Synchrophasors Measurement for Intentional Islanding with Realistic Considerations

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Abstract: Blackout is complete shutdown of power network. This paper present an optimal phasor measurement unit placement model considering one of the practical constraint of channel limit in power system intentional islanding so that power network remain observable under intentionally islanded scenario as well as in normal operating condition. Optimizing number of installed PMU and to have maximum measurement redundancy in normal as well as in intentionally islanded condition with constraint of channel limit is proposed in this paper. Finally, different IEEE standard systems and a practical Indian UPSEB 75-bus system are taken to validate the given algorithm. The algorithm is generic and can be applied to any other intentional islanding schemes.

Keywords: Smart Grid, Intentional Islanding, Optimal phasor measurement units (PMU), controlled islanding.

Introduction

With the ever-increasing demand for power, the limited one-way interactions of previously designed grids were proving to be insufficient. Outdated engineering, obsolete system framework, and modern deregulated loading levels and traditional tools for power delivery and planning are ineffective in addressing current demands. Sometimes minor problems in the grid may multiply and cause blackouts i.e. the complete shutdown of power networks. When a sequence of low probability event is cascaded by a minor disturbances such blackouts tend to occur. Blackouts even though rare, when occur have a disastrous effect.

Smart Grid [1,2], represents a vision of the future power systems integrating advanced sensing technologies, control methodologies and communication technologies with existing infrastructure at transmission and distribution levels in order to supply electricity in a smart and user friendly way. Success of Smart Grid is possible only if we can get the dynamic snapshot of the system at any instant of time. All these operations can be possible only if the monitored data is accurate, received at reasonably fast rate and most importantly contains the accurate time information of the measuring instant.

Synchro-phasor measurement is a technology which is used to measure/estimate voltages and voltage angles of the system utilizing GPS technology to perform the measurements with accurate time information of the measuring instant embedded with each measurement. With these measurements, voltage angles of various remote locations can actually be compared which was not possible in conventional measuring devices. However, PMU and its associated communication facilities are costly. Furthermore, the voltage phasor of the bus incident to the bus with PMU installed can be computed with branch parameter and branch current phasor measurement. So it is neither economical nor necessary to install PMUs at all system buses. Thus, one of the important issues is to find the optimal number and placement of PMUs for power system network. Different PMU placement methodologies can be taken from [3].

In this paper, an ILP model of OPP considering controlled/intentional islanding (OPP-CI) is proposed with PMU having different number of channel limit as well as infinite channels. This model is able to determine the minimum number and optimal location set of PMUs to provide the full network observability in normal operation and in controlled islanding operation. To obtain the best solution out of multiple optimal solutions, measurement redundancy is used.

The rest of the paper is arranged as follows. In Section II, the concepts and rules of network observability are introduced and improved algorithms for PMU placements considering controlled islanding with PMU channel limits and better network observability having high measurement redundancy is given. The proposed model is tested on different IEEE standard systems and on a practical Indian 75 bus system whose results is given in Section III. Finally, conclusions are given in Section IV.

Optimal PMU Placements for Intentional Islanding Considering Channel Limit

Observability is defined as the condition in which all the system bus voltages and branch currents are known. To know the observable bus in a system following simple rules have been implemented [4].

- Using Ohm's law voltage phasor of the other end can be obtained if voltage phasor and current phasor at one end of a branch are known.
- The current phasor through any branch can be calculated, if voltage phasors at both ends of a branch are known.

Modification for OPP Problem in an Islanded Condition

Till date, a lot of investigations have been conducted on this topic and various methods for controlled islanding [6]-[12] have been proposed; for example, a method of controlled islanding with constraint of observability is presented in [13]. Since our research is focused on the OPP problem, our work does not study methods of controlled islanding in detail but only uses the controlled islanding results of several IEEE standard systems presented by different researchers, and assumes a suitable controlled islanding scheme for the Indian 75-bus system of Uttar-Pradesh electricity board (UPSEB) considering a practical constraint of channel limit. However, the proposed OPP method can be applied to any other controlled islanding schemes. For controlled islanded condition, the OPP problem can be formulated using equations given by L. Huang et. al [14].

