An Optimal PMU Placement Techniques for complete Power System Observability

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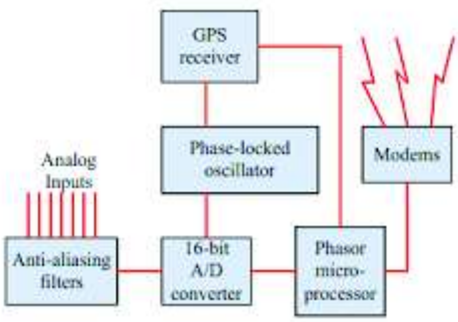
***Abstract* — Phasor Measurement Unit (PMU) device which is considered to be the most important device in future for power system observability. It provides phasor information means both magnitude and phase angle which can be used in the real-time control of power systems. In this paper, optimal PMU placement problem (OPP) is pronounced as an integer linear programming (ILP) that methodology is offered for the optimal placement of Phasor Measurement Unit that minimizes the cost of installation and provide the complete power system observability. A binary connectivity matrix-based integer linear programming (ILP) is used as an optimization tool to obtain the minimal number of Phasor measurement units and their corresponding locations. Simulation results for IEEE 14-bus, IEEE 30-bus, IEEE 118-bus and Indian Utility 62-bus test systems are presented and associated with the present techniques, to justify the effectiveness of proposed method In All researches, the zero-injected buses are considered to obtain the best answers.**

Index Terms — Phasor Measurement Unit; Integer Linear Programming (ILP); **Network observability**

I. INTRODUCTION

In modern power system planning, design, operation, speed reliability, efficiency, safety and economic are important factor which is evolution of great performance of transmission grid. Due to lack of observability, a series of blackouts have been encountered in Indian power systems. For better, secure, reliable, operation of power systems, close monitoring of the system operating conditions is essential. Now a day availability of global positioning system is technology which is quite possible to Advance monitoring the operation of power system network. Throughout this paper, it was presumed that PMU placed on a bus is proficient of monitoring voltage magnitude and phase angle of the bus as well as branch current of all the branch connected to that bus.

The methodology is needed to define the optimal location of Phasor measurement units in a power system. In addition to its talent to measure voltage and current phasors, an advanced PMU may enclose other features such as protective actions. The objective of the present work is to find the minimum number of Phasor measurement units to make the system topologically observable, as well as the optimal locations of this Phasor measurement units. In recent year, there has been a significant research activity on the problem of finding the minimum number of Phasor measurement units and their optimal locations. In [3], a bisecting search method is implemented to find the minimum number of Phasor measurement units to make the system observable. The simulated annealing method is used to randomly choose the placement sets to the test for observability at each step of the bisecting search. In [1], the authors use a simulated annealing technique in their graph-theoretic procedure to find the optimal PMU locations.



A procedure which finds the minimal set of PMU placement desired for power system state estimation has been established in [2] and [3], where the graph theory and the simulated annealing method have been used to succeed the goal. Here in [4], a planned PMU placement algorithm is established to improve the bad data processing capability of state estimation by taking lead of the PMU technology. Methods for finding placement sites for PMUs in a power system based on incomplete observability are presented in [1], where simulated annealing method is used to solve the real-world communication-constrained PMU placement problem. In [5], a special custom-made non dominated sorting genetic algorithm is established for the PMU placement problem. The writers in [6] advanced an optimal placement algorithm for PMUs by using (ILP) integer programming. Though, the planned integer programming becomes a nonlinear integer programming under the presence of conventional power flow or power injection measurements.

II. PMUs (PHASOR MEASUREMENT UNITS) TECHNOLOGY

A PMU is a device that provides as a least, synchro-phasor and frequency measurements for more three-phase alternative voltage and/or current waveforms [16].These measures are marked with a GPS time stamp in time intervals down to 20 milliseconds [1].This same time sampling of voltage and current waveforms by a mutual synchronizing signal from the GPS ensure synchronicity between Phasor measurement units. This synchronicity makes the PMUs one of the most important devices for power system control and monitoring.

