Spreadsheets in Education (eJSiE)

Volume 8 | Issue 1 Article 1

November 2014

Power System State Estimation using Microsoft Excel

K. S. Sastry Musti
University of West Indies, musti.sastry@sta.uwi.edu

Balasubrahmanyam P.V.
Chaitanya Bharati Institute of Technology, Hyderabad, peribalu@gmail.com

Rajesh Reddy Malireddy
University of Southern California, maliredd@usc.edu

Recommended Citation

Power System State Estimation using Microsoft Excel

Abstract

This paper presents the design and development of a Microsoft Excel based tool for Power System Static State Estimation. This tool can be effectively used to understand the process of state estimation and its real-time application. The tool contains Newton-Raphson load flow that provides system measurements, which are used as inputs to the state estimator that uses the popular weighted least square (WLS) algorithm. The spreadsheet has features for corrupting the data to simulate wide ranging scenarios of data errors. With the user-friendly screens, this can be a versatile desktop tool for learning and experimenting with the Power System State Estimation. Different system loading and operating configurations and wide range of corrupted measurements can be simulated for obtaining the reliable state estimator. All intermediate numerical results are made available for verification purposes. For illustration IEEE 14 bus system is considered.

Keywords

Power System State Estimation, WLS method, Microsoft Excel, Visual Basic for Applications

Power System State Estimation using Microsoft Excel

Abstract

This paper presents the design and development of a Microsoft Excel based tool for Power System Static State Estimation. This tool can be effectively used to understand the process of state estimation and its real-time application. The tool contains Newton-Raphson load flow that provides system measurements, which are used as inputs to the state estimator that uses the popular weighted least square (WLS) algorithm. The spreadsheet has features for corrupting the data to simulate wide ranging scenarios of data errors. With the user-friendly screens, this can be a versatile desktop tool for learning and experimenting with the Power System State Estimation. Different system loading and operating configurations and wide range of corrupted measurements can be simulated for obtaining the reliable state estimator. All intermediate numerical results are made available for verification purposes. For illustration IEEE 14 bus system is considered.

Keywords: Power System State Estimation, WLS method, Microsoft Excel, Visual Basic for Applications (VBA).

Power System State Estimation using Microsoft Excel

Abstract

This paper presents the design and development of a Microsoft Excel based tool for Power System Static State Estimation. This tool can be effectively used to understand the process of state estimation and its real-time application. The tool contains Newton-Raphson load flow that provides system measurements, which are used as inputs to the state estimator that uses the popular weighted least square (WLS) algorithm. The spreadsheet has features for corrupting the data to simulate wide ranging scenarios of data errors. With the user-friendly screens, this can be a versatile desktop tool for learning and experimenting with the Power System State Estimation. Different system loading and operating configurations and wide range of corrupted measurements can be simulated for obtaining the reliable state estimator. All intermediate numerical results are made available for verification purposes. For illustration IEEE 14 bus system is considered.

Keywords: Power System State Estimation, WLS method, Microsoft Excel, Visual Basic for Applications (VBA).

1. Introduction

State Estimation is the process of identification of all states (such as system variables typically obtained through real time measurement in case of a power system) of a dynamically varying system. Usually the real time measurements contain errors and may not represent the true values. State Estimation helps in accurate estimation of an unknown system state variable and assigning it an appropriate value based on a statistical criteria. State estimation process uses redundant data measurement sets and then identifies the data errors in order to determine an optimal state estimate. In any power system, bus voltages, power flows are measured at different places and that information is relayed to a central dispatch facility. Sometimes, this information may contain bad values, missing values etc. Hence, Power System State estimation is a well-known technique for identification of bad data, missing data of a power system with a given number of states. In other words, state estimation essentially acts an online filter as it provides the data with high confidence despite the fact that online measurements might been inaccurate due to various factors. Obviously the state estimator has an important role in overall operation and control of power networks.

Typically, in power system state estimation, the vector consisting voltage magnitudes and phase angles of all the buses is considered as the state or state vector of the system. If the state vector is obtained for an instant of time, at which the set of measurements are collected, then it is known as a static state estimator. Since measurements are obtained continuously, state estimation needs to be executed repeatedly at frequent intervals to ensure data accuracy.

