Critical Elements Based Optimal PMU Placement Considering Substation Coverage

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Abstract: The Phasor Measurement Unit (PMU) is becoming the most prominent tool for power system applications like power system operation, control, and protection. In a robust and accurate wide-area measuring system, the PMU should observe not only the elements in its substation but also the critical elements and its incident busses. As the PMU cost limits their deployment, they must be installed optimally considering the substation installation and the critical lines in the power system. This paper introduces a new Optimal PMU Placement algorithm considering the optimal substations and the critical elements. This has been done based on the assumption that there must be a PMU in each constructed substation (optimal substation). This will assure the observability of all the elements in the substation. The proposed method has been tested on some standard test systems and then applied to a practical regional Indian grid.

Index Terms: Optimal PMU placement (OPP); Substation coverage; Critical lines; Critical bus; Binary Cuckoo Search (BCS);

1. Introduction

Optimization has become an important tool for solving many design problems [1-2]. This paper introduces the application of an optimization technique to the power system designing problems. The power system can be operated securely and accurately if it is possible to estimate the system state with a variety of measurements. With the integration of Phasor Measurement Unit into the measurement system, this has become easy to monitor, control and protect the power system observability. As the PMU costs considerably, the deployment and its number are needed to be optimized. In [3], the actual PMU optimum placement problem was introduced. Later, with the advent of heuristic methods, Genetic Algorithm (GA) in [4], Particle Swarm Optimization (PSO) in [5] and many more approaches were applied to the optimization problem for PMU placement.

After, a deterministic strategy like Integer Linear Programming (ILP) is applied in [6]. Thereafter, it is extended to the power systems, with and without conventional measurements in [7], and considering zero-injection bus (ZIB) effect in [8]. In practical substations, buses exist at different voltage levels as shown in Fig. 1. Circles in the figure represent substations. One should not forget that one bus being observed inside the substation should not transfer it to other buses inside the same substation. The above methods were developed based on the thumb rule that the PMU installed bus could observe all the buses connected to it including itself. And, as the practical tap ratios are not known, authors have assumed that the buses with different voltages were decoupled in-order to observe them in an individual manner which will increase both search space and bus number. So, it is clear that they have only concentrated on reducing the number of PMUs rather than reducing substation number.

Wide-area system planning studies say that the major part of the cost of synchrophasor measurement system deployment is associated with transmission network outages and maintenance costs but not with PMU devices. So, optimization must be towards reducing substation number. Moreover, the blackout reports suggest that critical lines which may connect zero injection buses must also be observed directly to design a robust security system and so to avoid major blackouts.



Figure 1. A sample transmission system

Even though many methods have tried placing PMUs using different strategies and different optimization algorithms, they haven't considered zero-injection buses, contingency of critical lines, and the substation coverage. Later, the paper [9] has considered few pre-specified contingencies based on the system stability studies. But the chances for these contingencies to occur are very less. Similarly, paper [10] presents a solution to an Optimal PMU placement (OPP) with single contingency as additional constraint. But no-where it considers the criticality of lines. In [11], fuzzy-logic based classification for critical elements based on the transient behaviour is suggested. But, it founds to be complicated with the definition of fuzzy variables. Later, papers [12, 13] have suggested methods for identifying criticality of network elements, but are indefensible. So, the modelling policy that considers the role of the system elements in driving the system to a blackout is highly recommendable. These considerations have been done in the proposed paper. It has done the optimal coverage of substation by assuming that one PMU could observe the whole substation provided the tap ratios are known, and then introduces critical elements identification in the Blackout point of view. Finally, it proposes a new OPP problem considering the critical elements whose outage lead to system blackout and the optimal substation coverage.

The remaining work has been presented as follows. In section 2, the objective function is introduced along with the subjective constraints. The Binary Cuckoo Search algorithm is briefly discussed in section 3. Section 4 explains the solution methodology with the help of IEEE-14 bus system. It also shows the results obtained for the test systems like IEEE-30, IEEE-57, IEEE-118 and Indian Grid (IG-75).

