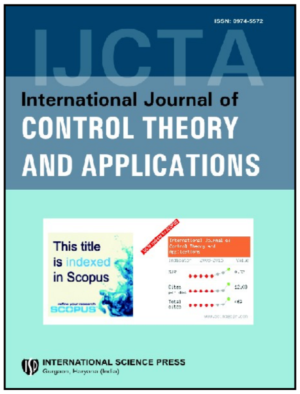

International Journal of Control Theory and Applications

ISSN : 0974-5572

© International Science Press

Volume 9 • Number 50 • 2016

Power System State Estimation Using Minimal Placement of Phasor Measuring Units

Sandeep Manda[1], Siva Sankar G[2], Bala Krishna K[3] and Moturu Bindu[4]

[1,3] Assistant Professor, Department of EEE, VFSTR University, Vadlamudi, Andhra Pradesh
E-mail: sandeep.manda984@gmail.com
[2] Assistant Prfofessor, Department of EEE, VLITS Vadlamudi, JNTUK, Andhra Pradesh
[4] M. tech Student, Department of EEEE, VFSTR University, Vadlamudi, Andhra Pradesh

Abstract: This paper aims at finding a minimal placement technique for placing Phasor measuring units for reducing the cost of state estimate. The method used in this technique is binary integer linear programming. The results show that the method adopted can be effectively used in practical. This paper suggests the use of phasor measurement units for improving power system state estimation and observability. Objective of this paper is to get solution for minimal placements of Phasor Measuring Units for complete power system state estimation and observability by using binary integer linear programming technique. This method is tested with several test systems like IEEE14 bus, IEEE 39 bus, IEEE 57 bus and the results have been verified for complete system observability.

Keywords: Phasor Measurement Unit (PMU); Binary Integer Linear Programming(BILP) ; Optimization; State Estimation.

I. INTRODUCTION

Phasor representation means magnitude and angle representation of a sinusoidal signal. Synchronizedphasor means magnitude and phase representation of a sinusoidal signal with respect to absolute time reference that means phasor reference is arbitrary and synchronized phasor reference is absolute in time. Real time monitoring of a power system is possible with the help of synchrophasors. Synchronized phasor measurements are not only helpful in monitoring it is also helpful in managing power quality.

Synchronized phasors are used in measuring the voltage and currents at different parts of power system by using time sampled voltage and current phasors. As these phasors are synchronizedphasors it is possible to compare previous and present states of voltage and current phasors. By using these comparisons we can easily access system conditions like stability margins, maximum loading conditions, disturbance identification, and analysis of dynamic response of system. This entire process can be achieved using GPS satellite-synchronized clocks, phasor data concentrator, and phasor measuring units.

At present state estimation is the main requirement for energy management and system control. State estimation gives the real-time monitoring status for power system control and analysis. Traditional method utilizes the measurements from Supervisory Control and Data Acquisition System. For power system secure operation, complete monitoring of state estimation data is needed. This task perfectly taken care by Phasor Measuring units. This improvement in data monitoring is possible with synchronized phase angle measurements. The real time fault detection is also determined by using synchronized phase angle measurements using PMU. The discussions on the attractiveness of PMU in power system and real-time data monitoring is carried in [1].Graph theory method ,simulated annealing method to find the optimal set of PMU placements and algorithms have been published in [2] and [3]. A strategic PMU placement method has been published in [4] to improve the real time data monitoring using synchronized phasors. The practical development of PMU and usage is explained by phadke in [7] and [8]. The measurement of voltage followed by measurement of current by using phasor measuring units is discussed in [9]. The proper placement of PMU among the buses using problem formulation and also solution method using simulated annealing is discussed in [9].the usage of binary integer linear programming in finding a optimum placements PMU for power system state estimation is discussed in [10].

