N V Phanendra babu[1,*], P Suresh Babu[2]

J. Electrical Systems 12-1 (2016): 45-67

Regular paper

A Robust Wide-Area Measurement System for Southern Region of Indian power Grid Using Binary Cuckoo Search (BCS): A Case Study

Journal of Electrical Systems

The current state estimators need to estimate the power system by means of the state variables i.e. voltage and current phasors accurately. Phasor measurement unit (PMU) is becoming a most prominent tool for monitoring, control and protection of electric networks, and hence it is required to employ them for the present and future power system networks. An optimal PMU placement (OPP) is quite important during planning studies for both existing and future power networks. So, when a new state estimator commissioned, or an existing estimator is up-graded, the problems of minimizing the number of PMUs and their optimal location for system complete observavbility will come into picture. The approach, in this paper, a Binary Cuckoo Search(BCS) method for system complete Observability based optimal PMU placement problem subjected to all possible contingencies and PMU communication channel limitations is suggested. The suggested method is tested with some of standard IEEE test systems and have been practiced for different State Level Regional power Grids (SLRGs) of the Indian power system. The results from the suggested method are also compared with the methods that have been already applied for standard IEEE test systems and SLRGs, and were proved to be best and effective.

Keywords: optimal PMU placement (OPP), Binary Cuckoo Search(BCS), power system obsrevability, Line/PMU outage, channel limits.

Article history: Received 30 July 2015, Accepted 11 February 2016

1. Introduction

The optimization problem was actually brought out in [1], later, many methods like genetic algorithm [2], particle swarm optimization [3] and many others were applied. Recently , deterministic strategies have also been developed. This includes integer linear programming(ILP) based[4] optimal pmu placement for system observability. An ILP based method for electrical networks with and without conventional measurements , was implemented in[5]. Later this method was extended in [6] to include the zero-injection bus (ZIB) effect. The integer quadratic based PMU placement policy was suggested in [7] without including zero-injection effect. A participation factor-based method was implemented in [8] to observe the system completely with better accuracy. However the zero-injection buses, which are generally switching stations, cannot be ignored completely from monitoring. So, the proposed OPP problem is considering zero-injection buses also for placing PMUs.

Also a binary search scheme was proposed in [9] for solving the OPP. But all these methods were failed in limiting their execution times and in offering an insight regarding the propinquity to the current OPP solution. All these papers aimed to minimize the number of PMU units for observing the power system completely .But no-where they consider transmission line outage or measurement failure. So, obviously the resultant optimal placement would never assures the system observability completely under any contingency. Therefore it is essential to a system implement a policy that considers both the transmission line outages and WAMS component failures.

[1] Research Scholar, Dept. of Electrical Engineering, National Institute of Technology Warangal-506004, India.
[2] Assistant Professor, Dept. of Electrical Engineering, National Institute of Technology Warangal-506004, India.

So, to make the wide-area monitoring system (WAMS) robust, the OPP problem should offer a complete system observability by considering the outage of any transmission line or a loss of PMU(or loss of its communication link). A very few papers have considered these two aspects as critical, and implement efficiently. For instance , the paper[10] presented an OPP solution by considering some pre-specified contingencies which could drive the system into instability . But there were very few chances for these contingencies to occur even though they are critical for the system stability. References [11-13] recommended the OPP methods considering contingencies for conventional measurement devices. Also, the method in [14] presented an optimal solution for OPP problem taking a single contingency into account. But all these methods were computationally expensive. Recently papers [15]and [16] have proposed an ILP based OPP problem considering measurement redundancies , but they haven't considered channel limits and , also they were failed in optimizing the number of PMUs. The objective of the proposed Binary Cuckoo Search(BCS) based OPP problem is to obtain minimum number of PMUs for system complete observability by considering line outages, channel limits and measurement failures. The proposed method is tested with standard IEEE-9,IEEE-14, IEEE-39, IEEE-57 and IEEE-118 bus systems, and then applied to Southern Region of Indian Power Grid for PMU placement for finding PMU locations optimally.

2. Optimal PMU Placement for Observability

2.1. Phasor Measurement Unit

The Phasor Measurement Unit (PMU) measures power system parameters like voltage, current, frequency etc. It is capable of measuring voltage and current phasors which are synchronized. Synchronism can be achieved by time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite (GPS). This makes the PMU the best and most important measuring device in the foregoing power system monitoring, protection and control.

Phasor measuring unit (PMU) uses GPS transmission for synchronizing the sampling clocks in-order to estimate phasors with a common reference. The first PMU was developed in Virginia Tech laboratory. PMU provides instantaneous state of the entire power system. The GPS provides pulses at an accuracy of 1µs, which corresponds to 0.018^0 for a 50Hz system. The GPS signal with 1PPS is used a PLL to create the sampling pulses, which in turn used for sampling analog signals [17].

2.2. concept of Observability

The bus whose measurements are performed directly by a PMU from the same bus is called a 'directly observable bus'. The bus whose measurements are performed by a PMU at any one of the buses connected to actual bus is called an 'indirectly observable bus'. The bus can be called as an unobservable bus if it is neither a direct bus nor an indirect bus. If all adjacent buses of an unobservable bus are observable by at-least one PMU, then it can be termed as depth of one unobservability [19, 20]. It is indispensable that, for an electric network to be a completely observable system, all of its nodes should be observable either directly or indirectly. If there is at-least one unobservable in the system, then the system becomes unobservable.

2.3 Significance of ZIB in OPP problem

Generally zero-injection buses are switching-stations, whose monitoring cannot be ignored. So, they should be considered as normal buses while forming OPP problem .The idea of locating PMUs at zero-injection buses makes the monitoring system more reliable by helping it in finding optimal solution for the current problem, even though this consideration is increasing the search space which may reduce the solution speed. Moreover, planning studies will be done for the system before it is being installed and so, they must be judged with their accuracy than their speed of operation. Hence the present problem, which is a planning study, is mainly concentrated on accuracy in placing PMUs than the speed of operation.

3. Proposed Optimal PMU Placement formulation

Since the PMU located at a bus not only measures its own bus voltage phasor but also current phasors in the all lines connected to it. Hence the PMU located at one bus observes its own and all buses which are connected to it, by Kirchhoff's Law, as the line parameter are already available . The goal of OPP problem is to calculate the minimal set of PMUs along with their placement to observe the system completely. The problem can be formulated as follows.

minimize

$$\sum_{q\in N} x_q \tag{1}$$

subjected to

$$s_p(X) \geq 1, \quad \forall p \in N \tag{2}$$

where

$$s_p = \sum_{q\in N} c_{pq} x_q, \quad \forall p \in N \tag{3}$$

Equation (1) represents the objective function for PMU installation which can also be represented as cost function just by replacing x_q with $f_q x_q$. However, this representation doesn't affect the linearity of the proposed idea. From equation (2), S_p represents observability function at bus p. The binary connectivity parameter c_{pq} can be defined as ,

$$c_{pq} = \begin{cases} 1, \text{if } p = q \\ 1, \text{if buses p, q are connected} \\ 0, \text{otherwise} \end{cases} \tag{4}$$

For the bus to be observable , it must be connected to at least on bus which is installed with PMU. so, for a bus and all its incident buses to be observable the value of observability function S_p should be equal to or greater than 1. This the OPP problem will works if and only if there are no abnormal conditions like line outage (fault) or PMU failure(communication channel failure). So, in-order to consider these situations which are more probabilistic to occur in power system, this paper formulates a new approach for observing the system completely even under the situations that are mentioned above.

3.1. OPP considering only line outage

This section considers only line outage as the only abnormal condition that would occur on the power system. In this proposed method, the line outage is solved by changing the equation (2). To consider line outage, equation (2) can be rewritten as

$$s_p^l \geq 1 \quad \forall p \in N, \quad \forall l \in L \tag{5}$$

where

$$s_p^l = \sum_{q \in N} c_{pq}^l \; x_q \tag{6}$$

Now, all the equations from (1) to (3) will be rewritten to represent the l^{th} line outage contingency. If all the contingencies are required to be considered, then one must repeat these equations over $l \in L$. But this is a tedious procedure as the constraints are needed to be modified every time whenever some line gets outage. This complexity was handled efficiently and solved accurately in the proposed methodology.