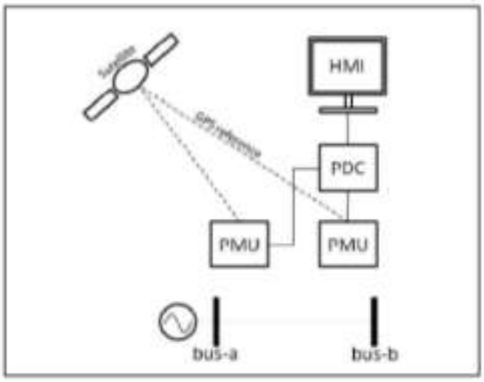


Fig.1 : PMU Layout with GPS time stamped Signal

Fig. 1 demonstrations Phasor measurement units geographically isolated to form a wide area monitoring system (WAMS) in which the Phasor measurement units send GPS time-tagged measurements to a Phasor Data Concentrator (PDC).The PDC sorts the incoming phasor measurements already signal processing converts PMU data into actionable information that can be presented to an operator in the form of a Human Machine Interface (HMI).This HMI provides an operator with critical evidence about the state of the power system.

III. POWER SYSTEM OBSERVABILITY

A system is called entirely observable when each of its buses is observable either directly or indirectly. A bus is directly observable if a PMU directly estimates the bus voltage, while a bus is indirectly observable if it is adjacent to a directly observable bus. A bus or a line is observable if at least one of following rules is satisfied with it [15].

1. A bus/line to which a PMU is allocated is straight observable. In this case, voltage phasor of the bus/line and current phasors of connected branches are directly available.

2. Any transmission line for which the voltage and current phasors are available at one end, using the line parameters, voltage phasor at the other end is calculated.

3. If in a zero-injected bus, current phasors of all connected branches are available except one, the current phasor of the unavailable line is calculated using KCL equations.

4. A zero injected bus with unknown voltage is observable if voltage phasors of all adjacent buses are available, using node equations.

It is apparent that the combination of Phasor measurement units into the power network will provide substantial benefits. One of the key issues for PMU applications in power system observability is the selection of placement locations. Therefore, an algorithm should be developed that can incorporate the above-said rules.

IV. FORMULATION OF THE ILP

Linear Programming (LP) problem is an optimization method related to the solution of problems in which the objective function and the constraints are linear functions of the decision variables. The constraints in a linear programming problem may be in the form of equalities or inequalities [19]. Integer Linear Programming (ILP) problem is an extension of linear programming that some or all the variables in the optimization problem are restricted to take only integer values. Integer linear programming can be used to find the minimum of a linear function over a feasible set defined by a finite number of linear constraints.

A. ILP without Considering Zero Injection Buses

In this Work on optimal PMU placement using linear integer programming has been pioneered by [10, 11]. For an n-bus system, optimal PMU placement problem (OPP) can be formulated as a problem of integer linear programming, as follows:

$$OPP = Min \sum_{i=0}^{n} xi$$

Subject to constraints: A. X = U

Where U is observability matrix, which shows the number of PMU observing a group of buses in a power system. In the general case it is a unit vector of the length of n, so

$$U = [\, U_1\ U_2\ \ldots\ldots\ U_n]^T_{1xN}$$

Here X is the PMU placement vector having element xi in such a way so,

$$X = [\, X_1\ X_2\ \ldots\ldots\ Xn]^T_{1xN} \qquad Xi \in \{0, 1\}$$

If a PMU is installed at bus i. 0, Otherwise

Here A is the connectivity matrix of the system, which can be obtained from bus admittance matrix, with ai,j {0, 1}

B. ILP Considering Zero Injection Buses

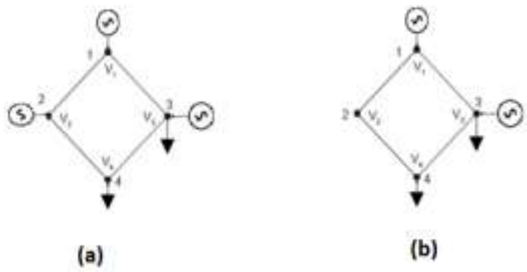


Fig. 2: A 4-bus system consisting **(a) injection bus at 2** and **(b) zero injection bus at 2**

Here Zero injection buses are those buses through which no external current is existence injected into the system nor extracted [9]. They are analogous to the transshipment buses or supernode and have the potential to reduce the number of PMU required for complete system observability. For a better understanding of above statement, consider a 4-bus system shown in Fig. 2.

