Optimal PMU Placement and Observability of Power System using PSAT

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***Abstract*— Improvements in power system control and protection is achieved by utilizing real time synchronized phasor measurements. The trend in recent years is the steady increase of Phasor Measurement Unit (PMU) installations worldwide for various applications those targeted for State Estimation enhancement. In this paper, Power System Analysis Toolbox (PSAT) is used for power system analysis and control. PSAT is used to solve the PMU placement problem using different methods such as Depth First, Annealing, Direct Spanning Tree and Graph Theoretic procedure. Several test systems were considered and the results pertaining to IEEE-14 bus system and the subnetwork of Tamil Nadu are presented and validated for complete sytem observability.**

***Index Terms*—Integer Linear Programming (ILP), PMU placement, State Estimation, Complete Observability**

I. INTRODUCTION

Secure operation of power systems requires close monitoring of the system operating conditions. This is traditionally accomplished by the state estimator which resides in the control centre computer and has access to the measurements received from numerous substations in the monitored system. These measurements are commonly provided by the remote terminal units (RTU) at the substations and include real/reactive power flows, power injections, and magnitudes of bus voltages and branch currents.Phasor measurement units (PMU) are devices, which uses synchronization signals from the global positioning systems (GPS) satellites and provide the positive sequence phasor voltages and currents measured in systems.

In [1], a phasor measurement placement method based on the topological observability theory using graph theorem analysis is proposed. A minimal number of buses with measurements is found through both a modified bisecting search and simulated annealing-based method. In [2], the PMUs are installed so that the entir\

e system becomes observable while voltages of all system pilot buses can be monitored in real-time which increase the speed of voltage control scheme considerably. The OPP problem was solved using Branch and Bound algorithm. The optimal PMU placement (OPP) problem is formulated as to minimize the number of PMU installation subjecting to full network observability and enough redundancy [3]. Xu and Abur employed Integer Programming to solve optimized PMU placement problem. In order to properly take advantage of zero injection buses, topology transformation and non-linear integer programming were tested [4]. The two level approaches for solving optimal PMU placement in order to achieve complete observability of the power system is proposed in [5].The approaches are numerical observability and topological observability.Numerical observabiltiy utilizes the gain matrix or the measurement Jacobian, reflecting the configuration of the system.However, in case of large power systems, the measurement matrix may become ill conditioned and may result in poor computation speed.

On the other hand, the topological observability based methods e.g. Depth First Search [6], Spanning Tree method ensures full topological observability, but do not ensure full ranked measurement Jacobian Matrix. The algorithm is used to partition the spanning tree of the network using Integer Linear programming (ILP).The objective is to minimize the installation cost of PMU. In [7], a unified approach is proposed for determining the optimal number and location of PMUs required making the entire power system observable. It considers the impacts of both exiting conventional measurements and the possibility of single or multiple PMU loss into the decision strategy of the optimal PMU allocation problem.

In [8], an algorithm to identify buses for PMU placement based on certain requirements. The monitoring of certain grid events like transmission line failure or generator failure must be possible from the selected PMU locations. In addition, the PMU must be distributed evenly so that the critical parts of the grid are observable. There should be no or little redundancy in the PMU readings unless it is intentional to provide additional data reliability.

This paper describes four methods for phasor measurement unit placement namely Depth First Search, Graph Theoretic Procedures, Bisecting Search-Simulated Annealing and Direct Spanning Tree. A description of the PMU placement and the results for IEEE 14-Bus system and the subnetwork of Tamil Nadu are reported.

II. PHASOR MEASUREMENT UNIT

Phasor Measurement Unit (PMU) – a device which by employing widely used satellite technology offers new opportunities in power system monitoring, protection, analysis and control. PMUs facilitate innovative solutions to traditional utility problems and offer power system engineers a whole range of potential benefits, including precise estimates of the power system state can be obtained at frequent intervals, enabling dynamic phenomena to be observed from a central location and appropriate control actions taken. Post-disturbance analysis will be much improved with the precise snapshots of the system states through GPS synchronization. Advanced protection based upon synchronized phasor measurements could be implemented, with options for improving overall system response to catastrophic events. Advanced control using remote feedback becomes possible, thereby improving controller performance.

PMU measures voltage and current phasor in a power system. Synchronism among phasor measurements is achieved by same time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite [8]-[10]. PMUs have higher accuracy than conventional measurements. They reduce effects of time-skew among measurements, useful for many other applications such as system protection, control and stability assessment, aid topology error identification, parameter error detection and correction and improve accuracy of state estimation.