State estimation is required for real time monitoring and control of power system, but it is computationally demanding if performed at shorter intervals (Jain and Shivakumar, 2009). The conventional state estimation assumes the variances of the random errors are known and the measurements will be weighted by the inverses of random error variances to suppress their influences various methods for state estimation have been introduced in the past decades. Among those methods, Weighted Least Squares (WLS) algorithm is the most popular one. The objective function to be minimized of this method is chosen as the weighted sum of squares of the measurement residuals. Since this kind of problem can be solved by efficient numerical techniques, state estimators based on WLS approach have been installed in several Energy Management (EMS) systems all over the world (Gomez-Exposito et al, 2011). However, it should be noted that the classical, steady state estimators will not be able to capture the dynamic system with higher accuracy as SCADA systems need greater time intervals to update the data. This means, computation of state transition, and Jacobian Matrix are essential (Wenzhong Gao and Shaobu Wang (2010)). Importance of state estimation in modern smart grids is such, even with fewer measurements it is possible to estimate the state of the system accurately (Alam et al, 2014). Hence it is important that power engineers and students learn the process of State Estimation, including the know-how of computing the intermediate steps. The objective of this paper is to provide a simple tool to assist the teaching and learning process, as well as in the system analysis of smaller power systems with state estimators by utility engineers.

The content of this paper is divided into seven sections. Section 2 outlines the conventional static state estimation algorithm and the overall computational process. However, exhaustive theoretical treatment of the algorithms and their derivations is avoided in this paper, as many resources (Sastry et al 2014; Abur and Exposito 2004; Chen 2013) provide basics of state estimation process. Details on features of the developed tool, overall design, input and output data are presented in section 3. Section 4 presents detailed information on how the design is implemented in a modular fashion, details of visual basic programming, some of the macros and sub routines. Section 5 presents the application of the developed tool to the standard IEEE-14 bus system. Section 6 provides an effective strategy for using the tool in a typical university classroom. Finally Section 7 presents concluding remarks.

2. State Estimation using the WLS Method

The power system state estimation solution is based on non-linear least-square algorithm. Among state estimators based on the normal equations approach, the weighted least-square (WLS) estimator provides reliable estimates but it is slow, mainly due to its requirement for updating and factorization of the full-matrix within every iteration. The process involves different vectors - a measurement vector, a vector of nonlinear functions that relate the states to the measurements, error vector and the state vector that needs to be determined. The error vector is assumed to be a zero mean Gaussian measurement noise vector. The measurement variances are assumed to be uncorrelated. The optimal state estimate vector can be determined by minimizing the sum of weighted squares of residuals.

A flat start for the state variables is usually utilized, where all bus voltages are assumed to be 1.0 per unit and in phase with each other. The iterative process will be terminated when the maximum number of iterations is reached or measurement mismatch reaches a prescribed threshold, e.g. 0.001. The gain matrix may be ill conditioned for some systems. In such cases the algorithm fails as direct inverse of the gain matrix cannot be computed as the matrix becomes singular. The causes for ill conditioning may be high weights of the covariance matrix, underdetermined condition of the system, singularity of the system. To overcome this problem, singular value decomposition (SVD) is used.

The condition number of the gain matrix indicates the extent to which a matrix is ill-conditioned. Large condition number indicates that a matrix is ill-conditioned. Condition number depends on the underlying norm. However, regardless of the norm, it is always greater or equal to 1. If it is close to one, the matrix is *well conditioned* which means its inverse can be computed with good accuracy. If the condition number is large, then the matrix is said to be *ill-conditioned*. Practically, such a matrix is almost singular, and the computation of its inverse, or solution of a linear system of equations is prone to large numerical errors. A matrix that is not invertible has the condition number equal to infinity.

2.1. Bad Data Detection, Identification and Elimination

When the system model is correct and the measurements are accurate, there is good reason to accept the state estimates calculated by the weighted least squares estimator. But if a measurement is grossly erroneous, then it should be detected so that it can be removed from the estimator. Removal of bad data is essential for estimating the overall state of the system for real time analysis. The statistical properties of the measurement errors facilitate such detection and identification. The removal comes in two parts: detecting the existence of bad data in the measurement vector, and identifying the bad elements of that measurement vector. The well-known Chi-Square test is used for bad data detection in this work. If this test is failed, then the presence of bad data in the measurements can be suspected. The bad data then can be identified using the methods of largest normalized residuals test.

2.2. Redundancy of the measurements

The complex voltages at all the buses in a power system are not directly available for measurements. These are to be estimated from other variables of the system which can be measured (to be more precise, which can be metered). The power injections, power flows and voltage magnitudes can be normally obtained from the metered buses of the system.

