INTERNATIONAL JOURNAL OF ADVANCED RESEARCH IN ENGINEERING, SCIENCE & MANAGEMENT

ELECTRICAL POWER SYSTEM STATE ESTIMATION: THEORY AND IMPLEMENTATION

Mr. Rakesh J. Motiyani[1], Dr. Ajitsinh R. Chudasama[2], Mr. Ankur P. Desai[3]
Associtate professor, Electrical Department, S.N.P.I.T&R.C., Umrakh, Gujarat, India[1]
Academic Director, Electrical Depar., Neotech Technical Campus, Vadodara, Gujarat, India[2]
Assistant professor, Electrical Department, S.N.P.I.T&R.C., Umrakh, Gujarat, India[3]

Abstract*: *This paper discuses theory and implementation of electrical power system state estimation. State estimation is the key function for building a network real time model. A real time model is a static mathematical representation of an interconnected power system. This paper gives idea of generalized state estimation that includes network model, topological processor, observability of power system network and bad data processing.

Keywords: **Bad data detection, network observability, network topological processor, static state estimator.**

I. NOMENCLATURE

V	**Bus voltage magnitude**
δ	**Bus angle**
WLS	**Weighted Least Square**

II. INTRODUCTION

The state of electrical power system is defined as the vector of voltage magnitude and angles 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.

Static state estimator is related to conventional power flow calculations. However, the static state estimator is designed to handle the many uncertainties associated with trying to do an online power flow for an actual system using meter reading telemetered in real time to a digital computer. Uncertainties arises because of meter and communication errors, incomplete metering, error in mathematical model, unexpected system changes etc. These uncertainties make difference between the usual power flow studies done in office and online state estimation done as a part of control system.

The static state estimation is based on classical mathematical technique such as estimation, detection, probability, statistic and filtering. The static state estimation results from the combination of power flow and estimation theory.

A power system rarely achieves a true steady state (static state) operating point, as loads and generation parameters are continuously changes. However, it is reasonable to consider power system to be in steady state over some short interval of time.

The state estimator plays the essential role of a purifier, creating a complete and reliable database for security monitoring, security analysis and the various controls of a power system. The state estimator thus employs statistical methods to act as a tunable filter between the field data measurements and security and control functions.

Static state estimator requires as input a set of real-time measurements that redundantly observes the system state along with a topology processor that determines the system topological model based on the telemetering of circuit breaker statuses.

The paper by Robert E. Larson and William F. Tinney [1], gives basic theory and computational requirements of static state estimation.

The paper by F. C. Schweppe [2], gives the most fundamental concept of power system static state estimation. In part II of the same paper [3], the approximate model of the static state estimation is discussed. In part III of the paper by F.C.Schweppe [4], the implementation part of the power system static state estimation is discussed.

The paper by A. Monticelli [5], gives idea of generalized state estimation that includes network model, topological processor, observability of power system network and bad data processing. By the same author [6], WLS state estimator, topological processor, observability analysis and bad data analysis is discussed in detail. This paper also includes concept of observable islands.

The paper by E. Handschin and F.C. Schweppe [7], describes sum of squares of residuals method of bad data detection and identification.

The paper by G.R Krumpholz and K.A Clements [9], outlines the theoretical basis of an algorithm for determining observability. Algorithm for observability of network containing both bus injections and line flows measurements is presented.

The paper by Alessandra B. Antonio, R. A. Torreao and Milton Brown [10], presents selection of measurement systems aims at attending to requirements such as observability and reliability taking in to account the associated monetary costs. In the same paper best measurement system configuration is given for IEEE 30 bus system.

III. MATHEMATICAL MODEL

A. WLS State estimator

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

$$z = h(x) + e \qquad (1)$$

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) [11].