The introduction of PMUs in power systems significantly improves the possibility for monitoring and analyzing power system dynamics. A number of synchronized phasor measurement terminal installed in different locations of a power system provides important information about different AC quantities e.g. voltages, currents, active and reactive power, all of them based on the same GPS time reference. Synchronized measurements make it possible to directly measure phase angles between corresponding phasors in different locations within the power system. Improved monitoring and remedial action capabilities allow network operators to utilize the existing power system in a more efficient way. Improved information allows fast and reliable emergency actions, which reduces the need for relatively high transmission margins required by potential power system disturbances. Instead of merely surviving the worst credible contingency, the power system should survive the worst credible contingency followed by remedial actions initiated by various new functions based on phasor measurement.

Thus Phasor measurement opens a wide range of new applications, like monitoring and recording of power system dynamics , improved State Estimation, System Wide Power Oscillation mitigation, robust two side transmission line fault locator, emergency control during large disturbances, voltage control in a power system and synchronised event recording.

III. PROBLEM FORMULATION

The Optimal placement of PMU becomes an important problem to be solved in power system state estimation. The PMU placement problem is formulated as a binary integer linear programming, in which the binary decision variables (0, 1) determine whether to install a PMU at each bus, while preserving the system observability and lowest system metering economy. It is neither economical nor necessary to install a PMU at every node of a wide-area interconnected network.

The cost of a PMU depends on a number of factors, including the number of measuring terminals (channels), CT and PT connections, power connection, station ground connection, and GPS antenna connection. The main purpose of performing PMU placement problem is to minimize the number of installed PMUs, so that for an n-bus system the optimization problem is given as:

$$\text{Minimize} \sum_{i}^{n} w_i x_i$$

$$\text{Subject to } f(X) \geq \hat{1}$$

Where w_i is the installation cost of the PMU at bus i.

Assume $w_i = 1$

$x_i = 1$, if a PMU installed at bus i

0, Otherwise

f(X) is a vector function representing the constraints

$\hat{1}$ is a vector whose entries are all equal to 1.

IV PMU PLACEMENT RULES

The following PMU placement rules were proposed in [Baldwin et al. 1993]:

Rule 1: Assign one voltage measurement to a bus where a PMU has been placed, including one current measurement to each branch connected to the bus itself.

Rule 2: Assign one voltage pseudo-measurement to each node reached by another equipped with a PMU.

Rule 3: Assign one current pseudo-measurement to each branch connecting two buses where voltages are known. This allows interconnecting observed zones.

Rule 4: Assign one current pseudo-measurement to each branch where current can be indirectly calculated by the Kirchhoff current law. This rule applies when the current balance at one node is known, i.e. if the node has no power injections (if N-1 currents incident to the node are known, the last current can be computed by difference).

V CASE STUDY AND RESULTS

The IEEE-14 bus system is shown in Figure.1. Table 1 shows the bus in which the PMU has been placed for the IEEE 14 bus system using different methods like Depth First method, Annealing, Direct spanning and Graph Theoretic Procedure.

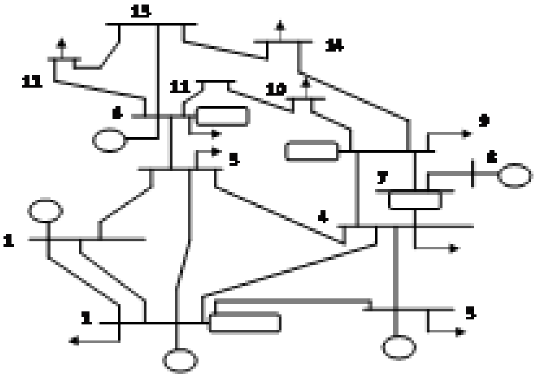

Figure 1. IEEE 14 bus system

TABLE 1: DIFFERENT METHODS OF PMU PLACEMENT SET FOR IEEE 14 BUS SYSTEM

Placement Method	Depth First Method	Annealing Method	Direct Spanning Tree Method	Graph Theoretic Procedure
Bus Name	**SET**	**SET**	**SET**	**SET**
Bus1	1	0	0	1
Bus2	0	1	1	0
Bus3	0	0	0	0
Bus4	1	0	0	1
Bus5	0	0	0	0
Bus6	1	0	0	1
Bus7	0	1	1	0
Bus8	1	0	0	1
Bus9	0	0	0	0
Bus10	0	1	0	0
Bus11	0	0	1	0
Bus12	0	0	0	0
Bus13	0	1	1	0
Bus14	1	0	0	0

The same test system namely, IEEE 14 bus system has been considered for finding the optimum PMU placement using Binary Integer Linear Programming. The Multi partitioning algorithm is applied to the system to form blocks. For each block the objective function and the constraint equations are formulated and solved using ILP.

A few real time systems have also been considered and the optimal location of PMUs for the networks have been found out. The different sub networks of Tamil Nadu namely 110KV (North), 230KV, 110KV (South) and 400KV have been considered. They are shown in Fig 2,3,4 and 5 respectively.