3.2. OPP considering only measurement failure

Here , the effect of measurement failure is added into account by modifying the equation (2) as follows,

$$s_p \geq 2 \quad \forall p \in N \tag{7}$$

As the location of zero-injection buses were also considered for PMU placement and, they were observable by at least two PMUs, the proposed method is more reliable for measurement under any loss of PMUs.

3.3 OPP formulation considering line outage/PMU failure.

This part will really model a new generalised policy for our OPP problem under either line outage case or PMU loss, any one at a time. This model derives the required constraints as follows,

$$s_p^l + S_p \geq 2, \forall p \in N, \quad \forall l \in L \tag{8}$$

This is because of the fact that the set of Observability functions for PMU failure case will also have the connectivity parameters, C_{pq}^l, for l^{th} line outage case. This idea will also reduces the complexity that has occurred with an OPP problem formulation for line outage.

3.4. OPP formulation considering channel limitations

The data measured from PMUs will be communicated to the data concentrators located at regional and national level dispatch centres. This process needs an exclusive communication channel or equipment. In general multi channel communication will be used, but this paper considers the effect of limited channel communication. This consideration is taken into account by replacing $\sum C_{pq}\ X_q$ with $\sum C_{pq}\ m_{pq}\ \ Xq$ in (6). So, the observability function becomes

$$s_p = \sum_{q\in N} c_{pq} m_{pq} x_q \qquad \forall p \in N \tag{9}$$

in addition with

$$s_p = \sum_{q\in N} c_{pq} m_{pq} \leq m_q^{max} \tag{10}$$

and

$$m_{pq} \leq x_q \qquad \forall p, q \in N \tag{11}$$

Here the variable m_{pq} represents measurement at bus p ith the PMU located at q bus. Here the equation (13) becomes additional constraint to limit the number of channels. In this paper it is assumed that each PMU can have at most four measurements including its own bus.

4. Proposed Binary Cuckoo Search(BCS)

The peculiar behavior of the cuckoo bird is, it lay eggs in another bird's nest to let that bird to hatch eggs [21, 22]. Then it follows different strategies to minimize the chances of destroying eggs by the host bird. This strategy and behavior has led to the introduction of a new naturally-inspired optimization algorithm called Cuckoo Search(CS) algorithm. This metaheuristic algorithm was invented by Xin-SheYang and Suash Deb in the year of 2009. From the basic cuckoo search algorithm, each cuckoo uses Levy's flights to search a new nest for laying its egg. Levy flight is a model walk function to direct a cuckoo towards a new nest, which is random and characterized by some pre-defined step lengths for obeying power-law distribution [23]. These levy flights are very helpful in optimizing any problems of engineering and sciences. According to standard CS, every cuckoo will searches for nest on ensuring the following rules ideally.

Rule1: Each cuckoo should lay only one egg at a time, and choose nest randomly.

Rule 2: The best nest with an egg of most and highest fitness should be passed on to the next generation.

Rule 3: The number of host nests should be fixed, and the probability(p_a) with which the host bird can discover the egg laid by the cuckoo should lies in the range of [0,1], i.e. $p_a \in [0,1]$.

The equations 12 and 13, given below, together help in generating new solution using levy flights with their random steps from the levy distribution function [23]. Moreover the random walk process helps cuckoo in its consecutive jumping by obeying power-law step-length distribution with a heavy tail.

$$x_i^{t+1} = x_i^t + \alpha \oplus levy(\lambda) \tag{12}$$

$$levy \sim u = t^{-\lambda} \tag{13}$$

Where x_i^{t+1} and x_i^t are the solutions at instants t and t+1. α represents step size, whose value varies according to the scale of the problem of interest. The operator ⊕ does the entry-wise multiplications. Even though this operator is as similar as that of PSO, the random walk in CS is more efficient than that of PSO.

The present OPP problem is binary optimization problem whose solution is a set of zeros (0s) and ones (1s). Here binary one represents presence of PMU and binary zero represents absence of PMU. But the search space for the standard CS is continuous, means its solution is a set of real number. Hence, it cannot be applied for the problems like binary optimization problems (example, OPP problem) whose solution should be in terms of bits. So, a new version of CS algorithm, called Binary Cuckoo Search, is introduced here, which can handle binary optimization problems.

4.1. Binary Cuckoo Search (BCS)

Essentially the BCS contains two functional blocks. First block contains two cuckoo dynamic operations namely Levy flights and binary solution representation (BSR). Here Levy flight will be used to search a new cuckoo. As the main intension of applying BCS is to handle binary optimization problems efficiently, the BCS has to transform a real valued solution (x_r) to binary value (x_b). This can be done with the help of sigmoid function. Sigmoid function will calculates the flipping chances of each cuckoo [24]. Later, these flipping chances will be used to compute the binary value of that particular cuckoo. This transformation can be done as follows.

$$\sigma(x_r) = \frac{1}{\left(1+e^{-x_r}\right)} \tag{14}$$

where $\sigma(x_r)$ represents the flipping chance of bit 'x_b'. After getting $\sigma(x_r)$, we will compare it with a randomly generated number γ, where γ ϵ[0,1] for each dimensions of 'r'. Then the transformation will be done as follows [23].

$$x_b = \begin{cases} 1, if \gamma < \sigma(x_r) \\ 0, otherwise \end{cases} \tag{15}$$

These two operations (Levy flights and BSR) will combine the basic CS algorithm, as shown in Fig 1, with sigmoid function to achieve BCS. The second functioning block consists the selection operator and the objective function. Here, the selection operation is nothing but the elitism phenomenon that is applied in genetic algorithm.

4.2. BCS Algorithm

step1: Read P_a and objective function step2: Initialize the population of N host nests

step3:while (t<maximum generation) or (convergence criterion), repeat the steps 4 to 12.Otherwise, stop the procedure.

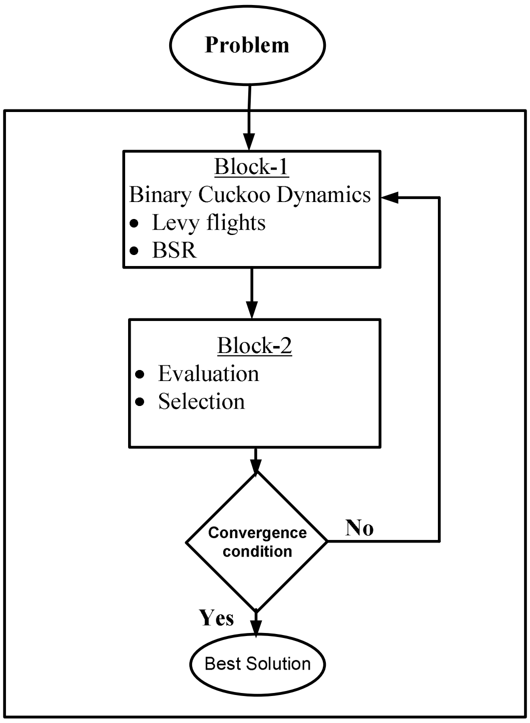

Fig 1: Flow-chart of the proposed Binary Cuckoo Search (BCS)

step4: Obtain a cuckoo(let i) randomly using Levy flights

step5: obtain its binary representation by BSR algorithm and calculate its fitness $S_{i.}$

step6: select a nest from N(let j) arbitrarily

step7: obtain its binary representation by BSR algorithm and calculate its fitness $S_{j.}$

step8: if (S_i>S_j), replace j by the new solution and go to next step9, else go directly to step9.

step9: Obtain the binary representation from the BSR algorithm for all nest and, evaluate their fatnesses.

step10: Abandon a fraction (P_a) of worse nests. Build a new nests at new locations via Levy flights.

step11: Obtain the binary representation there, using BSR algorithm and, calculate their fitness.

step12: Keep the nests with highest fitness and order the solutions in descending order of their fitness and find the latest best.

