Effective Optimal Placement of PMUs for Power System Observability

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***Abstract*—This paper presents a new algorithm for optimal placement of PMU's to make the given power system network observable under normal operating conditions. Observability test is carried out based on topological connectivity of network, using "root vector" without any need for triangularisation of a matrix. The root vector indicates the number of buses observed due to the placement of PMU at a bus. The aim of the optimal PMU placement problem is to minimize the number of PMU's employed in the power system to make it observable. The proposed technique is tested on IEEE 14-bus and 30-bus systems. Further, this technique is also tested on partial network of Southern Grid of India. The test results are compared with the existing algorithms and the results of the proposed algorithm are very promising with significant reduction in CPU time. Therefore, evidently this algorithm can be employed very effectively for well grown large size power systems for optimal placement of PMU's.**

Keywords—Observability analysis; NLCONT; ITAGF; ITAGTO; ADJQ; phasor measurement units; part of South Grid Of India.

I. NOMENCLATURE

A	connectivity matrix (nxn) in which
	A_{ij}=1 if bus i is connected with bus j
	A_{ij}=0 if bus i is not connected with bus j
	A_{ii} =1
i	bus number
n	number of buses
NLCONT(i)	number of lines connected to i^{th} bus
Nline	total number of lines in given power system
Lp(k)	sending end bus of line-k
Lq(k)	receiving end bus of line-k
k	line number
ADJQ	is a vector used to store the adjacent bus numbers of given bus

II. INTRODUCTION

As the complexity of power system increasing day by day there is a need of using advance technology for monitoring the entire power system. The phasor measurement unit (PMU) device, which was introduced in the early 1990s, permits to obtaining synchronous measurements (via global synchronous time stamps) at a much higher sampling rate[1]. The PMUs are able to provide data of high accuracy to within 1 μs[2]-[5]. The PMU uses the GPS (global position system) to make all the measurements as synchronous measurements i.e GPS uses a common time source hence it is possible to obtain real time measurements of several remote measurement points on the power grid at the same time. In practice, PMUs accurately measure positive sequence components of voltage and current phasors. Phasor measurement units (PMUs) are considered the most probable Synchronized Measurement Technology (SMT) devices and also an important constituent of wide-area monitoring, protection and controls systems (WAMPAC) [6].

Placement of PMU units at each bus of a power system is an ineffective approach. Thus, the optimal placement of PMUs in power system is very important to make the power system as observable with minimum set of PMUs. In [7], the author has proposed integer programming based method for optimal PMU placement for complete and incomplete observability with and without considering the conventional measurements. In [8], the author has proposed an algorithm for placement of PMU with channel limit along with considering zero injection bus. In [9], Optimal PMU placement (OPP) problem is formulated and solved using graph theory based observability analysis and Simulated Annealing optimization method. In [10], 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 [11], Tabu Search

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[12], Genetic Algorithm [13] and Binary Particle Swarm Optimization [14] have been suggested for OPP problem. The potential impact of PMUs on power system network and its applications is discussed in [15]. Several research works are centered on the topological observability criterion, which essentially specifies that power system states should be uniquely estimated using minimum number of PMU measurements [16]. Based on such criterion, many solutions were proposed, such as mixed integer programming [17]&[18], binary search [19], and metaheuristics [20]&[21].

In this paper, the proposed algorithm uses effective data structure to offer the total information of the graph of a power system using NLCONT, ADJQ, ITAGF, and ITAGTO vectors [22].

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

III. PROPOSED PROBLEM FORMULATION FOR OPTIMAL PLACEMENT OF PMU (OPP)

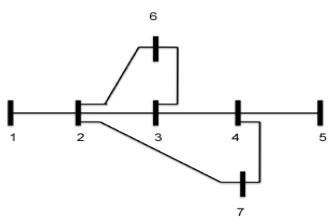

Fig.1. The 7-bus system

To make the given power system to be observable with minimum set of PMUs, the following key observations are very useful on any given size of power system network.

The important observations are as bellow

1). Identify the buses which having only one line incident with them. Then place a PMU at adjacent bus of that particular bus.