1. PHASOR MEASURMENT UNIT

(A) Introudaction to PMU

The Phasor Measurement Unit (PMU) helps us to find the voltage and current phasors at given measurement points in a power system. This synchronized phasor representation is the key to determine the power system state at a particular time. To find these synchronized phasors microprocessor controlled synchronization techniques are used to design Phasor Measuring Units.

Phasor Measurement Unit (PMU) able to provide quick access to the information providing the new opportunities to understand, analysing performance of power systems. It has a capacity of both recording long duration electrical disturbances in phasor format and providing continuous phasor measurements in support of real time applications, the PMU adds a new dimension to power system monitoring.

The main building blocks of Phasor Measurement Units are Global Positioning System (GPS) modems, anti-aliasing filters, A/D converter, phasor micro- processor, phased locked oscillator. Synchronization of sampling is very important for proper data analysis. This synchronization is achieved using a common timing signal which is available at local substation points. The accuracy of this timing signal will be in the order of milliseconds.

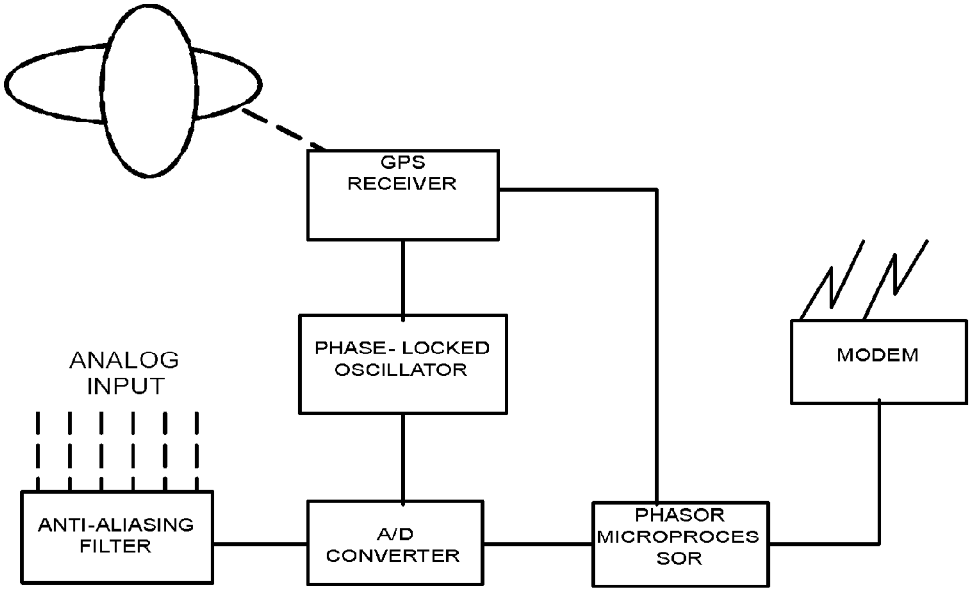

Figure 1: Block diagram Representation of PMU

The main Problem in PMU is to improve the accuracy of timing signal. It can be solved by commercializing the use of GPS, which is capable to provide a timing signal in the order of 1 micro second.

Voltage clock takes the responsibility to coordinate the sampling process in PMU and it also ensures that the data is rightly sampled by taking a absolute time reference. The current transformer and potential transformer secondary's provides the input to phasor measuring units. The anti-aliasing filter gets the inputs from current transformers and potential transformers. Input signals from the CT and PT are isolated, filtered and sampled at a proper sampling rate to ensure the accuracy of state estimation.

The anti-aliasing filter is responsible for filtering the input wave frequencies above the nyquistrate.Phase locked oscillator generate a high speed timing pulses used in sampling process

The microprocessor performs discrete Fourier transform analysis on phasors and finally time sampled phasor are given to the data concentrator which collects the data. Through synchronized accurate phasor measurements PMU help in finding power system state more accurately.

