Electrical Power and Energy Systems 33 (2011) 1658–1665

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Optimal placement of PMU and SCADA measurements for security constrained state estimation

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ARTICLE INFO

*Article history:*
Received 14 December 2010
Received in revised form 15 June 2011
Accepted 12 August 2011
Available online 17 October 2011

*Keywords:*
Integer programming
Genetic algorithm
Observability analysis
Phasor measurement units
SCADA measurements

ABSTRACT

This paper presents a method for the use of Supervisory Control and Data Acquisition (SCADA) and synchronized measurements for complete observability of a power system. Under normal operation, both Node Phasor Measurement Unit (NPMU) and SCADA measurements are optimally placed using integer programming and Genetic Algorithm (GA) respectively. The minimum condition number of the Jacobian matrix is used as a criteria in conjunction with GA to obtain a completely determined condition. Next, a triangular factorization approach is used to search for the necessary candidates for single branch outage and single/multiple measurement loss. These candidate measurements are optimized by the binary integer programming method. Numerical results on the IEEE test systems are demonstrated. The results clearly show the robustness of the method to obtain reliable measurements under both normal and contingency conditions.



## 1. Introduction

In the deregulated environment, accurate monitoring of power system network is becoming most important function. State Estimator (SE) has been widely used as a vital tool for online monitoring, analysis and control of power systems. Entire power system measurements are obtained through Remote Terminal Unit (RTU) of SCADA systems which have both analog and logic measurements. SE uses a set of these measurements and it cannot be solved unless the system fully observable. Therefore the measurement placement becomes a significant problem in SE.

Network observability analysis determines whether the state vector of a whole system is able to calculate with available number and location of measurements. If so, the network is said to be observable, otherwise it is unobservable. Observability methods and Optimal Meter Placement (OMP) of state estimation for maintaining observability has been explained in detail by Clements [1]. In order to reduce the metering cost, meters are to be placed only at the essential location in the system. The meter placement method was first proposed in [2], which minimize the variance of estimated quantities. The same problem was addressed based on measurement reliability by Ariatti et al. [3]. Baran proposed a meter placement method for minimizing the meter cost based on state estimation accuracy [4]. Observability analysis can be solved by topological [5,6] and numerical [7,8] methods. Topological observability is found based on the graph theory. Maximal forests of full rank for a measured network are found in the topological observability algorithm. If the maximal forest of full rank is a spanning tree, then the network is topologically observable. Clements has contributed more works based on topological observability [6,9,10]. Numerical observability algorithm is based on the numerical determination of gain matrix. The network is observable, when the gain matrix is non singular and the rank is $N$, where $N$ is the number of buses in the power system network. Gou and Abur have contributed an algorithm for meter placement using numerical observability [11,12]. In addition to the observability, bad data measurements have been done in [13]. Optimal meter placement during contingencies are also presented in [14]. The numerical observability method is complicated which requires iterative algorithms. Krumpholz et al. [6] explained algebraic observability where bus injection and line currents are considered as measurements.

The synchronized phasor measurements make significant improvements in control and protection functions of the entire power system and also improve the accuracy of state variables. The PMU is a device capable of measuring voltage and current phasor in a power system. Synchronism among phasor measurements is achieved using a common synchronizing signal from Global Positioning Satellite (GPS) [15]. Many researchers have focused on the optimal location of PMU for a system to be observable [16–20]. The general PMU placement criteria is presented in [21]. Bad data detection is done along with optimal PMU placement by Chen and Abur [22]. Gou [23] has proposed a new integer linear programming approach for optimal PMU placement with and without considering traditional SCADA measurements. The number of PMU requirements in a power network poses a problem to meet

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doi:10.1016/j.ijepes.2011.08.002

sufficient measurements. Due to the factor of price, technology, communication ability the PMU could not be implemented at all the buses in the system. When few phasor measurements are added to sufficient numbers of traditional measurements, accuracy in state estimates can be improved [24].

Heuristic methods are also contributed for optimal meter/PMU placement with and without contingencies. Simulated annealing and genetic algorithm are used for obtaining optimal location of meters in [25–27] respectively. In addition to above, Tabu search algorithm is applied to solve the problem [28]. The complete survey of meter placement for power system state estimation is enlightened in [29]. Recently placement of PMU problem has been solved optimally using differential evolution [30], binary particle swarm optimization algorithm [31] and tabu search [32]. Optimal PMU placement has been solved by iterated local search method [33].

In this paper, the optimal location of PMU and SCADA measurements for hybrid state estimation are identified in two stages under normal power system operation. In the first stage, the few PMUs are selected based on the priority index among the optimal PMU sets, which are found using integer programming. In the next stage, genetic algorithm is used to choose the SCADA measurements for the unobservable bus in a power network. The network observability problem is a combinatorial problem; therefore many measurements sets satisfy the observability criteria. In spite of the observability well-posedness, ill-conditioned Jacobian matrix also provides the unreliable state variables or the unsolvable state estimation [34]. Hence, the measurement set having the low condition number is chosen as the optimal one. Under single and multiple contingencies, the optimal reliable measurements are selected by LU factorization and binary integer programming method. The candidate measurements for contingencies are power injection, power flow of SCADA measurements and branch PMU measurements.

