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A Review of Various Optimization Strategies for Handling Optimal PMU Placement Problems

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Abstract: ***The Phasor Measurement Unit (PMU) is the most fundamental power system technology that is utilized to protect, monitor, and control power networks. It not only allows real-time, synchronized voltage measurements on the buses but also the current phasor of lines connected to the buses where these PMUs are placed. The positioning of PMUs at each bus node is unnecessary and is restricted by the installation's high cost and complexity. As a result, the fundamental goal of Optimal PMU placement (OPP) is reducing the total no. of PMUs along with maximum observability, while simultaneously considering measurement redundancy. There are several methods for fixing this problem, and they fall into two categories: Metaheuristic methods and mathematical approaches. This study examines a variety of optimization strategies for handling OPP problems.***
Keywords: Phasor Measurement Unit (PMU), Optimal Placement of PMU (OPP), State Estimation (SE), Supervisory Control and Data Acquisition (SCADA), Zero Injection Buses (ZIB), Wide Area Monitoring Protection and Control (WAMPAC), Meta-Heuristic algorithm, Conventional techniques;

I. INTRODUCTION

Due to technological breakthroughs and rising living standards worldwide, there has been an increase in the need for power in recent years. In such a situation, a system that not only monitors but also precisely measures instruments is required for proper and steady power system function. This duty was priorly accomplished by SCADA, which relies on unsynchronized measurements to estimate system states [1]. The voltage magnitudes of buses, as well as their real and reactive powers, are provided by SCADA, although measurements based on SCADA are delayed due to their slow duty cycle. Furthermore, traditional measurement instruments do not offer bus voltage angles. The WAMPAC technology is utilized to solve these restrictions in the SCADA and to measure the angles of the bus [2] [3]. “A. G. Phadke et al. (2005) the main components of this system are Phasor Measurement Units (PMUs), which offer real-time and synchronized voltage as well as current phasor measurement. Synchronized data is collected when voltage and current signals get sampled along with the timing signals from the GPS (Global Positioning System) satellite at the same time [4] [5]”. PMUs directly calculate the voltage phasor data of all the buses on which they are located, even the current phasor data of the lines that intersect that bus. Unfortunately, the cost of PMUs and their communication services are uneconomical, so it’s impractical to put these units on all of the buses.

“Cherukuri Murthy et al. (2016) PMU accumulates the analog waveform as input data i.e. current and voltage signals from the current transformer (CT) and potential transformer (PT) respectively and then passes to the anti-aliasing filter which is used to avoid an aliasing error. Afterward, these signals are forwarded to the A/D converter which samples the analog voltage and current signals using a sampling clock that is in phase synchronization with the GPS receiver. The central processing unit (CPU) receives the transformed digital signals, processes them as per the algorithm, and outputs the magnitude and phase values of the primary input signal [6]”. Figure 1.1 depicts the acknowledged process quite clearly.

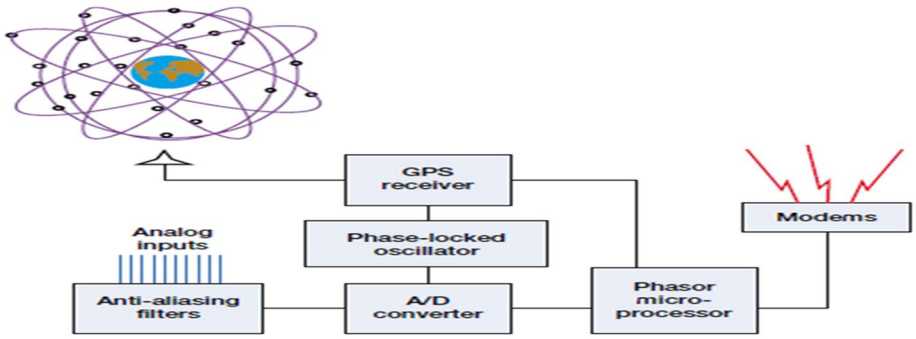


Fig.1. 1 PMU Block Diagram

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II. OPTIMAL PMU PLACEMENT PROBLEM(OPP)

To place no. of PMUs optimally for observing the whole power network thoroughly, an ideal methodology is necessary. Several approaches are developed for solving the Optimal PMUs Placement (OPP) problem. These techniques are usually classified into 2 classes: conventional and metaheuristic. To tackle OPP, traditional techniques such as Linear Programming are offered. "Heuristic and Metaheuristic optimization methodologies such as Simulated Annealing, Spanning Tree, Particle swarm optimization, Cat Swarm Optimization, Ant Colony Optimization, and many more algorithms are mentioned [7] that overcome issues such as difficulties to obtain local minima and handle constraints in conventional techniques". This study presents a review of research and studies on traditional and advanced heuristic and metaheuristic optimization strategies for solving the OPP problem i.e., placing PMUs optimally in a power system.