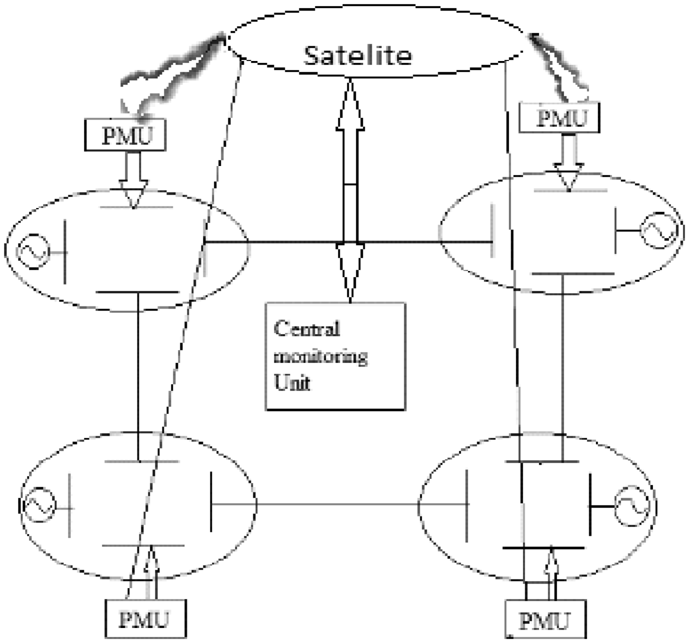

Figure 2: Conceptual Diagram of a Synchronized Phasor Measuring System

Remote triggering capacity among the PMU allows us to capture the disturbance from all locations in a power system.it is also identified that placing a PMU at each and every bus is a major economic problem. This problem should be addressed for improving the accuracy in state estimation of a power system. It is very important to develop an alternative method to reduce the number of PMU for proper estimation of system performance.

Research in this area showed that for a n bus system the number of placements will be around n/4 to n/5 for complete observability of system. For a large system it is observed that the number will be very low for proper estimation of state.

(B) Comparison of Scada & PMU

SCADA provides analogue measurement while the PMU provides digital measurements. So SCADA is restricted to local monitoring and PMU is capable of wide area monitoring of power system. The Observability of PMU is more dynamic than SCADA because the resolution of SCADA is only 2 ~ 4 samples per cycle. Whereas the resolution of PMU is up to 60 samples per cycle. More over importantly PMU provides phasor angle measurement whereas SCADA doesn't provide phasor angle measurement.

II. PROBLEM FORMATION USING ILP

Simulations and practical experience suggests that these PMU can change the way that the system is monitoring and controlling. However it is observed that cost is an major factor which affects the number of placements. This paper aims at finding a simple and strategic method to find the optimum placements for proper power system state estimation.

To place PMU's to ascertain system observability there have been two options given by

1. Placing of PMU's at all buses in the system
2. Placing of PMU's at selected buses in the system.

Option 1 is more expensive due to PMU and communication costs. It is very clear that the extent of communication facilities also affects the number PMU placements. This problem of where to place the PMU is formulated and can be solved using mathematical optimization techniques. These mathematical optimization techniques can be solved effectively by using binary integer linear programming [10].

The cost to install the PMU limits the placement of PMU. Although research is going on to reduce the cost of PMU at present we need to reduce the number of instalments to reduce cost of monitoring the system. PMU placed at each bus capable to measure the voltage phasor at that bus and current phasors from the all transmission lines incident to the bus. So it is important to note that PMU placed at strategic buses have capability to monitor the entire power system. This PMU placement problem objective is to find the minimum number of PMU required and location to be installed. This problem formulated as a optimization problem and solved with the help of mathematical optimization technique using binary integer linear programming. In this binary variables (0,1) decides the where to place a PMU.

(A) Integer Linear Programming

Integer Linear Programming is a linear optimizationtechnique which is a mathematical method for finding a way for minimization and maximization of variables by considering the constraints. In mathematical optimization techniques Integer Linear programming is a technique to optimize the linear objective function by considering the linear or nonlinear inequality constraints.

