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Global-Binary Algorithm; New Optimal Phasor Measurement Unit Placement Algorithm

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ABSTRACT. *This paper proposes a new algorithm for the optimal placement of the phasor measurement unit. The proposed algorithm is based on the concept of finite space solution of any binary problem. This algorithm has considered all possible cases; therefore, the possibility of obtaining a global solution is very high. The large system is divided into several subsystems. The buses (transmission lines) connected between the subsystems are called interconnected buses (lines). The proposed algorithm is implemented through two steps. First step identifies the optimal placement for each subsystem by checking on all possible solutions, the overall optimal placement for the entire system is gathered in the second step. Finally, all possible placements of the phasor measuring units with the optimal numbers are identified to select the best placement based on the user applications. In this work, the Jordanian power system is considered as a case study to validate the proposed algorithm. Four algorithms in the literature are used for the comparison using different IEEE test systems. The algorithm is computed in MATLAB 2020a.*

Keywords: Wide-area monitoring system, Phasor measurement units, Optimal PMU placements, Jordan power system, Global Binary Algorithm, Connectivity matrix algorithm.

1. Introduction.

Wide Area Monitoring Systems (WAMS) can be defined as a collective of information, communication, and measurement technologies to measure, transfer, and manage data of the power system dynamically. Different main applications of WAMS are presented in the literature for various power system aspects [1-5]. Phasor measurement units (PMUs) can provide synchronized phasor measurements of voltages and currents in a wide geographical area based on a standard reference time frame. Considering the financial cost, data transmission and analysis, and technical benefits, the suitable placement of PMUs in power systems becomes critical [6]. The concept of Optimal PMU Placement (OPP) is to install the minimum number of PMUs that can provide full observability [7-8].

Different OPP algorithms are presented in the literature. Artificial intelligence techniques based on the Practical Swarm Optimization (PSO) algorithm are used to improve the result of OPP algorithms in [9]. Other algorithms [10] use the linear optimization technique to solve the binary problem of OPP. Multi-Stage OPP considering substation infrastructure is presented in [10]. An integer linear program (ILP) is a fast and easy-to-implement algorithm, and it is used to solve the OPP problem [11-13]. In [14], a hybrid ILP-based method is proposed to cover all possible solutions to the OPP problem. Some common OPP approaches are the Depth-First Search (DFS), Graph-Theoretic (GTH), and Simulated Annealing (SA) Methods. A more detailed summary of these common methods is in [15]. The Modified Simulated Annealing Method is proposed in [16]. Generally, OPP can be categorized into: Heuristic, Meta-Heuristic, and Deterministic Methods [17], where DFS [18-19] Domination Set [12,20], and Greedy Algorithm [21] are examples of Heuristic Method. GA [22] and PSO [23] are examples of Meta-Heuristic Method, and Integer Programming [24]. Binary Search Method [25-28] are examples of Deterministic Method.

The significant difference among the previous algorithms is the number of PMUs required in a specific system [29-32]. Some algorithms give an acceptable solution for some systems and are not sufficient for others. Therefore, there is a necessity to develop a new algorithm for the OPP problem for any scenario [33-35]. In this paper, the proposed algorithm searches for all optimal PMU placements of any power system.

2. The Problem Definition.

The main application of the WAMS plays a significant role in the selection of the OPP (number of PMU and their locations) in any system; on the other hand, the primary application of WAMS is monitoring. For monitoring application, the system should be fully observable by the PMUs where the definition of the fully visible system is derived from the linear state estimator. The phasor voltage at all buses (substations) can be known by direct measurements or pseudo measurements. The phasor voltage is obtained by direct measurement when a PMU is installed at a bus. The pseudo measurements can be summarized as follow:

- If a PMU is installed at a bus, all adjacent buses are observable using Ohm's law on the interconnected lines.

- If the voltages of two adjacent buses are known, the current in the connection line can be calculated.

In addition to these two straightforward relations, any ideal node (does not have any load or generator), called zero-injection bus (ZIB), has another two concerns:

- If ZIB and all connected buses are observable except one, then the non-observable bus's voltage can be estimated using ohms law.

- If all adjacent buses to a ZIB are observable, then the voltage of the ZIB can be estimated using nodal analysis.

