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Economical design of WAMS through soft computing: co-optimal PMU placement and communication infrastructure

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ABSTRACT

Recently, utilities have developed and deployed wide area measurement systems (WAMS) to improve the electricity grid's ability to monitor, manage, and defend itself. In a typical WAMS setup, multiple measuring devices, communication systems, and energy management systems work together to gather, transmit, and then analyze data. Although there is substantial interdependence among these three capabilities, most research treats them independently. The work presented here minimizes the total cost of the communication infrastructure (CI) by taking into account the price of phasor measurement units (PMUs) and the placement of a phasor data concentrator (PDC) at the same time. The optimum CI and PDC placement has been built with Steiner tree optimization's help. There have also been practical operating scenarios of more realistic working conditions containing pre-installed PMU, pre-installed fiber optic and N-1 contingency. The optimization hurdle has been overcome by utilizing the binary firefly algorithm (BFFA), which has undergone testing on IEEE 14, 30, and 118 bus systems to demonstrate its effectiveness. A comparison has been offered, and it clearly demonstrates the proposed approach's superiority over previously published articles.

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1. INTRODUCTION

An economic feasibility study is necessary for improving the efficiency of the electrical system. Report on the economic design of the electricity system for the proposed case study, taking into account the features of the economy and the communication infrastructure (CI). Planning, operating, and protecting the power system has become more challenging as a result of the deregulation of electrical networks. A supervisory control and data acquisition (SCADA)-based system, which still needs technical development, is used to monitor the state of a traditional power network using conventional metres that then transmit the measured data to it. It is the goal of electric utility to transition from a SCADA-based system to a wide area measurement systems (WAMS) that is dominated by phasor measurement units (PMUs) [1]-[4].

PMU simultaneously monitor, preserve, and control the electrical network in a substation online. Nonetheless, the PMU is overpriced. Currently, utilities and researchers both pay more attention to the best PMU placement. They are looking for the best optimal PMUs placement (OPP) problem solutions. PMUs are quite pricey machinery; hence, the objective of the OPP issue is to achieve complete power system observability by deploying the PMUs in optimal places [5]. When a PMU is installed at a particular bus, the voltage phasor can be measured directly, and the voltage phasors at other buses can be calculated. Additionally, power system observability is determined by the dependability of the PMUs that cover each bus. It is observable if the voltage phasor at a bus can be calculated. Hence, if all buses are equipped with one or more PMUs, the power system will be completely visible. The failure of just one PMU, on the other hand, result in full loss of system observability and may cause system failure if none of the PMUs were redundant [6]. Multi objective optimization (MOO) problems include the simultaneous optimization of several objectives, and most of the time there is no single best solution. Instead, the best compromise solution is used to find a solid trade-off option that meets the goals [7].

Similarly graph theory [8]-[12], mult-criteria decision making [13], particle swarm optimization [14], teaching-learning based optimization [15], and binary dragonfly algorithm [16] has been used to find a solution to the OPP issue in various scenarios, including the outage of a single PMU and an entire line. While examining the best places for PMUs to achieve various goals, the CI cost was not taken into consideration in the work mentioned above. Nonetheless, CI is crucial to WAMS, and its cost makes up a significant amount of the overall WAMS expense. Moreover, the location of placement of a phasor data concentrator (PDC) and PMU affects CI costs. Thus, it is crucial to reduce cost of WAMS by positioning PMU effectively while considering installation cost of both PMU and CI. Firefly algorithm (FFA), an innovative nature-inspired metaheuristic optimization technique, has been used in this research to locate the CI optimally such that they connect all of the PMU with the minimum distance [17].

Following is the outline of the paper. Mathematical modifications to the OPP issue were detailed in section 2 for various scenarios, such as a PMU failure, a previously installed PMU, and a previously established CI connection. The binary firefly algorithm (BFFA), or modified binary FFA, was discussed in detail along with a corresponding flowchart in section 3. Findings and analysis, if applicable, are discussed in section 4. Following the conclusion in section 5, we provide a scenario comparison.