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

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

$$\Delta x = \left(H^T R^{-1} H\right)^{-1} H^T R^{-1}\left(z - h\left(x^k\right)\right) \tag{3}$$

$$x^{k+1} = x^k + \Delta x \tag{4}$$

Where,

$$H = \frac{\partial h(x)}{\partial x} = \begin{bmatrix} \frac{\partial h_1(x)}{\partial x_1} & \frac{\partial h_1(x)}{\partial x_2} & \cdots & \frac{\partial h_1(x)}{\partial x_{Ns}} \\ \frac{\partial h_2(x)}{\partial x_1} & \frac{\partial h_2(x)}{\partial x_2} & \cdots & \frac{\partial h_2(x)}{\partial x_{Ns}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial h_m(x)}{\partial x_1} & \frac{\partial h_m(x)}{\partial x_2} & \cdots & \frac{\partial h_m(x)}{\partial x_{Ns}} \end{bmatrix} \tag{5}$$

Where, $N_s = 2n-1$

$$W = R^{-1} = \begin{bmatrix} \frac{1}{\sigma_1^2} & & & \\ & \frac{1}{\sigma_2^2} & & \\ & & \cdots & \\ & & & \frac{1}{\sigma_m^2} \end{bmatrix} \tag{6}$$

For n bus system, considering one of the bus as a reference, n-1 angles and n voltage magnitudes are to be calculated. The state estimation jacobian (H) always has 2n-1 columns and large number of rows based on number of measurements made.

The gain matrix is defined as

$$G = H^T R^{-1} H \tag{7}$$

IV. Network Topology Processor

The topology processor identifies network configuration based on the network connectivity model and dynamic switch status. It produces the visual and modeled indication of energized and de energized portion of the distribution system for display and analysis purposes.

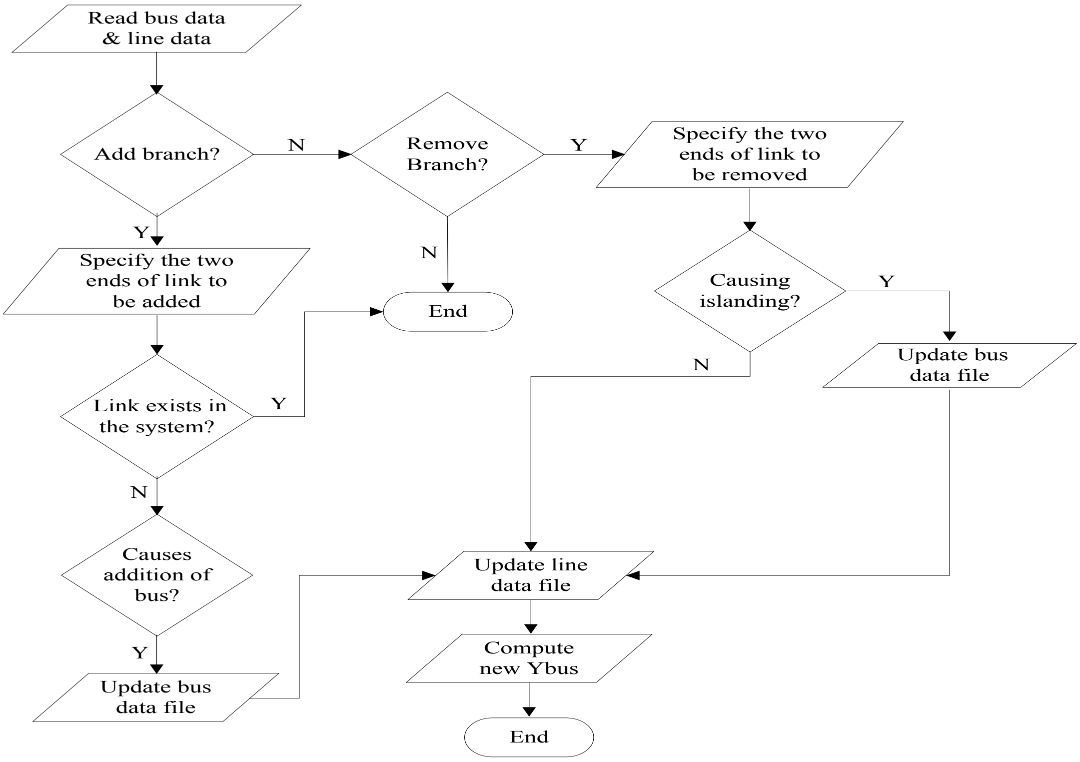

Fig. 1. Flow diagram: Network topology processor

A. *Addition of bus and line*

Here it is required to specify two ends (bus numbers) of the line to be added in the existing power system network. All the data related with newly added line are required to be specified. The line data file will be updated to reflect that change in the network topology.

