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Optimal PMU Placement Techniques for the Topological Observability of a Partial network of the Southern Grid of India

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Abstract: This paper presents algorithms for optimal placement of phasor measurement units (PMU's) to make the power system *observable* using i)Integer Linear Programming formulation (ILP) and ii)Genetic Algorithm (GA). *Observability* test is carried out based on topological connectivity of network, using "root vector" without any need for triangularisation of a matrix. The root indicates the number of buses observed due to the placement of PMU at a bus. Computational time required for *observability* test is very low as there is no formulation of matrix or triangularaisation of a matrix. The proposed techniques are tested on IEEE 14-bus and IEEE 30-bus systems. Further, these techniques are also tested on partial network of Southern Grid of India (72 bus system). The results are compared with the existing algorithm (ILP) and the results of the proposed GA algorithm are very promising with significant reduction in CPU time. This algorithm can be employed very effectively for large size power systems for optimal placement of PMU's.

1. INTRODUCTION

Modern power system requires fast, accurate and synchronised data from wide area locations for monitoring the operating conditions of the system. In the beginning the data collection from wide area is done by SCADA. But these measurements are unsynchronised in nature and state estimators are offering inaccurate results. The utilization of global positioning system (GPS), in addition to sampled data processing techniques, for computer relaying applications, has led to the development of PMU's. Phasor measurement units are monitoring devices that provide extremely accurate positive sequence time tagged measurements [IEEE Standard]. A PMU installed at a bus can make direct synchronized measurements of the voltage phasor of the installed bus and the current phasors of some or all the branches incident to the bus, assuming that the PMU has sufficient number of channels. If the usage of PMU's increased in the modern power system, improved monitoring, protection, and control of power networks can be achieved [J. S. Thorp], [A.G. Phadke, 1986], [A.G. Phadke, 2008]. Cost of communication is higher than that of PMU cost and hence there is a need for optimal placement of PMU's without compromising *observability* of the power system.

For optimal placement of PMU's in a network, we need to place PMU's at particular buses so that system is observable and cost of PMU's becomes low. In [Bei Gou], the author proposed a generalized approach for integer programming based method for optimal PMU placement for complete and incomplete *observability* with and without considering conventional measurements. In [Korkali], the author proposed placement of PMU with channel limit with considering zero injection bus. Optimal PMU placement (OPP) problem is formulated and solved using graph theoretic *Observability* analysis and an optimization method based on Simulated Annealing in [T. L. Baldwin]. In [M. Rice], the optimal PMU placements are obtained by minimizing or maximizing accordingly some condition indicators related to the condition number of the gain matrix. Several intelligent search techniques such as Simulated Annealing [A.B. Antonio], Tabu Search [J H. Mori], Genetic Algorithm [B. Milosevic] and Binary Particle Swarm Optimization [S. Chakrabarti, Dec2008] have been suggested for OPP problem. Phasor measurement units are first introduced and their potential impact on power network applications is discussed in [A.G. Phadke, 1993]. One particular reason is that most researches center around the topological *observability* criterion, which essentially specifies that power system states should be uniquely estimated using minimum number of PMU measurements [T. L. Baldwin]. Based on such criterion, many solutions were proposed, such as the ones based on mixed integer programming [B. Xu and A. Abur], [B. Gou], binary search [S. Chakrabarti, Aug2008] , and metaheuristics [B. Milosevic], [F.Aminifar].

In this paper it is assumed that the adjacent buses of PMU placed bus are observable (solvable using ohms law) and PMU has sufficient number of channels for connection of lines which are incident to it.

2. OPTIMAL PMU PLACEMENT (OPP) PROBLEM FORMULATION

2.1 Binary Integer linear programming

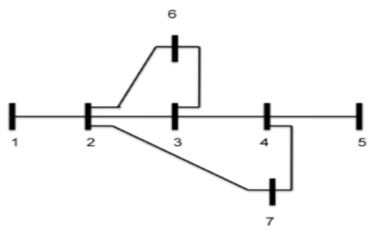


Fig.1.The 7-bus system

$$\min imize \sum_{i=1}^{N} x_i$$

$$such \quad that \quad X = [x_1 \quad x_2 \quad x_3 \ldots \quad x_n]^T$$

$$x_i = \{0,1\}$$

$$AX \geq 1$$

Where,

$$x_i = \begin{cases} 1 & if \ PMU \ at \ i^{th} \ bus \\ 0 & other \ wise \end{cases}$$