OPP-CI Model Considering Channel limit

The infinite channel capacity of available PMUs is not a realistic assumption on which the earlier work was based. But in practice the PMU has a limited channel capacity, usually 3 or 4 [15]. Here it may be noted that in the present work a PMU channel implies how many branch currents the PMU can measure in addition to the bus voltage at which it is installed. The actual number of PMU channels may be more as it has to measure three phase current and voltage. The primary objective of the present work is to show that the channel capacity of PMU should be an integral consideration while devising an intentional islanding methodology.

Reference [15] has presented a method to incorporate channel limit for OPP. So considering the constraint that a PMU have fixed number of channels in practical applications, the equations can be formulated as

$$\text{Min } \mathbf{F}^T\mathbf{X}$$

Which can be written as:

$$min \sum_i^n w_i . x_i \tag{1}$$

Subject to constraints

$$f(\boldsymbol{X}) \geq \boldsymbol{b} \tag{2}$$

where

X is a binary decision variable vector, whose entries are defined as:

$$x_i = \begin{cases} 1; if\ a\ PMU\ is\ installed\ at\ bus\ i \\ 0; otherwise \end{cases} \tag{3}$$

w_i is the ith element of the column vector i.e. the cost of PMU installed at bus i. If costs of all PMUs are equal, all the entries in $\boldsymbol{w}$ vector will be 1. $f(\boldsymbol{X})$ is a vector function, whose entries are non-zero if the corresponding bus voltage is solvable using the given measurement set and zero otherwise.

$f(\boldsymbol{X})$ can be found as:

$$f(\boldsymbol{X})=\mathbf{A.X} \tag{4}$$

$\boldsymbol{b}$ vector represents how many times a bus is needed to be observable. It tells the required redundancy level of measurements for a bus. If any element of $\boldsymbol{b}$ matrix is greater than one, it simply means that the corresponding bus is observable from more than one direction. Thus, such a system in which each bus is observable more than once is more robust and reliable. So, $\boldsymbol{b}$ matrix can be used to fulfill the minimum requirements of robustness. In present work, all the entries of b are taken as 1.

For channel limit c_i having n number of buses, **A** is formulated as

A(l , :) = **a** (i,:) if branches incident on bus i $\leq$ channel limit c_i where l is a scalar in this case

If branches incident on bus i > channel limit c_i, then for c_i no of channel limits for the PMU placed at bus i, ${}^{k_i}C_{c_i}$ number of possible combinations of branches that can be covered by PMU can be formed because at a time only c_i branches can be covered by a PMU at bus i. where k_i is no of incident lines on bus i.

Hence, equation (10) is solved to obtain the solution vector **X** which gives the required PMU locations.

Now to incorporate the islanding condition, **A** matrix is formed as the same manner as before except that the connections which are opened during islanding condition are not considered. In other words **A** is formed in the light of matrix $\mathbf{a}^{\mathbf{CI}}$ rather than **a.**

For more clarity, the algorithm is represented as:

(1) $\mathbf{A}^{\mathbf{CI}}(l, :) = \mathbf{a}^{\mathbf{CI}}(i, :)$, if branches incident on bus i in islanded condition < PMU channel limit c_i

Where l is scalar

(2) If branches incident on bus i in islanded condition > PMU channel limit c_i
Then for c_i number of channel limits for PMU placed at bus i, ${}^{k_i}C_{c_i}$ number of possible combinations of branches that can be covered by PMU at a time can be formed. This is so because at a time only c_i number of branches can be covered by a PMU at bus i.
Therefore, each such row of $\mathbf{a}^{\mathbf{CI}}$ can be replaced by these rows of possible combinations to form matrix $\mathbf{A}^{\mathbf{CI}}$.