III. MATHEMATICAL PROGRAMMING METHODS

Integer Programming (IP), often known as mathematical programming, is one of the most widely used approaches for numerical programming [7]. This approach has been used to resolve issues involving integer design components. Based on the variety of objective functions and constraints, which may be linear or quadratic, integer programming is divided into integer linear programming (ILP) and integer quadratic programming (IQP).

A. Integer Linear Programming (ILP)

Reference [8] presents a technique for reducing the no. of PMUs strategically placed, resulting in the elimination of criticality in power network measurement. Traditional measurements are included in the approach during PMU placement. Furthermore, when a specific level of redundancy is required, the method is proven to have the same formulation. Then, by extending the placement problem, typical conventional measurement was integrated. If a preferred amount of general redundancy is taken into account, the same algorithm can be used to locate the optimum positions. The identification of bad data improves as the redundancy level rises.

"In reference [9] C.Rakpenthai (2007) introduced a modern algorithm for placing the no. of PMUs optimally observe the entire system in case of any contingency. The proposed algorithm works in 4 stages, with the first stage determining the essential measurement for an entirely known state. It then selects duplicate measurement sets in case of any contingencies in the next stage. To select the Suitable measurement location, both stages use the least condition no. in the normalized measurement matrix. Furthermore, using the binary integer programming technique, the least redundant measurement set is selected out of all accumulated measurements." Finally, these measurements, both important and minimally redundant, are organized for optimal PMU placement. The heuristic method is utilized for this.

"Bei Gou proposed a universal formulation in ref. [10], for optimally placing PMU, which is required for entire system observability considering and not considering zero injection buses. In [11], he introduced the PMU placement model of ILP".

ILP is suggested to do the multistage placement of PMUs in Ref. [12]. Constraints on ZIBs are expressed as linear constraints. "The OPP problems have various results, two best ones which are been proposed: The number of times a bus is seen by a set of PMUs is known as the bus observability index (BOI), whereas the system observability redundancy index (SORI) is calculated as the total of all the BOIs at each bus location [12]. The best set for PMU placement is the one with the highest SORI. The outcomes of the proposed technique are shown in Tables 3.1.1 and 3.1.2.

Table 3.1.1- Minimum no. of PMUs while excluding and including ZIBs

S. No.	IEEE Systems	No PMU Outage		Single PMU Outage	
		Without Modeling Zero-Inj	Modeling Zero Inj	Without Modeling Zero-Inj	Modeling Zero inj
1	14 bus	4	3	9	7
2	57 bus	17	14	33	29
3	118 bus	32	29	68	64

Table 3.1.2- Comparing SORI while excluding and including ZIBs (Initial SORI - Final SORI)

S. No.	IEEE Systems	No PMU Outage		Single PMU Outage	
		Without Modeling Zero-Inj	Modeling Zero Inj	Without Modeling Zero-Inj	Modeling Zero Inj
1	14 bus	16-19	15-15	34-39	31-33
2	57 bus	67-72	58-61	126-130	111-113
3	118 bus	156-164	148-152	298-309	290-297

"N.H. Abbasy (2009) [13] proposes a unified technique for concluding the OPP problem as well as making the entire system completely observable. Under standard measurements with either single or several PMU losses contingency, the suggested method considers a choice strategy for the best PMU allocation. Placement problem as BILP (Binary Integer Linear Programming) is formulated by the branch–bus model of this system."

To estimate the optimum number of PMUs, reference [14] offered ILP with a rapid and new practical model. Line outages and measurement losses are examples of power system contingency conditions. Because various situations can be handled independently or all at once in the power system, the suggested model is more flexible than the existing model. In addition, the model includes measurement concerns, such as power network communication constraints. This strategy has a key benefit, in that it provides a local optimum solution for large-scale power systems in a short amount of time. The outcomes of the technique are shown in Tables 3.1.3 and 3.1.4.