The connectivity matrix A is such that

$$A_{i,j} = \begin{cases} 1 & if \quad i = j \\ 1 & if \quad i \ and \ j \ are \ connected \\ 0 & if \quad other \ wise \end{cases}$$

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Subjected to,

$$F_1 : x_1 + x_2 \geq 1$$
$$F_2 : x_1 + x_2 + x_3 + x_6 + x_7 \geq 1$$
$$F_3 : x_2 + x_3 + x_4 + x_6 \geq 1$$
$$F_4 : x_3 + x_4 + x_5 + x_7 \geq 1$$
$$F_5 : x_4 + x_5 \geq 1$$
$$F_6 : x_2 + x_3 + x_6 \geq 1$$
$$F_7 : x_2 + x_4 + x_7 \geq 1$$

The operator '+' indicates logical OR and inequlity constraint indicates atleast one variable is '1'.

2.2 Genetic algorithm

The objective is minimising the use of PMU's and make the entire given power network as observable. N is number of buses in the given system.

$$\min imize \sum_{i=1}^{N} x_i$$

$$x_i = \begin{cases} 1 & if \ PMU \ at \ i^{th} \ bus \\ 0 & other \ wise \end{cases}$$

The fitness function can taken as

$$f = \frac{1}{1 + N_{pmu}} \qquad (1)$$

Where N_{pmu} =Number of PMU's that are required for power system observable and the *observability* is checked based on topology of network (Appendix)

The algorithm steps for optimal PMU placement problem as follows

Step 1: Read the power system structure
Form ITAGF,ITAGTO,ADJQ,ADJL vectors
Step2 Take chromosome size equals to number of buses.
Step 3: Create the initial population
Step 4: For each individual chromosome, check *observability* and calculate fitness function By using equation(1).
Step 5: Apply selection and elitism operator
Step 6: Apply crossover operator
Step 7: Apply mutation operator
Step 8:Go to step 4 until specified no. of generations are completed

3. RESULTS

CASE (i): IEEE 14-bus system
The IEEE 14-bus system [Ma pai] has 14 buses has shown in Fig.2.The PMU locations are found by ILP using MATLAB are at buses 2, 6, 7 and 9. With Genetic algorithm using MATLAB code results found as 2,7,10 and 13.

CASE (ii): IEEE 30-bus system
The IEEE 30-bus system [Ma pai] is shown in Fig.3. The OPP formulation is done with ILP similar to IEEE 14-bus system and results found as 10 PMU's are required at locations 1, 7, 9, 10, 12, 18, 24, 25, 27 and 28 . With Genetic algorithm using MATLAB code results found as 1, 7, 10, 11, 12, 18, 23, 25, 28 and 29

CASE (iii):400/220/132 kV Part of the Southern Grid of India

The practical 400/220/132 kV reduced network with 72-bus system along with geographical diagram is shown in Fig.5. The states Andhra Pradesh, Karnataka and Tamil Nadu are considered in this single line diagram Fig.4. The lines under in construction and outage are not considered.

The OPP formulation is done with ILP similar to 14-bus system and the results found as 26 PMU are required at locations 26, 30, 31, 33, 34, 35, 40, 41, 43, 44, 46, 47, 49, 52, 55, 57, 58, 59, 60, 62, 65, 66, 67, 68, 69 and 71. With Genetic algorithm using MATLAB code results found as 26, 27, 30, 31, 33, 34, 35, 40, 41, 43, 44, 45, 46, 47, 49, 52, 55, 58, 59, 60, 65, 66, 67, 68, 69 and 71 for full *observability* of given southern grid of India.

TABLE I

System	Number of PMUs	Location of PMU at buses using ILP	Location of PMU at buses using GA
IEEE 14-Bus system	4	2, 6, 7, 9	2, 7, 10, 13
IEEE 30-Bus system	10	1, 7, 9, 10, 12, 18, 24, 25, 27, 28	1, 7, 10, 11, 12, 18, 23, 25, 28, 29
72 Bus system	26	26,30,31,33,34,35, 40,41,43,44,46,47, 49,52,55,57,58,59,60, 62,65,66,67,68,69,71	26,27,30,31,33,34, 35,40,41,43,44,45, 46,47,49,52,55, 58,59,60,65,66, 67,68, 69,71

The optimal location of PMU's using ILP method for IEEE-14, IEEE-30 bus and 72 bus(southern grid of India) system are shown in their respective single line diagrams (fig.2 for IEEE-14bus system, fig.3 for IEEE-30 bus system, fig.4 for 72 bus system) with "★" symbol.