Dealing with Multiple Optimal Solutions

Rewriting OPP problem

$$\text{Min } \mathbf{F}^T\mathbf{X} \qquad (5)$$

$$\mathbf{A}^{\mathbf{CI}}\,\mathbf{X} \geq \mathbf{b} \qquad (6)$$

PMUs placement through the objective function (5) and inequality constraints (6) can be used to obtain multiple optimal solutions with the same minimum number of PMUs. For example, For the 14-bus system, installations of 5 PMUs lead the system to complete observability in controlled islanding scenario but there are 12 different optimal solutions in this case. If channel limits are used then by the use of the objective function (5) and inequality constraint (6) the following possible optimal solutions can be obtained {2 5 6 7 9}, {4 5 6 7 9}, {1 4 6 7 9}, {1 4 6 8 9}, {3 5 6 7 9}, {1 2 6 7 9}, {1 3 6 7 9}, {4 5 6 8 9}, {1 2 6 8 9}, {3 5 6 8 9}, {2 5 6 8 9}, {1 3 6 8 9}. To get these different combinations we have to modify our algorithm so that it is compelled to give different multiple solution in each iteration until all the possible combinations such that number of PMUs remain 5 and inequality (6) holds. This is necessary because the algorithm would otherwise give the same solution every time and other optimal solutions will be unknown. To ensure that different combinations result in each iteration the algorithm can be modified as

$$A_{It+1}^{CI} = \begin{bmatrix} A_{It}{}^{CI} \\ x \end{bmatrix} \qquad (7)$$

$$b_{It+1} = \begin{bmatrix} b_{It} \\ n-1 \end{bmatrix} \qquad (8)$$

Where 'It' is the iteration step and

$$x_i = \begin{cases} -1\,; if\ PMU\ is\ palced\ on\ i\ in\ previous\ solution \\ \ \ 0\,; otherwise \end{cases} \qquad (9)$$

n = no. of PMUs

Measurement and Maximum Redundancies

In this work, maximizing the measurement redundancy is considered as an additional objective to pick out the most suitable OPP scheme for power systems along with the constraint of finite PMU channel limits. Conventionally, measurement redundancy is defined as the ratio of the number of measurements to the number of states [14]. Considering that the most important state variables in state estimation are bus voltage phasors, the measurement redundancy can be redefined as the ratio of the number of voltage measurements to the number of system buses.
For any bus i, the max. redundancy can be calculated as

$$max.red = \begin{cases} no.of\ branches\ incident\ ; \\ if\ no.of\ branches\ < channel\ limit \\ \\ channel\ limit\ ; \\ if\ no.of\ branches > channel\ limit \end{cases} \quad (10)$$

Redundancy, t_i = no. of incident branches on bus i through which PMU is making a bus observable
To keep consistency with OPP which is a minimization problem, the objective function of maximizing measurement redundancy is formulated as a minimization problem as well:

$$\min f_2 = \frac{1}{n}\sum_{i=1}^{n}[w_1(m_i^N - t_i^N) + (1-w_1)(m_i^I - t_i^I)] \quad (11)$$

Where the total no of system buses is represented by *n*, in normal operation, the maximum number of times the *i*th bus can be made observable has been represented by the constant m_i^N, which is equal to one plus the number of its incident lines; whereas variable t_i^N denotes the number of times that the *i*th bus is observed by the solved OPP scheme under normal operation; corresponding constant and variable under islanding operating condition are represented by m_i^I and t_i^I, respectively; w_1 and $(1-w_1)$ are weighting factors assigned to the two components of the objective function. A power system is operated more often under normal condition as compared to islanding condition, so in this work we can assume w_1 and $(1-w_1)$ to be 0.7 and 0.3, respectively.
m_i and t_i can be formulated as
let

$$\boldsymbol{M}_{n\times 1} = \boldsymbol{a}_{n\times n} \times ones(n,1) - 1$$

Then

$$m_i = \begin{cases} M_{(i)};if\ M_{(i)} \le c_i \\ c_i\ ; otherwise \end{cases} \quad (12)$$