Table 3.1.3- Characteristics of IEEE standard test systems

Test Bus Systems	IEEE 14-Bus	IEEE 30-Bus	IEEE 39-Bus	IEEE 57-Bus	IEEE 118-Bus
No. of lines	20	41	46	80	186
No. of ZIBs	1	6	12	15	10
Max. no. of lines connected to the bus	5	7	5	6	12

Table 3.1.4- Minimum no. of PMUs for the IEEE test systems in a different state

Test Bus Systems	IEEE 14-Bus	IEEE 30-Bus	IEEE 39-Bus	IEEE 57-Bus	IEEE 118-Bus
Base Case State	3	7	8	11	28
No PMU at ZIBs	3	7	8	11	28
Line Outage	7	13	15	19	53

"In ref. [15], a Binary Integer Linear Programming (BILP) approach for the entire observability of a power system along with the no. of PMUs placed optimally is shown, as well as a strategy to maximize redundancy not only under normal conditions but also in the fault conditions like PMU failure or line outage". OPP issue is expressed as a binary integer problem with linear variables constraints. In the power system, the suggested method included the zero-injection bus effect. This method was put to the test on both IEEE standards and wide-scale systems, results are mentioned in Table 3.1.5.

Table 3.1.5- No. of PMUs for observability & SORI

IEEE systems	Number of PMUs	Execution time (s)	SORI
14-Bus	3	<1	16
30-Bus	7	<1	41
39-Bus	8	<1	43
57-Bus	11	<1	59
118-Bus	28	<1	156

B. Integer Quadratic Programming (IQP)

The connectivity matrix represents network topology and is used to describe the OPP problem. The optimization of the quadratic objective function can be done by including both linear constraints as well as the variable integer value [7]. This procedure going to help in optimizing the number of PMUs by providing complete observability both in normal conditions as well as during an outage situation.

The system is topologically observable using the optimum PMU placing strategy discussed in [16]. IQP technique minimizes the no. of PMUs along with keeping the power system completely observable under the normal condition as shown in Table 3.2.1 and the time required by the CPU to find the optimal PMU locations for various bus systems is mentioned in Table 3.2.2. This strategy also maximizes the system's measurement redundancy.

Table 3.2.1- Minimum no. of PMUs for observability of the entire system under normal conditions

Minimum no. of PMUs	Test Systems
4	IEEE-14 bus
10	IEEE-30 bus
17	IEEE-57 bus
32	IEEE-118 bus

Table 3.2.2- Computational time needed to find the optimal PMU sites

Test System	Computational time	
	Normal operating conditions	Considering PMU outages
IEEE 14-bus without conventional measurements	3.09s	9.72s
IEEE 14-bus with conventional measurements	5.31s	8.77s
IEEE 30-bus	2.60s	4.24s
IEEE 57-bus	4.24s	4.51s
IEEE 118-bus	3.09s	4.70s

IV. HEURISTIC AND META-HEURISTIC METHODS

A. Simulated Annealing (SA)

Simulated Annealing (SA) is a metaheuristic inherited probabilistic technique. Its major goal is to obtain a roughly reasonable solution independent of the optimal solution for a certain period. This method is generally utilized for discrete search areas. The goal is to discover a fine enough solution other than the most feasible answer in a certain period.

Based on the incomplete observability of the system, the SA approach proposed in [4] suggests a strategy or optimum placement of PMU. First, it makes the system observable and determines the no. of PMUs required by considering the spanning trees of the system graph. This effect of an innovative concept called "depth of unobservability" on the no. of PMUs placed is then presented. This approach also produces appropriate solutions for the PMU placement issue with a communication restriction.

SA was used in [17] to maximize the measurement's redundancy. Moreover, the impact of zero injection bus on system visibility is considered to lessen the no. of installed PMUs without having a significant effect on complete observability. To verify the consistency, efficiency, and effectiveness of the technique, several IEEE standard-bus systems have been examined. Another study [18] uses a multistage SA technique to determine the ideal location for combining PMUs and conventional measurement units. This approach can discover the optimum locations more quickly than other algorithms based on uphill motions across multiple phases, which enables it to arrive at the best solution. It is quicker than other standard SA methods.