2. PROBLEM FORMULATION

While ensuring complete system observability, the aim is to reduce the overall WAMS cost, which PMUs and CI, among others. In order to improve maximal observability and cover the impact of zero-injection buses (ZIBs), the objective function increases the system's reliability.

$$\text{Minimize } (PMU_c + CI_c) \tag{1}$$

$$PMU_c = \sum_{n=1}^{N} W_n \times \left(F_p + F_l \times C_n\right) \times V_n \tag{2}$$

$$CI_c = F_{fb} \times T_{lfb} + F_{sw} \times \sum_{j=1}^{n} ESW_j \tag{3}$$

Observability matrix of element n given by (4).

$$OM = M_c \times V_n \geq 1 \tag{4}$$

Connectivity matrix (C_{mn}) and defined as (5).

$$C_{mn} = \begin{cases} 1 \; if \; m = n \; or \; bus \; m \; and \; n \; connected \\ 0 \; otherwise \end{cases} \tag{5}$$

The ZIB effect has been obtained by (6).

$$OZ_{new} = CM \times V_n \geq 1 \tag{6}$$

The connectivity metrix (OZ_{new}) obtained from [18].
The mathematical formulation has been modified as follows.

2.1. Wide area measurement systems design with N-1 contingency

In the event of a PMU or single-line interruption, the observability of the whole network is altered. A PMU or line interruption reduces the system's observability becausethere is no longer a source or path that can be observed. The methods that follow have been developed to take into account ZIBs and how N-1 contingencies may affect PMU placement concerns.

2.2. p^{th} line outage procedures

- A zero would be entered in the connectivity matrix instead of the p^{th} line.

– Taking ZIBs into account requires the development of a new connection matrix ($C_{new,p}$) for p^{th} line interruptions.

2.3. q^{th} phasor measurement units outage procedures
– To include the impact of ZIB, Cnew would be created.
– For every qth PMU failure, a new connection matrix (Cnew,q) would be generated by setting the qth column entry to zero.

2.4. Wide area measurement systems design under pre-installed phasor measurement units contingency
PMU placed anywhere would offer visibility of that bus and connected buses. As a result, during the best WAMS design, the pre-installed constraint is applied in addition to the observability constraint in (4).

2.5. Wide area measurement systems design under pre-installed fiber links contingency
Observability of the bus and connected buses is provided via PMU installed any location. The constraint associated to preinstall is therefore incorporated during the best WAMS design together with the observability constraint in (4).

2.6. Design of communication infrastructure
Powerline communication and the optical power ground wire (OPGW) are taken into account as transmission media, and the cost related to each device is taken into account while designing the CI. Steiner tree-based methodology [19] is employed for the CI's economic design [20]. Figure 1 shows the flowchart for the Steiner tree issue to determine the minimum cost.

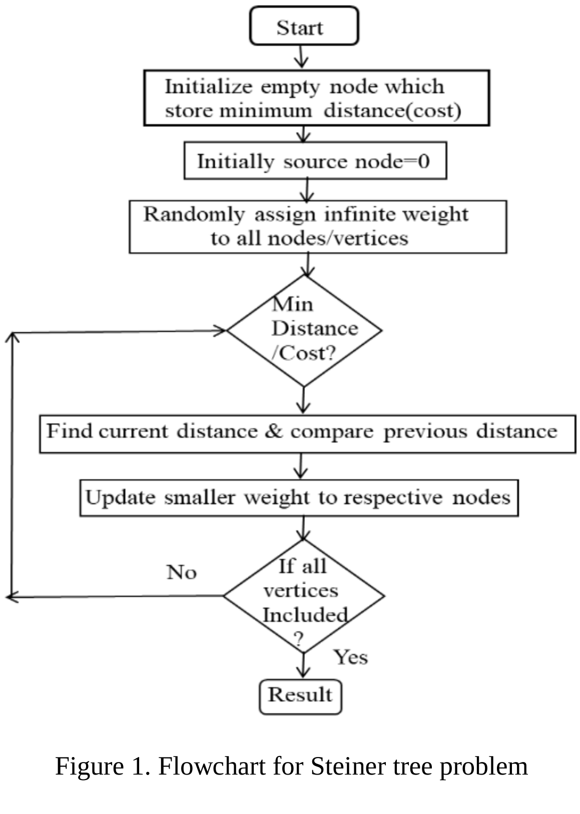

Figure 1. Flowchart for Steiner tree problem

3. FIREFLY ALGORITHM
The FFA was created by modelling the coordinated actions of swarms of fireflies, with a primary emphasis on the objective function represented by the fireflies' absolute brightness the systematic procedure of Yang's FFA. Binary values 0 and 1 are utilized in the PMU problem's optimal placement to represent the PMU state (i.e., observable or unobservable). It requires certain adjustments in order to handle the binary optimization problem. The random number generated between zero and one is the third term. The (8) accepts between 0.3679 and 2.7183 when β_0=1 and δ=1.