Let

$$T_{n\times 1} = A_{n\times l}^T X_{l\times 1}$$

Then

$$t_i = \begin{cases} t_{(i)};if\ t_{(i)} \le c_i \\ c_i\ ;\ otherwise \end{cases} \quad (13)$$

For controlled islanded condition m_i and t_i are obtained by replacing **a** with $\mathbf{a}^{CI}$ and **A** with $\mathbf{A}^{CI}$ in the above equations
The complete algorithm can be represented by this flow chart which is as follows:

Results

The proposed OPP-CI model was tested on the IEEE 14-, 30, 39, 118-bus systems, and practical 75-bus System of Uttar-Pradesh State Electricity Board (UPSEB), as detailed in Table 1. All simulations are executed in a laptop having a 1.70-GHz Intel-core processor and 4 GB of RAM. The OPP problem is modeled in MATLAB and solved by CPLEX Toolbox for MATLAB.
To perform the OPP-CI procedure, the controlled islanding plans for different IEEE systems should be known a priori. In our dissertation work, these controlled islanding schemes are extracted from [8], [9] and [10]. For clarity, they are listed again in Table 2. As for IEEE 14-bus system, two islands with 6 buses and 8 buses in each island respectively, are included in the islanding scheme.
However, as mentioned earlier, the proposed OPP-CI model is not just suitable to the above controlled islanding cases but also can be applied to any other controlled islanding schemes. Table 3 to 7 provides the comparison of the number and locations of required PMUs resulting from OPP with or without consideration of controlled islanding with channel limits as 2, 3, 4, 5, 6 and infinite channels having maximum redundancy.
Results of tables 3 to 7 reveal that generally more PMUs are required by power network to maintain observability in case of controlled islanding scenario as compared to normal operating condition. It can also be seen from these table that with increase in channels of PMU, the number of PMUs required also decreases for normal as well as controlled islanding condition. It can also be seen from the table that on increasing the no of channels of PMU, after certain limit the number of PMUs become constant usually after 3 or 4 channel limit.

Table 1. Specifications of Test Systems

Test System	Number of Lines	Bus With Maximum Number of Incident Lines	Maximum Number of Incident Lines
IEEE 14-Bus [16]	20	4	5
IEEE 30-Bus [16]	41	6	7
IEEE 39-Bus [16]	46	16	5
IEEE 118-Bus [16]	186	49	12
UPSEB 75-Bus[17]	97	30	7

