ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

Optimal Placement of Phasor Measurement Units Using Binary Integer Programming

Banda Srinivas[1], Dr. S.F. Kodad[2]

Associate Professor, Dept. of EEE, Krishna Murthy Institute of Technology and Engineering, Hyderabad, TS, India[1]

Professor & HOD, Dept. of EEE, PES Institute of Technology and Management, Shivamogga, Karnataka, India[2]

ABSTRACT: The increasing availability of phasor measurement units (PMUs) at substations enables the synchronized measurements to various applications, such as the monitoring of system state under normal operating conditions or the protection and control of power system during abnormal conditions. This paper presents an optimal placement algorithm of PMUs by using binary integer linear programming in MATLAB for complete observability of a power system for normal operating conditions. Simulation results show that the proposed algorithm can be used in practice.

KEYWORDS: phasor measurement units, binary integer linear programming, observability.

I.INTRODUCTION

The 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 center computer and has access to the measurements received from numerous substations in the monitored system. Until recently, available measurement sets did not contain phase angle measurements due to the technical difficulties associated with the synchronization of measurements at remote locations. Global positioning satellite (GPS) technology alleviated these difficulties and lead to the development of PMUs. Phasor measurement units are devices, which use synchronization signals from the global positioning system (GPS) satellites and provide the phasors of voltage and currents measured at a given substation. Phasor measurement units are monitoring devices that provide extremely accurate positive sequence time tagged measurements [1]. An algorithm which finds the minimal set of PMU placement needed for power system state estimation has been developed in [2, 3] where the graph theory and the simulated annealing method have been used to achieve the goal. A generalized formulation [4], considering situations with and without zero injections, shows that the problem of optimal PMU placement can be modelled linearly and solved by ILP for full and incomplete observability. A simplification of [4] is proposed in [5]. In this paper a similar formulation of optimal PMU placement problem is proposed by using binary integer linear programming in MATLAB. Therefore, the solution of the optimal PMU placement problem is simple, efficient and can be used in practice.

II.LITERATURE SURVEY

The solution methodologies for the optimal PMU placement (OPP) problem can be classified into two categories: mathematical and heuristic algorithms. Mathematical algorithms may be of *Integer Programming or Exhaustive Search* type.

A. *Integer Programming*

The objective of method [6] is to accomplish the task of PMU placement at strategic buses making the entire system observable. The existence of constraints considering PMU measurements and injections that may be zero injections or measured injections as well as PMU measurements and conventional injections and flows, is also discussed. In [7], a feasible numerical method is presented for PMU placement that transforms existing critical measurements into redundant ones. The main goal is to improve bad data detection and identification capability of the state estimator for a given system by taking advantage of the PMU technology. An IP formulation of the OPP problem is proposed in [8]. This proposal improves the bad data processing capability of the state estimator, assuming that any bad data appearing on a single measurement will be detectable. Depending on the measurement configuration and the system topology, the

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

critical measurements are transformed into redundant. The problem is extended to incorporate conventional measurements as candidates for placement and can be used to determine optimal locations when a desired level of local redundancy is considered in the system. The description of a simple modified ILP based optimal placement method, ensuring complete topological observability of the system under intact and critical contingency cases, is presented in [9].

B. *Exhaustive Search*

Exhaustive search is a general optimization technique that systematically enumerates all possible candidates for the solution and selects the candidate that satisfies the constraints at the optimum value of the objective function. Its main advantage is that it guarantees the finding of the global optimum. However, it is not suitable for large-scale systems with huge search space. An exhaustive binary search method is implemented in [10] to solve the OPP problem considering single branch outages with or without the existence of zero injections. In case of multiple solutions, an algorithm is proposed to select the most preferable set based on measurement redundancy.

III.FORMULATION OF THE PROBLEM

In a power system, if a node voltage of one bus is directly measured or calculated by using other known node voltage and branch currents, then that bus is said to be observable. If all buses are observable in the system then the power system can be defined as fully observable. There are two methods to find observability of a power system: numerical and topological**.** Numerical observability consists of large number of computations and can be easily affected by cumulative error, while topological observability method is fast and practical. In PMU placement problem, three rules can be used to analyze the topological observability of each bus within the target power system.