5. Results and discussions

The proposed BCS technique is tested, as given in Tables 1, 2, 3, 4 and 5, on IEEE-9, IEEE-14, IEEE-30, IEEE-57 IEEE-118, and then, applied for different state level regional grids and SRIG. It is observed that it has improved the results for all systems, particularly for large systems. When this technique is applied for IEEE-9, IEEE-14, IEEE-30, IEEE-57and IEEE-118 systems, it produced best results, as shown in Tables 3 and 6, for all the cases like complete observability with and without considering channel limits, complete observability under line/measurement outage with and without considering channel limits. Later, the proposed BCS based OPP method is applied to different regions of Southern Region of Indian power Grid(SRIG), India and the complete SRIG.

Table 1: complete observability under normal operating conditions, without considering channel limits.

System	Locations of PMUs	Number of PMUs
IEEE-9 bus	4,6,8	3
IEEE-14bus	2,6,8,9	4
IEEE-30bus	2,4,6,10,11,12,19,24,26,29	10
IEEE-57bus	1,4,9,20,24,27,29,30,32,36,38,39,41,45,46,51,54	17
IEEE-118bus	2,5,9,12,13,17,21,23,26,29,34,37,42,45,49,53,56,62,64,71,75, 77,80,85,86,90,94,101,105,110,115,116	32

Table 2: complete observability under normal operating conditions, considering channel limits.

System	Locations of PMUs	Number of PMUs
IEEE-9 bus	1,6,8	3
IEEE-14bus	2,6,8,9	4
IEEE-30bus	1,2,6,9,10,12,19,23,26,27	10
IEEE-57bus	1,6,9,15,19,22,25,27,29,32,36,38,39,41,46,50,54	17
IEEE-118bus	3,5,10,12,15,17,21,23,25,29,34,37, 42,45,49,53,56,62,64,68,71,75,77,80,85,87,90,92,96,100,105, 110,115	33

Table 3: Results comparison for complete observabiity under normal conditions

method	IEEE-9	IEEE-14	IEEE-30	IEEE-57	IEEE-118
proposed	3	4	10	17	32
Ref[26]	n/a	4	10	17	32
Ref[27]	n/a	4	10	17	32
Ref[28]	n/a	4	n/a	17	32
Ref[29]	n/a	4	n/a	n/a	32

Table 4: complete observability under Line/PMU failure, without considering channel limits.

System	Locations of PMUs	Number of PMUs
IEEE-9 bus	1,2,3,4,6,8	6
IEEE-14bus	1,2,3,6,7,8,9,11,13	9
IEEE-30bus	1,2,4,6,7,8,9,10,11,12,13,15,17,18,19,21,24,25,26,29,30	21

IEEE-57bus	1,2,4,6,9,11,12,15,19,20,22,24,25,26,28,29,30,32,33,35,36,38, 39,41,45,46,47,50,51,53,54,56,57	33
IEEE-118bus	1,3,5,7,9,10,11,12,15,17,19,21,22,24,26,27,28,30,31,32,34,36, 37,40,42,44,45,46,49,50,52,53,56,58,59,62,63,64,66,68,71,73, 74,75,77,78,80,84,85,86,87,89,90,92,94,96,100,101,105,107,1 08,110,111,112,114,116,117,118	68

Table 5: complete observability under Line/PMU failure, considering channel limits.

System	Locations of PMUs	Number of PMUs
IEEE-9 bus	1,2,3,4,6,8	6
IEEE-14bus	2,4,5,6,7,8,9,10,13	9
IEEE-30bus	1,3,5,6,7,8,9,10,11,12,13,15,17,18,19,21,24,25,26,29,30	21
IEEE-57bus	1,3,4,6,9,11,12,15,19,20,22,24,26,28,29,30,31,32,33,35,36,38,3 9,41,45,46,47,50,51,53,54,56,57	33
IEEE-118bus	2,3,5,6,9,10,11,12,15,17,19,21,22,24,25,27,29,30,31,32,34,35,3 7,40,42,44,45,46,49,50,51,52,54,56,59,62,64,65,66,68,70,71,73, 75,76,77,78,80,84,85,86,87,89,90,92,94,96,100,102,105,107,10 9,110,111,112,115,116,117	68

Table 6: Results comparison for complete observabiity under normal conditions

method	IEEE-9	IEEE-14	IEEE-30	IEEE-57	IEEE- 118
BCS	6	9	21	33	68
Ref[26]	n/a	n/a	n/a	n/a	n/a
Ref[27]	n/a	n/a	n/a	n/a	n/a
Ref[28]	n/a	n/a	n/a	n/a	n/a
Ref[29]	n/a	n/a	n/a	n/a	n/a

5.1. Regional Power Grids in India

Indian power grid, before December, 2013, was divided into five regions namely northern region of Indian power grid(NRIPG), north-eastern region of Indian power grid(NERIPG), southern region of Indian power grid (SRIPG),western region of Indian power grid(WRIPG), eastern region of Indian power grid(ERIPG). In this paper, Practical study is carried out on two regions, WRIPG consisting of four states (Chhattisgarh, Maharashtra, Madhya Pradesh and Gujarat) with 77 buses of UHV, EHV and HV connected through 145 lines, and, SRIPG consisting of Kerala(KL), Karnataka(KA), Tamil Nadu(TN) and Andhra Pradesh(AP) as four states. SRIPG is known as second largest region after NRIPG, geographically. It consists of 208 buses of UHV, EHV and HV among which 22 are from Kerala, 76 are from Andhra Pradesh, 25 are from Karnataka and remaining 83 are from Tamil Nadu [25]. The BCS presented in previous section is applied to each State Level Regional Grid and then to southern Region of Indian Power Grid.

5.1.1 Andhra Pradesh (AP)

This is one of the state level regional grid(SLRG) in SRIPG, and it consists of 76 buses connected through 112 lines. The proposed BCS optimization technique described above has been applied to the grid for both complete observability and observability under line outage/ PMU failure cases, and the results are given in Tables 7 and 8. These two cases are again repeated with and without considering channel limits. With the help of a single-line diagram obtained PMU number and locations in AP grid under normal and line/PMU failure conditions are presented in Fig 2 and Fig 3. The location of PMUs for the above two cases and, with and without considering the measurement channel limits are given in Table 9 and Table 10. The selected buses for PMU location are highlighted with a rectangular red box around them.

From the Table 7 it is clear that Andhra Pradesh SLRG can be monitored, under normal operating conditions, completely just by placing 21 PMUs. From Table 8, if we place 51 PMUs, then the AP SLRG measurement system will become more robust, which can monitor the grid even under line outage or PMU outage. Tables 9 and 10 reveals that AP SRLG needs 22 and 52 PMUs for complete observability under normal and line/PMU outage conditions on considering limiting measurement channels. It is just because of the fact that many buses in AP SLRG have more than 4 channels.

Table 7: Number of PMUs and their locations for AP SLRG under normal operating conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	28	107,110,112,115,121,122,127,128,132,134,135,136,145,147,150,157,159,163,165,169,170,171,179,180,182,183,184,185
BCS	21	107,110,112,115,117,118,121,122,127,128,132,136,145,147,154,157,159,163,165,181

Table 8: Number of PMUs and their locations for AP SLRG under Line/PMU failure conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	51	106,107,108,110,111,112,115,116,117,118,119,120,121,122,123,124,127,128,129,132,133,136,138,141,143,145,146,147,148,150,152,154,157,158,159,160,162,163,164,165,166,167,169,170,171,174,175,176,179,180,181.

