A Comprehensive Measurement Placement Method for Power System State Estimation

Rakesh J Motiyani* and Dr. Ajitsinh R Chudasama**
*Principal, Pacific School of Engineering (Diploma Studies), Research Scholar-Rai University, Ahmedabad
motiyani_me@rediffmail.com
**Academic Director, Neotech Campus, Vadodara
jyotiajit@yahoo.com

Abstract: Power System State Estimators requires a set of redundant measurements. The meter placement problem involves selection of number, type and place of meters. The main objective in designing a metering scheme is to satisfy cost, accuracy, observability and bad data processing requirements for power system state estimators. This paper presents a comprehensive method using graph theoretic approach to solve the problem of measurement placement for power system state estimators. The measurement configuration on IEEE 30 bus system is presented. The suggested technique ensures reliable and accurate estimation of state variables at lower cost.

Keywords: Bad data detection, Graph theory, Measurement placement, Network observability, State estimation.

Introduction

Within the energy management system, state estimation is a key function for building network real time model that is static mathematical representation of current condition of an interconnected power system. The state of electrical power system is defined by the vector of voltage magnitude and angle at all network buses. The static state estimator is the data processing algorithm for converting redundant and not so reliable meter readings and other available information about the network connectivity in to an estimate of the static state vector [1]-[4].

The real-time modelling of a power network usually follows following procedure involving [5]:

- Data gathering
- Network topology processing
- Observability analysis
- State estimation (SE)
- Processing of bad data and
- Identification of network model

Network topology processor identifies energized and de-energized electrical islands and is performed before state estimation and other related functions such as observability analysis and bad data processing [5], [6]. The network observability can be tested for P-δ and Q-V models by triangular factorization of the gain matrix. The obsevability algorithm checks that the information available in the form of measurements is sufficient to fulfil the computational needs of state estimator or not [7].

Power system state estimators requires a set of redundant measurements, which are appropriately chosen according to the type, number and location of the measurement points in the supervised electric network [8]. The main objective in designing metering scheme is to satisfy the requirements like cost, accuracy, reliability, and bad data processing for power system state estimator [9]. In late 90's, researchers started giving importance to the development of cost effective and reliable metering scheme which can yield accurate state estimation. The measurement data are usually power flows, power injections and bus voltages [10]. In 1996, a meter placement method developed by Mesut E Baran et al. The developed method was utilized for designing the measurement system configuration on IEEE 14 bus system. The measurement placement method using Simulated Annealing (SA) aims at attending to the requirements such as observability and reliability- taking in to account the associated monetary costs was developed by Alessandra B Antonio et al. in 2001. The developed method was utilized for designing the measurement system configuration on IEEE 30 bus system.

In 2006, the optimal meter placement method using hybrid Genetic Algorithm and Simulated Annealing (GA/SA) was developed by Thawatch Kerdchuen et al. [11]. The metering configuration on 10-bus and IEEE 14 bus system was presented. In 2011 the metering schemes for IEEE-10, 14, 30 and 57 bus systems was presented by K. Jamuna and K.S.

Swarup using Biography Based Optimization [12]. In 2013, the metering schemes for IEEE-10 and 14 bus systems were presented using Key Cutting Algorithm (KCA) by Yuttana Kongjeen et al. [13].

State Estimation

The state estimation is a mathematical procedure by which the state of electric power system is extracted from a set of measurement. In standard SE, in order to relate measurements and non linear equations, the following model is used:

$$z = h(x) + e$$

Where, z is the (m×1) measurement vector, h(x) is the (m ×1) vector of non linear functions, x is the (2n ×1) state vector, e is the (m×1) measurement error vector, n is the total number of buses in the power system network and m is the total number of measurements.

The state estimator is a mathematical algorithm formulated to minimize the error between a real time measurement and a calculated value of the measurement. The minimization criterion often selected is the weighted sum of error squares of all the measurements. The estimator favors accurate measurements over the less accurate ones by weighing the errors with the measurement standard deviation (σ_j) [14].