Rule 1: a bus with PMU installation is observable, and its adjacent buses are all observable because their voltages can be calculated by Ohm's law with the help of the PMU measurement.
Rule 2: if a bus is adjacent to an observable zero-injection bus (a bus with zero net injection of power from the connected loads and generators) to which all other adjacent buses are observable, then the bus is observable because its voltage can be calculated by KCL and Ohm's law.
Rule 3: if all buses adjacent to a zero-injection bus are observable, then the zero-injection bus is observable because its voltage can be calculated by KCL and Ohm's law.
The present paper proposes a binary integer programming approach to determine the minimum number and optimal placement of PMUs for complete observability. A numerical method based on Binary Integer Programming is used to solve the optimal PMU placement problem. The formulation of problem is shown as below.
For an n-bus system, the PMU placement problem can be formulated as follows:

$$Min \sum_{i}^{n} W_i \; X_i$$

$$s.t. \; f(X) \geq \hat{1}$$

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

X_i = {1 if a PMU is installed at bus i
X_i = {0 otherwise
W_i is the cost of the PMU installed at bus i, $f(X)$ is a vector function, whose entries are non-zero if the corresponding bus voltage is solvable using the given measurement set and zero otherwise. $\hat{1}$ is a vector whose entries are all ones. Inner product of the binary decision variable vector and the cost vector represents the total installation costs of the selected PMUs. Constraint functions ensure full network observability while minimizing the total installation cost of the PMUs.

The procedure for building the constraint equations will be described for the case where there are no conventional measurements or zero injections. Description of the procedure is explained using IEEE 14-bus system example for

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

clarification. However, the entire procedure is actually programmed and successfully tested on different size systems with diverse measurement configurations.

Consider the IEEE 14-bus system and its measurement configuration shown in Figure 1. The black dot near bus 7 represents that bus 7 is a zero injection bus has an injection measurement installed while the black box on line 5-6 represents a paired flow measurement on line 5-6.

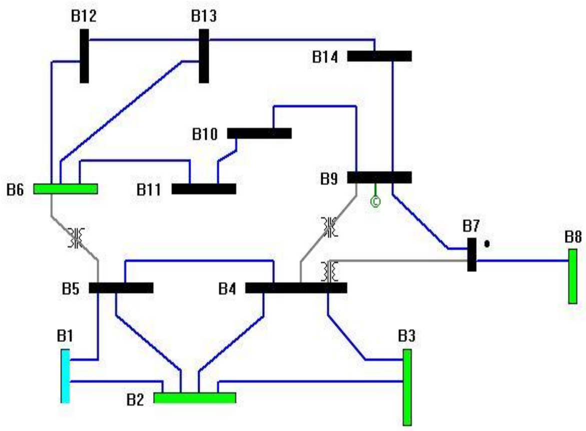

Fig. 1 IEEE 14 bus system

In this case, the flow measurement and the zero injection are ignored. In order to form the constraint set, the binary connectivity matrix A, whose entries are defined below, will be formed first:

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

Matrix A can be directly obtained from the bus admittance matrix by transforming its entries into binary form. Building the A matrix for the 14-bus system yields:

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

The constraints for this system can be formed as

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

$$f(X) = A\cdot X = \begin{cases} f_1 = x_1 + x_2 + x_5 & \geq 1 \\ f_2 = x_1 + x_2 + x_3 + x_4 + x_5 & \geq 1 \\ f_3 = x_2 + x_3 + x_4 & \geq 1 \\ f_4 = x_2 + x_3 + x_4 + x_5 + x_7 + x_9 & \geq 1 \\ f_5 = x_1 + x_2 + x_4 + x_5 + x_6 & \geq 1 \\ f_6 = x_5 + x_6 + x_{11} + x_{12} + x_{13} & \geq 1 \\ f_7 = x_4 + x_7 + x_8 + x_9 & \geq 1 \\ f_8 = x_7 + x_8 & \geq 1 \\ f_9 = x_4 + x_7 + x_9 + x_{10} + x_{14} & \geq 1 \\ f_{10} = x_9 + x_{10} + x_{11} & \geq 1 \\ f_{11} = x_6 + x_{10} + x_{11} & \geq 1 \\ f_{12} = x_6 + x_{12} + x_{13} & \geq 1 \\ f_{13} = x_6 + x_{12} + x_{13} + x_{14} & \geq 1 \\ f_{14} = x_9 + x_{13} + x_{14} & \geq 1 \end{cases}$$

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. For example, consider the constraints associated with bus 1 and 2 as given below:

$$f_1 = x_1 + x_2 + x_5 \quad \geq 1$$
$$f_2 = x_1 + x_2 + x_3 + x_4 + x_5 \quad \geq 1$$

The first constraint $f_1 \geq 1$ implies that at least one PMU must be placed at either one of the buses 1, 2 or 5 in order to make bus 1 observable. Similarly, the second constraint $f_2 \geq 1$ indicates that at least one PMU should be installed at any one of the buses 1, 2, 3, 4, or 5 in order to make bus 2 observable.