The organization of the paper is as follows. Section 2 describes the problem of meter placement against normal and contingency operation. Section 3 talks about the optimal selection of a essential measurements containing both PMU and SCADA measurements, which explicated in two stages. In order to meet observability criteria, required measurements are chosen from candidate measurements against contingencies, which are explained in Section 4. Section 5 shows the simple test case and also with IEEE standard test systems. Finally, concluding remarks are given in Section 6.

## 2. Meter placement problem

The linear measurement model used in power system state estimation is represented by

$$Z = HX + \epsilon \tag{1}$$

The power system states are estimated using Weighted Least Square (WLS) method. The estimator equation is given in the following equation:

$$\widehat{X} = (H^T R^{-1} H)^{-1} (H^T R^{-1} Z) \tag{2}$$

A unique solution is obtained when $G = (H^T R^{-1} H)$ is non singular or $H$ has full rank ($N$). The measurements which make the system observable are known as essential measurements. The $P$–$\delta$ and $Q$–$V$ decoupled linear measurement model can be written as follows:

$$Z_p = H_{p\delta}\delta + \upsilon 1 \tag{3}$$

$$Z_q = H_{qv}V + \upsilon 2 \tag{4}$$

where $Z$ is the measurement vector formed by voltage magnitude, real power flow and power injection; $H$ the measurement Jacobian matrix; $X$ the state vector $(V, \delta)$; $\epsilon$ the noise in measurements; $G$ the gain matrix; $R$ the error covariance matrix; $Z_p$ the real power measurement vector; $Z_q$ the reactive power measurement vector; $H_{p\delta}$ the real power measurement Jacobian $\left(\frac{\partial H_{p\delta}}{\partial \delta}\right)$; $H_{qv}$ the reactive power measurement Jacobian $\left(\frac{\partial H_{qv}}{\partial V}\right)$; $\upsilon 1 \upsilon 2$ are the noise in real and reactive measurements respectively.

Usually $P$, $Q$ measurements are received as pairs in control centers, so $P$–$\delta$ and $Q$–$V$ observability analysis can be separately performed. In this paper, $P$–$\delta$ decoupled linear measurement model is used for observability analysis.

Note that the measurement matrix should be linearly independent to minimize the number of measuring devices in the power system networks. But the condition number of $H$ matrix is one of the essential factors for solving the above equation. A large condition number may lead to unsolvable or inaccurate solutions. Therefore the low conditioned minimal measurements should be designed.

The defined contingencies are measurement loss and branch outage occurring due to communication failure and change in system configuration respectively. These contingencies lead the system unobservable. Therefore, the reliable measurement configurations with low conditioned number are designed under normal and contingencies. One of the indicators for numerical observability is rank of $H$ matrix, which should be equal to number of network buses ($N$). The elements of the $H$ matrix are not affected by the operating point, but depend on measurement configuration. It is enough to evaluate $H$ as flat start.

## 3. Choice of essential measurements

SCADA system receives the power system measurements from Remote Terminal Units (RTU). These measurements are used to evaluate the state estimates. A new measuring device PMU are classified as node PMU and branch PMU based on its measuring capability. A node PMU is able to measure the voltage phasor of the installed bus and current phasor of the branches connected to this node. Each node PMU provides more phasor measurements which is limited by their channel numbers [35]. Similarly a branch PMU measures the voltage phasor of the corresponding bus and one of the branch current phasor incident to the bus where the PMU installed [36]. Thus each branch PMU provides two phasor measurements or the channel limit for a branch PMU is two. These kinds of PMUs are installed and they are used for utility companies in the world [37].

The essential measurements are identified in two stages:

- The optimal PMUs are found using Integer Programming (IP) [23]. These PMUs are sorted based on Priority Index (PI) and highest PI valued PMUs are selected. The number of PMUs is chosen as 10% of the network buses. The buses observed and not observed by PMU are identified. The unobservable buses are become observable using SCADA measurements.
- The genetic algorithm is used to select the SCADA measurements which include power injection and power flow measurements. The final essential $H$ matrix ($H_{ESS}$) is formed. Ill conditioned measurements of SE lead to singularity problem. The condition number of $H_{ESS}$ matrix should be lower than the remaining possible essential measurement sets. Well conditioned system gives more accuracy in the solution.

### 3.1. Selection of PMUs Measurements using IP and PI

In the first stage, optimal location of PMU is identified to make the system observable using integer programming. Priority Index (PI) is defined for each PMU based on number of buses to be observed using that particular PMU. Among these optimally located PMUs, certain PMUs (10% of network buses) are chosen for implementation according to their PI. The remaining buses are considered