Either the first or the second relation should be used at a ZIB, not both. The selection between these relations gives the problem additional Freedom of Solution (FOS). The merging technique in [7] is applied to implement the ZIB in this algorithm. The OPP problem can be translated into a constrained optimization problem where the objective function (cost) minimizes the total number of PMUs needed to be placed, and the constraint is the observability of each bus in the network. In general, the optimization problem can be written as follow:

$$objective = \min \sum x_i \quad , \quad f_k = \sum_{i=1}^{N} a_{ik} x_i, F \geq I \qquad (1)$$

Where F is the observability vector $[f_1, \dots, f_N]$, $f_k = 1$ if bus k is observable and 0 if not. X is a binary vector that represents the placement of the PMUs $[x_1, \dots\dots x_N]$, $x_k = 1$ if a PMU is placed at bus k and 0 if not. N is the total number of buses. I is a unit $1 \times n$ vector $[1\ 1\ 1 \dots 1]$. The connectivity matrix A is a square $n \times n$ matrix represents the network topology $[a_{11}, .. a_{ij} ., a_{NN}]$. If bus i and bus k are connected, $a_{ik} = 1$ and zero if not. The elements in the main diagonal of A are always ones.

If the redundancy on measurements is needed, the observability condition ($F \geq I$) shall be changed to ($F \geq B$). The new term (B) represents the order of measurement redundancy. Hence, in the power system, to apply the n-1 criteria, the B vector should be twos. Based on the concept of the connectivity matrix and redundancy vector, equation (1) can be updated to:

$$F = A \times X \quad , \quad F \geq B \qquad (2)$$

3. The Proposed Algorithm.

The proposed algorithm assumes that the local bus does not affect the observability of the remote one. Hence, the vast interconnected power system can be divided into multi areas (subsystems). The observability of each subsystem is independent of the others. As the space solution of binary problems is finite, it can check all possible solutions without exceptions. The probability of getting a global solution here is 100% because all potential cases are considered. The proposed algorithm has three major stages: split the system into smaller subsystems, obtain the OPP of each subsystem, and gather the OPP for the overall system.

3.1 Splitting Algorithm.

This algorithm provides a new connectivity matrix (modified matrix) to make the global binary method more efficient. The necessity of this algorithm comes from the problem of vital size space solutions for massive systems. At 30-bus system, the size of the space solutions is $(r = 2^{30} - 1)$. The division process must ensure the minimum number of interconnected buses to improve the algorithm's behavoiur and reduce the operation of the second step.

The systematic procedure of the splitting algorithm can be summarized as follow:

1- Select the minimum integer number greater than or equal to (N/30), the number of subsystems, and select the size of each subsystem.

2- Start from the first row and sum all the first subsystem, second, third, … to the end. The summation should not include main diagonals elements.

3- The maximum summation in the k row corresponds to the appropriate group. Then, move the k^th^ row and the k^th^ column to a position in the best group.

4- Carry on until all buses are selected in their best group and make a modified connectivity matrix that is all centralized around the main diagonal. Change the size of any subsystem if it is necessary.

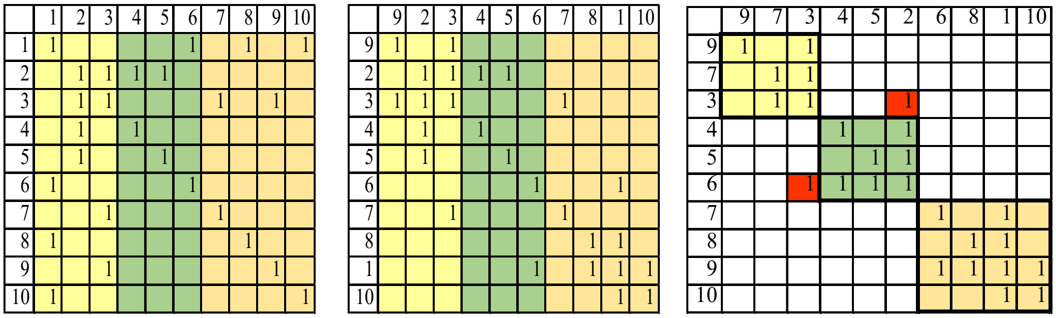
5- Identify the inter-connected buses.

For example, consider a small system with ten buses is used. The connectivity matrix is shown in Figure 1(a). The empty elements refer to zeros. Applying the previous steps as follow:

1. Suppose that the system is divided into three subsystems (3, 3, and 4 buses, respectively). In the connectivity matrix, Figure 1(a), the matrix is colored by yellow, green, and brown to distinguish between subsystems.
2. From the figure, the summation of the elements of the first row is zero in the first area, one in the second, and 2 in the third (Do not consider main diagonal in summation).
3. The first row is classified in the third area, so the appropriate group of the first bus is the

third. The first row should be replaced by bus 7 or 9, classified in the first area. Let us select bus 9; the ninths must replace the first column and row. The new matrix will be as shown in Figure 1 (b).