If addition of line causes introduction of new bus in the power system network, then all the data related with newly added bus are also required to be specified. In this case, both bus data and line data files will be updated to reflect changes in the network topology. After updating data files new Y_{BUS} is required to be calculated to obtain power flow solution.

B. *Removal of bus and line*

Here it is required to specify two ends (bus numbers) of the line to be removed from the existing power system network. The data related with that line are required to be removed from the line data file. The line data file will be updated to reflect that change in the network topology.

If removal of line causes islanding of any bus, the data related with that bus will be removed from the bus data file to reflect that change in network topology. After updating data files new Y_{BUS} is required to be calculated to obtain power flow solution.

V. STATIC STATE ESTIMATOR

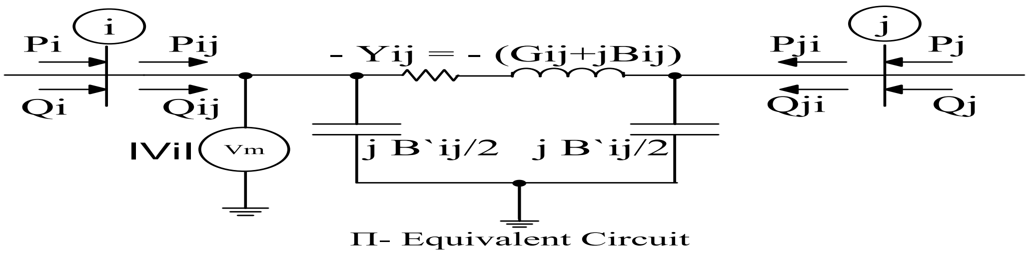

Fig. 2. Possible measurements.

The basic purpose of the state estimator is to determine the system state i.e. the voltage magnitude and angle at each system bus. In order to determine the system state, one of the bus angle is chosen as a reference, which leaves n-1 angles and n voltage magnitude (for n bus in the system) to be calculated. Hence, the state estimation jacobian Hx, unlike the square jacobian J of conventional Newton-Raphson power flow, always has (2n-1) columns and a large number of rows based on the number of measurements. Each row of Hx corresponds uniquely to one of the measured quantities indicated in the transmission-line equivalent circuit shown figure 2.

The following are the possible measurements.

- The voltage magnitude |Vi| at a typical bus.
- The active power Pi injected in the network at bus i.
- The reactive power Qi injected into the network at bus i.
- The active power flow Pij at bus i or Pji at bus j in the line connecting bus i and j.
- The reactive power flow Qij at bus i or Qji at bus j in the line connecting bus i and j.

If |Vi|, Pi and Qi are measured at every bus and the flows Pij, Pji, Qij and Qji are measured at every line, the measurement set is full and Hx has total of (3n + 4b) number of rows, where b is the number of network branches and N is the number of network buses. The ratio of rows to column in Hx is called the redundancy factor, and it equals (3n + 4b) / (2n -

1), or approximately 4.5 in a large fully monitored power system with average of 1.5 branches per bus.

For the State Estimators in the power system- the meters reads the present flows, injections and the voltage magnitudes at the given buses or the lines and then, they are telemetered through the communication network and the estimation is carried out.

To generate simulated measurements for state estimator, updated bus data and line data files depending upon the change in network topology can be utilized. The power flow solution of the network is first carried out. From power flow solution power injections, flows and voltage magnitudes are obtainable.