The equivalent fluctuation of the r_{pq} value, which can be determined using (9), ranges from -1 to 1.

$$\beta(r) = \beta_0{}^{-\gamma r2} \tag{7}$$

$$V_p^{'} = V_p + \beta(r) * (V_p - V_q) + \alpha(rand - 0.5) \tag{8}$$

V_p, V_q, and $V_p^{'}$ are firefly current position and next generation.

$$r_{pq} = I_p - I_q \tag{9}$$

When firefly position is modified, I_p' vary between 2.2180 to 4.3 and calculated using (10).

$$I_p' = I_p + \beta(r) \times \left(I_p - I_q\right) + \alpha(rand - 0.5) \tag{10}$$

To determine if observability is 1 or 0, a predetermined threshold level between 0 and 1 is used.
If the sigmoid function [10] is employed to develop the performance of the BFFA,

$$f\left(I_p'\right) = \frac{1}{1+\exp(-I_p')} \tag{11}$$

if tanh function used as given in:

$$f\left(I_p'\right) = \tanh\left(\left|I_p'\right|\right) = \frac{\exp(2^*|I_p'|)-1}{\exp(2^*|I_p'|)+1} \tag{12}$$

The BFFA flowchart is displayed in Figure 2.

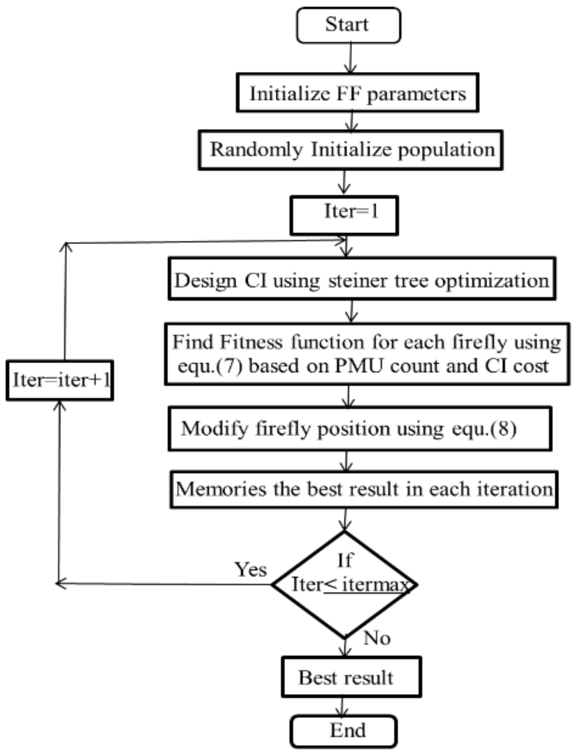

Figure 2. Flow chart of FFA for economic design of WAMS

Application of Binary coded FFA for OPP problem in PMU are as follow:
- Specify the sample size and iteration count.
- Assign a value to the control parameter within the range of ($\boldsymbol{\gamma}$, β_0, and n).
- Using (2), determine each firefly's fitness of objective function.

- Use (3) to determine fitness of objective function using Steiner tree-based technique.
- Using (1), determine each firefly's fitness of the total objective value.
- Decide which position using the objective function's lowest and greatest values.
- Using (11) to update the movement by (12).
- Use (10) to update position vector for the following iteration.
- Continue from steps 3 to 8 until the maximum number of iterations has been reached.

4. RESULT AND DISCUSSION

The optimization problem was tackled using FFA through the MATLAB R2014b software, and subsequent test cases were conducted on the IEEE 14, 30, and 118 bus test systems. Preinstalled PMUs, preinstalled fibre optic links, and N-1 contingency were taken into consideration during implementation.To address this optimization problem, information from the IEEE standard test system [21], ZIB and radial bus number and their locations [22], the line length to design CI [23], the cost of PMU installation and associated CI [20], and other sources are employed. Table 1 contains the control parameters for BFFA. The four case studies below have all been examined using BFFA for OPP problem.

- Case 1: initial baseline condition
- Case 2: N-1 contingency
- Case 3: pre-installed (PI) PMUs
- Case 4: pre-installed (PI) fiber

Table 1. BFFA control parameters

Control parameter	14 bus	30 bus	118 bus
γ	1	1.5	1.5
β_0	0.8	0.4	0.5
Constant, n	1	1	1
Population size	100	100	100

4.1. Case 1: initial baseline condition

For various standard IEEE test systems, case 1 is addressed to minimize both CI costs and the PMU quantity. Table 2 outlines the parameters selected following 30 BFFA trials, yielding the optimal outcomes for identifying suitable PMU sites and Steiner vertices. Table 3 supplements this with data on PMU count, channels, switches, optical fiber length, and WAMS costs.