4. The second iteration shows that bus two is classified in the second zone, while bus six is ranked in the third and bus 7 in the first zones. The final modified matrix is shown in Figure 1 (c).
5. From Figure 1 (c), the interconnected buses are buses 2 and 3.



	1	2	3	4	5	6	7	8	9	10
1	1					1		1		1
2		1	1	1	1					
3		1	1				1		1	
4		1		1						
5		1			1					
6	1					1				
7			1				1			
8	1							1		
9			1						1	
10	1									1

	9	2	3	4	5	6	7	8	1	10
9	1		1							
2		1	1	1	1					
3	1	1	1				1			
4		1		1						
5		1			1					
6						1			1	
7			1				1			
8								1	1	
1						1		1	1	1
10									1	1

	9	7	3	4	5	2	6	8	1	10
9	1		1							
7		1	1							
3		1	1			1				
4				1		1				
5					1	1				
6			1	1	1	1				
7							1		1	
8								1	1	
9							1	1	1	1
10									1	1

(a) original matrix (b) the first modification (c) the last modification

FIGURE 1. Split Algorithm, Example of 10-bus system.

From Figure 1(c), the density of the ones is around the main diagonal. All subsystem connectivity matrices can be identified by ignoring all ones out of the selected area, Figure 1(c). The connectivity matrix of the first subsystem is the yellow 3 × 3 matrix. The green 3 × 3 matrix represents the second subsystem connectivity matrix. Finally, the third subsystem connectivity matrix is represented by the orange 4 × 4 matrix. Based on this algorithm, any vast system can be divided into any number of smaller subsystems.

3.2 Step one: OPP of each subsystem

In the first step, as shown in Figure 2 (a), the proposed binary global algorithm is applied to each subsystem to obtain sub-space solutions. It uses the concept of limited space solutions for any binary problem. Figure 1 consists of 13 blocks described below:

- The split algorithm, previous section, defines blocks 1,2 and 3. This algorithm is repeated for each subsystem.
- Block 4: select a random number of PMUs (K) around (N/4) where N is the subsystem's size. Set Y=2 for termination condition to stop the algorithm when the OPP is achieved.
- Block 5: generate all possible combinations of K digits on N space, representing the different distribution of K PMUs in the N-Bus system. The total variety of K PMU on the N-bus system is given by equation 3. The set of solutions are saved in matrix X.

$$M = \frac{N!}{K! \times (N-K)!} \tag{3}$$

- Block 6: compute observability condition Equation 2.
- Block 7: check on observability based on required redundancy on measurements.
- Block 8: If K PMUs make the system observable, check on the value of Y. If Y = 1, stop the algorithm, and K is the optimal number. If Y is not equal to one, try to reduce the number of PMUs (K) in block 9, set the Y =0, and go back to block 5.
- Block 10: if K PMUs are not sufficient to obtain the required observability level, check on the value of Y. If Y is zero, then the optimal number of PMU is greater than the current (K) block 12 and generate the location using the observability condition, block 13. If Y is not zero, try to add a PMU to the current number (K), set the y value to 1 and go back to block 5.

Once this step computes the optimal number of PMUs, the space solution of each subsystem (X1, X2, ….) called sub-space solution is identified. A sub-space solution defines all combinations of optimal PMU placements for a specific subsystem. Each subspace solution matrix has many rows (vectors); each vector represents a particular placement of PMUs.