Essential parameters of SE are the redundancy rate of the measurements. This is the ratio between the number of usable and the number of state-variables. This ratio should be greater than 2 and be obtained with measurements distributed uniformly over the system in order to be able to detect erroneous measurements. In practice, the redundancy of the installed measurements should be slightly greater than two, so it can take into account the various operation layouts used and to cover for the unavailability of transmission and telemetering equipment failures. Redundant measurements do contain useful information about the system. Though, increased redundancy improves the accuracy of the estimator; the solution may still be obtained without redundancy. It should be noted that the effect of each measurement on the quality of the estimates is non-uniform and is affected by other factors as well.

3. Implementation of Power System Static State Estimation using Microsoft Excel

Microsoft Excel is used to develop the State Estimation tool. In fact, this work is based on our previous contribution on Power System Load Flow analysis using Microsoft Excel (Sastry and Ramkhelawan, 2012). For state estimation, the previously developed tool is tweaked, only Newton-Raphson Load flow module is retained and rest of the load flow methods were omitted. Major steps in State Estimation using WLS method are outlined below:

1. Obtain the power flows using the Newton-Raphson Load flow method.
2. Corrupt the load flow data or remove any data to form the measurement set for the State Estimator
3. Test the redundancy of the measurement set. If the number of measurements is greater than number of states, go to step 4. Else, end the program and display an error message.
4. Run the WLS Algorithm and get the state estimates.
5. Perform Chi-Square test. If test passes, solution is obtained, program ends.
6. If the test fails, calculate largest standardized error
7. Delete row from measurement matrix corresponding to largest standardized error
8. Go to step 3

On obtaining the state estimates successfully, this MS Excel based tool allows the user to get an estimate of the missing measurements. The tool also provides information on the erroneous measurements that are eliminated from the measurement set during the Chi-square test.

3.1. Working with the MS Excel tool

The static state estimation tool is divided into two parts with several worksheets.

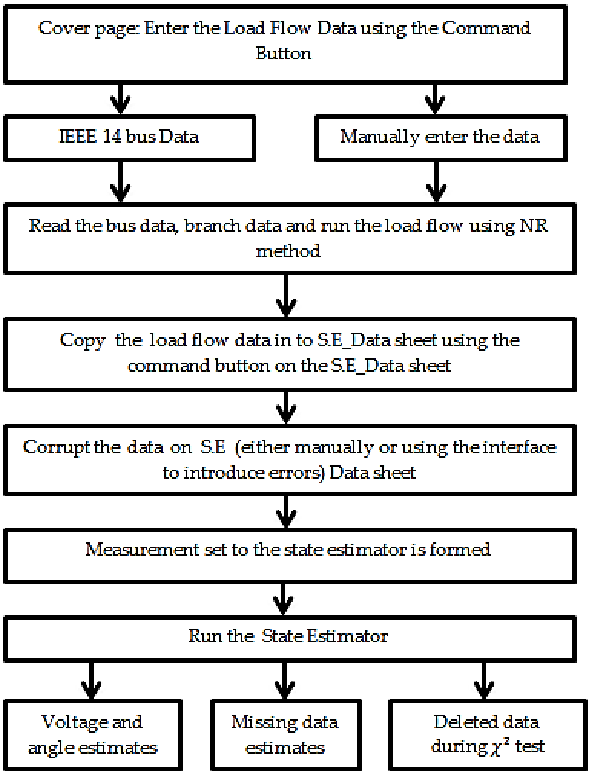

Cover page: Enter the Load Flow Data using the Command Button
IEEE 14 bus Data
Manually enter the data
Read the bus data, branch data and run the load flow using NR method
Copy the load flow data in to S.E_Data sheet using the command button on the S.E_Data sheet
Corrupt the data on S.E (either manually or using the interface to introduce errors) Data sheet
Measurement set to the state estimator is formed
Run the State Estimator
Voltage and angle estimates
Missing data estimates
Deleted data during χ^2 test

Figure 1: Flow diagram with sequence of steps for operating the developed tool

First part is for the Load Flow using the Newton-Raphson method. Load Flow results from this part provide the set of measurements to the State Estimator. The second part is the State Estimation Analysis. Both the parts are included in the single spreadsheet with their intermediate pages showing the data, user inputs and controls and computational results. Since this MS Excel based tool for State Estimation uses the previous version, performing the load flow study remains the same. Users who are familiar with the previous version, will not have any difficulty in handling the tool up to completion of the load flow of the system. Fig.1 gives the sequence of steps involved in operating the SE tool. The bus data and branch data required for the load flow. The "Enter Data for Load Flow" button on the cover page which is shown in figure 2, can be used to perform the load flow. The command button "State Estimation Analysis" displays the "S.E Data" sheet which is used to input the measurement set to the state estimator.