B. Genetic Algorithm(GA)

One of the most popular heuristic algorithms is the genetic algorithm (GA), an adaptive search method that can replicate the process of natural evolution to discover the solution [7].

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In ref [19] a non-dominated sorting evolutionary algorithm is mentioned that addresses the issue of placing the PMUs optimally along with other objectives, namely reducing the no. of PMUs while optimizing measurement redundancy. The Pareto optimum solutions are obtained using this optimization method. To achieve an individual solution, the proposed technique first employs graph theory and then employs a basic GA procedure. As a result, the Non-dominant Sorting Genetic Algorithm is used to determine the most desirable solution, from which the decision-maker can be chosen (NSGA). The primary aspect of NSGA is providing the best Pareto-optimal solution instead of just a particular solution for multi-objective optimization problems and having a vast search space. Phasor Measurement Units are optimally installed using the Genetic Algorithm in ref. [20] so that the location of the fault in the associated network can be detected. This is categorized into two: the first involves obtaining a small no. of PMUs and placing them in the network, and the second involves detecting the location of the defect using the values collected by the placed PMUs. The method is not only just cost-effective but can also be used on any network that is connected. In ref. [21] genetic algorithm is considering complete power system observability as a mono objective while optimally placing the PMUs. OPP is accomplished in both normal and contingency situations utilizing a genetic algorithm with measurement redundancy and observability evaluation [22].

C. Spanning tree search

In Ref.[23], the spanning tree method and the tree search algorithm were used to improve the OPP problem's solution by taking into account the least channel and multichannel PMUs for optimal observability, also known as spanning tree search. The goal of this study is to investigate how observability depth affects the total number of installed PMUs in the smart grid. The spanning tree method was used to create electricity grid graphs, and the best location for PMUs was found using the tree search method. The same method was also enhanced to identify PMU channels with the least number. This method was evaluated on IEEE standard bus systems in a MATLAB environment to accomplish the objective of the problem.

D. Pollination algorithm

For solving the OPP issue, Ref. [24] offers a unique method termed the flower pollination algorithm (FPA). The pollination process of flowering plants inspired the FPA. With encouraging findings, FPA is now upgraded for various other optimizations. To provide full observability with maximum measurement redundancy at system buses, this problem tries to limit the number of PMUs used. The standard IEEE bus test systems have all been utilized to validate this method. The suggested method's results are compared to those achieved by various conventional optimization methods in Table 4.4.1.

Table 4.4.1- Comparing optimal PMUs placement results of different algorithms

IEEE Test System / Algorithm	The proposed FPA	BPSO	Greedy Algorithm	BILP
IEEE 14-bus	4	4	4	4
IEEE 30-bus	10	10	NA	10
IEEE 57-bus	17	17	NA	17
IEEE 118-bus	32	31 NFO	NA	32

E. Tabu Search (TS)

“This algorithm [25] is a local search metaheuristic technique. By tracing and guiding the search, this approach is utilized to solve problems involving combination optimization.”

The OPP problem is formulated with great accuracy and minimal processing cost using the proposed algorithm. Using a quick observability analysis method, the network's full observability is ensured. As a result, as compared to conventional observability analysis, this method provides faster and more accurate results. TS consist of an augments incidence matrix that manipulates an integer number of state estimate models to fast and easily obtain network observability [25].

F. Best-first search algorithm

The best-first search (BFS) algorithm is utilized in Ref. [26] to attain the OPP with complete observability. A pruning strategy was used to cut down on the overall number of measurement devices already determined by BFS as well as the measurement redundancy of systems created by BFS.

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In an IEEE test system, such as the IEEE 14, 30, and 246-bus systems, the aforementioned tactic is shown in operation. After excluding all the radial buses from every PMU placing site it is well known that the amount of PMUs needed for complete observability of the entire system is now reduced. In Table 4.6.1 comparison of the results demonstrates that this technique is significantly more precise than other techniques, such as ILP.