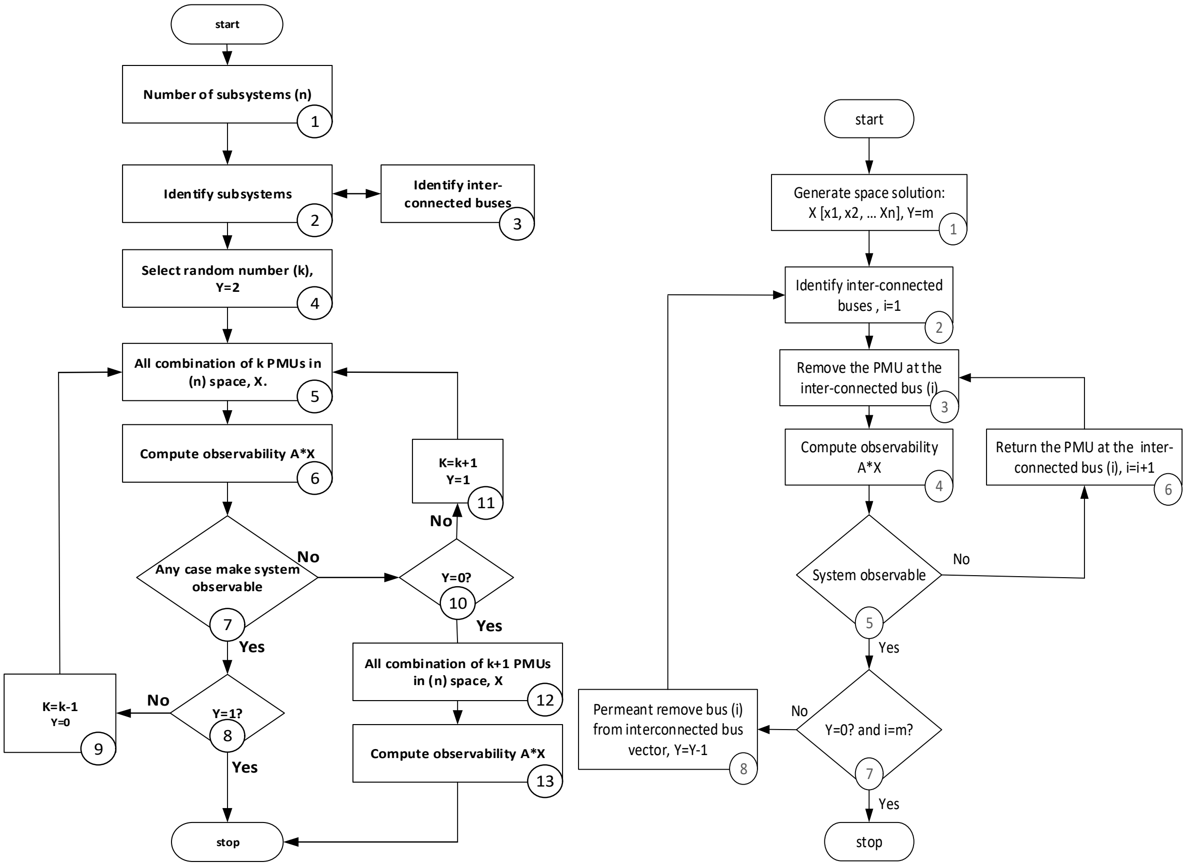
3.2. Step two: Global OPP solution.

The second step, Figure 2 (b), selects the new space solution from the combination of sub-space solutions. By trying to remove PMUs at interconnected buses (which connect one zone to another), the final optimal PMU placements will be defined. All sub-space solutions aggregation should take all possible crossing between vectors in each sub-space matrix, step 1. The second step tries to remove the PMU placed at the interconnected bus and check for system observability, see Figure 2 (b). The flow chart of this step is described below:

- Block one generates a space solution by gathering all subspace solutions from step 1. The space solution should cover all combinations between the subspace vectors. In this block, the stop criterion (y) is initialized, where (m) is the number of interconnected buses.
- Block 2: Identify interconnected buses from the split algorithm and initialize counter (i).
- Block 3: remove the PMU at i^{th} interconnected bus if exist from all space solution matrix.
- Block 4: compute the observability vector (F) from equation 2 using the complete system connectivity matrix.
- Block 5: check on observability. If any space solution makes the system observable, check on stop condition in block 7, return the removed PMU from block 3 and increase the counter (i) by one, block 6.

- Block 7: check the stop conditions.

Two conditions are defined: Y for an external loop and (i) for an internal loop. If the stop criteria are not achieved, and the system is observable, the removed PMU is permanently absent from the space solution to obtain a new space solution with a lower number of PMUs and return to block 2.



(a) (b)

FIGURE 2. Flow chart of the global binary algorithm, (a) step 1, (b) step 2.

Finally, the proposed algorithm generates the final space solution consisting of all possible combinations of PMU placements with the minimum number. Jordanian power network is considered as an example in the next section to illustrate the previous sub-sections.