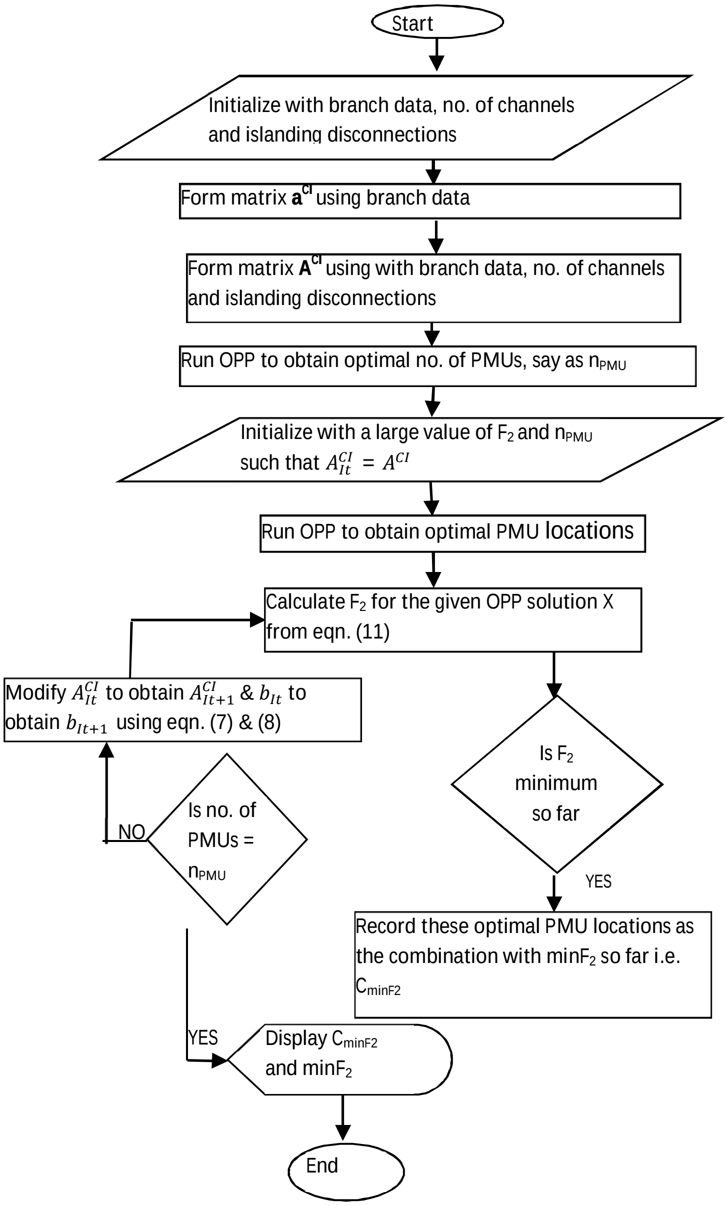

Fig. 1. Flow Chart of Proposed Algorithm

Table 2. Controlled Islanding Schemes for Different Systems

Test System	Controlled Islanding Information		
	Islands number	*Buses*	*Opened lines*
14-Bus [16]	2	6(1, 5-6, 11-13) 8(2-4, 7-10, 14)	1-2, 2-5, 4-5, 10-11, 13-14
30-Bus [27]	2	15(1-4, 12-20, 23-24) 15(5-11, 21-22, 25-30)	2-5, 2-6, 4-6, 10-17,10-20, 22-24, 24-25
39-Bus [28]	3	26(4-8, 10-24, 31-36) 10(2-3, 25-30, 37-38) 3(1, 9, 39)	8-9, 3-4, 3-18, 17-27, 1-2
118-Bus [28]	3	35(1-23, 25-32, 113-115, 117) 54(24, 33-81, 97-98, 116, 118) 29(82-96, 99-112)	15-33, 19-34, 30-38, 23-24, 77-82, 96-97, 80-96, 98-100, 80-99
UPSEB 75-Bus	4	14(6,7,22,25,38,39,60,62,70,72) 14(3,11,18,20,27,40,48,49,51,52,64,66,68,71) 23(4,8,14,15,21,28,29,34,43,44,45,53-58,61,63,65,73) 23(1,2,9,10.12,13,16,17,19,23, 4,26, 35- 37,41,42,46,47,50,67,74)	22-26,22-29,25-43,31-59,61-62,29-38,23-29,24-54,73-74,19-20,24-27, 26-27,18-47

Table 3. Comparison of OPP Results with and without Consideration of Controlled Islanding with Channel Limits Having Maximum Redundancy for IEEE14 Bus System

	OPP neglecting controlled islanding			**OPP considering controlled islanding**		
No of channels	*No of PMUs*	*location of PMUs*	*PMUs installation Percentage*	*No of PMUs*	*location of PMUs*	*PMUs installation percentage*
2	5	3 5 7 11 13	35.71	6	4 5 6 7 9 13	42.85
3	4	2 6 7 9	28.57	5	2 5 6 7 9	35.71
4	4	2 6 7 9	28.57	5	2 5 6 7 9	35.71
5	4	2 6 7 9	28.57	5	2 5 6 7 9	35.71
6	4	2 6 7 9	28.57	5	2 5 6 7 9	35.71
Infinite	4	2 6 7 9	28.57	5	2 5 6 7 9	35.71

