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Complete and Incomplete Observability Analysis by Optimal PMU Placement Techniques of a Network

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Abstract – State estimation of power systems has become vital in recent days of power operation and control. SCADA and EMS are intended for the state estimation and to communicate and monitor the systems which are operated at specified time. Although various methods are used we can achieve the better results by using PMU technique. On placing the PMU, operating time is reduced and making the performance reliable. In this paper, PMU placement is done in two ways. Those are 'optimal technique with pruning operation' and 'depth of unobservability' considering incomplete and complete observability of a network. By Depth of Unobservability Number of PMUs are reduced to attain Observability of the network. Proposed methods are tested on IEEE 14, 30, 57, SR-system and Sub systems (1, 2) with bus size of 270 and 444 buses. Along with achieving complete observability analysis, single PMU loss condition is also achieved.

Keywords: Observability, Depth of unobservability, Phasor Measurement Unit (PMU), Energy Management Systems (EMS), Redundancy, Wide-area Measurement Systems (WAMS).

1. Introduction

Energy Management Systems (EMS) plays an important role in state estimation. It can be done by relaying the sensed data of SCADA (Supervisory Control and Data Acquisition) system. By using SCADA, it is difficult to monitor the system within the available time. Phasor Measurement Units (PMUs) that depends on WAMS (Wide-area Measurement System) replaces the SCADA system. PMU is a device which is capable of measuring voltage and current phasors as well as rate of change of frequency with time stamping obtained from GPS (Global positioning System) satellite. PMUs measure estimated phasor quantities precisely at any instant of time. Tasks like power system Real time monitoring, control and partial protection [1] are done by PMU based state estimation.

Comparing with the conventional methods, PMU based operation and control leads to better results as follows:

1. PMU placement mainly gives phase angle information of measured quantities while remaining methods end up giving only RMS values of voltage and current phasors.
2. Placement of PMUs makes the system monitoring more accurate than other methods.
3. Time stamping factor removes issues affected by time delay.

PMU placement methods are based on the following criteria:

- Based on the observability criteria
- Based on critical dynamics i.e., on stability analysis

Some of the important PMU placement techniques that contribute to get improved solutions are Phasor Measurements in power systems [1] and PMU placement by linear integer programming techniques [2]. Which are enhances the requirement of phase angle and their uses in power system, involves real-time supervising of important buses in the network, voltage security assessment by optimal PMU placement gives usage of graph theory based algorithm for PMU placement by voltage measurement and finally placement of PMU for incomplete observability [3] explains first PMU placement technique for incomplete observability.

Placement of PMUs in this paper adopts the advantages of both complete and incomplete observability analysis. Topological observability based PMU placement technique for achieving complete observability involves three stages with pruning operation and 'Depth of Unobservability' Technique for Finding the unobservable buses placed in between the observable buses of the system. PMU number is reduced and Observability analysis is quick by using this Technique. This Technique is completely explained in proposed concept and it is executed by determining the 'depth of bus' as case at each and every bus in the system. Complete observability analysis is done in two different approaches viz topological observability and numerical observability. The topological observability method is chosen for complete observability analysis involving three

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stages. First two stages selects the location of PMU and placement are made and finally pruning operation is performed in third stage. By this, an optimal placement of PMU operation is performed for complete and incomplete observability analysis. In addition to that if fault occurs in any PMUs, single PMU loss analysis is considered in complete observability case.

The rest of the paper, is originated as follows section-2 deals with topological observability based pruning operation for complete observability. Section-3 deals with the Depth of unobservability techniques for incomplete observability analysis, section-4 deals with case study (blackout in India) and extension about this paper. Finally, conclusion is expressed in section-5.

2. Complete Observability Analysis

Complete observability analysis can be evaluated in two approaches.