$$\min \quad J(x) = \sum_{j=1}^{m} \left(\frac{e_j}{\sigma_j} \right)^2$$

The condition for optimality is obtained at a point when the gradient of J(x) is zero. From weighted least square method, the iterative equation can be obtained as follows:

$$x^{k+1} = x^k + \Delta x$$

$$\Delta x = \left(H^T R^{-1} H\right)^{-1} H^T R^{-1}\left(z - h\left(x^k\right)\right)$$

$$H = \frac{\partial h(x)}{\partial x} = \begin{bmatrix} \frac{\partial h_1(x)}{\partial x_1} & \frac{\partial h_1(x)}{\partial x_2} & \cdots & \frac{\partial h_1(x)}{\partial x_{Ns}} \\ \frac{\partial h_2(x)}{\partial x_1} & \frac{\partial h_2(x)}{\partial x_2} & \cdots & \frac{\partial h_2(x)}{\partial x_{Ns}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial h_m(x)}{\partial x_1} & \frac{\partial h_m(x)}{\partial x_2} & \cdots & \frac{\partial h_m(x)}{\partial x_{Ns}} \end{bmatrix}$$

Where, $N_s = 2n-1$

$$W = R^{-1} = \begin{bmatrix} \frac{1}{\sigma_1^2} & & & \\ & \frac{1}{\sigma_2^2} & & \\ & & \cdots & \\ & & & \frac{1}{\sigma_m^2} \end{bmatrix}$$

$$G = H^T R^{-1} H$$

While the power system not only has Supervisory Control and Data Acquisition System (SCADA), but also has Phasor Measurement Units (PMUs) placement, the sub problem is formed by PMU placement and SCADA measurements. The state variables measured by PMU are assumed true value and the known state variables are x_1. The unknown state variables are required to be estimated by reduced power system state estimation model [15].

Hence, equations can be rewritten as follows:

$$z = h(x_2) + e$$

$$\Delta x_2 = \left(H_2^T R^{-1} H_2\right)^{-1} H_2^T R^{-1}\left(z - h\left(x_2^k\right)\right)$$

$$H_2 = \frac{\partial h(x_2)}{\partial x_2}$$

$$G_2 = H_2^t R^{-1} H_2$$

Measurement Placement

The state estimator uses a set of measurement consisting of bus injections, branch flows and bus voltages. If all the quantities are measured as shown in the Fig. 1, the measurement set will become full and Jacobian (H) has 3n + 4b rows. Where, n is the total number of network buses and b is the total number of network branches.

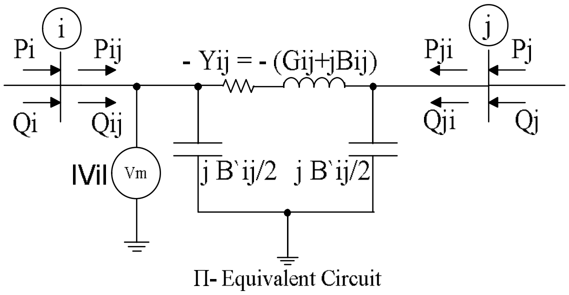

Figure 1. The per phase representation of transmission line- showing possible measurements

Factors Affecting Measurement Placement

1. Cost: The total investment cost for the metering scheme – meter, Remote Terminal Units (RTUs) and communication system should be kept to minimum.
2. Accuracy: The measurements obtained through metering scheme should yield a state estimation with desired accuracy.
3. Reliability: The power system network should be observable with the measurements obtained from the metering scheme and there should be enough redundancy so that the state estimation can be carried out even after loss of measurements or meter failure.
4. Bad Data Processing: The measurement system should allow state estimator to detect and eliminate bad data from the measurement set.

Considering the cost of a voltage measurement, a power measurement and an RTU as 1, 4.5 and 100 Money Units (MU) respectively, Mesut E Baran et al. designed a metering scheme for IEEE 14 bus system. The total cost of metering scheme is 1112 MU. The metering scheme acquires redundancy of 1.92. The metering scheme designed for IEEE 30 bus using SA acquires redundancy of 1.9 and considering meters cost as mentioned above, the total cost of metering scheme is 3052 MU. The metering scheme designed using hybrid GA/SA and KCA gives redundancy of 1.04. The metering scheme obtained through Biography Based Optimization acquires redundancy of 1.02.

The measurement system obtained through hybrid GA/SA, KCA and Biography Based Optimization provides poor redundancy. Hence, the cost of measurement system configuration will become less. But, the metering scheme will fail to satisfy requirement of execution of bad data finding and abolition because; after loss of one measurement pair the redundancy will become less than 1. Always measured quantities should be more than the necessary minimum number to make provision for eliminating erroneous quantities from the measurement set to ensure accurate state of the power system.