TABLE II

System	CPU time using ILP (sec)	CPU time using GA (sec)
IEEE 14-Bus system	1.872095	0.814439
IEEE 30-Bus system	2.189516	1.725254
72 Bus system	2.756149	2.356865

4. CONCLUSION

This paper presents Optimal PMU placement problem using ILP and Genetic algorithm. They are tested on the on IEEE 14-bus system, IEEE 30-bus system and finally implemented on 72 reduced practical bus system of southern grid of India. For 72 bus system, 26 PMUs are required for full *observability* of the system. The synchrophasor technology is not fully introduced in India, It is better to install PMU's at proper locations as suggested for complete monitoring, control and protection point of view for southern grid of India.

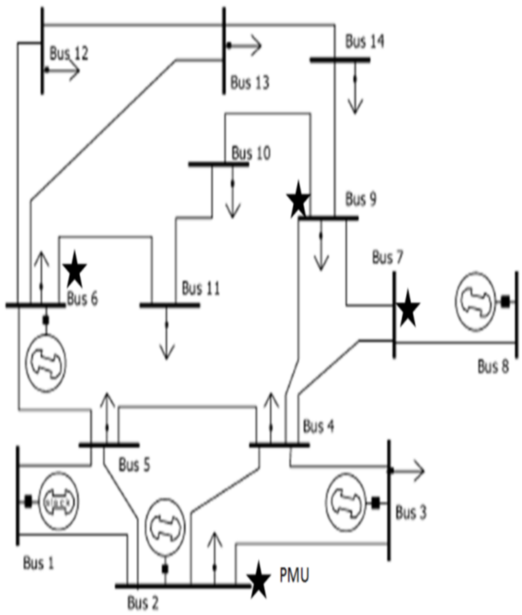


Fig.2. IEEE 14-bus system

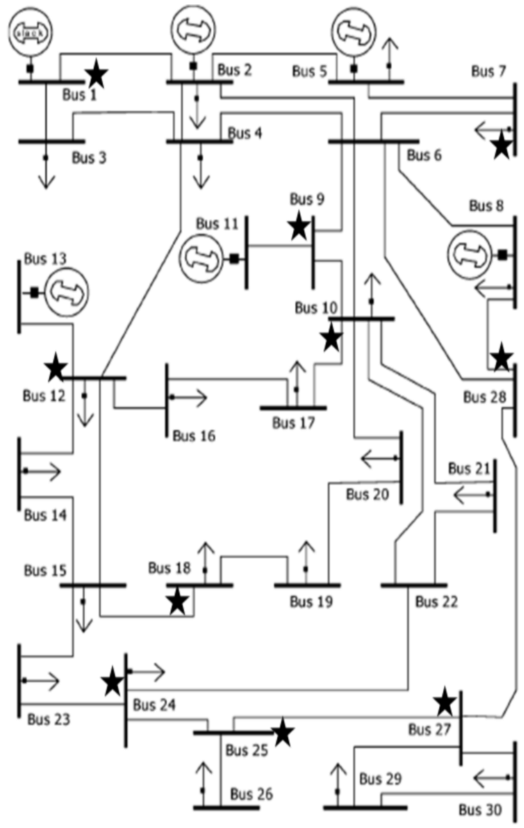


Fig.3. IEEE 30-bus system

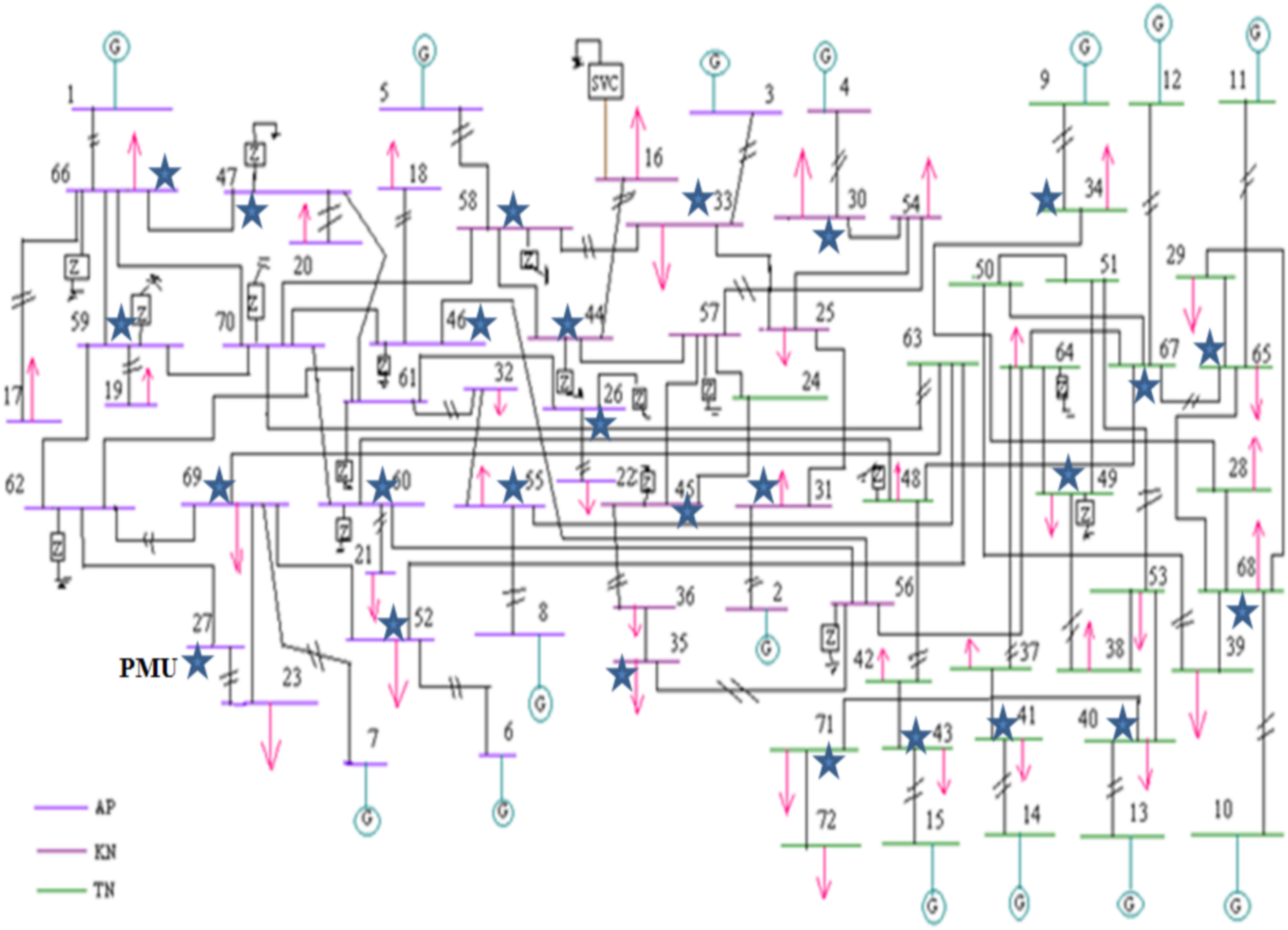
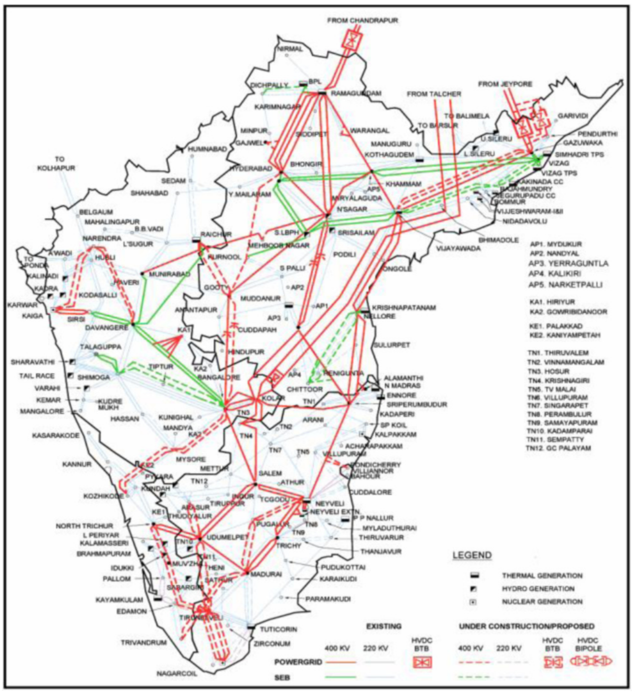