Table 9: Number of PMUs and their locations for AP SLRG under normal operating conditions, considering channel limits

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	21	107,110,112,115,120,122,127,128,132,136,138,145,146,152,154,157,159,162,165,169,170

Table 10: Number of PMUs and their locations for AP SLRG under Line/PMU failure conditions, considering channel limitations

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	52	106,107,108,110,111,112,113,115,116,117, 118,119,120,121,122,123,124,127,128,129, 132,133,136,137,141,143,145,146,147,148, 150,152,154,157,158,159,160,161,162,163, 164,165,166,167,169,170,174,175,177,179, 180,181

5.1.2 Tamil Nadu (TN)

This is the biggest state level regional grid(SLRG) in SRIPG with 83 buses connected through 126 branches. On applying the proposed optimization technique to this grid, it is cleared that TN SLRG requires 20 and 48 PMUs for both complete observability and observability under line outage/ PMU failure cases, as shown in Tables 11 and 12. Obtained PMU locations in TN grid with and without considering line/PMU failure are presented with the help of single-line diagram in Fig 4 and Fig 5. And, interestingly the same TN SLRG needs again 20 and 48 PMUs with the locations given in Table 13 and Table 14 for complete observability on considering channel limits for both the normal and line/PMU outage cases. The reason for this is that every bus has atmost 4 channels on average.

Table 11: Number of PMUs and their locations for TN SLRG under normal operating conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	20	6, 7, 9, 12, 19, 22, 27, 30, 33, 35, 47, 48, 50, 54, 58, 60, 63, 67, 73, 75
BCS	20	6, 7, 9, 12, 19, 22, 27, 30, 33, 35, 47, 48, 50, 54, 58, 60, 63, 67, 73, 75

Table 12: Number of PMUs and their locations for TN SLRG under Line/PMU failure conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	48	1,4,6,7,9,10,12,13,14,16,19,22,23,25,27,28,3 0,31,32,33,35,36,37,42,43,44,47,48,50,54,56, 57,58,59,60,61,63,64,65,67,71,72,73,74,75,7 6,79,83,

Table 13: Number of PMUs and their locations for TN SLRG under normal operating conditions, considering channel limits

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	20	1,4,10,12,22,25,27,28,30,33,40,44,48,54,58, 60,63,67,73,75,

Table 14: Number of PMUs and their locations for TN SLRG under Line/PMU failure conditions, considering channel limitations

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	48	1,4,6,7,9,10,12,13,14,16,19,22,23,25,27,28 ,30,31,32,33,35,36,37,38,40,44,47,48,50,5 2,54,55,56,58,60,62,63,64,66,67,70,72,73, 74,75,76,79,83

5.1.3 Kerala (KL)

The Kerala SLRG for the above two conditions are identified, as shown in Fig 6 and 7, tabulated in Tables 15 and 16 respectively. From the tables it is proven that it needs 7 and 15 PMUs for normal and line/PMU failure conditions respectively. Later, on considering channel limitations for the two conditions mentioned above, it is confirmed that the grid needs 7and 15 PMUs, as given in Tables 17 and 18, with changed locations from the above two cases. The method proposed in [15] is failed in observing bus number 105. But the proposed BCS has successfully found a solution with 7 PMUs which could even observe bus number 105.

Table 15: Number of PMUs and their locations for KL SLRG under normal operating conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref [15]	-	-
BCS	7	88,89,93,95,99,103,105

Table 16: Number of PMUs and their locations for KL SLRG under Line/PMU failure conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref [15]	-	-
BCS	15	84,85,86,87,89,92,93,95,97,98,99,101,102,104 ,105

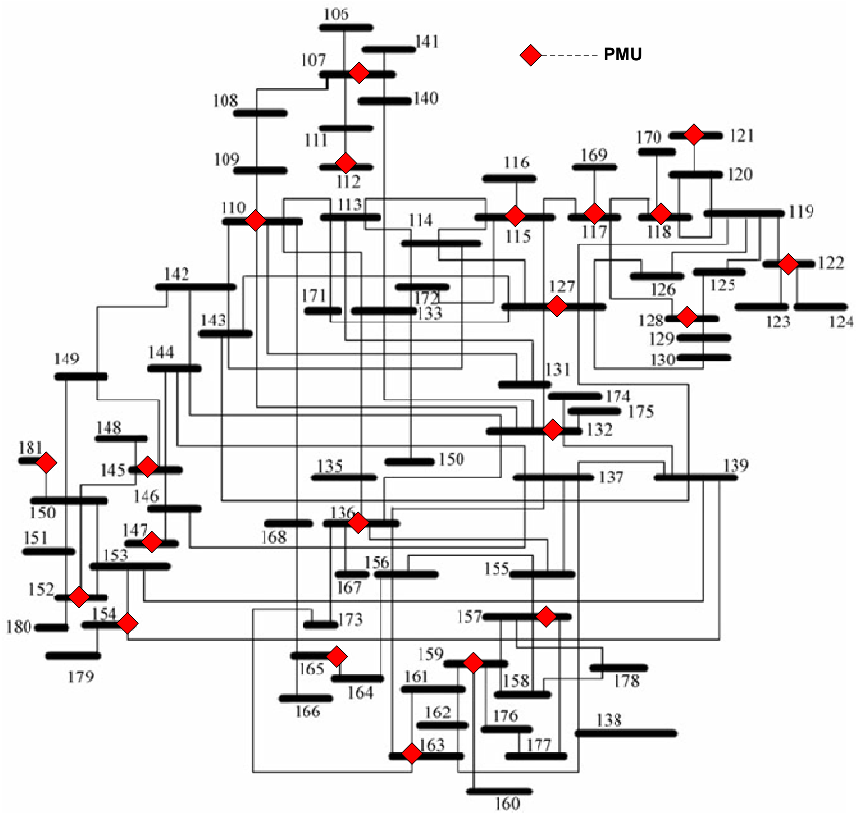

Fig 2: location of PMUs for AP SLRG for complete observability under normal conditions without considering channel limitations

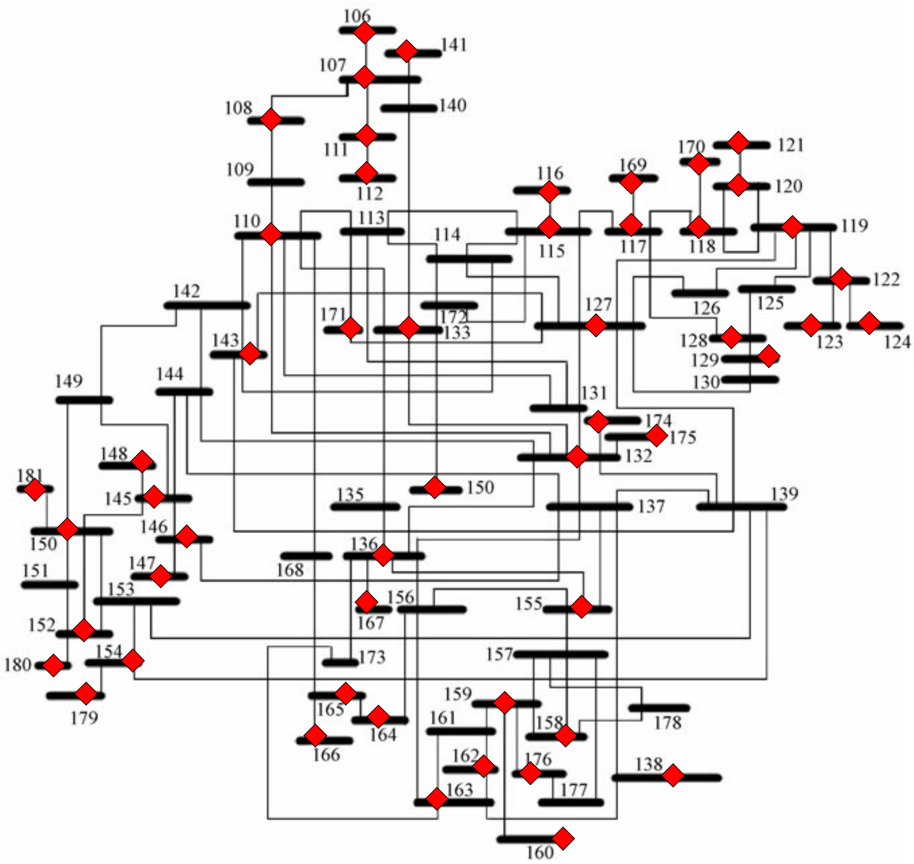

Fig 3: location of PMUs for AP SLRG for complete observability under line/PMU failure conditions without considering channel limitations