Table 2. PMU placement numbers and bus locations-base case

IEEE system	PMU no	Location of PMU	Steiner vertices
14 bus	4	4,5,6,9	-
30 bus	7	3,7,10,12,15,20,27	4,6
118 bus	31	2,8,11,12,17,21,27,28,32,34,37,40,45,49,53,56,61 ,66,70,71,75,77,80,85,86,89,92,96,100,105,110	5,15,16,19,20,31,39,41,42,54,60,62,64,65,68, 69,78,81,82,83,84,88,94,95,103,113,114,115

Table 3. Cost analysis and result comparison-base case

IEEE system	Method	PMU no.	MO	PDC site (Bus No.)	Switc count	Additional channels	OPGW length (km)	WAMS cost ($ millions)
14 bus	Proposed	4	21	4	4	9	21.0	0.296
	[20]	4	21	4	4	9	21.0	0.296
	[22]	3	15	5	5	6	108.6	0.598
	[24]	4	21	4	4	9	21	0.296
30 bus	Proposed	7	32	3	10	11	129.3	0.881
	[20]	7	32	3	10	11	129.3	0.881
	[22]	7	31	5	15	10	218.7	1.255
	[24]	7	32	3	10	11	129.3	0.881
	[25]	7	32	3	10	11	129.3	0.881
118 bus	Proposed	31	172	17	59	79	2136.6	10.338
	[20]	31	162	21	57	69	2304.1	10.96
	[22]	28	141	50	61	57	2641.0	12.156
	[24]	30	154	21	58	64	2386.8	11.235
	[25]	30	150	21	60	60	2428.0	11.392

The acquired PMUs or additional channels are more than what is seen in the most recent research, even though the WAMS cost is lower as a consequence [22]. This phenomenon is attributed to a notable fall in optical fiber length, underscoring the opted implementation of CI design through Steiner tree optimization. Figure 3 visually presents the optimized CI achieved via the Steiner tree approach, depicting the PMU placements for the 30-bus system and PMU locations are denoted in green, connections between optical fibers are emphasized in blue, and Steiner vertices are shown in yellow.