I. Numerical observability analysis
II. Topological observability analysis

2.1 Numerical observability analysis

For state estimation, the measurement model is represented as

$$Z = h(x) + e \tag{1}$$

Here, Z is measurement vector
h(x) is non-linear function
e is error vector

PMU gives the accurate measurement of voltage and currents in magnitude and phase angle. Therefore 'e' can be neglected, and

$$Z = hx \tag{2}$$

Here 'x' is the system state vector
'h' is measurement function matrix

By solving the Eq. (2) as linear state estimator equation, it provides observability analysis by rank of the set matrix i.e., if 'N' number of buses are existing in a network then

$$\text{Rank} = 2N\text{-}1 \tag{3}$$

To place a PMU in optimal order, numerical observability is evaluated in two approaches.

I. Placement of PMUs in a network in order to enhance the rank of measuring matrix. After satisfying equation 3, no further PMU placement takes place.
II. Place PMUs at each and every bus of the network and then eliminate PMUs in sequential order which is to be prohibited where the rank of measured matrix is inferior.

From the above two methods, least possible number of PMU placement is obtained by checking large number of combinations which enhances the combination of rank testing makes the system burden.

2.2 Topological observability

It involves a network having number of nodes as 'N' and edges as 'C' is presented in graphical representation as G (N, C). In this analysis, each bus in a system is discernible by no less than one PMU. This method is used for complete observability analysis and if any PMU fails then single PMU loss condition is considered [4].

Let us consider N-bus framework with situation of PMU is represented by

$$\text{Min} \sum_{i=1}^{N} C_i V_i \tag{4}$$

Subjected to F(x) ≥ K
Here 'x' is PMU's binary decision variable vector
i.e., V_i = 1 if PMU is present
= 0 otherwise
for i = 1,2,3, ..., N

'K' represents unit vector of length N, K= [1 1 1 ....] ^{T}, C_i represents cost of PMU introduced at ith bus and F(x) represents observability constraint vector function.

where F(x) = 1 for the buses which are observable with given measurement set
= 0 otherwise

If 'C_i' is unity, problem become

$$\text{Min} \sum_{i=1}^{N} V_i \tag{5}$$

Subjected to F(x) ≥ K

On satisfying equation (5), set of minimum 'V_i' values are to be found. Corresponding vector function is formed by matrix 'A' said to be connectivity matrix and the components of the matrix are,

$a_{p,q}$ = 1 if p=q
= 1 if bus p and bus q are linked
= 0 otherwise

Now, the vector function for test system for any ith bus is given as

$$F(x) = Ax \geq K \tag{6}$$

$$f_i = a_{i,1}V_1 + \ldots\ldots a_{i,i}V_i + \ldots\ldots.. + a_{i,N}V_N \tag{7}$$

In Eq. (7), $a_{i,n}V_i$ disappears if $a_{i,n}$ is zero. If any V_i appearing in f_i is nonzero, f_i is observable. The framework

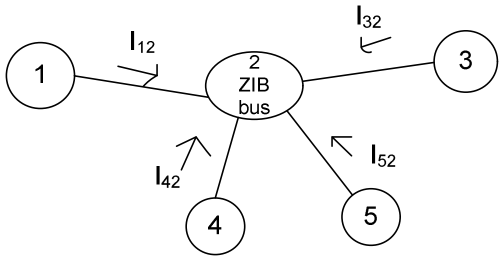


Fig. 1. Modeling of zero injection buses

is totally observable if all f_i in F are nonzero.

2.3 Proposed Technique

The objective of the recommended technique is to decrease count of PMU locations. Zero Injection Buses (ZIB) act as pseudo buses in PMU placements so ZIBs are not considered for PMU placement.

Zero injection Bus:

These are the buses which have neither any load nor any generation. In the system, no current is injected at ZIBs. Comparing with non-ZIBs, ZIBs are utilized as pseudo data buses to make framework observable with limited number of PMUs. Consider 5 bus system where bus 2 act as ZIB. Applying KCL at bus 2 gives

$$I_{12} + I_{32} + I_{42} + I_{52} = 0 \tag{8}$$

In Fig (1) out of five buses, four bus voltages are known then 5th bus voltage can be computed by adopting above equation. With all bus currents super node is formed by N number of linked ZIBs.