2. Problem Formulation

Before the network is being considered for OPP problem, it must be undergone one modification given below.

A. Network reconsideration

This section identifies the optimal substations. In this step, based on the assumption that the tap settings are known, the buses connected through the transformers will be modelled as single equivalent bus called optimal substation with equivalent generation and load. The identification of optimal substations is purely based on the connectivity of existing network. And, all the remaining buses without any interfacing transformers will be renamed as substations. The

estimation of tap settings is explained in section 2.2.1. Now, all these substations will be considered virtually as single buses to place PMU on it. The optimal substation locations for different test systems are listed in Table 1.

System	optimal substations
IEEE-14	(5, 6), (4, 7, 8, 9).
IEEE-30	(4, 12, 13),(6, 9, 10, 11),(27, 28).
IEEE-57	(10, 51),(15, 45),(14, 46),(13, 49),(7, 29),(20, 21),(24, 46),(39, 57),(40, 56), (32, 34),
	(4, 18),(9, 55),(11, 41, 43).
IEEE-118	(8, 5), (17, 30),(63, 59),(66, 65),(80, 81), (25, 26),(37, 38),(61, 64),(68, 69).
IG-75	(1, 2, 16, 17),(12, 41),(23, 24),(5, 31), (7, 33),(13, 42),(6, 32),(3, 18),(26, 27).

Table 1. Optimal substations of different test systems

A.1. Estimation of transformer taps settings

The accuracy of a state estimator lies in the modelling of tap setting which could degrade the estimator performance if it is not modelled properly. Sometimes the tap settings may not be communicated to load dispatch centre while taking local preventive or controlling actions. So, it is to be estimated accurately in order to take local protection schemes. If the tap ratios are unknown, it is not possible to calculate the parametrs on another end of the transformer using the parameters on one end. So, the transformer branches can be ignored from the point of observability, which may consider the transformer as a open circuit. However, the parameters should not be modelled as an open circuit since this modelling may rule out the chances of estimating the tap ratios. An OPP method was introduced in [14] for observability and estimation of transformer tap settings, but they tried in reducing buses which is not desired. So, this paper proposes a new policy for tap settings estimation. As shown in Fig. 2, let us consider v_{I} , i_{I} , and v_{2} , i_{2} are the voltages and currents on sending end and receiving ends respectively. The observability will be possible if and only if there exists at most one unknown variable among the variables (v_{I} , i_{I} , v_{2} , and i_{2}). Let E is the e.m.f induced in the primary coil which can be determined as

$$E = v_1 - i_1 \left(r_1 + j x_1 \right)$$
 (1)

$$=k(v_2+i_2(r_2+j_{x_2}))$$
(2)

Then, the procedure for estimating the unknown variable is given below: If i_l is unknown: After calculating E from equation (2), it will be used for calculating k from

Equation (3). After calculating E and k, i_l can easily obtained using the equation (1).

$$(v_1 - E)/(r_1 + j_{x_1}) = (i_2/k) + E \times \left(\frac{1}{r_c} + \frac{1}{j_{x_m}}\right)$$
 (3)

If v_1 is unknown: Calculation of E from equation (2) in terms of k and then substituting it in equation (4), we can obtain k value as well as v_1 value.

$$i_1 = E \times \left(\frac{1}{r_c} + \frac{1}{jx_m}\right) + \left(i_2/k\right) \tag{4}$$

If i_2 is unknown: From the equations (1) and (5), the variable k can be obtained. Then, using equation (2) and k value obtained, i_2 will be calculated easily.

$$i_1 - E \times \left(\frac{1}{r_c} + \frac{1}{x_m}\right) = (E - kv_2) / \left(k^2 \left(r_2 + jx_2\right)\right)$$
(5)

If v_2 is unknown: On solving equations (1) and (4), the tap ratio k and unknown v_2 will be known.