Proposed Measurement Placement Method

The proposed measurement placement method is based on network graph theory. The metering scheme assures that each branch of power system network is incidental by power injection measurements at either ends or a flow measurement and an injection measurement at one of its terminal node. Selection of meter locations also assures least requisite of RTUs.

Preliminarily, to reduce meter requirements for observability, the proposed method gives the greatest priority to power injection measurements at the buses of maximum adjacency.

The redundancy can be considered as a function of the accuracy requirement in the state estimation. Always measuring quantities should be more than the necessary minimum number to make provision for eliminating erroneous quantities from the measurement set to ensure accurate state of the power system.

Hence, in the second stage, branches consisting power injection measurement at one of it terminal node are identified and power flows are measured through such branches to increase redundancy. Further, to enhance redundancy, voltages at all additional RTU locations are measured.

The proposed meter placement method proceeds as follows:

- Read bus data, initialize measurement set of interest by injection measurements at all the zero injection buses in the power system network.
- For n bus power system network, read line data and prepare n x n adjacency matrix A= $[a_{ij}]$ where; $a_{ij} = 1$, if i^{th} bus is incident to j^{th} bus and $a_{ij} = 0$, if otherwise. Modify adjacency matrix by making all $a_{ii} = 0$, as these elements of matrix represent the bus itself.
- Compute total ones for each row of modified adjacency matrix. Identify buses of maximum (p) and minimum (q) adjacency. Place RTUs and measure power injections at the buses of adjacency p, p-1, p-2 ……., till p, p-1, p-2 ……., = q+2.
- Identify branches contain no power injection measurement at one of its end, place RTU and measure injection at any end. Add power injection measurements at the buses of q+1 adjacency and voltage measurements at all RTU locations till redundancy becomes ≥ 1.
- Update line data file by removing all the lines comprising of injection measurements at both ends. Measure power flows through the remnant lines such that minimum requisite of additional RTUs. Measure voltages at additional RTU locations.

When SCADA measurements are combined with PMU, the direct measurement of state variables with enough accuracy will be available through PMU data. Hence, excluding the buses of PMU locations, the proposed measurement placement method can be utilized to configure SCADA measurements on modified power system network. Making the use of proposed measurement system configuration, the state variables can be estimated using reduced state estimation model.

Test Results

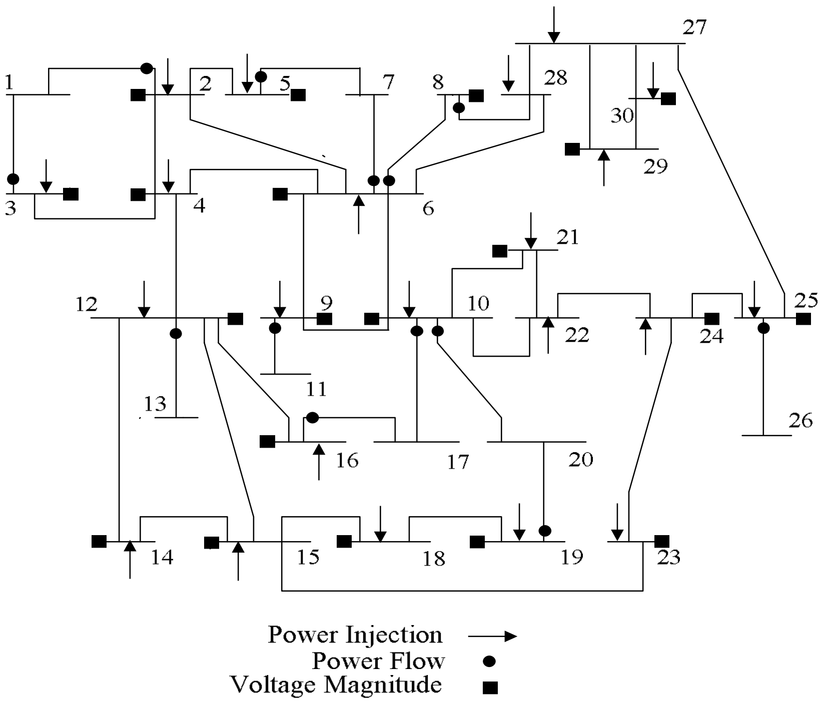

Figure 2. Meter placement on IEEE 30 bus system using proposed method

The simulation study is performed on IEEE 30 bus system. Fig. 2 shows measurement system configuration obtained through the proposed method of measurement placement. Out of 254 possible measurements, metering scheme utilizes 90 measurements and redundancy becomes 1.52.