(B) Integer Linear Programming Solver in Matlab

Integer Linear Programming solver in MATLAB that helps in solving the binary integer programming problems

ILP solver solves integer programming problems of the form

$$\min_b p^T b \; Such\,that \begin{cases} A, b \leq c, \\ Aeq.b = ceq, \\ b\,binary. \end{cases}$$

f, b, and beq are vectors, A and Aeq are matrices, and the solution x is required to be a binary integer vector—that is, its entries can only take on the values 0 or 1.

III. REPRESENTATION OF PROBLEM AS ILP PROBLEM

The reduction of number of PMU is to be addressed to optimize the cost of power system state estimation. For this the problem should be analysed to obtain the solution. To solve this problem PMU placement variable b is assumed as one if PMU is installed and it is assumed as zero if PMU is not installed at that bus.

Installation of PMU at each bus increases the cost of monitoring the power system. Cost is the major factor that determines the installation of PMU. This high cost of installation at a bus depends on number of factors like current transformer and potential transformer installations, power connection, GPS antenna connection and number of measuring channels.

PMU placement problem is converted to a mathematical optimization problem by considering the linear constraints. For that we need to represent the network with anmathematical model. The problem is formulated as given below.

For an n-bus system, the PMU placement problem can be formulated as follows:

$$\min \sum_{i}^{n} w_i , b_i$$

Such that p(b) ≥ Î

Where

b is a binary decision variable vector, whose entries are defined as:

$$b_i = \begin{cases} 1 & if\ a\ PMU\ is\ installed\ at\ bus\ i \\ 0 & otherwise \end{cases}$$

Where Wiis the cost of the PMU is installed at bus i.

p(b) is a vector function, this function is formed using bus incidence matrix and PMU placement binary variable b. The product of bus incidence matrix and binary variable matrix forms a set of equations. For entire state estimation each bus should be covered at least one time by one PMU. That means a PMU placed at one bus cover that bus and also neibouring buses.

Î is a vector whose entries are all ones.

Function p(b) should be always greater than or equal to one so that each bus is covered at least one time. Inner product of the binary decision variable vector and the cost of PMU placementrepresent the total installation costs of the PMU for power system state estimation. Constraint functions ensure full network observability while minimizing the total installation cost of the PMU. So we have to minimize the installation cost function $\Sigma_i^n w_i , b_i$ at the same time maximization of constraint functions $p(B) \geq \hat{I}$ is to be maintained.

IV. SOLUTION FOR TEST SYSTEM

PMU installed at particular bus has a capability to measure the voltage phasor at that particular bus and also a current phasors from a transmissions lines incident to that bus. That means PMU has a capacity to make the installed bus and neighbouring buses observable. The objective of placing PMU's in power systems is to measure the voltage and current phasors of the bus and the lines connected to that bus. The aim of this paper is to decide a minimal set of PMU's for different test systems like IEEE 14,39 and 57 bus such that the whole test system is system is observable.

