case);
while true
    c = input('Press 1 for Normal case without consideration of ZIB
\nPress 2 for single PMU outage without considertion of ZIB \nPress 3
for case with consideration of ZIB  \n');
    if c == 1
        alg = 'SAnoZIB';
        break;
    elseif c == 2
        alg = 'SAoutage_noZIB';
        break;
    elseif c == 3
        alg = 'SAwithZIB';
        break;
    end
end
clear c;

%% Import data for selected bus system
%Import Connecivity matrix
A=data.A;
% Import Zero injection buses
ZI_buses= data.ZI_buses;
% The number of buses in the system
[num_buses, ~] = size(data.A);
```

```
%radial bus import
radial_buses=data.r_buses;
%% Begin Solving the Optimal PMU placement
fprintf('\nSolver starts work...\n');
%Function call PMU_SA with input of connectivity matrix, ZI_buses and
radial bus
eval(sprintf('[p, m] = PMUv1_%s(A, ZI_buses, radial_buses);', alg));
fprintf('\n======================================================\n')
fprintf('Test Case: %s', test_case)
fprintf('\n======================================================\n')
fprintf('\n');
fprintf('No. of PMUs: %d\nPlacement (bus no.):\n', length(p));
for i=1:1:size(p,1)
    fprintf('  ')
    fprintf('%d ', p(i,:));
    fprintf('\n')
end
fprintf('\nTime taken:%fs\n\n', m.time)
clear p alg test_case;
%% BOI and SORI Information
%BOI
fprintf('\nBus obsevability index')
BOI=(m.BOI)'
%SORI
fprintf('\nSystem obsevability Redundency index')
SORI= sum(m.BOI)
clear m;
%% Clear global system variables
clear data num_buses A ZI_buses radial_buses;
```

II. Proposed Modified SA with Consideration of ZIB

```
%OPP for the case with consideration of ZIB

function [ placement, msg ] = PMUv1_SAwithZIB( A, ZI_buses,
radial_buses, varargin)
%% Input Check
narginchk(1, inf);
if nargin() < 2
    ZI_buses = [];
end
%% The name of the method currently is employed.
msg.method = 'Simulated Annealing Method ';
%% Initialize the timer, and the search will begin right now.
SA_timer = tic;

%% The amount of buses in the given system
num_buses = length(A);

%% Initialize X vector
% X is a vector composed of 1 and 0, where 1 represents a PMU is
installed at that bus and 0 otherwise.
%initialize all bus with PMU first
p=ceil(1*num_buses);
X = zeros(1, num_buses);
X(1,randperm(num_buses,p))=1;

%% load r to be radial bus
r=radial_buses;
```

```
%% Unobservability check
% E is the amount of unobservable buses
E = @(observability) length(find(observability<1));

%% Initialize Temperature Parameter
T0 = 15;

%% Change the adjacent matrix into the vector format for searching
speed
adj = cell(num_buses, 1);
for i=1:1:num_buses
    A(i,i)=0; %make diagonal element zero
    adj{i} = find(A(i,:)~=0);
    A(i,i)=1;
End

%% formulate constraint function F(X)in the form cell array equ{}
% Construct the linear function without consideration of ZI buses
% e.g f(1)=X(2)+X(4) if bus 1 is connected to bus 2 and 4
equ = cell(1,num_buses);
for i=1:1:num_buses
    equ{i} = sprintf('f(%d)=X(%d)%s;', i, i, sprintf('+X(%d)',
adj{i}));
end
% Inclusion of ZIB i.e Revise the linear constraint function into a
nonlinear function.
%e.g f(4)=X(4)+X(3)+f(5)+(f(3) or f(5)) if bus 4 is zib and connected
to  bus 3 5
for i=1:1:length(ZI_buses)
    equ{ZI_buses(i)} = sprintf('%s+~any([%s]==0);',
equ{ZI_buses(i)}(1:length(equ{ZI_buses(i)})-1), sprintf('f(%d) ',
adj{ZI_buses(i)}));

    num_of_incidents = length(adj{ZI_buses(i)});
    for j=1:1:num_of_incidents
        incidents = adj{ZI_buses(i)};
        incidents(j) = [];
        incidents(num_of_incidents) = ZI_buses(i);
        equ{adj{ZI_buses(i)}(j)} = sprintf('%s+~any([%s]==0);',
equ{adj{ZI_buses(i)}(j)}(1: length(equ{adj{ZI_buses(i)}(j)})-1),
sprintf('f(%d) ', incidents));
     end
end
% Construct the function
constraint_function = strjoin(equ, '\n');
function f = F(X) %here f is function name input X i.e placement set.
To return the evalutated constraint function for given X locally
    f=zeros(num_buses,1);
    c_f = f;
    % non linear constraint function should be calculated several
times until its value could not change anymore.
    while true
        eval(constraint_function);
        if c_f == f
            break;
        else
            c_f = f;
        end
    end
```

```
end

%% Consider the initial solution as the best solution found i.e all
bus with indivisual PMU
X_best = X;
% Warning message may appear due to a too huge value
warning('off','all');

%% Search starts
T = T0;
T_diminished = 0;
while T_diminished < num_buses
    X = X_best;
    E_X = 0;
    for i = 1:1:num_buses
        % Achieve a new placement
        X_new = Randomize(X,r);
        % the observabiltiy of the newly generated placement
        ob = F(X_new);

        % the the number of unobservable buses when the newly
generated placement is applied
        E_nX = E(ob);

        % If fully observable when the newly generated placment is
applied
        if E_nX == 0 && nnz(X_new) < nnz(X_best)
            % better solution
            X_best = X_new;
           T_diminished = -1;
            break; %break from inner nested loop
        end
    delta_E = E_nX - E_X;
         % reject the worse, new solution in probability
        if delta_E > 0 && rand > exp(-1 * delta_E / T)
            continue;
        end
        X = X_new;
        E_X = E_nX;
    end
    % The times of continuously failing
    T_diminished = T_diminished + 1;
    % Annealing
    T = 0.879 * T;
end
%% Arrange the result
placement = find(X_best == 1);
%% Timer should be over
msg.time = toc(SA_timer);
%% BOI calculation
X=zeros(1,num_buses);
X(1,placement)=1;
f=zeros(num_buses,1);
eval(constraint_function);
  for loop=1:1:num_buses
      if f(loop)==0
          f(loop)=1;
      end
 end
msg.BOI=[f];
end
```

```
%% Randomly generate a new configuration from the given configuration
function new_configuration = Randomize(X,r)
    os = find(X==1);
    zs = find(X==0);
    if or(or(isempty(zs), isempty(os)), rand > 0.5)
        % Flip
        new_configuration = X;
        tar_index = unidrnd(length(X));
        if X(tar_index) == 0
            new_configuration(tar_index) = 1;
            new_configuration(r)=0; % exclude Radial bus
        else
            new_configuration(tar_index) = 0;
            new_configuration(r)=0; % exclude Radial bus
        end
    else
        % Exchange
        candidate1 = zs(unidrnd(length(zs)));
        candidate2 = os(unidrnd(length(os)));
        new_configuration = X;
        new_configuration(candidate1) = 1;
        new_configuration(candidate2) = 0;
        new_configuration(r)=0; %exclude radial bus
    end
end
```

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