A super node can be formed by adjacent bus voltages with 'K' number of connected ZIBs, and then ZIB is obtained by

$$\sum_{j=1}^{M} v_j y_{ij} = 0 \quad \text{for i=1,…k} \tag{9}$$

The proposed algorithm is conveyed in three stages:

1. Recognizing the important bus locations for PMU placement is depending on valency concept.
2. Some buses are still unobservable with PMU placement, from those buses which are having high connectivity and connected to ZIBs are preferred for PMU placement, the elimination and retention of PMU is done by checking the observability of the system one by one.
3. Pruning operation is done by removing PMUs which are obtained from step – 1 & 2 and placing at some other bus, after that check whether the newPMU placement makes the count of already placed PMU buses are redundant or not and also redundancy of individual PMUs for satisfying system observability constraints.

Elimination and retention of PMU are as follows:

a. Elimination of PMU from the buses one by one to satisfy Eq. (6).
b. Retention of PMU is obtained for any of the higher valency bus.

2.4 Single PMU loss consideration

The complete observability of PMU placement is achieved as stated above**.** When any line of the bus or any one of the PMU fails, then observability of the buses connected to the failed PMU are lost. To compensate the loss of single PMU, extra PMUs are to be placed to get optimal result. Selection of extra PMUs are done in such a way that final set of PMUs are making the framework totally observable in typical condition and in addition single PMU loss condition. The ideal arrangement of problem is adjusted as:

$$\text{Min} \sum_{i=1}^{N} V_i$$

$$\text{Subjected to } F(X) \geq K$$

where K = [2 2 2 2….] ^{T} length of K is N and for single PMU loss condition, singly observable buses are either observable by using KCL at ZIB or a PMU. Doubly observable buses are observable either by using two PMUs or a single PMU and KCL at ZIB. KCL at ZIB makes foreign bus as doubly observable by all but one bus involves with any ZIB are doubly observable.

Steps for optimal set of PMU placement in the single PMU loss case as follows:

1. In addition to ideal arrangement of PMUs for full observability at normal operating conditions place the PMU at all radial buses which are not associated with any ZIB.
2. Get a set of buses which are singly observable and store those buses in Set{Y}.
3. In the event that the quantity of buses in Set{Y} is zero then go to step (6) otherwise go to step (4).
4. Get the maximum valency buses from Set{Y} excluding PMU buses.
5. Choose any one bus from maximum valency buses as PMU placed bus and eliminate the buses that are doubly observable because of extra PMU from Set {Y} then go to step (2).
6. Do pruning operation for removing redundant PMU which makes the system buses doubly observable.
7. Optimal PMU set is obtained for single PMU loss condition and normal operating conditions in complete observability analysis.

Whole analysis is applied for IEEE 14, 30, 57 and SR

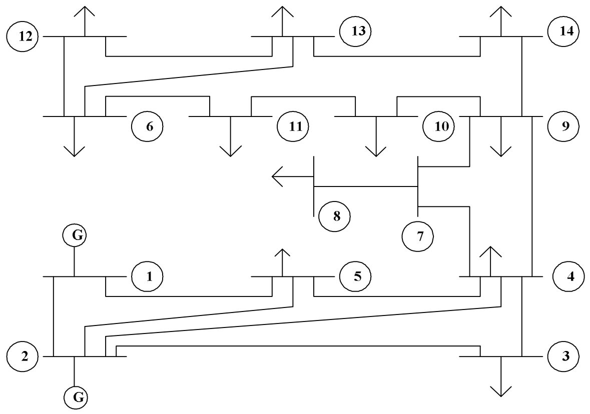


Fig. 2. IEEE 14-bus system

Table 1. Different valency buses of IEEE 14-bus system

Valency (V)	Bus number
2	8
3	1,3,7,10,11,12,14
4	5,6,13
5	2,9
6	4

systems along with sub systems and basic representation and valences are expressed for 14-bus system on Fig. 2 with valences are noted in Table 1.

3. Incomplete Observability Analysis

To find the total observability of a network, if the number and locations of PMUs are not sufficient then in that condition if we place the PMU to achieve complete observability, it refers to "incomplete observability" criteria. Compared to Complete Observability analysis this technique requires less no of PMUs and time in this technique.