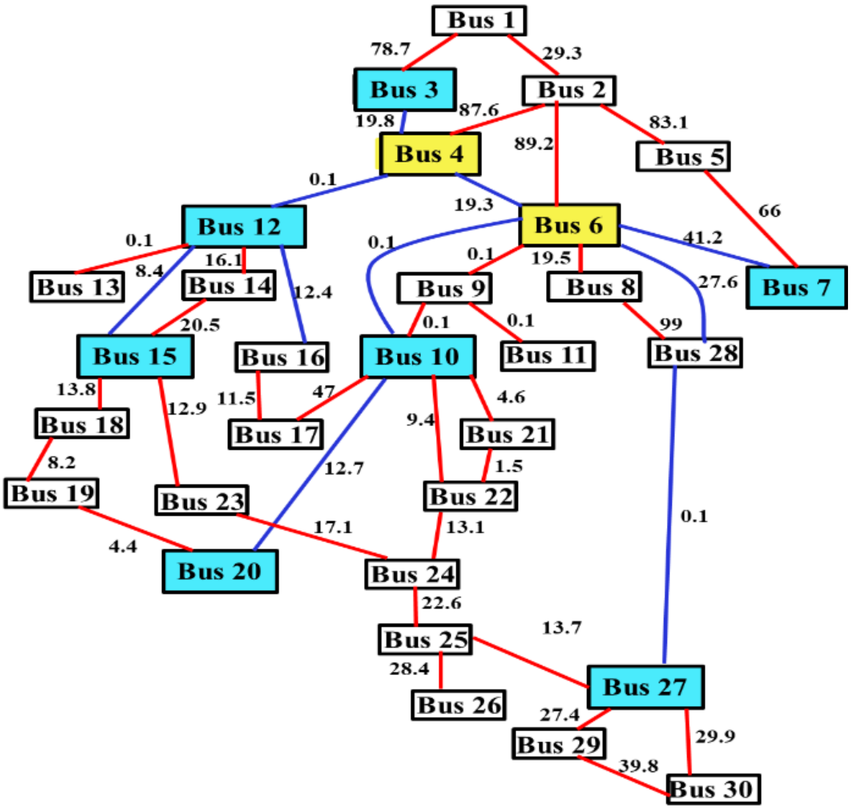

Figure 3. PMU location and Steiner vertices for IEEE 30 bus system

4.2. Case 2: N-1 contingency

Regardless of how vast the power system is, a single line or PMU failure affects just a small number of buses, considering N-1 contingency is usually sufficient to prevent losing the system's observability. PMU number was optimized due to enhanced system observability, under single PMU failure or line outage status. In Table 4, the position of the PMU and Steiner vertices based on the improved WAMS cost is shown.The cost analysis and comparison with previous literature are shown in Table 5. Tables 4 and 5 in 30 bus and 118 bus systems show that, under N-1 contingency scenario, there is a large increase in total cost, but that system observability also increases at the same time.

Table 4. PMU placement number and bus location - N-1 contingency

IEEE system	PMU no.	Location of PMU	Steiner vertices
14 bus	7	2,4,5,6,9,11,13	Nil
30 bus	15	2,3,4,7,10,12,13,15,16,19,20, 24,27,28,29	6,21,22
118 bus	65	2,3,5,7,8,9,10,11,12,15,17,19,20,21,23,24,25,27,29, 31,32,34,36,37,40,42,44,45,46,49,51,53,54,56,57,5962,66 ,68,70,72,75,77,78,80,83,85,86,87,89,90,92,94,96,100, 102,105,106,09,110,111,112,114,117, 118	6,16,39,47,58,61,63,65,69, 71,82,84,88,103,108,115

Table 5. Cost analysis and result comparison - N-1 contingency

IEEE system	Method	PMU no.	MO	PDC site (Bus no.)	Switch count	Additional channels	OPGW length (km)	WAMS Cost ($ millions)
14 bus	Proposed	7	33	5	7	12	129.4	0.874
	[20]	7	33	5	7	12	129.4	0.874
	[22]	8	33	1	11	9	177.6	1.110
	[24]	7	33	11	7	12	129.4	0.874
30 bus	Proposed	15	61	10	18	17	280.3	1.861
	[20]	15	61	6	18	17	281.9	1.868
	[22]	17	60	24	23	9	397.8	2.399
	[24]	15	65	5	21	20	361.5	2.210
	[25]	16	58	1	22	10	388.4	2.322
118 bus	Proposed	65	299	69	81	109	3180.9	16.084
	[20]	61	283	53	81	100	3629.0	17.680
	[22]	65	289	21	89	94	3869.3	18.809
	[24]	61	279	50	82	96	3706.2	17.977
	[25]	64	282	21	88	90	3799.7	18.471

4.3. Case 3: pre-installed phasor measurement units

Table 6 presents information on pre-installed PMUs that was collected from [25]. Table 7 provides a cost analysis and comparison with previous research based on maximal observability and overall cost. According to the findings, based on maximal observability and overall cost, situations PI-1 to PI-4 for 14 and 30 bus systems are comparable to existing literature, whereas situations PI-5 to PI-6 for 118 bus system produce better results.

Table 6. PMU placement number and bus location - pre-installed PMU

IEEE System	PMU No.	PI PMU bus	Location of PMU	Steiner vertices
14 bus (PI-1)	4	1	1,4,6,9	5
14 bus (PI-2)	4	13	4,5,11,13	6
30 bus (PI-3)	7	2,12	2,4,10,12,15,20,27	6,28
30 bus (PI-4)	7	2,24	2,4,10,12,19,24,27	6,20,21,22,28
118 bus (PI-5)	37	2,15,37,49, 60,100	2,5,8,11,12,15,17,19,21,23,27,28,32,34, 37,40,45,49,53,54,56,60,61,66,70,71,75 ,77,80, 85,86,89,92,96,100, 105,110	4,16,20,22,24,30,35,36,38,62,65, 67,68,69,72,81,82,83,84,93, 94,106,108,109, 118
118 bus (PI-6)	34	15,32,51,60, 89, 100	2,8,11,12,15,17,21,27,28,32,34,37,40, 45, 49, 51, 53,56,60,61,66,70,71,75, 77,80,85,86, 89, 92,96, 100, 105,110	4,5,16,19,20,22,23,24,30,38,39,5 2,54,62,65,67,68,69,72,81,82, 83,84,93,94,95, 103,113