Figure 2. Two winding transformer equivalent circuit

B. Objective function

The PMU installed on one bus observes not only the bus to which it is connected but also the incident buses connected to it. The objective of the proposed OPP problem is to find the least number of PMUs for system complete observability. The optimization problem is formulated as below.

Minimize

$$\sum_{q \in N} x_q \tag{6}$$

Here, the Binary decision variable (x_q) is equal to 0 if q is not a PMU installed bus and lotherwise. It is to be noted here that the bus actually refers the substation to which it belongs but not the actual bus. This will reduce the PMU number considerably. This objective function will be then subjected to two constraints mentioned below.

B.1. Network complete observability constraint

This makes each substation observable by providing at least one PMU on the same substation or the substations that are being connected to it directly. In this way, it achieves complete observability for the whole network. This constraint can be written as below.

$$s_p(X) \ge 1, \quad \forall p \in N$$
 (7)

Where

$$s_p = \sum_{q \in N} c_{pq} x_q, \ \forall p \in N$$
(8)

From equation (8), the Binary decision variable (x_q) is equal to 0 if q is not a PMU installed bus and 1 otherwise, S_p is the pth bus observability function and its value should be greater than or equal to 1 for all the buses incident to pth bus to be observable. Here, N represents set of buses, c_{pq} is binary connectivity parameter and is described as,

$$c_{pq} = \begin{cases} 1, \text{if } p = q \\ 1, \text{if buses } p, q \text{ are connected} \\ 0, \text{otherwise} \end{cases}$$
(9)

B.2. observability of optimal substations

Let B_i is the critical bus at node *i*, and L_{jk} is the critical line connecting j^{th} and k^{th} nodes. If the nodes i and j are covered under single substation, the PMU placement on a particular bus in a substation should be according to the rules given below:

i. If the optimal substation doesn't have a critical bus and/or a bus connected to a critical line, then, the bus (*i*) with high connectivity should accommodate with a PMU.

$$x(i) \ge 1 \tag{10}$$

Where, *i* is the bus with high connectivity.

ii. If the optimal substation has a critical bus, then, the critical bus must hold the PMU.

$$x(i) \ge 1 \tag{11}$$

Where, *i* is the critical bus.

iii. If the optimal substation has a bus connected to a critical line, then that particular bus should be equipped with a PMU.

$$x(j) \ge 1 \tag{12}$$

(13)

Where, j is the bus in the optimal substation connected to critical line.

iv. If the optimal substation has both of them, then a PMU should be allocated to a critical bus, provided the other end of the critical line is installed with PMU.

$$x(i) \ge 1$$

Where, *i* is the critical bus.

B.3. Observability of critical elements

In every system, there will be few elements (either buses or lines, maybe both) which are needed to be given high priority. They are most important for the system to be healthy. This may be because of their relevance to the system stability. The critical lines will be made observable directly by using the following constraints.

$$x(j) + x(k) \ge 1, L_{jk} \in critical \ lines \tag{14}$$

$$x(i) = 1, i \in critical \, buses \tag{15}$$

Where, j and k are the sending and receiving end buses of line L. This is because of the fact that for monitoring a line directly, at least one substation on either side of the line must have a PMU. Similarly, the critical bus must have a PMU on it.

B.4. Identification of critical elements

Generally, these are the elements with high connectivity, or with control devices like Flexible AC Transmission System (FACTS) and High voltage DC (HVDC) links, etc... In this paper, the concept of Blackout has been introduced to identify the critical elements. So, here, the critical element can also be defined as the system element whose outage will drive the complete system into a halted state in terms of power availability. This identification is done using Newton Raphson's method [15]. The workflow for identifying the critical elements is depicted in Fig. 3. The procedure for identification of critical elements is given below.

Step 1: Read the system data.