4. Case Study: Jordanian Power System.

The Jordan transmission power system has 68 substations after considering the ZIBs, Figure 3. The proposed split algorithm divides the system into three subsystems, as shown in Figure 3. The first subsystem, brown color, consists of 22-bus, the second subsystem, green color, consists of 22-bus, and the third subsystem, black color, consists of 24-bus. The interconnected buses are: 34, 36, 40, 7, 2, 30, 35, 40, 15, 18, 28, 29, 49, 43 and 44.

At each subsystem, the global binary algorithm is applied separately, step one. The optimal numbers of PMUs are 7, 7 and 8, and the size of each subspace solution is 30, 5, and 55, respectively. The total space solution, Figure 2 (b): block 1, consist of (7+7+8=21) PMUs with size (30×5×55=8250).

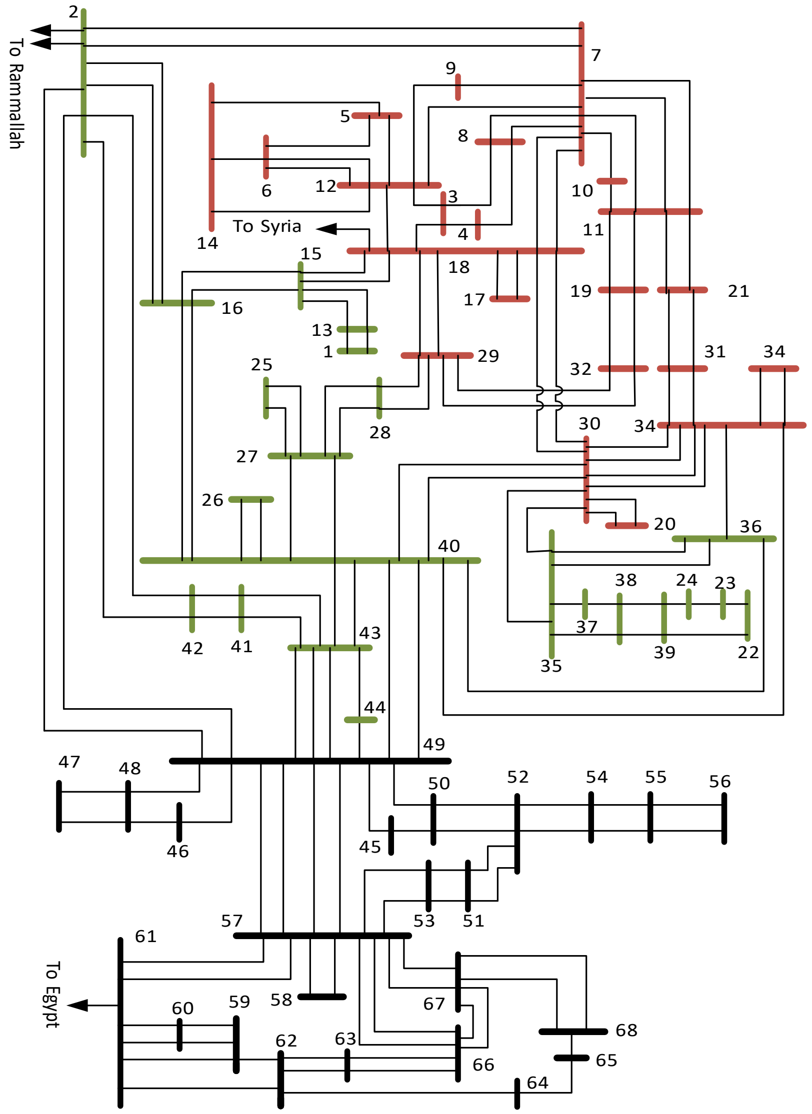


FIGURE 3. Single Line Diagram of Jordanian power system

When applying the second step by removing inter-connected buses, the result shows that 21 PMUs are enough to observe the overall system with 2760 placement options. The second step results show that the PMU at bus 43 or bus 44 (not both) is unnecessary. Based on this result, 2760 placement options are available for the linear state estimation to get full observability. Other criteria could be achieved to select one of these placements like:

- Maximum redundancy: which solution gives the maximum number of redundant buses?
- Oscillation monitoring and analysis: which solution covers the maximum number of generator substations and tie-lines?
- Stability assessments: Which solution consists of the maximum number of critical buses and the maximum number of loge transmission lines?
- Remedial Action Scheme (RAS): the solution's priority can be defined based on special applications like load rejection, reactive power compensation control, HVDC controls, local generation units trip based on transmission line outages, wide-area generation tripping based on extra-high voltage line outages.
- Other applications like black start monitoring, model validation, disturbance analysis, frequency response analysis,