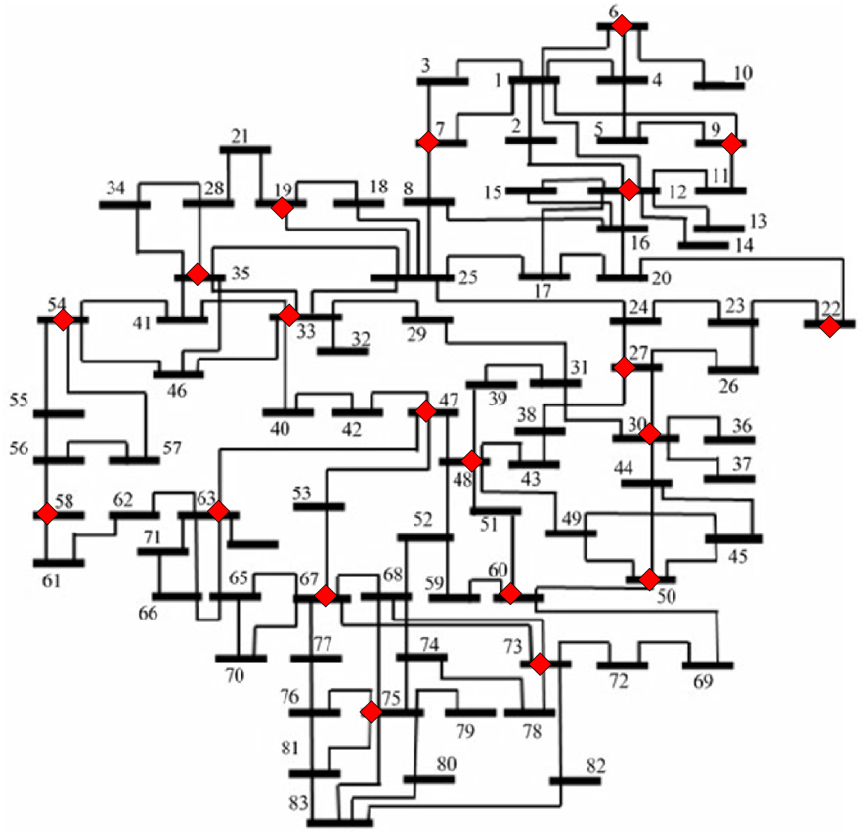

Fig 4: location of PMUs for TN SLRG for complete observability under normal conditions without considering channel limitations

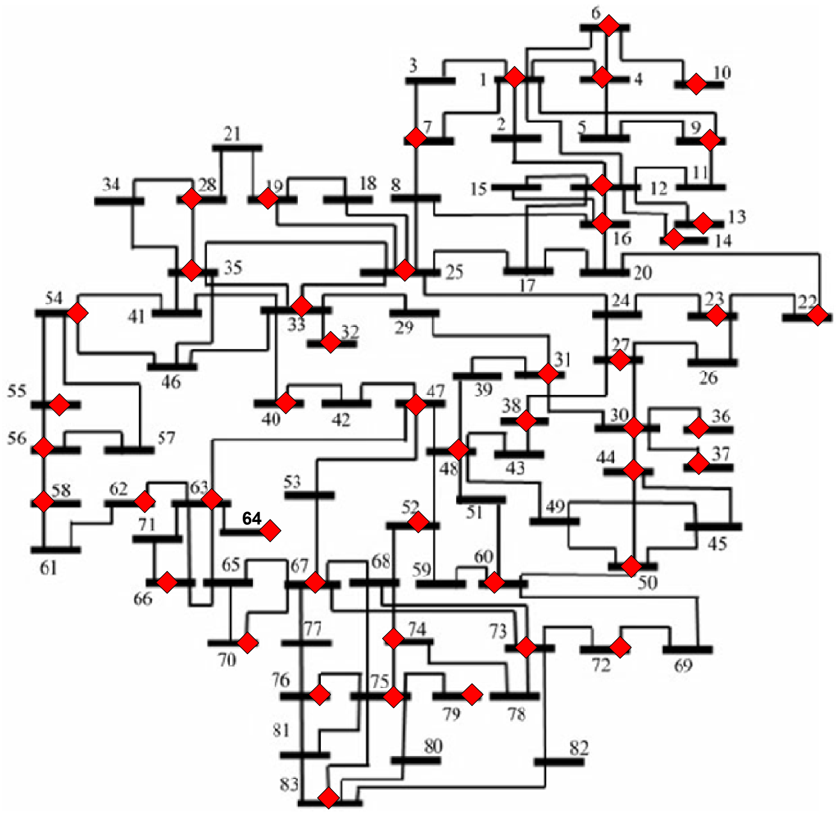

Fig 5: location of PMUs for TN SLRG for complete observability under line/PMU failure conditions without considering channel limitations

Table 17: Number of PMUs and their locations for KL SLRG under normal operating conditions, considering channel limits

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	7	88,89,92,95,99,102,105

Table 18: Number of PMUs and their locations for KL SLRG under Line/PMU failure conditions, considering channel limitations

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	15	84,85,86,87,89,92,93,95,96,98,99,100,101, 104,105

5.1.4 Karnataka (KA)

The Karnataka SLRG consists of 25 buses of UHV, EHV and HV. It has 44 interconnections among these 25 buses. The optimal locations of PMUs in this SLRG for the both system complete observability and observability under any line/PMU failure are obtained using the proposed BCS technique. The obtained results are shown in Fig 8 and Fig 9, and are given in Tables 19 and 20 respectively. The PMU locations in grid are represented by means of red boxes over that particular bus. The paper[15] proposed with ILP based OPP has again failed in locating PMUs for KA SLRG.

But from the BCS results, it is clear that KA SLRG needs 10 PMUs for system complete observability under normal condition and 19 PMUs for complete observability under line/PMU failure condition. The results of OPP for both system observability under normal condition and observability under line/PMU outage condition while considering measurement channel limits are given in Table 21 and Table 22.

Table 19: Number of PMUs and their locations for KA SLRG under normal operating conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
Proposed	10	185,188,192,194,196,201,203,205,207,208

Table 20: Number of PMUs and their locations for KA SLRG under Line/PMU failure conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	19	183,185,188,189,191,192,194,196,197,198,199,201,202,203,204,205,206,208

Table 21: Number of PMUs and their locations for KA SLRG under normal operating conditions, considering channel limits

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	10	184,189,191,194,196,202,203,205,207,208

Table 22: Number of PMUs and their locations for KA SLRG under Line/PMU failure conditions, considering channel limitations

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	19	183,184,188,190,191,192,194,196,197,198,199, 201,202,203,204,205,206,207,208.

5.1.5 Southern Region of Indian Grid (SRIG)

The Southern Region of Indian Grid(SRIG) has 208 buses including HV, EHV and UHV buses. This section optimally locates PMUs for complete SRIG by applying the proposed HGAPSO algorithm to the grid formed by interconnecting all four (AP,TN, KA and KL) SLRGs. The results for both, the system complete observability under normal and line/PMU failure, conditions are given in Table 23 and Table 24. The locations of the obtained PMUs are shown in the Fig 10 and Fig 11. From the results it is clear that SRIG needs 56 and 132 PMUs for complete system observability under normal and line/PMUs outage conditions respectively. The results of OPP for both system observability under normal condition and observability under line/PMU outage condition while considering measurement channel limits are given in Table 25 and Table 26.