Table 4. Comparison of OPP Results with and without Consideration of Controlled Islanding with Channel Limits Having Maximum Redundancy for IEEE 30 Bus System

	OPP neglecting controlled islanding			**OPP considering controlled islanding**		
Number of channels	*No of PMUs*	*location of PMUs*	*PMUs installation %*	*No of PMUs*	*location of PMUs*	*PMUs installation percentage*
2	11	3 5 6 9 12 16 19 23 24 25 27	36.66	12	1 7 8 9 10 12 15 16 19 23 25 30	40.00
3	10	1 5 6 9 10 12 15 20 25 27	33.33	11	1 6 7 9 10 12 16 19 23 25 27	36.33
4	10	2 3 6 10 11 12 19 23 26 27	33.33	11	1 7 8 9 10 12 16 19 24 25 27	36.33
5	10	2 3 6 9 10 12 19 23 26 27	33.33	11	1 7 8 9 10 12 16 19 24 25 27	36.33
6	10	1 5 6 9 10 12 15 18 25 30	33.33	11	1 7 8 9 10 12 16 19 24 25 27	36.33
Infinite	10	2 4 6 10 11 12 18 23 26 27	33.33	11	1 7 8 9 10 12 16 19 24 25 27	36.33

Table 5. Comparison of OPP Results with and without Consideration of Controlled Islanding with Channel Limits Having Maximum Redundancy for IEEE 39 Bus System

	OPP neglecting controlled islanding			**OPP considering controlled islanding**		
No of channels	*No of PMUs*	*location of PMUs*	*PMUs installation Percentage*	*No of PMUs*	*location of PMUs*	*PMUs installation percentage*
2	14	2 5 6 10 11 15 17 19 20 22 23 25 29 39	35.89	15	2 6 8 10 12 14 17 19 20 22 23 25 27 29 39	38.46
3	14	2 5 6 10 13 16 17 19 20 22 29 36 37 39	35.89	15	2 5 6 10 13 15 17 19 20 22 23 25 26 38 39	38.46
4	14	2 6 9 13 14 17 19 20 22 23 29 32 37 39	35.89	15	2 5 6 13 15 17 19 20 22 23 25 26 29 32 39	38.46
5	14	2 6 9 13 14 17 19 20 22 23 29 32 37 39	35.89	15	2 5 6 13 15 17 19 20 22 23 25 26 29 32 39	38.46
6	14	2 6 9 13 14 17 19 20 22 23 29 32 37 39	35.89	15	2 5 6 13 15 17 19 20 22 23 25 26 29 32 39	38.46
Infinite	14	2 6 9 13 14 17 19 20 22 23 29 32 37 39	35.89	15	2 5 6 13 15 17 19 20 22 23 25 26 29 32 39	38.46

Table 6. Comparison of OPP Results with and without Consideration of Controlled Islanding with Channel Limits Having Maximum Redundancy for IEEE 118 Bus System