Step 2: Identify load buses and voltage controlled buses.

Step 3: calculate ΔP_p^k and ΔQ_p^k using the following equations.

$$\Delta P_p^k = P_p^{actual} - P_p^k \tag{16}$$

$$\Delta Q_p^k = Q_p^{actual} - Q_p^k \tag{17}$$

Step 4: Calculate the elements (J_1, J_2, J_3, J_4) of Jacobian matrix using the following equations,

For J_1 ,

$$\frac{\partial P_p}{\partial \delta_q} = \sum_{q \neq p} |V_p| |V_q| |Y_{pq}| \sin(\theta_{pq} - \delta_q + \delta_p), \forall q \neq p$$
(18)

$$\frac{\partial P_p}{\partial \delta_p} = -\sum_{\substack{q=1\\q \neq p}}^n |V_p| |V_q| |Y_{pq}| \sin(\theta_{pq} - \delta_q + \delta_p)$$
(19)

For J_2 ,

$$\frac{\partial P_p}{\partial |E_q|} = |E_q| |Y_{pq}| \cos(\theta_{pq} + \delta_p - \delta_q), \forall q \neq p$$
⁽²⁰⁾

$$\frac{\partial P_p}{\partial |E_p|} = 2|E_q||Y_{pq}|\cos\theta_{pp} + \sum_{\substack{q=1\\q\neq p}}^{n} |E_q||Y_{pq}|\cos(\theta_{pq} + \delta_p - \delta_q)$$
(21)

For J3,

$$\frac{\partial Q_p}{\partial \delta_q} = -\left|E_p\right| \left|E_q\right| \left|Y_{pq}\right| \cos\left(\theta_{pq} + \delta_p - \delta_q\right), \forall q \neq p$$
(22)

$$\frac{\partial Q_p}{\partial \delta_p} = \sum_{\substack{q=1\\p\neq q}}^n \left| E_p \right\| E_q \left\| Y_{pq} \right| \cos\left(\theta_{pq} + \delta_p - \delta_q\right)$$
(23)

For J_4 ,

2 0

$$\frac{\partial Q_p}{\partial |E_q|} = |E_p| |Y_{pq}| \sin(\theta_{pq} + \delta_p - \delta_q), \forall q \neq p$$
(24)

$$\frac{\partial Q_p}{\partial |E_p|} = 2|E_p||Y_{pq}|\sin\theta_{pp} + \sum_{\substack{q=1\\q\neq p}}^{n} |E_q||Y_{pq}|\sin\left(\theta_{pq} + \delta_p - \delta_q\right)$$
(25)

With,

$$P_p = \sum_{q=1}^{n} |Y_{pq}| |V_q| |V_p| \cos(\theta_{pq} - \delta_q + \delta_p)$$
(26)

$$Q_p = \sum_{q=1}^{n} |Y_{pq}| |V_q| |V_p| \sin(\theta_{pq} - \delta_q + \delta_p)$$
⁽²⁷⁾

Step 5: Calculate new voltages and phase angles using

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}$$
(28)

And,

$$\delta_p^{k+1} = \delta_p^k + \Delta \delta_p^k \tag{29}$$

$$\left| V_{p}^{k+1} \right| = \left| V_{p}^{k} \right| + \Delta \left| V_{p}^{k} \right| \tag{30}$$

Step 6: Simulate the contingency

Step 7: Run the load flow i.e. repeat the steps 3 to 5.

Step 8: Identify the number of voltage violations and check whether load flows converge or not. Step 9: Repeat the steps 6-8 for all the remaining contingencies (i.e. both line and bus contingencies).