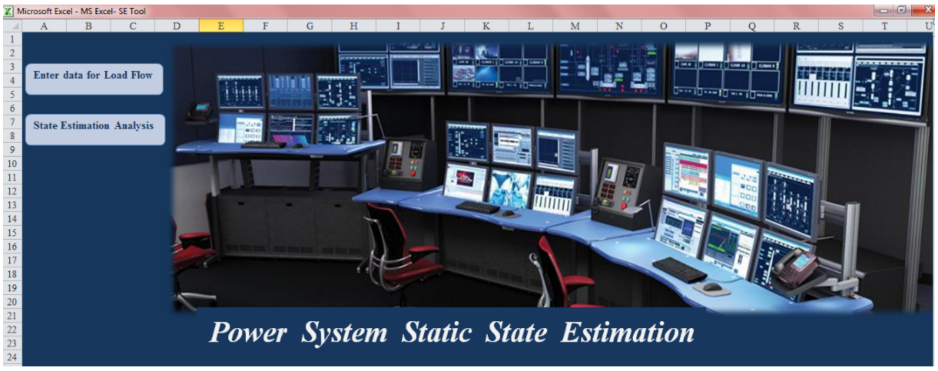
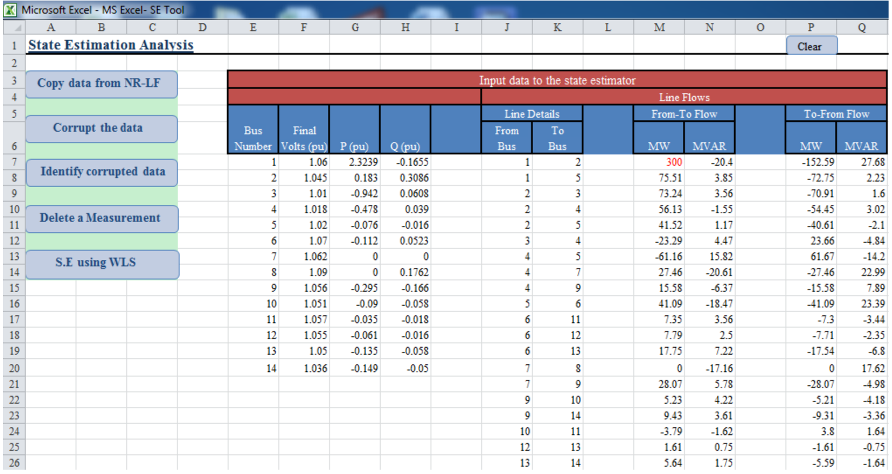

Microsoft Excel - MS Excel- SE Tool
Enter data for Load Flow
State Estimation Analysis
Power System Static State Estimation

Figure 2: Cover page of the developed MS Excel based State Estimation Tool

A screenshot of the "S.E Data" sheet with the IEEE-14 bus system data is shown in figure 3.



State Estimation Analysis

Input data to the state estimator

Bus Number	Final Volts (pu)	P (pu)	Q (pu)	Line Details From Bus	Line Details To Bus	From-To Flow MW	From-To Flow MVAR	To-From Flow MW	To-From Flow MVAR
1	1.06	2.3239	-0.1655	1	2	300	-20.4	-152.59	27.68
2	1.045	0.183	0.3086	1	5	75.51	3.85	-72.75	2.23
3	1.01	-0.942	0.0608	2	3	73.24	3.56	-70.91	1.6
4	1.018	-0.478	0.039	2	4	56.13	-1.55	-54.45	3.02
5	1.02	-0.076	-0.016	2	5	41.52	1.17	-40.61	-2.1
6	1.07	-0.112	0.0523	3	4	-23.29	4.47	23.66	-4.84
7	1.062	0	0	4	5	-61.16	15.82	61.67	-14.2
8	1.09	0	0.1762	4	7	27.46	-20.61	-27.46	22.99
9	1.056	-0.295	-0.166	4	9	15.58	-6.37	-15.58	7.89
10	1.051	-0.09	-0.058	5	6	41.09	-18.47	-41.09	23.39
11	1.057	-0.035	-0.018	6	11	7.35	3.56	-7.3	-3.44
12	1.055	-0.061	-0.016	6	12	7.79	2.5	-7.71	-2.35
13	1.05	-0.135	-0.058	6	13	17.75	7.22	-17.54	-6.8
14	1.036	-0.149	-0.05	7	8	0	-17.16	0	17.62
				7	9	28.07	5.78	-28.07	-4.98
				9	10	5.23	4.22	-5.21	-4.18
				9	14	9.43	3.61	-9.31	-3.36
				10	11	-3.79	-1.62	3.8	1.64
				12	13	1.61	0.75	-1.61	-0.75
				13	14	5.64	1.75	-5.59	-1.64