	OPP neglecting controlled islanding			**OPP considering controlled islanding**		
No of channels	*No of PMUs*	*location of PMUs*	*PMUs installation Percentage*	*No of PMUs*	*location of PMUs*	*PMUs installation percentage*
2	41	1 6 9 11 12 15 17 21 27 29 30 32 35 37 42 43 46 51 54 57 59 62 65 68 69 70 71 78 80 83 86 89 92 96 99 102 104 105 108 110 118	35.89	41	1 6 9 11 12 15 17 21 25 28 32 36 37 40 44 46 49 51 54 57 59 62 65 68 70 71 78 80 83 86 89 92 94 100 102 105 107 108 110 115 118	38.46
3	33	1 5 10 12 15 17 20 23 28 30 35 40 43 46 51 54 57 62 64 68 71 75 77 80 83 86 89 92 96 100 105 110 114	35.89	35	1 5 9 12 15 17 21 25 29 34 37 40 45 49 52 56 59 62 63 68 70 71 76 79 80 85 86 89 92 96 100 104 105 110 114	38.46
4	32	2 5 9 12 15 17 21 25 29 34 37 40 45 49 52 56 62 64 68 71 72 75 77 80 85 86 90 94 101 105 110 114	35.89	33	1 5 9 12 15 17 21 25 29 34 37 41 45 49 53 56 62 63 68 70 71 76 77 80 83 87 89 92 94 100 105 110 114	38.46
5	32	3 5 10 12 15 17 21 23 29 30 35 40 43 46 51 54 57 62 63 68 71 75 77 80 85 86 91 94 102 105 110 115	35.89	33	2 5 10 12 15 17 21 25 28 34 37 40 45 49 52 56 62 64 68 70 71 75 77 80 83 87 89 92 96 100 105 110 114	38.46
6	32	2 5 9 12 15 17 20 23 28 30 34 37 40 45 49 52 56 62 64 68 71 75 77 80 85 86 91 94 101 105 110 115	35.89	33	1 5 10 12 15 17 21 25 29 34 37 40 45 49 53 56 62 64 70 71 76 77 80 83 87 89 92 96 100 105 110 114 116	38.46
Infinite	32	3 5 9 12 15 17 21 25 29 34 37 40 45 49 53 56 62 64 68 70 71 75 77 80 85 86 90 94 102 105 110 114	35.89	33	3 5 9 12 15 17 21 25 29 34 37 40 45 49 53 56 62 64 68 70 71 75 77 80 85 86 89 92 96 100 105 110 114	38.46

Table 7. Comparison of OPP Results with and without Consideration of Controlled Islanding with Channel Limits Having Maximum Redundancy for UPSEB 75 Bus System

	OPP neglecting controlled islanding			**OPP considering controlled islanding**		
No of channels	*No of PMUs*	*location of PMUs*	*PMUs installation Percentage*	*No of PMUs*	*location of PMUs*	*PMUs installation percentage*
2	28	16 17 18 20 24 25 27 28 29 30 31 32 33 34 35 37 40 41 42 43 44 49 51 55 57 65 72 74	37.33	30	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 49 51 54 59 61 67 70 71	40
3	27	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 51 54 65 71 72 73	36	27	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 50 51 55 61 72	36
4	25	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 40 41 42 43 44 45 51 55 57 72	33.33	27	16 17 18 20 21 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 50 51 54 72	36
5	25	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 40 41 42 43 44 51 54 57 72 74	33.33	26	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 47 51 54 72	34.66
6	25	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 40 41 42 43 44 51 54 57 72 74	33.33	26	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 47 51 54 72	34.66
Infinite	25	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 40 41 42 43 44 51 54 57 72 74	33.33	26	16 17 18 20 24 25 28 29 30 31 32 33 34 35 37 39 40 41 42 43 44 45 47 51 54 72	34.66

Conclusion

An effective optimal PMU placement scheme should ensure complete observability of a power network under various operation conditions. To avoid wide-area blackout followingcascading failures, power system might be operated in controlled islanding mode. The OPP model considering controlled islanding of power system incorporates the practical constraint on PMU i.e. channel limit. The proposed model guarantees complete observability of power network for normal condition as well as controlled islanding condition. By introducing the measurement redundancy into the optimization objective, the proposed OPP-CI model can find the globally optimal solution with the minimum number of finite channel PMUs and maximum measurement redundancy. The case studies on several IEEE standard test systems and an Indian practical system provide verification of the effectiveness of the presented OPP models. A fast algorithm may be developed for the PMUs placed for distribution network where number of nodes are very large, and node connectivity is low and hence connectivity matrix **A** is sparser due to abundance of radial lines.

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