Table 23: Number of PMUs and their locations for SRIG under normal operating conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	58	1, 9, 10, 12, 22, 25, 27, 28, 30, 33, 47, 48, 50, 54, 58, 60, 63, 65, 73, 75, 76, 88,89,93,95,99,104,107,110,112,115,121, 122, 127, 128, 132, 135, 138, 145, 147, 152, 154, 157,159,163,165,167,169,170,171,181,182,185 ,188,192,196, 201, 203
BCS	56	5,7,10,12,19,21,27,30,33,35,47,48,49,54,58,60, 63,67,73,75,83,88,89,92,95,99,103,107,110,11 1,115,117,118,121,122,127,128,132,134,136,1 38,145,147,152,154,157,159,162,165,185,188, 190,192,196,201,208

5.2 Economies of OPP problem

This section gives the net cost savings that could be obtained by the proposed optimal PMU placement problem. For better illustration, consider AP state level regional grid that requires 21 and 48 PMUs for observing 76 buses completely under normal and line/PMU

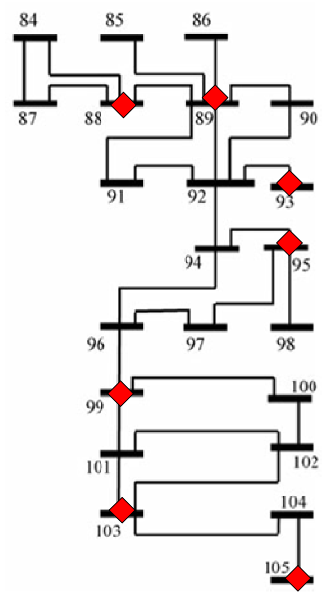

Fig 6: location of PMUs for KL SLRG for complete observability under normal conditions without considering channel limitations

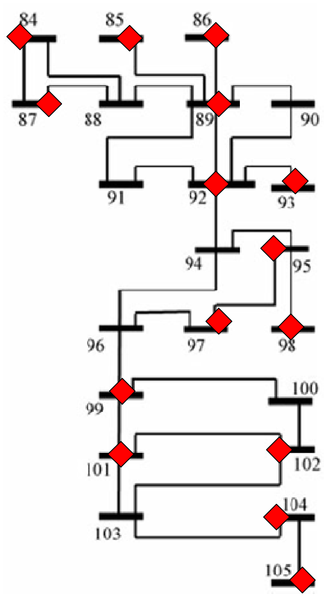

Fig 7: location of PMUs for KL SLRG for complete observability under line/PMU failure conditions without considering channel limitations

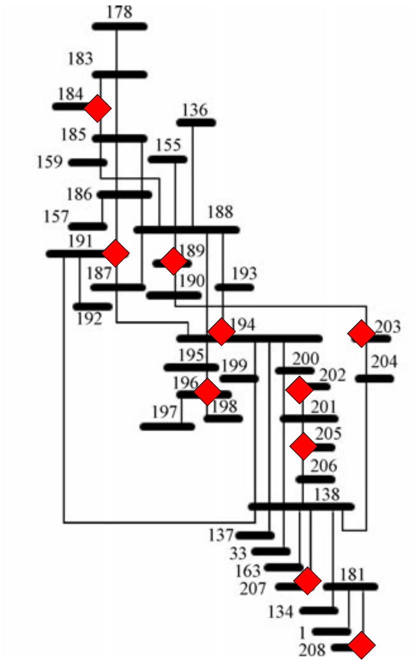

Fig 8: location of PMUs for KA SLRG for complete observability under normal conditions without considering channel limitations

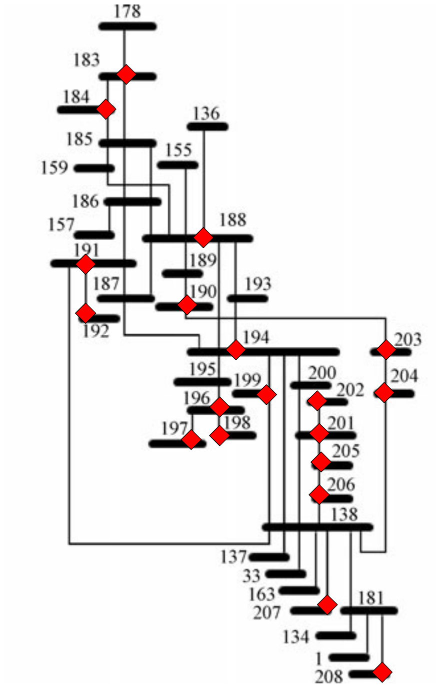

Fig 9: location of PMUs for KA SLRG for complete observability under line/PMU failure conditions without considering channel limitations

Table 24: Number of PMUs and their locations for SRIG under Line/PMU failure conditions

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	57	5,7,8,10,12,19,22,27,28,,30,33,42,48,49,54,58, 60,63,67,73,75,76,88,89,92,95,99,102,105,107, 110,111,115,117,118,121,122,127,128,132,136 ,138,145,147,152,154,157,159,161,165,181,18 4,188,190,191,196,201.

Table 25: Number of PMUs and their locations for SRIG under normal operating conditions, considering channel limits

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	132	1,3,4,6,9,10,12,13,14,16,19,22,23,25,26,27,28,3 0,31,32,33,35,36,37,42,43,45,47,48,49,54,56,57, 58,59,60,62,63,64,66,67,69,70,71,73,75,76,78,7 9,83,85,86,87,88,89,92,93,95,96,98,99,100,103, 104,106,107,108,110,111,112,113,115,116,117, 118,119,120,121,122,123,124,127,128,130,132, 133,134,136,138,141,142,145,146,147,148,150, 152,154,157,158,159,160,161,163,164,165,166, 167,169,170,174,175,177,179,180,181,184,185, 188,190,191,192,194,196,197,198,201,202,203, 205,207,208.

Table 26: Number of PMUs and their locations for SRIG under Line/PMU failure conditions, considering channel limitations

Method	No.of PMUs	Locations of PMUs
ILP, Ref[15]	-	-
BCS	134	1,5,6,7,9,10,12,13,14,16,19,22,23,25,27,28,30, 31,32,33,35,36,37,40,41,42,43,44,45,48,52,53, 54,56,58,60,61,63,64,66,67,69,73,75,76,78,79, 83,84,85,86,88,89,92,93,95,96,98,99,100,102,1 04,105,106,107,108,110,111,112,113,115,116, 117,118,119,120,121,122,123,124,127,128,130 ,132,133,134,136,137,138,141,142,145,146,14 7,148,150,152,154,156,157,158,159,160,161,1 63,165,166,167,169,170,171,174,175,176,179, 180,181,183,184,187,188,190,191,192,194,196 ,197,198,201,202,203,205,207,208