3.1 Depth of unobservability (DOU)

Finding the unobservable buses placed in between the observable buses of the system is said to be "Depth of unobservability'. Those are three types [5].

i. Depth of one Unobservability
ii. Depth of two Unobservability
iii. Depth of three Unobservability

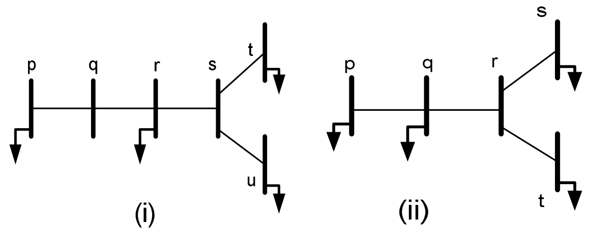
In a network if any one bus is placed between two observable buses either PMU placed or PMU connected bus considered as 'Depth of one Unobservability'. Correspondingly, Depth of two Unobservability, Depth of three Unobservability represents two; three unobservable buses are being set in the middle of two observable buses. Placement of next PMU in a network should be four buses away from First PMU along the Chosen path.

The proposed technique uses "Graph Theoretic Approach" instead of using 'Tree Branch' method which may reduces steps to achieve Optimal PMU locations and also time consumption process. It consists of two stages.

1. Network reduction
2. Network search

3.2 Network reduction

Consider a network having number of nodes as 'N' and edges as 'C' is presented in graphical representation as G (N, C) In the network reduction ZIBs play a key role. Depending on model of the network ZIBs are categorized into two types. Those are Z_R and Z_O tabulated in Table (3). Z_R represents the bus where the numbers of connections are at most two. Z_O represents the bus with more than two connections.



In figure (i), the buses q and s are zero injection buses. In network reduction, q and s belong to Z_R and Z_O. So, the network is reduced as (ii). Now N^I is decreased count of nodes and C^I is decreased count of edges in graph G (N^I, C^I) of the network.

3.3 Network search

There are four search modes illustrated with each with an array type the search mode. Let S_1 be the initial set and other designated sets are as follows:

S_A : buses allotted with PMU
S_B : observable buses with PMU
S_C : unobservable buses with PMU
S_D : based on the planning criteria of the network condition buses those are observable in order to achieve the objective.
S_D : decides the placement of PMU sets that the depth of unobservability of the system. Every bus in S_C set checked for PMU placement if S_N is non-empty. The bus in S_C observe the maximum number of buses in S_D set then that bus is next PMU bus. The process is terminated when the required network condition is satisfied and the set S_{12} holds the solution. This process is repeated for N^I times. The network algorithm steps are as follows:

i) Note the system elements as G (N, C), Z_O, Z_R
ii) G (N^I, C^I) is the altered network which is obtained after network degradation.
iii) Initial bus of the framework is considered as S_1.
iv) Renovate S_A, S_B, S_C, S_D.
v) Verify whether S_D is unfilled or not.

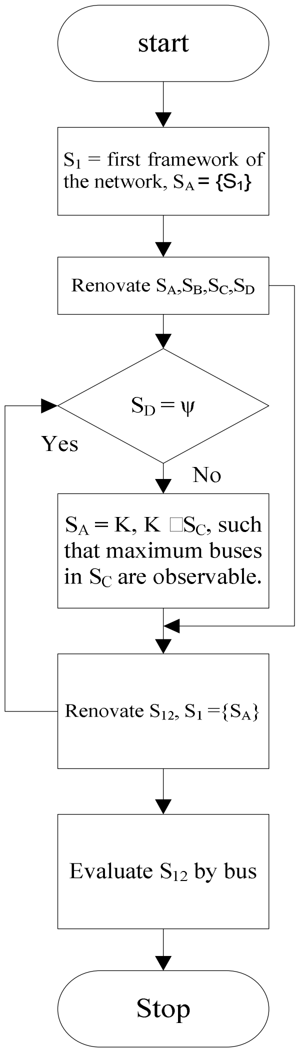


Fig. 3. Flow chart for network search

vi) S_D is unfilled move to step 9; otherwise go on.
vii) Find S_C for the following PMU bus which makes greater numbers of buses in S_D are observable.
viii) Move on to step 5.
ix) Renovate $S_{12.}$