(A) IEEE 14 Bus Test System

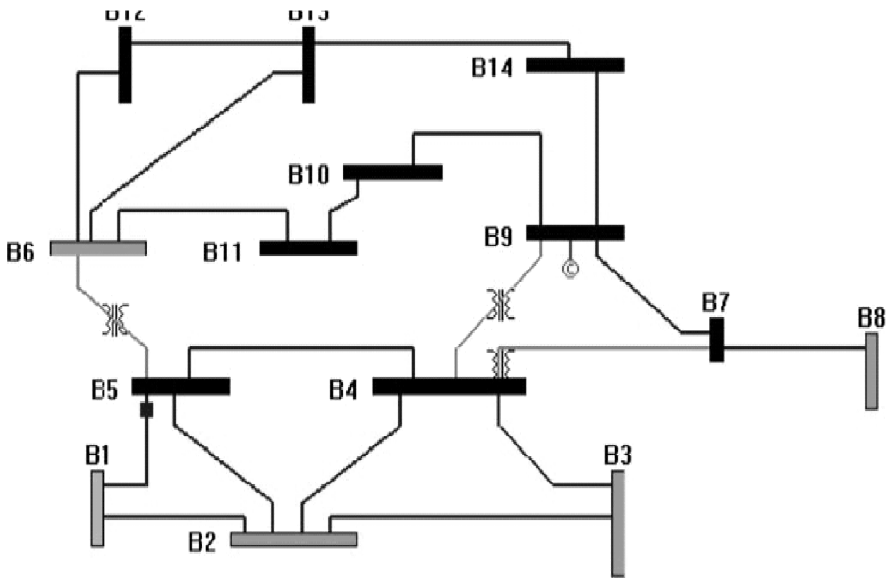

Figure 3: Test System-IEEE 14-BUS

Every system in the universe can be represented by mathematical equations. The test system IEEE 14 bus can be represented as a matrix known as bus incidence matrix.

(A) Test System Matrix Representation

The bus incidence matrix can be formulated as

$$P_{PMU}=\begin{bmatrix} 1&1&0&0&1&0&0&0&0&0&0&0&0&0\\ 1&1&1&1&1&0&0&0&0&0&0&0&0&0\\ 0&1&1&1&0&0&0&0&0&0&0&0&0&0\\ 0&1&1&1&1&0&1&0&1&0&0&0&0&0\\ 1&1&0&1&1&1&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&1&0&0&0&0&1&1&1&0\\ 0&0&0&1&0&0&1&1&1&0&0&0&0&0\\ 0&0&0&0&0&0&1&1&0&0&0&0&0&0\\ 0&0&0&1&0&0&1&0&1&1&0&0&0&1\\ 0&0&0&0&0&0&0&0&1&1&1&0&0&0\\ 0&0&0&0&0&1&0&0&0&1&1&0&0&0\\ 0&0&0&0&0&1&0&0&0&0&0&1&1&0\\ 0&0&0&0&0&1&0&0&0&0&0&1&1&1\\ 0&0&0&0&0&0&0&0&1&0&0&0&1&1 \end{bmatrix}$$

The above bus incidence matrix for IEEE 14-bus system in binary form can be obtained by following relation

$$P_{k,m}=\begin{cases}1 & if k = m or k and m are connected\\ 0 & if otherwise\end{cases}$$

We can able to predict the test system from this Bus incidence matrix. Here bus 1 is connected to busses 2, 5 Bus 2 is connected to busses 1, 3, 4, 5 bus 3 is connected to 2, 4; similarly we can able to predict the remaining connections as well as the whole system structure.

(B) Test System Problem Representation In Linear Programming

The objective of placing PMU's in power systems is to measure the voltage and current phasors of the bus and the lines connected to that bus.The aim of this paper is to decide a minimal set of PMU's for different test systems like IEEE 14,39 and 57 bus such that the whole test system is system is observable. Therefore, the placement of PMU's becomes a problem. This problem can be solved by using optimization technique which minimizes the cost function by taking a set of constraints. These constraints can be formed by considering the fact each bus should be covered by at least one PMU. Constraints can be formed by multiplying the bus incidence matrix with binary variable matrix. This gives us an idea to define a bus incidence matrix P_{PMU}.

From the discussion it is clear that the placement of PMU's becomes a problem that finds a minimal set of PMU's so that every bus connected to the system must be observed by a PMU at least once .for that first we need to convert the network into mathematical model using a bus incidence matrix. The bus incidence matrix is defined as P_{PMU}.

Now the optimal placement of PMU's can be formulated as a problem of integer linear programming, as follows:

$$min \sum_{k=1}^{N} b_k$$

So that $P_{PMU} B \geq C_{PMU}$

$$B = [b_1 b_2 \dots \dots b_N]^T$$

Where $C_{PMU}=[1\ 1\ 1 \dots \dots 1]^T_{NX1}$ and b_i is the PMU placement binary variable.