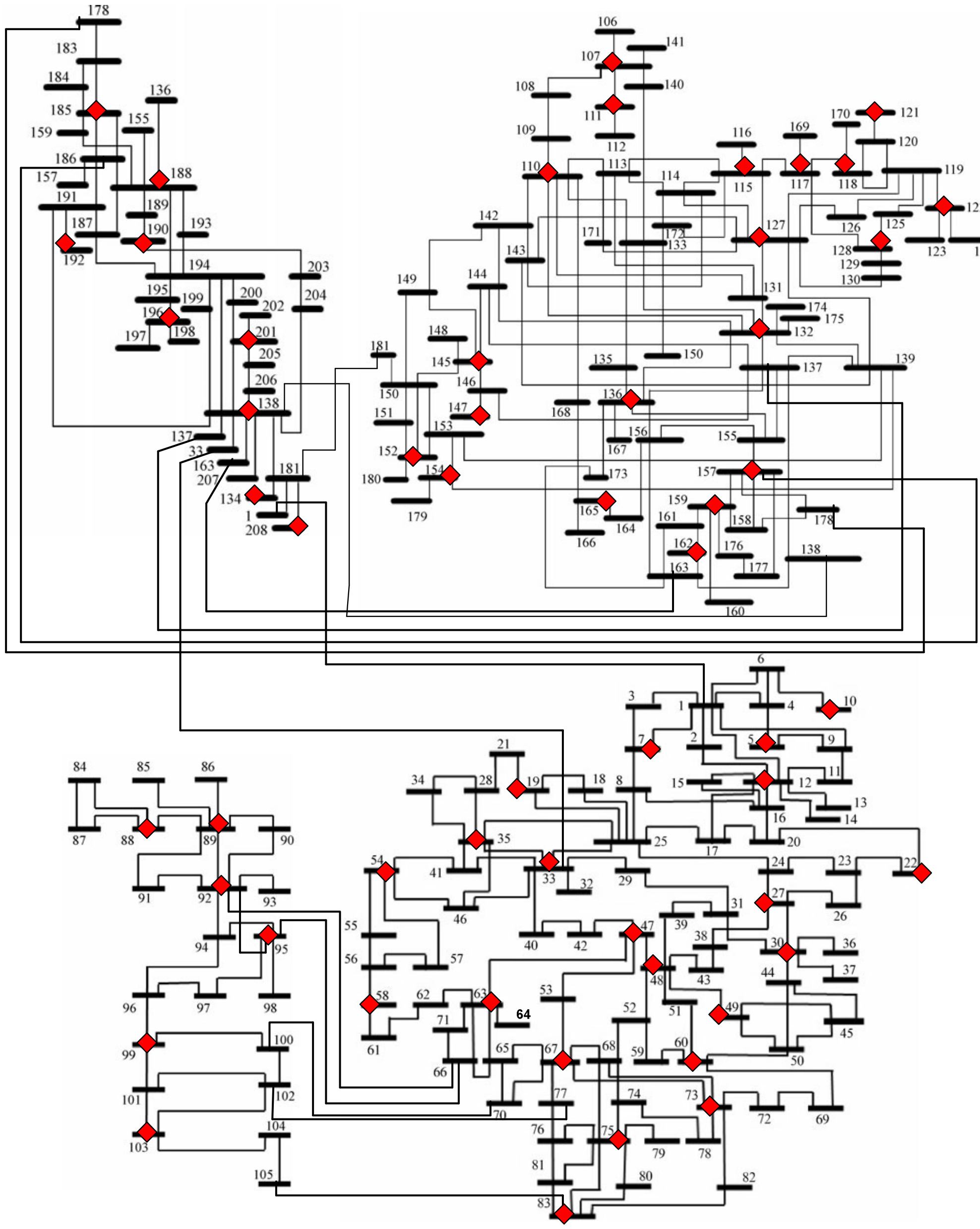

Fig 10:PMU locations in SRIG for complete Observability under normal operating conditions without considering channel limits

outage cases. If a PMU costs 1unit, then the cost incurred for AP SLRG is 76 units without considering optimal PMU placement. On considering optimal PMU placement under both conditions , AP SLRG needs to expend only 21 and 48units of cost which saves 72.37% and 31.58% . Similarly, by considering OPP, TN SLRG saves 75.90% and 42.17% , KL SLRG saves 68.18% and 31.82%, KA SLRG saves 60% and SRIG saves 73.07% and 24% respectively for system complete observability under normal and line/PMU outage conditions. The costs incurred for different SLRGs and SRIG for PMU placement under normal and line/PMU failure conditions are shown in Fig 12 and Fig 13, graphically.

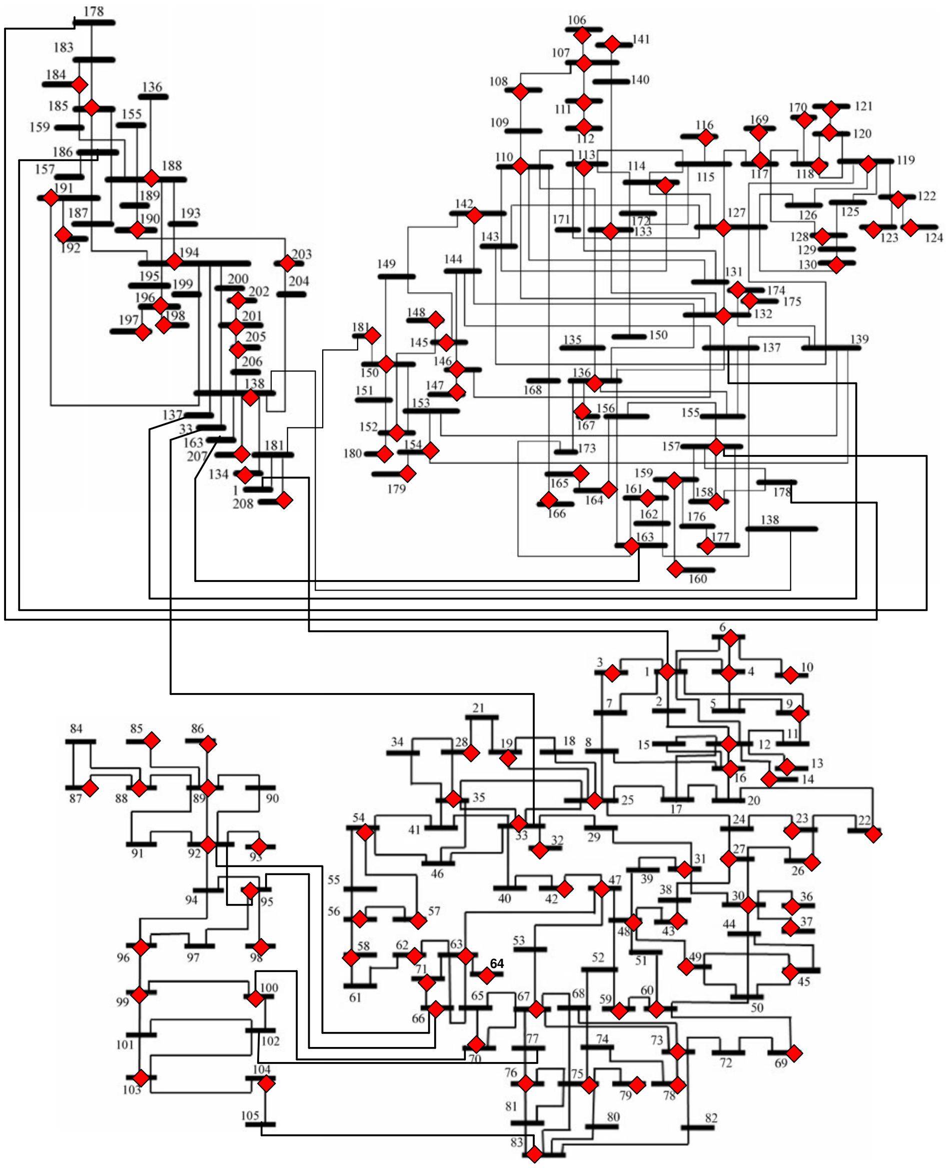

Fig 11:PMU locations in SRIG for complete Observability under line outage/ PMU failure condition without considering channel limits

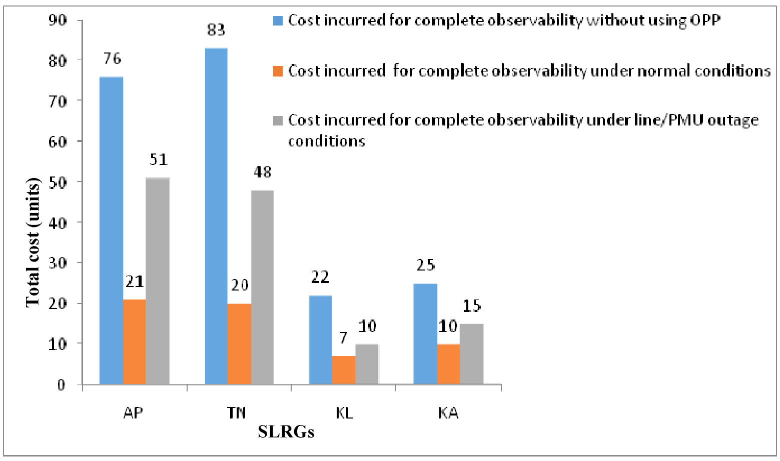

Fig 12: Comparison between number of buses and the number of PMUs required for State level power grids under both normal and line/PMU outage conditions