For example, each special function can be given a weight based on the user priority. Then, the optimal placement can be selected based on the maximum wights. Some applications with weights are defined for the Jordanian power system as follow:

1. Monitor the low-frequency oscillations with weight 40%
2. Voltage stability monitoring with weight 24 %
3. Disturbance analysis for some transmission lines (TL43-49, TL 49-40, TL 40-30, TL 30-18, TL 18-7, TL 7-2, TL 2-49, TL 49-57, TL 57-61) with weight 20 %
4. RAS: Wide area generation tripping based on tie-lines outages in addition to some extra-high voltage outages like (TL 57-61 and TL57-49) with weight 10%
5. RAS: Load rejection based with weight 5%.

In addition to these objectives, the maximum location that provides maximum redundancy in the measurements will be preferable. Table 1 shows the implementation of these objectives for each busbar. The cross indicates that the bus affects the goal. The summation of the weights is calculated in the last column to define the bus importance. From the space solution in the proposed algorithm, the maximum weights vectors are the best. Appling these objectives to the 2760 options in the proposed algorithm give us the optimal 18 locations with the maximum weights presented in Table 2.

TABLE 1. Implementation of real application in each substation (busbar)

Bus number	**Obj. 1 (40%)**	**Obj. 2 (25%)**	**Obj. 3 (20%)**	**Obj. 4 (10%)**	**Obj. 5 (5%)**	**Total (%)**
1					X	5
2		X	X	X		55
7	X	X	X	X		95
8					X	5
11	X		X			60
12	X		X		X	65
13					X	5
14		X				25
15					X	5
16					X	5
18	X	X	X	X		95
19					X	5
20	X					40
22	X					40
23					X	5
24					X	5
25					X	5
30	X	X	X			85
33					X	5
34		X			X	30
35		X			X	30
36					X	5
40	X	X	X	X		95
41					X	5
42	X	X	X			85
46					X	5
48					X	5
49	X	X	X	X		95
52	X	X				65
57	X	X	X	X		95
58	X					40
59	X	X				65
60					X	5
61	X	X	X	X		95
62	X	X				65

TABLE 2. optimal 18 PMU locations for Jordan power system considering some real applications

s.n	**Optimal 18 locations**																				
1	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	65
2	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	68
3	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	65
4	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	68
5	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	56	57	61	62	65
6	3	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	56	57	61	62	68
7	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	65
8	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	68
9	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	65
10	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	68
11	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	56	57	61	62	65
12	4	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	56	57	61	62	68
13	8	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	65
14	8	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	54	57	61	62	68
15	8	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	65
16	8	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	55	57	61	62	68
17	8	11	12	13	18	19	23	27	30	34	38	40	42	48	49	52	56	57	61	62	65

Table 2 shows the optimal 18 locations for the Jordanian power system considering the previous applications. The best solution should give the maximum number of redundant buses. The maximum number of redundant buses can be achieved by the first six solutions from the 18 cases, Table 2. For these six sets, 27 buses can be observed by more than one PMU.

Finally, the proposed algorithm is applied to different IEEE test systems with different scenarios. Table 3 shows the comparison of the proposed algorithm with the previous literature. The results of the second step in the proposed algorithm, observability for linear state estimation, are used in the table.

TABLE 3. comparison results with other methods

Test system	Case	Proposed Algorithm		Ref [7]	Ref [26]	Ref [27]	Ref [28]
		Space solution size	No. of PMU				
IEEE-14 Bus	Without ZIB	5	4	4	4	4	N/A
	With ZIB	1	3	3	3	3	3
	n-1 criteria	4	7	7	7	7	7
IEEE 30-bus	Without ZIB	858	10	10	10	10	N/A
	With ZIB	68	7	7	7	7	7
	n-1 criteria	184	15	15	15	17	16
IEEE 118-bus	Without ZIB	1457	31	32	32	32	N/A
	With ZIB	765	28	28	28	28	29
	n-1 criteria	3521	61	62	64	65	62

5. Conclusions.

This paper proposes a new algorithm to obtain a global solution to the OPP problem. This search algorithm considers all possible solutions without any exceptions. In this algorithm, the probability of getting the global solution for any system is 100 % because all space solutions are checked. Jordan Power system, which contains 68 buses, is taken as an actual system for validation purposes. Different WAMS applications are selected as examples to obtain the optimal placements that can achieve the maximum benefits for specific applications. Different IEEE test systems are used to validate the algorithm and compare it with others.