3.4 Evaluation of the problem

The placement process for Depth of one Unobservability is expressed by Fig. 3 on considering the graph of IEEE 14- bus system. For Depth of one Unobservability placement let us consider bus 4 as initial bus in S_1. Then the sets represent:

$S_A = 4$
$S_B = 2, 3, 4, 5, 7, 8, 9$
$S_C = 1, 6, 10, 11, 12, 13, 14$
$S_D = 11, 12, 13$

Foe next iteration, we choose one bus from S_C by considering a term 'K' that represents a bus in the system then K ε S_C is the condition which makes maximum buses in S_C are observable and then that bus is placed as next bus in $S_{A.}$ Here K=6 that satisfy the condition K ε $S_{C.}$ So bus 4 and 6 makes the network observable under Depth of one Unobservability condition. This process is repeated with different buses in S_1 on each time. When the entire cycle is completed set 'S_{12}' holds all the possible conditions satisfy Depth of one Unobservability condition. That is the final set of PMU placement. Test system details are given in Table 2 and 3.

Table 2. Details of test systems of the network

Test System	Bus/ Branches	ZERO INJECTION BUSES	
		No. of buses	Buses
IEEE 14 Bus	14,21	1	7
IEEE 30 Bus	30,41	6	5,6,9,11,25,28
IEEE 57 Bus	57,80	16	4,7,11,15,21,22,24,26,34, 36,37,39,40,45,46,48.
SR (Southern Region) system	83,182	5	46,64,65,80,81

Table 3. Zero Injection Bus categorization

Test System	ZERO INJECTION BUSES	
	Z_R	Z_O
IEEE 14 Bus	7	-
IEEE 30 Bus	6,25,28	5,9,11
IEEE 57 Bus	4,7,11,15,22,24,36,37,48	21,26,34,39,40,45,46
SR (Southern Region) system	64	46,65,80,81

4. Case Study and Extension

4.1 Case study

In power framework history, on 30th,31st July 2012 in INDIA one of the most noticeably bad power outages occurred which makes more than 620 million individuals lost power source.48 GW of load shedding occurred which effects 22 states in North-Eastern, Eastern and Northern regions of India [6]. Northern Region grid was damaged on July 30 and North-Eastern Region, Eastern Region, and Northern Region damaged on July 31. Main cause of this blackout is tripping of 400 kV Bina-Gwalior line. This is due to failure of distance relay because of over voltage, under frequency and internal power swings at different places in this line, multiple tripping happens in tie-lines of these regions.

PMU-based WAMS makes important role in Indian grid system by improving visibility with continuous checking, assurance and control of framework [7].

Some of the PMU based applications that save this blackout in India are [8]:

1. Avoid the mal operation of relays: By implementing PMU based security scheme heavy losses are been

Table 4. Optimal PMU placement for complete and incomplete observability analysis

Test System	Size	Complete Observability	Incomplete Observability		
	Buses, lines		DOU - 1	DOU - 2	DOU - 3
IEEE - 14	14,21	3	2	2	2
IEEE - 30	30,41	7	4	3	3
IEEE - 57	57,80	12	9	8	6
SR System	83,182	27	11	9	6
Sub Sytem-1	270,326	90	62	56	45
Sub Sytem-2	444,574	121	97	83	68

Table 5. Optimal PMU placement under normal operating conditions with considering ZIBs