This problem is similar to the integer linear programming problem, we have to minimise the function $\sum_{k=1}^{N} b_k$, at the same time we have to maximize the constraints $P_{PMU} B \geq C_{PMU}$. We cannot achieve minimization, maximization at the same time by using ILP solver. This can be solved by converting the maximization of constraints into minimization of constraints, i.e maximization of constraints is the minimization of negative of constraints .now minimization of functions and minimization of negative of constraints is achieved with the help of ILP solver in MATLAB.

(C) Solution To IEEE 14 Bus Test System

In order to form the constraint set, the absence of flow measurement and the zero injection is assumed in this case.

The constraints corresponding to the bus incidence matrix is denoted as

$$\mathrm{Ppmu\,.\,B} = \begin{cases} p_1 = b_1 + b_2 + b_5 \geq 1 \\ p_2 = b_1 + b_2 + b_3 + b_4 + b_5 \geq 1 \\ p_{3=}b_2 + b_3 + b_4 \geq 1 \\ p_4 = b_2 + b_3 + b_4 + b_5 + b_7 + b_9 \geq 1 \\ p_5 = b_1 + b_2 + b_4 + b_5 + b_6 \geq 1 \\ p_6 = b_5 + b_6 + b_{11} + b_{12} + b_{13} \geq 1 \\ p_7 = b_4 + b_7 + b_8 + b_9 \geq 1 \\ p_8 = b_7 + b_8 \geq 1 \\ p_9 = b_4 + b_7 + b_9 + b_{10} + b_{14} \geq 1 \\ p_{10} = b_9 + b_{10} + b_{11} \geq 1 \\ p_{11} = b_6 + b_{10} + b_{11} \geq 1 \\ p_{12} = b_6 + b_{12} + b_{13} \geq 1 \\ p_{13} = b_6 + b_{12} + b_{13} + b_{14} \geq 1 \\ p_{14} = b_9 + b_{13} + b_{14} \geq 1 \end{cases}$$

The operator “+” serves as the logical “OR” and the use of 1 in the right hand side of the inequality ensures that at least one of the variables appearing in the sum will be non-zero.

(D) Output for IEEE-14-bus Test System

a. Output For 14-BUS System

Problem Type	*Test System*	*Busses at Which PMU is Installed*
Without zero injection	IEEE 14 – bus	2, 6, 7, 9

b. Output for 14-BUS System with Conventional & With Zero Injection Measurement

Problem Type	*Test System*	*Busses at Which PMU is Installed*
With zero injection at bus 7	IEEE 14 - bus	2, 6, 9

c. Output For IEEE-39-Bus&57 Bus System Without Zero Injection Measurements

PROBLEM TYPE	*TEST SYSTEM*	*NUMBER OF PMU’S*	*BUSSES AT WHICH PMU IS TO BE INSTALLED*
WITHOUT ZERO INJECTION	IEEE-39 BUS	13	2, 6, 9, 10, 13, 14, 17, 19, 20, 22, 23, 25, 29

V. CONCLUSION

This paper suggests a first and simple practical method to find minimal placements of PMU for complete observability of system. This developed method is tested for several test systems IEEE 14,39 and 57 bus systems. The objective of this project is to make the entire system observable by optimal placement of PMUs. For IEEE 14bus test system, only 4 PMU’s are required to install at buses 2, 6 ,7,9 to make the entire 14 bus test system completelyobservable, in case of zero injection at bus 7 only 3 PMU’s are required to install at buses 2, 6,9. For IEEE 39 bus system only 13 PMU’s are required to make entire test system completely observable. For IEEE 57 bus system only 17 PMU’s are required to make entire test system completely observable. There is a possibility for reducing this number again for 39 bus and 57 bus whereas the optimum number for IEEE 14 bus system is 3.

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