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REFERENCES

[1] M. M. Almomani, A. Odienat, S. F. Al-Gharaibeh and K. Alawasa, "The Impact of Wind Generation on Low Frequency Oscillation in Power Systems," 2021 IEEE PES/IAS PowerAfrica, 2021, pp. 1-5, doi: 10.1109/PowerAfrica52236.2021.9543283.

[2] Mohammad M. Almomani and Seba F. Algharaibeh, "Modelling and Testing of a Numerical Pilot Distance Relay for Compensated Transmission Lines", International Journal of Scientific Research and Engineering Development, vol. 3, no. 6, pp. 776-786, 2020.

[3] M.M. Al-Momani, A.S.M. Hatmi and S.F. Al-Gharaibeh, "Performance analysis of the distance relay characteristics in a compensated transmission line", European Journal of Electrical Engineering, vol. 23, no. 3, pp. 197-205, 2021. https://doi.org/10.18280/ejee.230304

[4] Tauseef Gulrez, Abdullah Al-Odienat, "A New Perspective on Principal Component Analysis using Inverse Covariance", International Arab Journal of Information Technology (IAJIT), Vol. 12, Issue 1, 2015.

[5] K. M. Alawasa and A. I. Al-Odienat, Power quality characteristics of residential grid-connected inverter of photovoltaic solar system, 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 2017, pp. 1097-1101.

[6] Odienat, M. M. Al Momani, K. Alawasa and S. F. Gharaibeh, "Low Frequency Oscillation Analysis for Dynamic Performance of Power Systems," 2021 12th International Renewable Engineering Conference (IREC), 2021, pp. 1-6, doi: 10.1109/IREC51415.2021.9427818.

[7] I. Al-Odienat, K. Al-Awasa, M. Al-Momani and S. Al-Gharaibah, "Connectivity Matrix Algorithm: A New Optimal Phasor Measurement Unit Placement Algorithm", IOP Conference Series: Earth and Environmental Science, vol. 551, no. 1, pp. 012008, August 2020. Doi. 10.1088/1755-1315/551/1/012008

[8] A. I. Al-Odienat, B. Malahmeh and A. R. Tarawneh, The Optimal PMU Placement in the Power Systems for the Enhancement of State Estimation, 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 2020, pp. 1-6, doi: 10.1109/ICECCE49384.2020.9179214.

[9] B. Gou, Generalized integer linear programming formulation for optimal PMU placement, IEEE transactions on Power Systems, vol. 23, no. 3, 2008, pp. 1099–1104.

[10] S. Almasabi and J. Mitra, Multi-stage optimal PMU placement including substation infrastructure, in 2017 IEEE Industry Applications Society Annual Meeting, 2017, pp. 1–8.

[11] R. Manam and S. R. Rayapudi, Sensitive Constrained Optimal PMU Allocation with Complete Observability for State Estimation Solution, Eng. Technol. Appl. Sci. Res., vol. 7, no. 6, pp. 2240–2250, Dec. 2017.

[12] Almomani Mohammad, Ali S. Al-Dmour and Seba Algharaibeh, "Application of Artificial Intelligence Techniques for Modeling and Simulation of Photovoltaic Arrays", Jordan Journal of Electrical Engineering, vol. 6, no. 4, pp. 296-314, 2020.

[13] X. Chen, L. Sun, T. Chen, Y. Sun, K. J. Tseng, K. V. Ling, W. K. Ho, G. A. Amaratunga et al., Full coverage of optimal phasor measurement unit placement solutions in distribution systems using integer linear programming, Journal Energies, vol. 12, no. 8, 2019.

[14] N. M. Manousakis, G. N. Korres, and P. S. Georgilakis, Taxonomy of PMU placement methodologies, IEEE Transactions on Power Systems, vol. 27, no. 2, 2012, pp. 1070–1077.

[15] P. Xu, Power system observability and optimal phasor measurement unit placement, Master thesis, University of Minnesota - Twin Cities December 2015.

[16] N. Manousakis, G. Korres, and P. Georgilakis, Optimal placement of phasor measurement units: A literature review, 2011 16th International Conference on Intelligent System Applications to Power Systems IEEE, 2011, pp. 1–6.

[17] M. Farsadi, H. Golahmadi and H. Shojaei, Phasor Measurement Unit (PMU) allocation in power system with different algorithms, 2009 International Conference on Electrical and Electronics Engineering - ELECO 2009, Bursa, Turkey, 2009, pp. I-396-I-400.