Table 7. Cost analysis and result comparison - pre installed PMU

IEEE system	Method	PMU no.	MO	PDC site (Bus no.)	Switch count	Additional channels	OPGW length (km)	WAMS cost ($ millions)
14 Bus (PI-1)	Proposed	4	19	1	5	7	115.4	0.669
	[20]	4	19	1	5	7	115.4	0.669
	[24]	4	19	1	5	7	115.4	0.669
14 Bus (PI-2)	Proposed	4	18	4	5	6	41.7	0.371
	[20]	4	18	4	5	6	41.7	0.371
	[24]	4	18	4	5	6	41.7	0.371
30 bus (PI-3)	Proposed	7	36	12	9	15	155.9	0.999
	[20]	7	36	12	9	15	155.9	0.999
	[24]	7	36	12	9	15	155.9	0.999
	[25]	7	36	4	9	15	155.9	0.999
30 bus (PI-4)	Proposed	7	35	10	12	14	171.1	1.068
	[20]	7	35	10	12	14	172.7	1.075
	[24]	7	35	6	12	14	172.7	1.075
	[25]	7	35	10	12	14	172.7	1.075
118 bus (PI-5)	Proposed	37	204	17	62	93	2189.1	10.856
	[20]	38	191	21	59	77	2243.2	11.037
	[24]	33	175	21	61	76	2426.2	11.573
	[25]	31	172	21	58	79	2405.4	11.409
118 bus (PI-6)	Proposed	34	186	17	62	84	2166.9	10.612
	[20]	37	181	21	62	70	2314.5	11.266
	[24]	31	168	21	58	75	2438.6	11.526
	[25]	31	173	21	57	80	2422.0	11.476

4.4. Case 4: pre-installed fiber

The pre-existing fiber optic pathway, as outlined in [25], is considered. The optimal PMU and Steiner point placements are detailed in Table 8. Table 9 furnishes data on WAMS cost, measurement optimization (MO), and PDC positioning for both the 30 bus and 118 bus systems, juxtaposed against a comparison with the current body of literature. Table 10 depicts the calculation time required by BFFA, BDA, and BGSA in the basic scenario for a 14-bus system.

Table 8. PMU placement number and bus location-pre-installed fiber optic

IEEE system	Pre-installed OPGW path	PM no.	Location of PMU	Steiner vertices
30 bus	Route 1: 10 -17 – 16 - 12 Route 2: 21 – 22 – 24 - 25	7	3,7,10,12,19,24,27	4,6,16,17,20, 21, 22, 25
118 bus	Route 1:49-51-52-53-54-55-56-59 Route 2 :4 - 11 - 12 - 14 – 15 Route 3:80 - 96 - 95 - 94 - 100 - 106	37	2,8,11,12,14,15,19,20,23,24,27,28,32,34 ,37,40,43,47,49,52,56,59,66,70,75,77,80 ,83,86,89,92,94,95, 100,104,105,110	4,5,21,22,39,51,53, 54,55,65,68,69,81, 82,84,85,96,103,106

Table 9. Cost analysis and result comparison - pre-installed fiber optic

IEEE system	Method	PMUs number	MO	PDC site (Bus no.)	Switch count	Additional channels	OPGW length (km)	WAMS cost ($ millions)
30 bus	Proposed	7	31	10	15	10	96.6	0.766
	[22]	7	31	10	15	10	97.2	0.769
	[24]	7	31	10	15	10	97.2	0.769
118 bus	Proposed	37	194	69	56	83	1480.2	7.957
	[22]	37	194	22	56	83	1522.7	8.126
	[24]	32	157	23	65	61	1799.6	8.982

Table 10. Results comparison – IEEE 14 bus system-base case

Technique	Processing time (Sec)	Frequency of achieving best solution out of 30 trails
BGSA	5.31	18
BDA	3.52	21
BFFA	1.71	27

5. CONCLUSION

The WAMS infrastructure has been optimized via BFFA in this study, which involves reducing the total cost (cost of PMUs and CI) while retaining the system's complete observability. The observed findings justify the usage of a modified objective function to improve maximum observability. In order to achieve less PMUs while accounting for ZIBs, an improved model was used. A well-known Steiner tree optimization has been utilized to create CI with the lowest feasible cost and to determine the location of PDC for IEEE 14-bus, 30-bus, and 118-bus systems for the basic case with real-world operating situations. To show the success of recommended approach, the findings were compared to previously published results in terms of total cost and maximum observability. The obtained findings indisputably indicate the benefit of the proposed strategy.

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