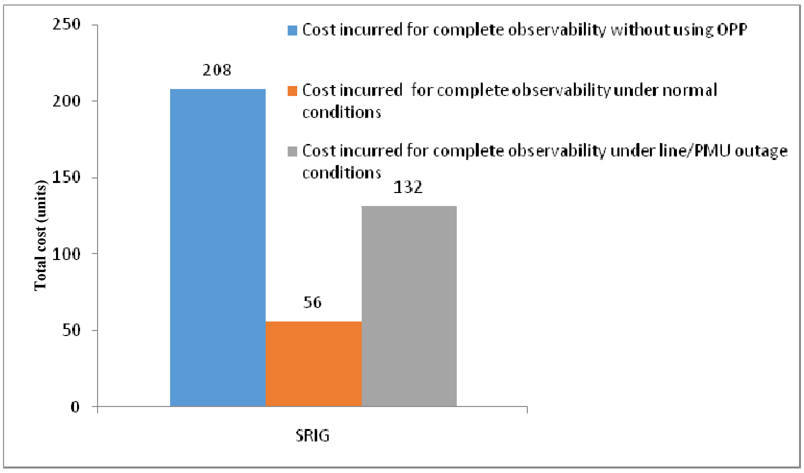

Fig 13: Comparison between number of buses and the number of PMUs required for SRIG under both normal and line/PMU outage conditions

6. Conclusion

The power system is highly prone to faults which may cause line outages or measurement system failures. This paper has considered even these conditions also for finding PMU placements. The proposed BCS method has solved the OPP problem for system complete observability under both normal and abnormal conditions in power system accurately. The proposed method has been tested on few IEEE standard test systems, and then applied for Southern Region of Indian power Grid (SRIG). From the results and discussions, it is verified that the proposed method has successfully optimized the OPP problem and, also has benefited economically.

References

[1]. Baldwin, T.L., Mili, L., Boisen, M.B., Adapa, R.: 'Power system observability with minimal phasor measurement placement', IEEE Trans. Power Syst., 1993, 8, (2), pp. 707–715.

[2]. Marın, F.J., Garcıa-Lagos, F., Joya, G., Sandoval, F.: 'Genetic algorithms for optimal placement of phasor measurement units in electric networks', Electron. Lett., 2003, 39, (19), pp. 1403–1405.

[3]. Hajian, M., Ranjbar, A.M., Amraee, T., Shirani, A.R.: 'Optimal placement of phasor measurement units: particle swarm optimization approach'. Proc. Int. Conf. Intelligent Systems Application Power Systems, November 2007, pp. 1–6.

[4]. Xu, B., Abur, A.: 'Observability analysis and measurement placement for system with PMUs'. Proc. IEEE Power Systems Conf. Exposition, October 2004, vol 2, pp. 943–946.

[5]. Gou, B.: 'Optimal placement of PMUs by integer linear programming', IEEE Trans. Power Syst., 2008, 23, (3), pp. 1525–1526.

[6]. Gou, B.: 'Generalized integer linear programming formulation for optimal PMU placement', IEEE Trans. Power Syst., 2008, 23, (3),pp. 1099–1104

[7]. S. Chakrabarti, E. Kyriakides, and D. G. Eliades, "Placement of synchronized measurements for power system observability," IEEE Trans. Power Del., vol. 24, no. 1, pp. 12–19, Jan. 2009.

[8]. Caro, E., Singh, R., Pal, B.C., Conejo, A.J., Jabr, R.A.: 'Participation factor approach for phasor measurement unit placement in power system state estimation', IET Gener. Transm. Distrib., 2012, 6, (9), pp. 922–929.

[9]. S. Chakrabarti and E. Kyriakides, "Optimal placement of phasor measurement units for power system observability," IEEE Trans. Power Syst., vol. 23, no. 3, pp. 1433–1440, Aug. 2008.

[10]. Sodhi, R., Srivastava, S.C., Singh, S.N.: 'Optimal PMU placement to ensure system observability under contingencies'. Proc. Power and Energy Society General Meeting, July 2009, pp. 1–6.

[11]. Y. M. Park, Y. H. Moon, J. B. Choo, and T. W. Kwon, "Design of reliable measurement system for state estimation," IEEE Trans. Power Syst., vol. 3, no. 3, pp. 830–836, Aug. 1988.

[12]. A. Abur and F. H. Magnago, "Optimal meter placement for maintaining observability during single branch outage," IEEE Trans. Power Syst., vol. 14, no. 4, pp. 1273–1278, Nov. 1999.

[13]. F. H. Magnago and A. Abur, "A unified approach to robust meter placement against loss of measurements and branch outages," IEEE Trans. Power Syst., vol. 15, no. 3, pp. 945–949, Aug. 2000.

[14]. C. Rakpenthai, S. Premrudeepreechacharn, S. Uatrongjit, and N. R. Watson, "An optimal PMU placement method against measurement loss and branch outage," IEEE Trans. Power Del., vol. 22, no. 1, pp.101–107, Jan. 2007.

[15]. Gopakumar P, Chandra G S, Reddy M J B, Mohanta D K. Optimal placement of PMUs for the smart grid implementation in Indian power grid — A case study. Frontiers in Energy, 2013, 7(3): 358–372.

[16]. pathirikkat gopakumar, g. surya chandra, m. jaya bharata reddy, dusmata kumar mohanta,"Optimal redundant placement of PMUs in Indian power grid— northern, eastern and north-eastern regions". Frontiers in Energy 2013, 7(4): 413–428.

[17]. A. G. Phadke, J. S. Thorp, "History And Applications of Phasor Measurements", IEEE Conference, 2006.

[18]. H. B. You, V. Vittal, Z. Yang, "self-healing in power systems: an approach using islanding and rate of change of frequency de-line based load shedding", IEEE transaction on power system, vol. 18, no.1, pp174-181, 2003.

[19]. Reynaldo F N, Phadke A G. Phasor measurement unit placement techniques for complete and incomplete observability. IEEE Transactions on Power Delivery, 2005, 20(4): 2381–2388.

[20]. Gou B. Generalized integer linear programming formulation for optimal PMU placement. IEEE Transactions on Power Systems, 2008, 23(3): 1099–1104.

[21]. Xin-SheYang,Nature-Inspired Optimization Algorithms.

[22]. Xin-She_Yang_(auth.),_Xin-She_Yang_(eds.)_Cuckoo.

[23]. Yang, X-S. & Deb, S. (2010) 'Engineering optimisation by cuckoo search', *Int. J. Mathematical Modelling andNumerical Optimisation*, Vol. 1, No. 4, pp.330–34.

[24]. Aziz Ouaarab, Belaıd Ahiod, Xin-She Yang," Discrete cuckoo search algorithm for the travelling salesman problem ", Neural Comput & Applic (2014) 24:1659–1669.

[25]. Power Grid Corporation of India, www.powergridindia.com

[26]. aruljeyaraj kulanthaisamy, rajasekaran vairamani, nandha kumar karunamurthi, chandrasekaran koodalsamy," Multi-objective PMU Placement method Considering Observability and measurement Redundancy using ABC Algorithm". Advances in Electrical and Computer Engineering Volume 14, Number 2, 2014.

[27]. B.K. Saha Roy , A.K. Sinha, A.K. Pradhan An optimal PMU placement technique for power system observability, Electrical Power and Energy Systems 42 (2012) 71–77.

[28]. A. Ahmadi, Y. Alinejad-Beromi and M. Moradi, "Optimal PMU placement for power system observability using binary particle swarm optimization and considering measurement redundancy",Expert System Applications, vol.38, pp. 7263-7269, May 2011.

[29]. R. Kavasseri, and S. K. Srinivasan, "Joint placement of phasor and power flow measurements for observability of power systems", IEEE Trans. Power Systems, vol.26, pp. 1929-1936, Nov. 2011.