Table 4.6.1- Comparing results of the proposed method with the ILP method

Test System	ZIB included		ZIB excluded	
	ILP	Proposed Method	ILP	Proposed method
IEEE 30-bus	4	4	3	3
IEEE 57-bus	10	10	7	7
IEEE 118-bus	84	77	70	57

G. Teaching–learning-based optimization technique

In Ref. [27] this method is utilized for OPP problems with and without involving ZIBs. This algorithm produces results that are distinct from those of other optimization approaches like GA and BPSO, and it is more effective overall. Moreover, the need for several constraint settings in GA and BPSO reduces the procedure's effectiveness. The teaching-learning-based optimization (TLBO) method, on the other hand, doesn't require a lot of adjustments to its settings and variables. The optimal number of PMUs without ZIB resulting from this method is compared to already existing techniques in the following Table 4.7.1. As can be seen in Figure 4.7.1, the suggested TLBO strategy is therefore easier to implement and converges more quickly than existing approaches.

Table 4.7.1: -Optimal number of PMUs without ZIB

Test Systems	The optimal number of PMUs		
	GA	BPSO	TLBO
IEEE-14 bus	4	4	4
IEEE-30 bus	10	10	10
IEEE-57 bus	17	17	17

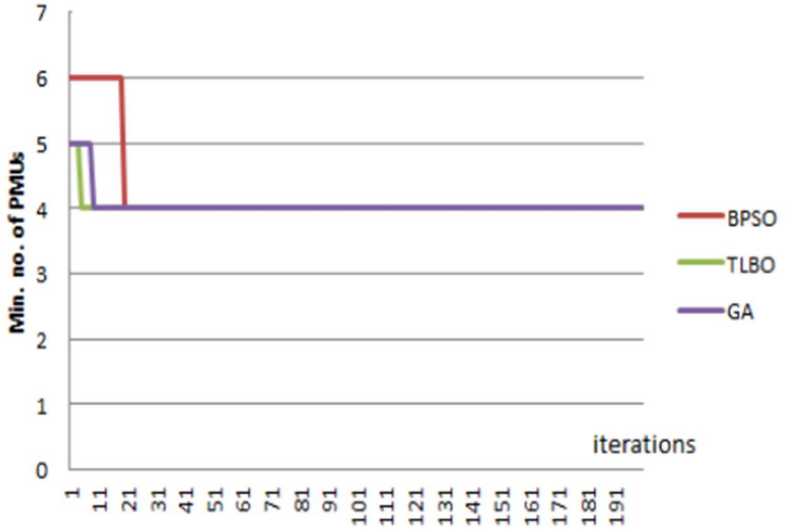


Fig. 4.7.1 Comparative analysis of convergence characteristics

H. Exhaustive Search (ES)

ES is an analytical approach & algorithmic pattern that considers all possible solution candidates and determines whether or not every candidate satisfies the problem statement. The approach is referred to as exhaustive since it guarantees to deliver all accessible states before terminating with a unit failure.

To achieve OPP in Ref. [28], ES is carried out utilizing the ILP. The suggested method included the ZIB. While observing the entire network, the single-line contingencies are even considered. Since the method requires less computing, therefore global optima can be obtained over a very short duration.

For approximate optimal PMU placement, a sophisticated technique known as LEA (Limited Exhaustive Approach) is utilized, which is declared from a complete examination of the power network system. LEA maintains the advantages of ES, which is extremely reliable, preventing it to stuck at local optima. It even reduces the search space, making it a lot quicker than ES [29]. The ES technique is used to perform OPP, with ZIB taken into account [30]. For the OPP problem, [31] proposes an upgraded optimized form of ES called reduced ES. In comparison to ES, it minimizes the search space and the no. of computations required while considering the presence of PMU outage and ZIB. The suggested algorithm out performs ILP and ES in terms of results i.e. mentioned in Tables 4.8.1 & 4.8.2.