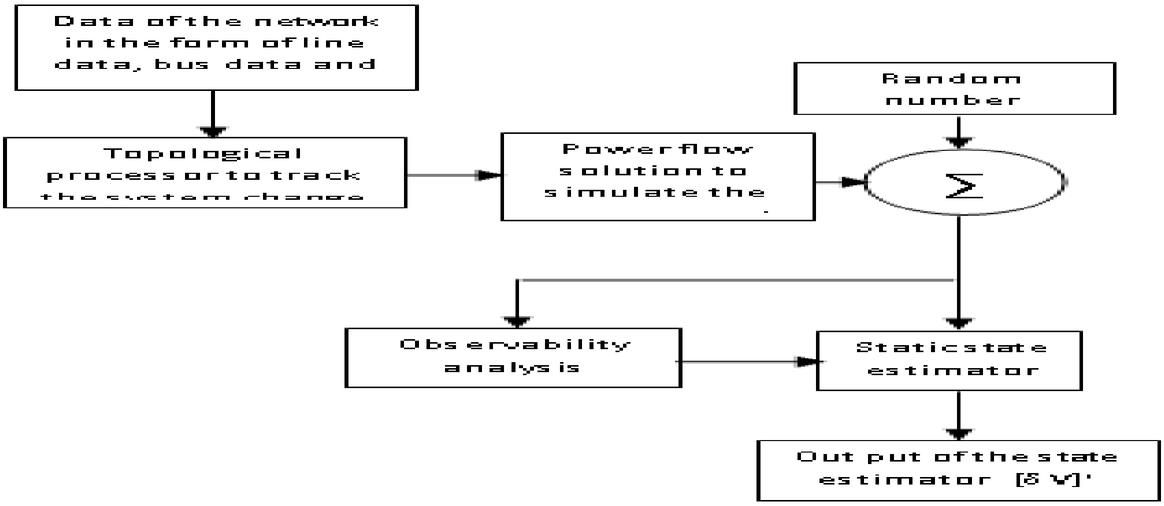

Fig. 3. Block diagram- State estimation.

To introduce measurement errors and telemetering noise, normalized value of random number is required to be added in power injections, flows and voltage magnitudes before they utilized by state estimator. Generated simulated measurements can be treated as the real time meter readings for state estimator. Required numbers and type of measurements can be used for state estimation simulation.

A. *Network Observability*

The linearized state estimation model can be used to check the observability of the system. The observability test is applied to the P-□ model and to the Q-V model. The intersections of the resulting observable islands from the two models above are the observable islands of the system. In the theory to follow, the vector **x** represents the true state vector.

For the network observability, we are concerned with the power flows in the network and the measurements made on the network. Given a state vector **x,** the power flow through the branch connecting buses k and m is equal to,

1/x km (□k - □m)

For observability, the presence or absence of the flow is of importance and not the numerical value of the flow. If a branch that neither has a flow measurement on it nor an injection measurement at one of its terminal nodes, that branch does not come into the matrix H and thus it does not play any role either in observability analysis or in state estimation. Such a branch may be discarded from further consideration.

B. *Bad Data Detection*

An important practical difficulty that often plunges the state estimation results for a given power system arises from the presence of unreliable data. The system data which include network configuration, values of the network parameters, the active and reactive injections,

 ISSN : 2394-1766

active and reactive line flows etc, are generally collected using different measurement systems and are telemetered to the central computing station at the load control center. One or more of these data may be affected by malfunctioning of either the measuring instruments or the data transmission system or both. If such faulty data are included in the measurement vector Z, the estimation algorithm will yield unreliable estimate of state.

The WLS estimator is highly sensitive to erroneous measurement, referred to as bad data. Therefore, post-state estimation procedures have been incorporated to the state estimation function for the identification and elimination of bad data.

VI. TEST RESULTS

Test was implemented on IEEE-14 bus system. To check the functioning of network topology processor, lines connecting bus number 2 - 3 and 3 – 4 are removed from the IEEE 14 bus system. After removal of both lines, bus number 3 is isolated from rest of the system. Bus data and line data files are found updated according to the change in network topology.

Power flow solution using NR method was carried out to generate simulated measurements for state estimator. Geographically well distributed 35 measurements were used for estimating the state.