IV. SIMULATION RESULTS

The proposed method is tested on IEEE 14, 30 and 57 bus systems.

TABLE I
Number of PMUs and Their Location for Complete Observability

Test System	No. of PMUs	Bus No's
IEEE 14 Bus	4	2,6,7,9
IEEE 30 Bus	10	1,7,9,10,12,18,24,25,27,28
IEEE 57 Bus	17	1,4,6,13,19,22,25,27,29,32,36,39,41,45,47,51,54

From the above table it is observed that total 4 PMUs are required and need to be placed at bus no's 2,6,7,9 for IEEE 14 Bus in order for the system to be completely observable. Similarly IEEE 30 bus and IEEE 57 bus systems require 10 and 17 PMUs respectively. It is noted that the number of required PMUs of the proposed binary integer programming algorithm for different systems is identical to that in [4]

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

V. CONCLUSION

This paper proposes a binary integer programming for optimal placement of PMUs for complete observability for normal operating conditions. Simulation results show that the proposed method is computationally efficient and can be used in practice.

REFERENCES

[1] IEEE Standard for Sychnrophasors for Power Systems, IEEE Standard C37.118-2005, Jun. 2005.
[2] L. Mili, T. Baldwin and R. Adapa, "Phasor Measurement Placement for Voltage Stability Analysis of Power Systems." Proceedings of the 29th Conference on Decision and Control, Honolulu, Hawaii, Dec. 1990.
[3] T. L. Baldwin, L. Mili, M. B. Boisen and R. Adapa, "Power System Observability with Minimal Phasor Measurement Placement." IEEE Trans. on Power Systems, Vol. 8, No. 2, May 1993.
[4] B. Gou, "Generalized integer linear programming formulation for optimal PMU placement", *IEEE Trans. Power Systems*, vol. 23, no. 3, pp. 1099-1104, Aug. 2008.
[5] B. Gou, "Optimal placement of PMUs by integer linear programming," *IEEE Trans. Power Systems*, vol. 23, no. 3, pp. 1525-1526, Sep. 2008.
[6] B. Xu and A. Abur, "Observability analysis and measurement placement for systems with PMUs," in *Proc.* 2004 *IEEE Power Eng. Soc. Conf. Exposition,Oct. 10-13,* vol. 2, pp. 943-946, *2004*.
[7] J. Chen and A. Abur, "Improved bad data processing via strategic placement of PMUs," *Proc. IEEE Power Eng. Soc. General Meeting*, pp. 509–513, 2005.
[8] J. Chen and A. Abur, "Placement of PMUs to enable bad data detection in state estimation," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1608–1615, Nov. 2006.
[9] R. Sodhi, S. C. Srivastava, and S. N. Singh, "Optimal PMU placement to ensure system observability under contingencies," in *Proc. IEEE* Power Eng. Soc. General Meeting, pp. 1–6, 2009.
[10] S. Chakrabarti and E. Kyriakides, "Optimal placement of phasor measurement units for power system observability," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1433–1440, Aug. 2008.

BIOGRAPHY

Banda Srinivas received the B.Tech in Electrical and Electronics Engineering from JNTU, Hyderabad, India in 1997 and M.Tech from NIT Karnataka in Power and Energy System in 2003. From 2003 to 2004, he worked as Asst. Professor in Department of Electrical and Electronics Engineering in CBIT, Hyderabad, INDIA. From 2004 to 2010 he worked as Asst. Professor in Department of Electrical and Electronics Engineering in Aurora Engineering College, Bhongir, Hyderabad. Currently he is working as Associate Professor in the Department of Electrical and Electronics Engineering, Krishna Murthy Institute of Technology and Engineering, Ghatkesar, Hyderabad. His main interests are in power flow studies, power system operation and control and power system state estimation.

Dr. S. F. Kodad received the B.E. degree in EEE from STJ Institute of Technology, Ranebennur, Karnataka, India from Karnataka University and the M.Tech. degree in Energy Systems Engg. from JNTU, Hyderabad, India in the year 1992. He received his Ph.D. degree in Electrical Engg. From JNTU, Hyderabad, India in the year 2004. He has got a teaching experience of nearly 25 years. Currently, he is working as Professor & HOD, Dept. of EEE, PES Institute of Technology and Management, Shivamogga, Karnataka, India. He has published a number of papers in various National, International journals and conferences. He has also presented a number of guest lectures and various seminars and participated in a number of courses, seminars, workshops, symposiums in the various parts of the country in different institutions and also conducted a few courses. He has guided 5 Ph.D students. His areas of interests are neural networks, fuzzy logic, power electronics, power systems, artificial intelligence and Renewable energy sources.