Step 10: Define the most critical contingencies which make system blackout as critical elements. This identification is carried out exclusively with the help of Power World Simulator 12.0. The details of the critical lines and buses are been listed the Table 2.

	rable 2. Official clements of unferent tes	i systems
System	Critical lines	Critical buses
IEEE-14	1-2	2
IEEE-30	1-2	2,6
IEEE-57	1-15, 3-15, 41-43,49-50, 50-51	8, 12
IEEE-118	68-65, 38-65	10, 26, 65, 66
IG-75	41-42, 55-63, 54-63, 74-73	13, 15, 41

Table 2. Critical elements of different test systems



Figure 3. Workflow for identifying the critical elements

3. Proposed Binary Cuckoo Search (BCS)

As it is well known that the cuckoo cannot hatch its eggs, it simply lay them down in any nest of other bird [16, 17]. The strategies, then the cuckoo will follow to let its egg hatched safely, have been modeled as the constraints for its optimization problem of finding the best nest. In this algorithm, cuckoos are said to have followed a levy flight search that characterizes a pre-defined steps to find a new nest [18]. Towards finding optimal nest, it certainly generates new solution (31) using the levy distribution (32) as follows:

$$x_i^{t+1} = x_i^t + \alpha \oplus levy(\lambda)$$
(31)

$$levy \sim u = t^{-\lambda} \tag{32}$$

It means, to calculate the new solution (x_i^{t+1}) from present solution (x_i^t) , it uses levy flight for the fixed length of α , which are continuous. Since the optimal placement of PMU is discrete optimization problem, a Binary Solution Representation (BSR) is used to convert continuous search space to discrete. For this, BSR uses a sigmoid (33) to determine flipping chances, $\sigma(x_r)$, to convert the solution of real-valued (x_r) to the solution of binary value (x_b) (34) [19].

$$\sigma(x_r) = \frac{1}{\left(1 + e^{x_r}\right)} \tag{33}$$

The transformation will be completed only after comparing $\sigma(x_r)$ with a $\gamma \in [0,1]$, a randomly generated number (34).

$$x_b = \begin{cases} 1, if\gamma < \sigma(x_r) \\ 0, otherwise \end{cases}$$
(34)



Figure 4. Flowchart of the proposed Binary Cuckoo Search

Then, after conversion, the selection operation will be performed to find the optimal solution for the given objective function.

3.1. Algorithm

Step1: Read the abandon factor, Pa and the objective function from the equation (6).

Step2: Read the objective function and initialize the population

Step3: If the convergence satisfied, perform steps 4 to 9. Else, go to stop.

Step4: Apply Levy flights to calculate the cuckoo (Nesti), randomly.

Step5: Determine its binary equivalent, and then evaluate fitness, S_{i.}

Step6: For the nest (Nest_j) chosen arbitrarily, evaluate the fitness S_{j.}

Step7: Check whether $S_i > S_j$ to update the solution, and then, to continue.

Step8: Evaluate the fitness for all the remaining nests.

Step9: Using the Abandon factor (P_a) , remove the worst solutions. And, replace them with the new solutions calculated using Levy flights. Then go to step 3.

Step10: Stop

4. Results and discussions

The methodology of the proposed technique is described using Fig. 5, in the form of a flowchart is given below. Consider an IEEE-14 bus system with 14 as shown in Fig. 6. On applying the network reconsideration, it can be modelled as a 14-bus with 2 optimal substations and 8 substations as shown in Fig. 7. Then, the critical elements are found to be L1-2and bus 2, as listed in Table 2. Now, on applying the proposed PMU placement algorithm considering all the critical elements, the optimal locations of PMUs are found to be 2, 4 and 5. From Fig. 7, it is cleared that the PMUs at substations 4 and 5 not only could observe the system completely but also covers the substations. And, the remaining PMU at substation 2 will observe the line L1-2 and bus 2 directly. Also, the PMU locations considering only substation coverage are given in Table 3.