Here in Fig. 2(a), shows the 4-bus system with no zero injection bus, while Fig. 2(b) shows a similar 4-bus system with bus-2 as zero injection bus.

From Fig. 2(b), it can be observed that the voltage at bus-2 and bus-4 can be resolute from the knowledge of voltage phasor and current phasor of bus-1 using Ohm’s law. This is because there is no external current injection at bus-2 and I12= I24. Thus it is clear that incorporation of zero injection buses in integer linear programming (ILP) will help, to observe the complete system with a reduced number of PMUs.

As per [8, 9], in optimal PMUs placement problem considering zero injection bus (OPP-Z), to incorporate zero injection buses into integer linear programming the constraints are modified as:

$$\boldsymbol{OPP - Z = Min \sum_{i=1}^{n} xi}$$

Subject to: **A.X ≥U**

Where A is the binary connectivity matrix, X is the PMUs placement vector and U is the observability matrix.

C. Proposed method

The other way to incorporate zero injection buses in integer linear programming is to modify the binary connectivity matrix. Binary connectivity matrix can be obtained by replaying the non-zero element of connectivity matrix by 1 and keeping zero elements as 0. In general binary connectivity matrix shows the connection between directly connected buses, but to incorporate the zero injection bus, the modified matrix will also consider the buses which are connected through ZIB.

Now again consider the example of the 4-bus system shown in Fig. 2(a), connectivity matrix can be written as

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

When bus-2 will be considered as zero injection bus, as shown in fig. 2(b), the modified connectivity matrix will become:

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

In the above statement, bus-4 was considered to be connected to bus-1 via bus-2, because by using the voltage phasor and current phasor data of bus-1, system model, and Ohm's law, the voltage phasor at bus-4 can be determined. Thus zero injection bus, i.e. bus-2, acted as a supernode between bus-1 and bus-4.

V. TEST SYSTEMS AND SIMULATION RESULTS

Matrix modification based integer linear Programming for optimization of the PMU placement was tested on three IEEE test network: IEEE 14 bus, IEEE 30 bus, IEEE 118 bus & Indian Utility 62 Bus system MATLAB® R2014a was used for simulation purpose. Here in this paper, it is considered that all the Phasor measurement units are working properly and providing the measurements continuously and, here no PMU outage is occurring.

Here Table I is displays the minimum number of PMU in various test systems.

Table I. Minimum Numbers of PMU for various Test Bus System

#Test system	*#Optimal Minimum No. of PMUs*
IEEE 14-Bus	*3*
IEEE 30-Bus	*8*
Indian Utility 62-Bus	*15*
IEEE 118-Bus	*28*

It can be seen in Table II that optimal PMU location of IEEE 30 bus system may differ for the different algorithm but an optimal number of PMU required for full system observability is 7.

Table II. Comparison of the Results for IEEE 30 Bus System

#Optimal Placement method	**#Zero Injection Bus**	**#No. of ZIB**	**#Optimal PMU location**	**#No. of Optimal PMU location**
Own program	5, 6, 9, 25, 28	5	3, 7, 11, 13, 19, 23, 26	7
Xu and Abur	5, 6, 9, 25, 28	5	3, 7, 11, 13, 19, 23, 26	7

VI. CONCLUSION

An integer linear programming (ILP) for optimal placement of PMU is presented in this paper. This method is based on modification in binary connectivity matrix of the system, to integrate the effect of zero injection buses. The effect of PMU loss or a branch outage was not taken into consideration. The proposed method obtains an optimal solution using binary connectivity matrix modification and makes the test systems topologically observable by placing a set of minimum Phasor measurement units. The method was applied to two IEEE benchmark systems and one Indian Utility system, simulation results for which shows the efficiency of the proposed method in obtaining the minimum number of PMUs required for complete observability of power systems network and also its advantage of computational proficiency.

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