Estimated state obtained is as following:

Degree of freedom = 10

No. of Iterations = 15

Maximum error = 0.00134122

Redundancy = 1.40

TABLE I ESTIMATED STATE

Bus No.	Voltage Magnitude (V)	Angle (Degree) (δ)
1	1.028	0
2	1.023	-0.444
3	1.027	-1.058
4	1.025	-1.346
5	1.093	-2.526
6	1.064	-2.072
7	1.066	-2.071
8	1.07	-2.343
9	1.073	-2.431
10	1.083	-2.503
11	1.089	-2.702
12	1.087	-2.666
13	1.075	-2.682

TABLE II

DIFFERENCE BETWEEN THE ACTUAL STATE AND ESTIMATED STATE

Bus No.	Voltage Difference (Magnitude)	Angle Difference (Degree)
1	0.032	0
2	0.032	-0.002
3	0.029	-0.006

4	0.03	-0.005
5	0.027	-0.007
6	0.026	-0.007
7	0.024	-0.007
8	0.026	-0.008
9	0.025	-0.008
10	0.026	-0.008
11	0.026	-0.008
12	0.026	-0.008
13	0.025	-0.009

VII. CONCLUSION

Simulation of Network Topology Processor was carried out to identify network configuration based on the network connectivity model and dynamic switch statuses. The data files of IEEE14 are considered to test the simulation of network topology processor. Depending upon the change in network topology the bus data line data files are found altered. The functioning of network topology processor was found satisfactory.

Measurements for state estimator are generated using the developed simulation. Simulation of WLS algorithm is also carried out successfully.

REFERENCES

[01] State estimation in power systems – part I: Theory and feasibility By Robert E. Larson, member, IEEE, William F. Tinney, senior member, IEEE, John Peschon, senior member, IEEE. IEEE transaction on power apparatus and system, vol. PAS-80, No. 3, March 1970.

[02] Power system static state estimation part I: Exact model. By Fred C. Schweppe member, IEEE, and J. Wildes member, IEEE. Transaction on power apparatus and system, vol. PAS – 89, NO. 1, January 1970.

[03] Power system static state estimation part II: Approximate model. By Fred C. Schweppe member, IEEE, and Douglas B. Rom, Student member IEEE. Transaction on power apparatus and system, vol. PAS – 89, No. 1, January 1970.

[04] Power system static state estimation part III: Implementation by Fred C. Schweppe member, IEEE. Transaction on power apparatus and system, vol. PAS – 89, No. 1, January 1970.

[05] Generalized state estimation .By A. Monticlli. IEEE transaction on power system, vol. 13, No. 3, August 1998.

[06] Electrical power system state estimation. By A. Monticlli. Proceeding of IEEE , vol. 88 , No. 2, February 2000

[07] Bad data analysis for power system state estimation. By E. Handschin, F.C Schweppe, J. Kohlas, A. Fiechter. IEEE Transaction on power apparatus and system, vol. PAS-94, no. 2, March/ April 1975.

[08] Bad data identification methods in power system state estimation – A comparative study. By L.Mili , Th. Van Cutsem and M. Ribbens-Pavella. IEEE transaction on power apparatus and system, vol. PAS-104, No. 11, November 1985.

ISSN : 2394-1766

[09] A power system observability: A practical Algorithm using network topology. By G. R. Krumpholz, K. A. Clements and P. W. Davis. IEEE transaction on power apparatus and system, vol. PAS-99, No. 4, July/Aug 1980.

[10] Meter placement for power system state estimation using simulated annealing. By Alessandra B. Antonio, Jose R. A. Torreao, and Milton Brown Do Coutto Filho, senior member, IEEE. IEEE porto power tech conference September 2001.

[11] A. Shafiu, N. Jenkins and G. Strbac. Measurement location for sate estimation of distribution networks with generation. IEEE proceeding: generation - transmission - distribution, vol. 152, No. 2, March 2005.

[12] Carlo Muscas, Fabrizio Pilo. Optimal Placement of Measurement Devices in Electric Distribution Systems. IMTC 2006 – Instrumentation and Measurement Technology Conference Sorrento, Italy 24-27 April 2006.

[13] Jian Chen and Ali Abur. Placement of PMUs to Enable Bad Data Detection in State Estimation. IEEE transaction on power systems Vol. 21, No. 4, November 2006.

[14] Sandhya Sankar,Noel. N. Schulz. Intelligent Placement of Meters/Sensors for Shipboard power System Analysis. IEEE proceeding, 2007.

Books:

[15] Power system analysis – Grainger and Stevenson.

[16] Power system analysis –Hadi Saadat.

 ISSN : 2394-1766