For the 7bus system as shown in fig.1, bus-1 and bus-5 are having only one line incident with them. Thus it is advised to put one PMU at 2nd bus (which is adjacent bus of 1st bus) and at 4th bus (which is adjacent bus of 5th bus).

2). After completing the process mentioned in observation (1), now process the buses which are in unobserved state and having interconnection of two lines (NLCONT(i)=2). Now place a PMU at the adjacent bus of i^{th} bus which is having maximum no. of lines interconnection.

This approach is to be repeated for NLCONT(i)=3 and so on. At each stage, update the "root vector" to identify the buses which are yet to be made observable.

IV. PROPOSED ALGORITHEM

Step1: Read n, nline, lp, lq.

Step2: Form NLCONT, ITAGF, ITAGTO, ADJQ, ADJL Vectors (see case study(i) on 7bus system).

Step3: Initialize "root vector" size of nx1 to zeros and pmuloc vector also to zeros.

Step4: If NLCONT(i)=1, then place a PMU at "adjacent bus(q)" of i^{th} bus. Now set pmuloc(q)=1 and update the root vector elements with 1 at i^{th} location and adjacent bases of i^{th} bus. Repeat this for all buses which satisfy NLCINOT(i)=1.

Step5: Now,if NLCONT(i^{th} bus)=2 and pmuloc(i^{th} bus)≠1, search for best location among the *adjacent buses* of that i^{th} bus so that more buses are going to be observable. Then place a PMU there (q^{th} bus) and make the adjacent buses of this q^{th} bus as observable by setting 'root vector' elements to 1. Also set pmuloc(q)=1. Repeat this for all possible caes satisfying NLCONT(i)=2 and pmuloc(i)≠1.

Step6: Repeat step 5 for NLCONT(i)=3 & pmuloc(i)≠1 and so on until system is observable.

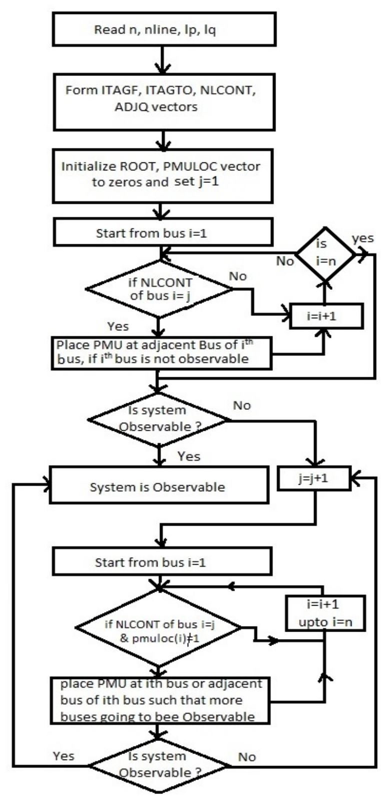

Fig.2. Flow Chart for proposed algorithm

V. RESULTS AND CASE STUDIES

CASE (i): Simple 7-bus system shown in fig1.

TABLE I. 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 II. 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, NLCONT(1)=1, so according to proposed algorithm place PMU at adjacent bus of 1st bus i.e at 2nd bus and NLCONT(5)=1 so place PMU similarly at 4th bus. 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 III. 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

CASE (ii): IEEE 14-bus system

The IEEE 14-bus system has 14 buses as shown in Fig.3. The PMU locations are found by the proposed algorithm using MATLAB code and the locations are: 2 7 11 and 13 buses.

CASE (iii): IEEE 30-bus system

The IEEE 30-bus system is shown in Fig.4. The OPP formulation is done with proposed algorithm similar to 7-bus system and found that 10 PMU are required at locations 1 5 6 9 10 12 15 19 25 and 27 buses.

CASE (iv): 400/220/132 kV Part Of The South Grid Of India

The practical 400/220/132 kV reduced network with 72-bus system[25] along with geographical diagram is shown in Fig.4. The states Andhra Pradesh, Karnataka and Tamil Nadu are considered in this line diagram. The lines under in construction and outage are not considered.

The OPP formulation is done with proposed algorithm and found that 26 PMU are required at locations 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 71buses for full Observability of given south grid of India.