Fig.4 Line diagram of southern grid 72-bus system(reduced system)



BUS NAMES

1. Ramagundam(Gen)
2. Sharavathi(Gen)
3. Cudapa2(Gen)
4. Kaiga2(Gen)
5. Cudapa4(Gen)
6. Nagarjun sagar(Gen)
7. Srisailam(Gen)
8. Vijayawada (Gen)
9. Myladuthurai2(Gen)
10. Neyvelli2(Gen)
11. N madras2 (Gen)
12. N madras4 (Gen)
13. Thanjavur2(Gen)
14. Madhurai2(Gen)
15. N madras2 (Gen)
16. Gowribidanoor
17. Ramagundam2
18. Gooty2
19. Gooty2
20. Khammam2
21. Chikadapalli2
22. Vizag2
23. APRDS
24. Nalamangala4
25. Davangiri
26. Visakapatnam4
27. APCBD4
28. Vilupuram2
29. Cuddalore2
30. Kaiga2
31. Sharavathi2
32. Vijayawada2
33. Rayachur
34. Myladuthurai2
35. Somanhally
36. Hoody
37. Salam2
38. Udumelpet2
39. Trichy2
40. Thanjavur2
41. Madhurai2
42. Sriperumbudur2
43. N madras2
44. Gowribidanoor4
45. Hoody4
46. Gooty
47. Khammam4
48. Sriperumbudur4
49. Udumelpet4
50. Trichy4
51. Madhurai4
52. Nagarjun sagar2
53. Madhurai2
54. Davangiri
55. Vijayawada2
56. Somanhally4
57. Davangiri4
58. Rayachur
59. Hyderabad4
60. Cudapa
61. Vijayawada4
62. Srisailam4
63. Tuticorn2
64. Salam4
65. N madras2
66. Ramagundam
67. N madras4
68. Neyvelli2
69. Srisailam
70. Nagarjun sagar4
71. Tuticorn
72. Thanjavur

AP
KN
TN

Fig.5 Geographical diagram of Indian Southern region Power transmission System (SRLDC DATA)

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Appendix A.

For Simple 7-bus system shown in fig1. The use full vectors are

TABLE III. NLCONT VECTOR FOR 7BUS SYSTEM

BUS NO(i)	1	2	3	4	5	6	7
NLCONT(i)	1	4	3	3	1	2	2
ITAGF(i)	1	2	6	9	12	13	15
ITAFTO(i)	1	5	8	11	12	14	16

The ITAGF(i) and ITAGTO(i) vectors are shown above. These vectors are to identify the 'from' and 'end' positions of the reserved locations of adjacent column vector ADJQ(J).

TABLE IV. ADJQ(J) VECTOR FOR 7BUS SYSTEM

J	1	2	3	4	5	6	7	8
ADJQ(J)	2	1	3	6	7	2	4	6
J	9	10	11	12	13	14	15	16
ADJQ(J)	3	5	7	4	2	3	2	4

Now, if PMU located at 2nd bus then 2nd bus and adjacent buses of 2nd bus i.e 1, 3, 6, 7 are observable. Similarly PMU at 4th bus makes 4th and 5th bus becomes observable. Because of this two PMU's all 7-buses becomes observable. It may be noted that in identifying the adjacent buses the ADJQ vector plays very effective role.

TABLE V. ROOT AND PMULOC VECTORS FOR 7BUS SYSTEM

Bus No. (i)	1	2	3	4	5	6	7
Root(i)	1	1	1	1	1	1	1
Pmuloc(i)	0	1	0	1	0	0	0

Appendix B.

Genetic Algorithm Parameters

Chromosome size equals to number of buses.

Probability of elitism (PE)=0.05

Probability of crossover (PC)=0.85

Probability of mutation (PM)=0.02