[18] T. Cai and Q. Ai, Research of PMU optimal placement in power systems, International conference on system theory and scientific computation, 2005, pp. 38–43.

[19] T. W. Haynes, S. M. Hedetniemi, S. T. Hedetniemi, and M. A. Henning, Domination in graphs applied to electric power networks, SIAM Journal on Discrete Mathematics, vol. 15, no. 4, 2002, pp. 519–529.

[20] X. A. Yuan, A linear algorithm for minimum phasor measurement units placement, 2010 Innovative Smart Grid Technologies (ISGT). IEEE, 2010, pp. 1–3.

[21] M. Zhou, V. A. Centeno, A. G. Phadke, Y. Hu, D. Novosel, and H. A. Volskis, A preprocessing method for effective PMU placement studies, 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, IEEE, 2008, pp. 2862– 2867.

[22] F. Marin, F. Garcia-Lagos, G. Joya, and F. Sandoval, Genetic algorithms for optimal placement of phasor measurement units in electrical networks, Electronics Letters, vol. 39, no. 19, 2003, pp. 1403–1405.

[23] J. Kennedy and R. Eberhart, Particle swarm optimization (PSO), Proc. IEEE International Conference on Neural Networks, Perth, Australia, 1995, pp. 1942–1948.

[24] F. Aminifar, A. Khodaei, M. Fotuhi-Firuzabad, and M. Shahidehpour, Contingency-constrained PMU placement in power networks, IEEE Transactions on Power Systems, vol. 25, no. 1, 2009, pp. 516–523.

[25] S. Chakrabarti and E. Kyriakides, Optimal placement of phasor measurement units for power system observability, IEEE Transactions on power systems, vol. 23, no. 3, 2008, pp. 1433–1440.

[26] Xu, Bei, and Ali Abur, Optimal placement of phasor measurement units for state estimation, Final Project Report, Power Systems Engineering Research Center (2005): 05-58.

[27] Roy, BK Saha, A. K. Sinha, and A. K. Pradhan, An optimal PMU placement technique for power system observability, International Journal of Electrical Power & Energy Systems, 42.1 (2012): 71-77.

[28] C. Lu, Z. Wang, M. Ma, R. Shen and Y. Yu, An Optimal PMU Placement With Reliable Zero Injection Observation, IEEE Access, vol. 6, pp. 54417-54426, 2018, DOI: 10.1109/ACCESS.2018.2865513.

[29] Abdullah Al-Odienat, Power System Blackouts: Analysis and Simulation of August 9, 2004, Blackout in Jordan Power System, Information Technology Journal, Vol. 5, 2006. pp. 1078-1082.

[30] M. M. Al-Momani, A. Odienate, S. F. Algharaibeh, K. Awasa and O. Radaideh, "Modified Connectivity Matrix Algorithm," 2022 Advances in Science and Engineering Technology International Conferences (ASET), 2022, pp. 1-6, doi: 10.1109/ASET53988.2022.9735116.

[31] K. Al-Maitah, A. Al-Odienat, The Improvement of Weighted Least Square State Estimation Accuracy Using Optimal PMU Placement, WSEAS TRANSACTIONS ON POWER SYSTEMS, Vol. 15, 2020, pp. 1-7.

[32] Abdullah I. Al-Odienat & Khaled Al-Maitah, A New Wide Area Protection Scheme Based on the Phase Angles of the Sequence Components, Electric Power Components and Systems, 2021, DOI: 10.1080/15325008.2021.1971335

[33] K. Al-Maitah, A. Al-Odienat, Wide Area Protection Scheme for Active Distribution Network Aided µPMU, 7th Annual IEEE PES/IAS PowerAfrica Conference (PAC 2020), August 25-28, 2020, pp. 1-5.

[34] Al-Momani, Mohammad M., and Seba F. Al-Gharaibeh. "Prediction of Transient Stability Using Wide Area Measurements Based on ANN." International Journal of Emerging Trends in Engineering

Research 9.11 (2021).doi:10.30534/ijeter/2021/029112021

[35] M. M. Al-Momani, A. Odienate, S. F. Algharaibeh, K. Awasa and I. Reda, "Ringdown analysis for Low-Frequency Oscillation Identification," 2022 Advances in Science and Engineering Technology International Conferences (ASET), 2022, pp. 1-6, doi: 10.1109/ASET53988.2022.9735122.