TABLE IV. RESULTS WITH DIFFERENT METHODS AND CPU TIMES

System Bus size	Number of PMUs	CPU time(sec)		
		ILP	WLSE	Proposed algorithm
14	4	1.872	0.8336	0.07163
30	10	2.089	0.978	0.07753
72 (400/220/132 kV South Grid of India)	26	2.156	*	0.14440

*not mentioned in that reference paper[23]

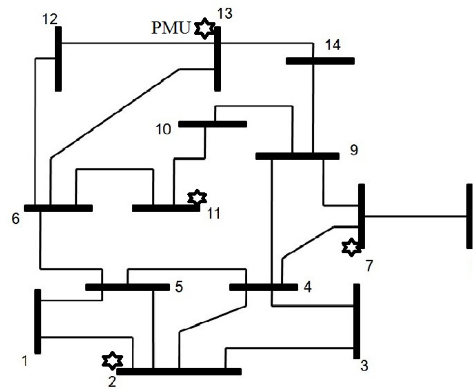

Fig.3. IEEE 14-bus system

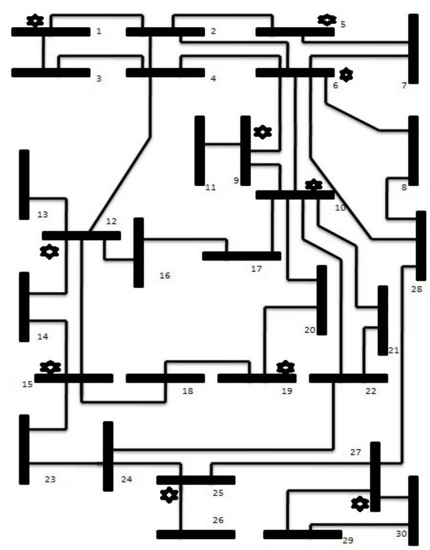

Fig.4. IEEE 30-bus system

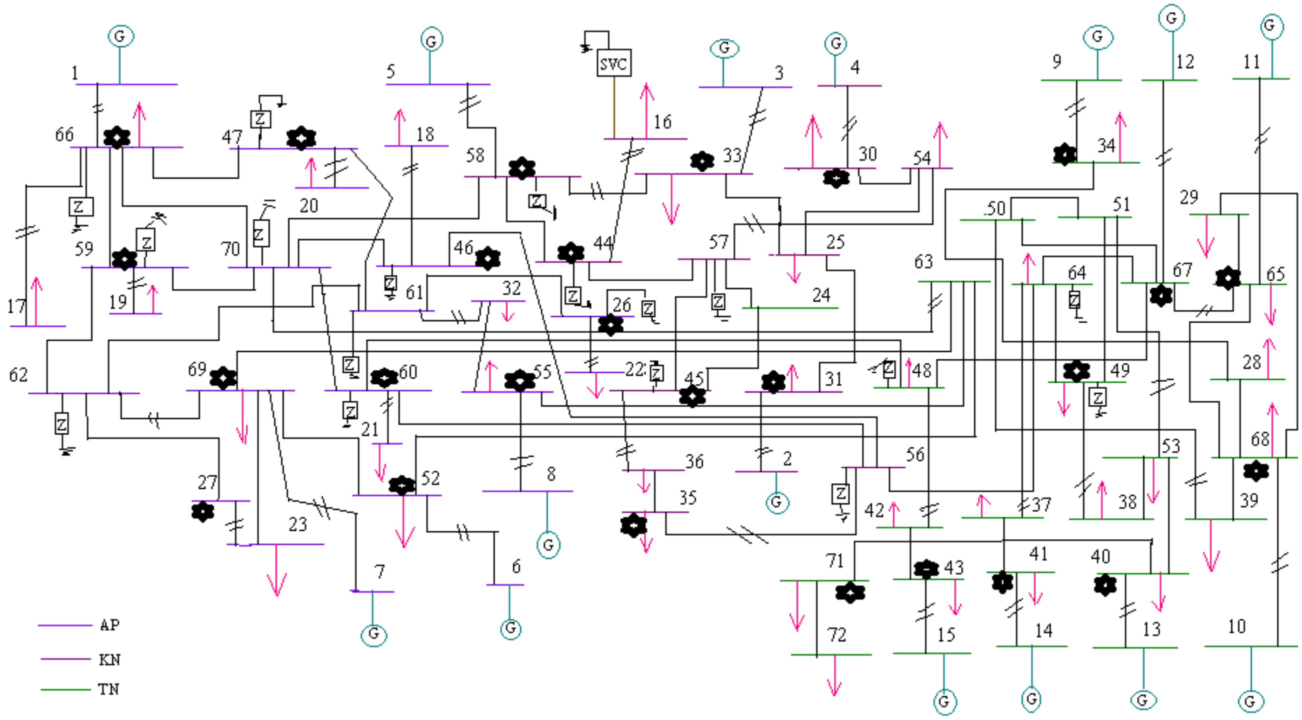

Fig.5. Single line diagram of southeran grid 72 (reduced)bus system

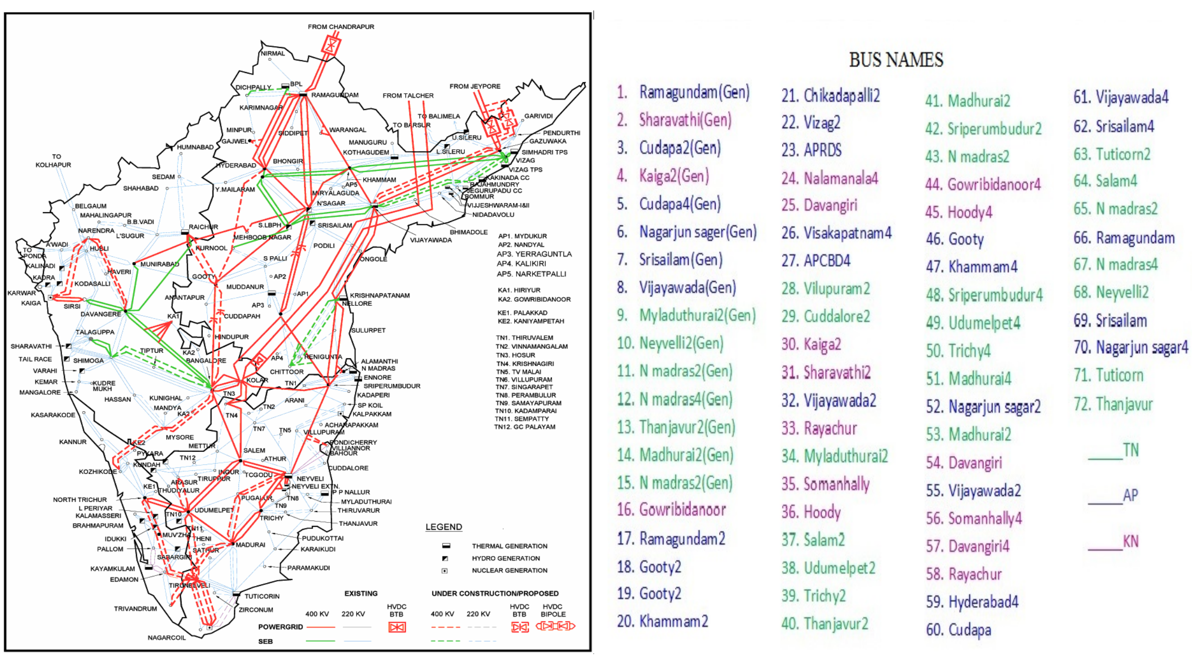

Fig.6 Geographical diagram of Indian Southern region Power Transmission System

IV. CONCLUSIONS

This paper has presented a new algorithm for optimal placement of PMUs problem. The proposed algorithm works on graph of the given power system and places the PMUs at potential locations with the help of ADJQ, 'Root' and 'pmuloc' vectors. It is verified on the IEEE 14-bus system, IEEE 30-bus system and finally implemented on 72 reduced practical bus system of south grid of India and results are found as 26 PMUs are required for full Observability of the system. The synchrophasor technology is not full 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 south grid of India. Future work includes implementing this algorithm with inclusion of conventional measurements.

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