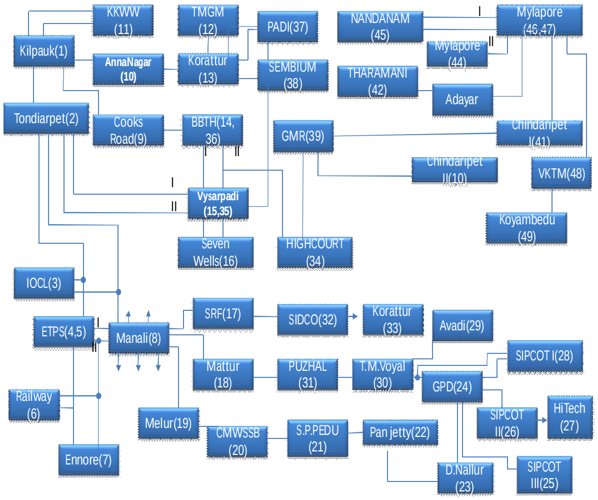

Figure 2. 110KV (North) Network of Chennai

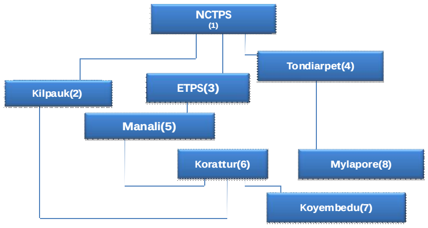

Figure 3. 230KV Network of Chennai

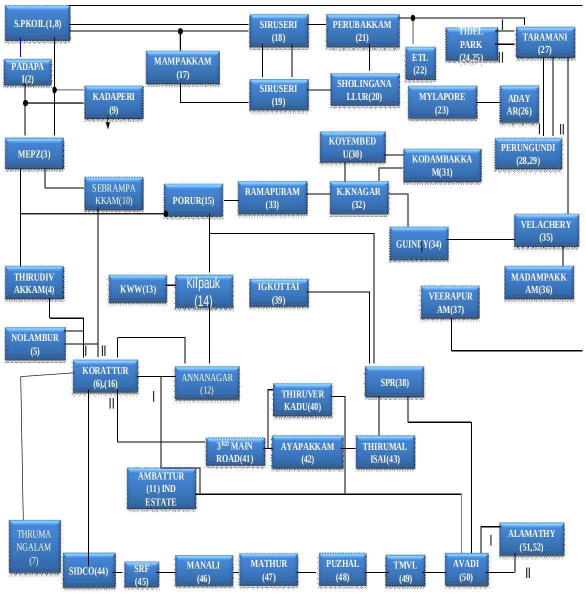

Figure 4. 110 KV (South) Network of Chennai

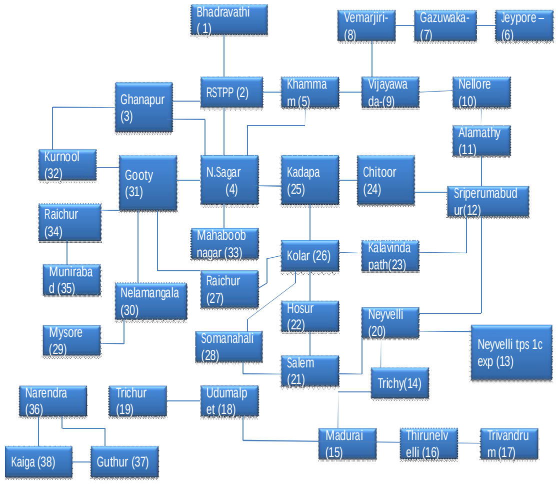

Figure 5. 400KV Network of Southern Region

Using Binary Integer Linear Programming and PSAT, the above networks were tested and the minimal number of PMUs and location of PMUs were found out. The optimum results thus obtained are given in Table 3.

TABLE 3.OPTIMAL NUMBER AND LOCATION OF PMUS

Network	Number of PMUs	Location of PMUs
IEEE 14 Bus	4	2,6,7,9
110 KV (North)	16	6-8-9-11-13-15-20-24-27-29-32-40-42-45-47-48
110 KV (South)	14	2-7-14-15-16-21-27-28-32-36-43-44-48-50
230 KV	3	3-6-8
400 KV	10	2-6-9-17-18-20-26-29-34-36

CONCLUSIONS

This paper solves a generalized integer linear programming formulation for optimal PMU placement for the IEEE-14 bus system and different sub networks for Tamilnadu.we used PSAT to test different algorithms,before any allocation of PMU,to obtain optimal PMU placement.Optimal PMU placement decreases number of PMUs that redounds costs declining.Using PMU in power system increases reliability of power system stability.It is therefore possible to fully monitor the system by using relative less number of PMUs than the number of system buses.

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