Table 4.8.1-OPP minimum PMU count

Test Systems	Base Case / ZIBs / Single PMU Outage								
	ILP			ES			RES		
IEEE 9-bus	3	2	6	3	2	6	3	2	6
IEEE 14-bus	4	3	9	4	3	9	4	3	9
IEEE 24-bus	7	6	14	-	-	-	7	6	14
IEEE 30-bus	10	7	21	-	-	-	10	7	21
IEEE 39-bus	13	8	28	-	-	-	13	8	28

Table 4.8.2-Runtime

Test Systems	Methods	IEEE 9-bus	IEEE 14-bus	IEEE 24-bus	IEEE 30-bus	IEEE 39-bus
Base Case / ZIBs / Single PMU Outage (sec)	ILP	1.60	3.847	2.439	-	-
		14.72	0.16	375.4	-	-
		0.27	3.77	22.88	-	-
	ES	0.09	3.573	-	-	-
		0.09	4.253	-	-	-
		0.109	3.004	-	-	-
	RES	0.003	0.011	0.264	43.80	14.08
		0.003	0.004	0.361	6.283	1.422
		0.001	0.016	0.148	22.59	1.320

I. Particle Swarm Optimization (PSO)

PSO is a population-based probabilistic optimization technique that was established according to the social activities of flocking (behavior shown by a group of birds flying).

"In Ref. [32] an updated discrete binary PSO (BPSO) is being used for placing PMUs optimally to solve OPP issue and even for acquiring maximum measurement redundancy at every bus in the power network system. "On a variety of standard IEEE bus systems, this technique has been successfully utilized. This method has been applied in a substantial portion of the Brazilian power system to further test its viability.

The method offers the advantages of simplicity, quickly optimizing adjustment, vast network scalability, and multiple solutions possibilities. Local optima are generated by the algorithm, and by improving the optimization dimensions such as the no. of particles, the algorithm runs and iterations their quality can be upgraded.

OPP is carried out in [33] utilizing an updated PSO technique to estimate the state of the power network system. The full observability of the network provided by the proposed technique is also checked using numerical analysis. The suggested method's results are compared to those achieved by existing optimization methods in Table 4.9.1.

Table 4.9.1- Comparing no. of PMUs stated by the proposed method and existing methods

Algorithm	No. of PMUs			Computational time		
	IEEE 14-bus	IEEE 30-bus	IEEE 118-bus	IEEE 14-bus	IEEE 30-bus	IEEE 118-bus
Proposed IPSO	3	8	31	2.31	10.13	12.54
PSO	4	10	31	2.52	12.20	14.50
ILP	4	10	-	-	-	-
Graph theory	6	10	35	-	-	-

A hybrid algorithm can offer a better solution since several methods can boost the OPP problem's feasibility in a practical situation. To solve the optimization issue and achieve maximum observability in a power system, the exponential binary PSO (EBPSO) technique has been proposed in Ref. [34].The proposed algorithm's solution potential is improved by using a non-linear inertia-weight coefficient. Two mathematical formulae are utilized to enhance the particle's position to include prior positions. For rapid and reliable convergence, two-stage filtering is used, and a single mutation operation is used conditionally to avoid stagnation. Together with the typical operational scenario, zero injection buses, single-PMU outages, and various practical scenarios are taken into account. A sigmoid function is used in the suggested method to dynamically upgrade the location of each element in the binary procedure.

J. Ant colony optimization (ACO)

ACO is a stochastic optimization technique that uses graphs to find the finest places for the installment of PMUs. It functions similarly to an ant in an ant colony.

The ACO method is composed to answer the OPP issue of making the total power network observable [35]. As it is not necessary to calculate the transition probability every time while selecting the target site, the ACS increases calculation efficiency. It got the potential to exhibit stagnation behavior and gets trapped in local minima. To enhance the ACS in two ways, an Adaptive Stochastic Perturbing ant Colony System (ASPACS) is proposed in this [35]. To improve the algorithm's ability to avoid stagnation behavior and speed up convergence, this method adds a mechanism for adaptively modifying the pheromone trail persistence coefficient as well as stochastic perturbing. The ASPACS is better than the ACS in terms of convergence speed and optimizing the required no. of PMUs for full observability of the system, results of a 46-bus system PMU placement problem are shown in figure 4.10.1.