System	No. of substa- tions for PMU placement before network reconsideration	No. of substa-tions for PMU placement after network reconsideration	Buses with PMU locations
IEEE-14	14	10	4,5
IEEE-30	30	24	2,4,6,15,20,25,27
IEEE-57	57	43	1,4,9,10,11,13,14,15,20,24,25,29,32 ,37,39,53,56
IEEE-118	118	109	2,5,9,12,15,17,21,24,25,29,36,37,40 ,43,46,50,51,53,59,61,66,69,71,75,7 7,80,85,87,91,94,101,105,110,114
IG-75	75	64	4,8,9,13,15,17,18,20,24,25,27,29,30 ,31,32,33,37,40,41,43,48,51,63,70,7 3

Table 3. PMU locations considering substation coverage



Figure 5. The flow chart of the proposed Method



Figure 7. Reconsidered IEEE-14 bus system

Table 4. PMU locations for direct measurement of critical	el	ements
considering substation coverage		

	•••••••	sering successfunction so retuge		
Sustam		PMU locations considering		
System	Critical lines	Critical buses	Both	
IEEE-14	1,4,5	2,4,5	2,4,5	
IEEE-30	2,6,12,18,23,25,27	2,6,12,15,19,26,27	2,6,12,15,19,26,27	
IEEE-57	1,4,9,10,11,13,14,15,2	3,4,8,9,10,11,12,13,14,15,2	3,4,8,9,10,11,12,13,14,15,20,2	
	0,24,25,29,32,39,43,5	0,24,25,29,32,39,52,56	4,29,30,32,39,41,50,54,56	
	0,54,56			
IEEE-118	1,5,10,12,15,17,21,23,	2,5,10,12,13,17,19,22,24,25	3,5,10,11,12,17,21,23,23,26,29	
	25,29,36,37,40,44,46,	,26,29,31,36,37,40,43,46,51	,34,37,40,45,46,49,53,56,59,61	
	50,51,53,59,61,6,5,66,	,52,57,59,61,65,66,69,73,75	,65,66,69,71,74,78,80,85,86,89	
	69,71,75,77,80,85,87,	,77,80,85,86,90,94,102,105,	,92,96,100,107,108,110,115,11	
	91,92,96,102,105,110,	110,115	8	
	114			
IG-75	4,9,13,17,18,20,24,27,	8,11,13,15,17,18,20,24,27,2	4,13,15,17,18,20,24,27,29,30,3	
	29,30,31,32,33,34,37,	8,29,30,31,32,33,35,41,43,4	1,32,33,34,35,40,41,43,49,52,6	
	40,41,43,44,48,52,60,	8,52,55,60,69,70,73	0,63,69,70,73	
	63,70,74			

		No. of PMUs required for Complete observability considering			
system	Only observability	Proposed method	high-voltage buses, [12]	High- connectivity buses, [12]	Transient stability of buses, [11]
IEEE-14	4	3	-	-	-
IEEE-30	10	7	-	-	-
IEEE-57	17	20	-	-	20
IEEE-	32	38	39	41	37
118					
IG-75	25	25	-	-	-

Table 5. Comparing the PMU number with literatur
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Similarly, the optimal locations of PMUs for different standard test systems i.e. IEEE-14, 30, 57, 118 and NRIG-75bus systems [20] with respective critical elements are listed in the Table 4. In Table 5, the resultant PMU number is compared with the PMU number required for only system observability. It also clearly witnesses the performance of the proposed algorithm when compared with the earlier techniques. This shows that, just by installing 15 percent of additional PMUs of total PMU installation cost, one can avoid major power blackouts that incur huge losses which may be many times the total PMU installation cost.

5. Conclusion

However, since the substation installation costs much high than the cost of the substation equipment, it is required to minimize the number of substations that install PMUs. And, the traditional PMU placement schemes were failed in reducing the substation installation cost as their aim is to reduce only the bus number. However, the proposed method reduces the number of substations and ensures system complete observability. It also provides the direct measurement of critical elements to avoid the most dangerous power interruptions like power system blackouts. Results obtained from the standard test systems witness the effectiveness and economics of the suggested method.

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