The metering scheme consists: 20 RTUs, 22 power injections, 20 voltage magnitudes and 13 power flows. Estimated state obtained by utilizing the proposed metering scheme, SA and biography based optimization is shown in the table 1.

Table 1. Estimated state

Bus No.	**--------------- Estimated State ---------------**					
	Proposed Metering Scheme		**Metering Scheme of SA Alessendra B Antonio et al.**		**K Jamuna, K S Swarup et al.**	
	Voltage Magnitude |V| pu	**Bus Angle δ (Degree)**	**Voltage Magnitude |V| pu**	**Bus Angle δ (Degree)**	**Voltage Magnitude |V| pu**	**Bus Angle δ (Degree)**
1	1.027	0.000	3.338	0.000	0.178	0.000
2	1.010	-2.679	0.578	-0.972	1.175	-11.489
3	1.001	-4.073	1.142	-6.801	0.787	-11.818
4	0.995	-4.890	0.949	-8.907	0.906	-13.143
5	0.977	-7.026	0.850	-10.654	1.014	-16.231
6	0.993	-5.778	1.149	-10.103	0.966	-14.072
7	0.983	-6.598	0.963	-10.801	0.945	-15.851
8	0.985	-6.064	0.692	-10.360	0.979	-14.390
9	1.033	-7.362	1.006	-15.851	0.974	-14.941
10	1.031	-8.219	0.994	-19.315	0.940	-15.336
11	1.052	-7.305	0.809	-15.928	1.023	-15.067
12	1.039	-7.844	0.996	-24.142	1.011	-14.247
13	1.036	-7.843	1.011	-26.010	1.021	-14.319
14	1.038	-8.400	0.978	-26.969	1.006	-14.120
15	1.034	-8.376	0.994	-25.920	1.025	-14.302
16	1.024	-8.156	1.003	-23.050	1.019	-14.937
17	1.024	-8.330	1.013	-20.236	0.985	-15.378
18	1.023	-8.774	0.999	-25.290	1.206	-7.558
19	1.016	-8.851	0.983	-24.512	1.055	-6.694
20	1.015	-8.747	0.643	-23.742	1.056	-6.923
21	1.030	-8.484	0.997	-19.819	0.940	-15.431
22	1.031	-8.481	1.000	-19.918	0.944	-15.373
23	1.038	-8.561	1.006	-25.467	1.036	-14.531
24	1.033	-8.611	1.021	-22.426	0.995	-15.357
25	1.037	-8.437	0.993	-18.359	1.045	-15.242
26	1.031	-8.754	0.966	-17.758	1.038	-15.462
27	1.040	-8.064	1.007	-16.754	1.082	-14.974
28	0.995	-6.170	1.031	-10.720	0.982	-14.435
29	1.039	-8.796	0.966	-17.628	1.133	-15.519
30	1.036	-9.207	0.970	-17.976	1.209	-16.738

Fig. 3 and 4 shows errors in estimated state variables computed with the use of proposed measurement system configuration and the metering scheme obtained through SA and Biography Based Optimization.