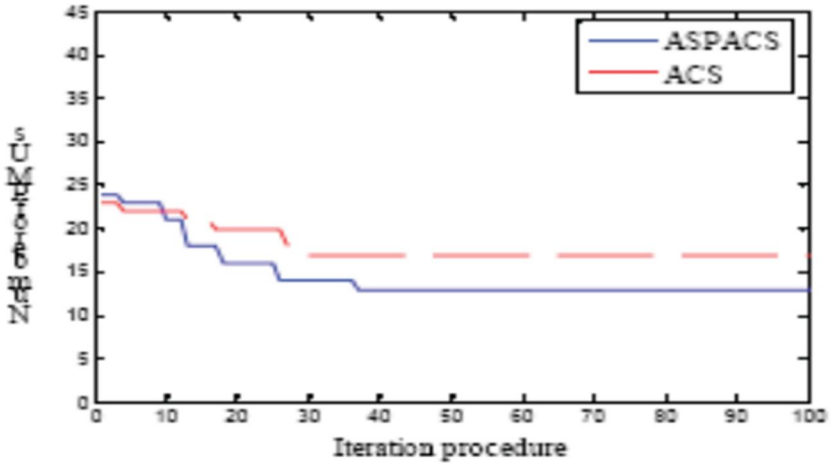


Fig. 4.10.1 Optimal PMU numbers in the iteration procedure

K. Cat Swarm Optimization Algorithm (CSO)

CSO is a transmutative strategy that is motivated by the cat's actions and even be applied to find solutions to various optimization issues. This technique has motivated many researchers in a short period and since then began to be used in a variety of areas. The cat swarm optimization (CSO) technique is also used to solve various power system challenges, one of which is determining the optimal location for distributed generators [36].

The BPSO has resulted in the proposal of a novel technique BCSO, which is an upgraded version of the above-mentioned CSO. The position vector is one of the primary differences that distinguish BCSO from CSO. The various combinations of zeros and ones in BCSO define the position vector. There are 2 stages in BCSO: Seeking and Tracing Mode. BCSO is presented in ref.[37] for the placement of PMUs optimally and for making the system fully observable. This research also compares the minimal no. of PMUs needed for making IEEE standard bus systems observable using various existing optimization strategies.

L. Binary Grey Wolf Optimization (BGWO)

GWO is a recently developed meta-heuristic algorithm based on grey wolf hunting behavior. A novel binary variant of the Grey Wolf Optimization technique (BGWO) is mentioned in this study [38] to handle the problem regarding optimal PMU placement as the results are limited to binary values (0,1). This novel method is not only feasible to implement but also tends to be the finest optimal solution. The BGWO technique is presented to reduce PMU numbers while increasing measurement redundancy (MR), considering the effect of ZIBs, single PMU failure, and channel restrictions. Four IEEE standard systems are used to validate this approach as demonstrated in figure 4.12.1. To demonstrate the superiority and efficacy of the suggested technique, it is compared to other heuristic methods as shown in Table 4.12.1.

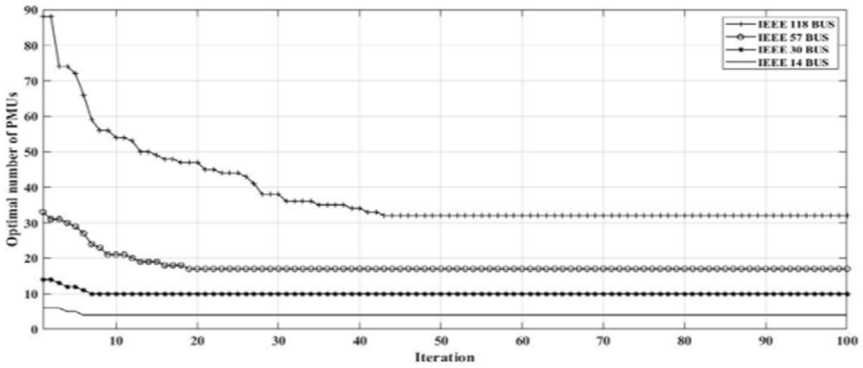


Fig. 4.12.1 Convergence graph for IEEE-14, IEEE-30, IEEE-57 &IEEE-118 under normal conditions

Table 4.12.1- Comparative results of existing algorithms with the proposed method at normal conditions.

Algorithm / IEEE bus systems	Number of PMUs			
	IEEE 14-bus	IEEE 30-bus	IEEE 57-bus	IEEE 118-bus
BPSO	4	10	17	-
Firefly	4	10	17	32
Flower pollination	4	10	17	32
GA	4	10	17	-
Proposed method	4	10	17	32

V. CONCLUSIONS

Several techniques have been executed to investigate and obtain the preferred solution for the optimal positions for the placement of PMUs. To discover the optimal placement of PMUs (OPP) in power system networks various works have been performed over the years. This paper reviewed the existing solutions for optimally placing PMUs which are categorized into two major categories: conventional mathematical methods and a heuristic algorithm. A review of various optimization approaches presented in this work to alleviate the Optimal PMU Placement problem (OPP) will serve as a guide and aid in the discovery of future optimization criterion trends.