Test System	With Zero Injection Buses Optimal PMU Locations			
	Complete Observability	Incomplete Observability		
		Depth of Unobservability		
		1	2	3
IEEE-14	2,6,7,9	4,6,7	5,7,9	4,7,13
IEEE-30	2,3,6,9,10,12,15,19,25,27	4,5,6,9,10,11,15,25,27,28	5,6,9,11,15,25,28	5,6,9,11,12,25,28
IEEE-57	1,4,9,20,24,27,29,30,32,36,38, 39,41,45,46,51,54	4,7,9,11,15,19,21,22, 24,26,31,34, 36,37,39,40,45,46,48,49,52,56	1,4,7,9,11,15,19,21,22,24,26, 29,30,34, 38,39,40,45,46,48,56	3,4,7,9,11,15,21,22, 24,25,26, 29,34,36,37,38,39,40,45,46,48,56
SR System	2,4,5,11,13,17,19,21,22,24,25,26 30,31,37,39,40,41,43,45,46,50, 53,58,59,61,63,64,65, 67,80,81	2,4,17,31,34,37,39,41,46,52, 60,64,65,73,80,81	1,2,17,20,25,34,37,41, 46,52,64,65,80,81	1,31,38,46,52, 64,65,67,73,80,81

Table 6. Optimal PMU placement under normal operating conditions without considering ZIBs

Test System	Without Zero Injection Buses Optimal PMU Locations			
	Complete Observability	Incomplete Observability		
		Depth of Unobservability		
		1	2	3
IEEE-14	2,6,9	4,6	5,9	4,13
IEEE-30	2,3,10,12,18,24,30	4,10,15,27	6,15,25	6,12,25
IEEE-57	1,6,13,19,25,29,32,38,51,54,56	4,9,15,19,24,31,49,52,56	1,4,9,19,29,30,38,56	3,9,25,39,38,56
SR System	2,4,5,11,13,17,19,21,22,24,25,26,30,31,37, 39,40,41,43,45,50,53,58,59,61,63,67	2,4,17,31,34,37, 39,41,52,60,73	1,2,17,20,25,34, 37,41,52	1,31,38,52, 67,73

prevented after the failure of protection relay on the Bina-Gwalior line.

2. Load shedding operations: By WAMS we can easily implement the frequency and df/dt based load shedding.
3. Perfect state estimation: By proper placement of PMU we can greatly improve the state estimation analysis because it plays a vital role in case of blackouts.

4.2 Extension

In order to place the PMUs for complete and incomplete observable analysis, there are extended ways to place the PMUs at buses which are formed into a group depends on the status of the network. The aim of this method is to reduce the PMU number by forming all the generator buses into a group through stability concept. Two steps involved in this process they are:

(1) Grouping the generators depend on the transient and steady state performance.

(2) Based on selection criteria representative buses are selected in each group, where PMU should have installed. This method mainly depends on transient stability of the power system.

Table 7. Comparison with different methods of PMUs placement

Method	Number of PMUs required for IEEE 14- bus system	
	Normal Condition	Single PMU loss Condition
Biogeography based optimization	4	7
Interactive method	4	7
Binary imperialistic method	4	7
Proposed method	3	7

Table 8. Optimal PMU placement for single PMU loss condition

Test System	Optimal PMU Placement for Single PMU loss condition with Zero Injection Buses
IEEE-14	1,2,4,6,9,10,13
IEEE-30	1,2,3,5,6,10,12,13,15,16,18,19,24,27,30
IEEE-57	1,2,4,6,9,12,15,18,19,22,24,25,27,29,30,32,36, 38,41,47,50,51,53,54,56

5. Results

The recommended techniques are tested on IEEE 14, 30, 57, SR system and Sub Systems (1, 2) with 270,444 buses respectively and the obtained results are tabulated in Table 4, 5 and 6 suitably. PMU placement positions for Sub Systems 1 and 2 are mentioned in count only because of large number of buses.

6. Conclusion

To monitor and control the important information of a network the placement of PMU is expressed for incomplete and complete observability analysis. For incomplete and complete observability analysis, the proposed method is analyzed by graphical approach for finding out the optimal PMUs count. While measuring the optimal locations of PMUs this proposed method eliminates redundant PMUs of a given framework. For all power system problems, this proposed technique is efficient and simple. To assure the framework in case of normal and single PMU loss conditions this technique will be useful. Simulated results are tested on IEEE 14, 30, 57, SR (Southern Region) system and sub systems (1, 2) and results are found confirmed to standard methods.

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