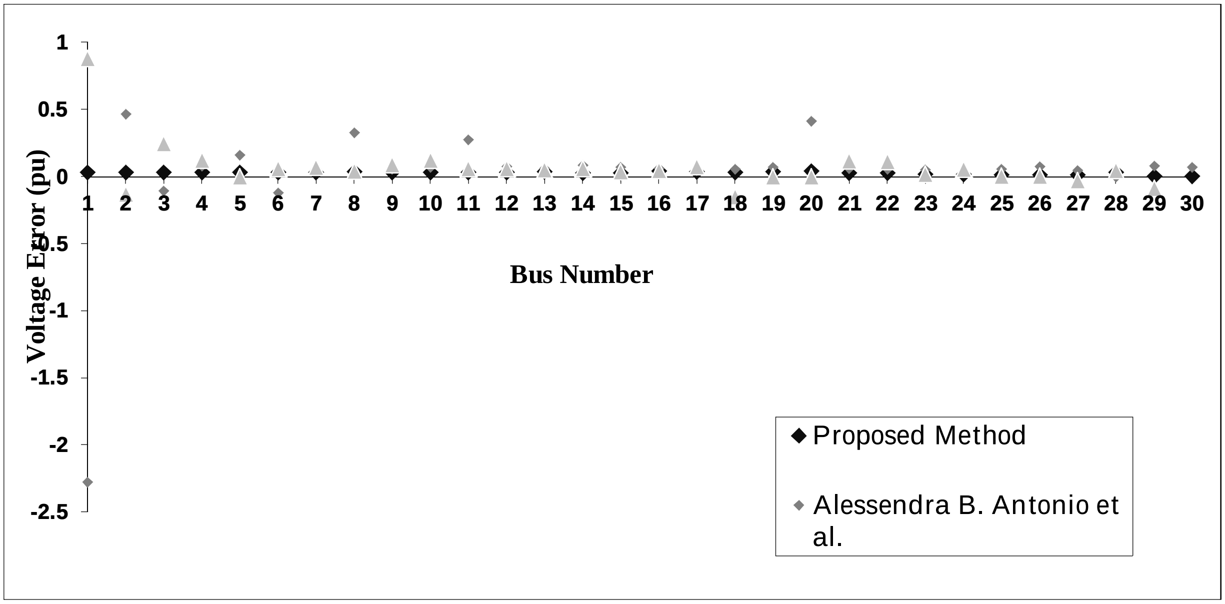

Figure 3. Voltage Magnitude Errors

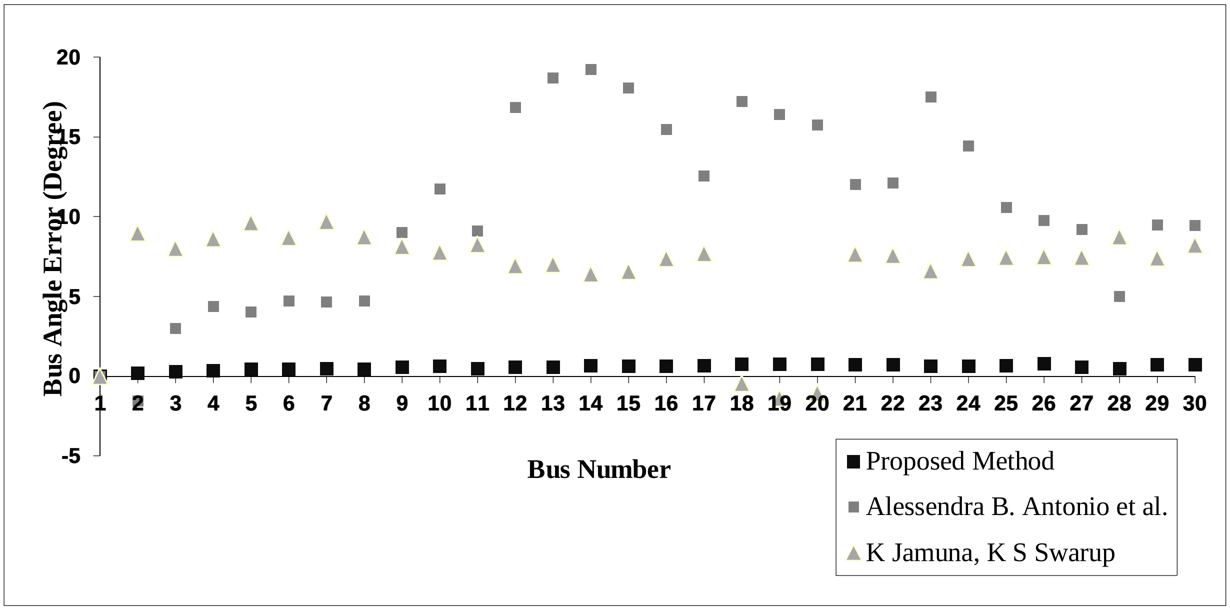

Figure 4. Bus Angle Errors

Conclusion

The suggested measurement system configuration accomplishes better bad data processing and observability requirements for state estimator compared with the metering scheme obtained through the Biography Based Optimization method. The proposed measurement configuration yields much accurate state of power system than the metering schemes obtained through SA and Biography Based Optimization method. Also, the suggested method acquires cost effective measurement system configuration compared with SA.

In presence of PMU, excluding the buses of PMU locations, the proposed measurement placement method can be utilized to configure SCADA measurements on modified power system network. Making the use of proposed method of measurement system configuration, the state variables can be estimated using reduced state estimation model.

The proposed method of measurement placement can be implemented in existing state estimators as an off- line measurement systems planning tool.

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