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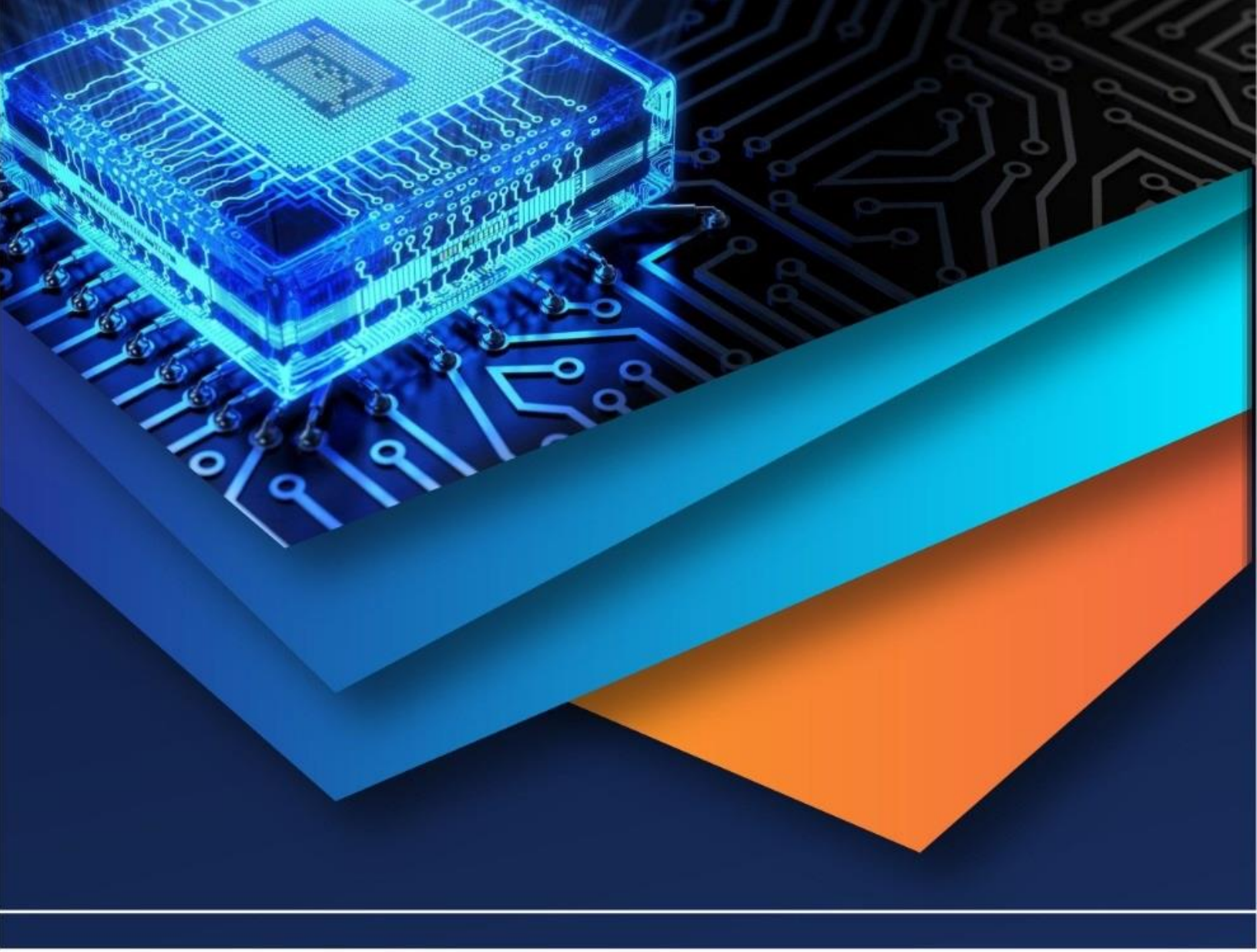
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