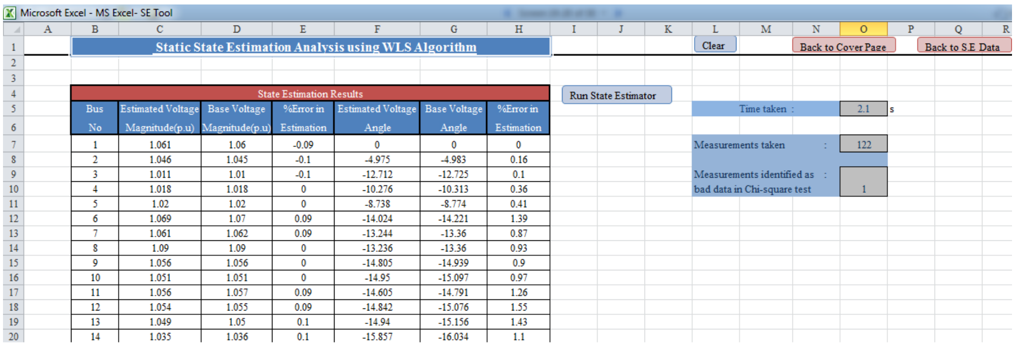
Figure 3: State Estimation page of the developed MS Excel based State Estimation Tool

It is desirable to use real time data of the power system for state estimation analysis. However, for the classroom learning purposes, it is desirable to use the load flow results with deliberately introduced errors in order to simulate a real time measurement set. Load flow results with or without introduction of errors are used as an input to the State Estimator. Command buttons are provided to run different cases such as: (1) corrupt the load flow results to introduce errors. (2) Delete a measurement from the load flow results to simulate a telemetry failure. (3) Corrupt as well as delete some load flow results. Table 1 provides a brief description of the buttons on the "S.E Data" sheet.

Table 1: Description of the command buttons on 'S.E Data' sheet

Clear	Clears the data on the sheet
Copy Data from NR-LF	Used to copy the load flow data got through Newton Raphson method from the "NR_Results" sheet
Corrupt the data	Shows the user form through which the user can add an error to one or more load flow data to simulate faulty metering.
Identify corrupted data	Used to detect the data corrupted by the user
Delete a Measurement	Used to delete a measurement from the load flow data to simulate a telemetry failure / meter failure.

State estimation for the desired case can be carried out using the "Run State Estimation "command button on the "Static S.E" sheet. Figure 4 shows a screenshot of the State Estimation results sheet of IEEE 14 bus system with full measurement set and active power flow from bus 1 to 2 corrupted.



Static State Estimation Analysis using WLS Algorithm

State Estimation Results

Bus No	Estimated Voltage Magnitude(p.u)	Base Voltage Magnitude(p.u)	%Error in Estimation	Estimated Voltage Angle	Base Voltage Angle	%Error in Estimation
1	1.061	1.06	-0.09	0	0	0
2	1.046	1.045	-0.1	-4.975	-4.983	0.16
3	1.011	1.01	-0.1	-12.712	-12.725	0.1
4	1.018	1.018	0	-10.276	-10.313	0.36
5	1.02	1.02	0	-8.738	-8.774	0.41
6	1.069	1.07	0.09	-14.024	-14.221	1.39
7	1.061	1.062	0.09	-13.244	-13.36	0.87
8	1.09	1.09	0	-13.236	-13.36	0.93
9	1.056	1.056	0	-14.805	-14.939	0.9
10	1.051	1.051	0	-14.95	-15.097	0.97
11	1.056	1.057	0.09	-14.605	-14.791	1.26
12	1.054	1.055	0.09	-14.842	-15.076	1.55
13	1.049	1.05	0.1	-14.94	-15.156	1.43
14	1.035	1.036	0.1	-15.857	-16.034	1.1

Time taken : 2.1 s

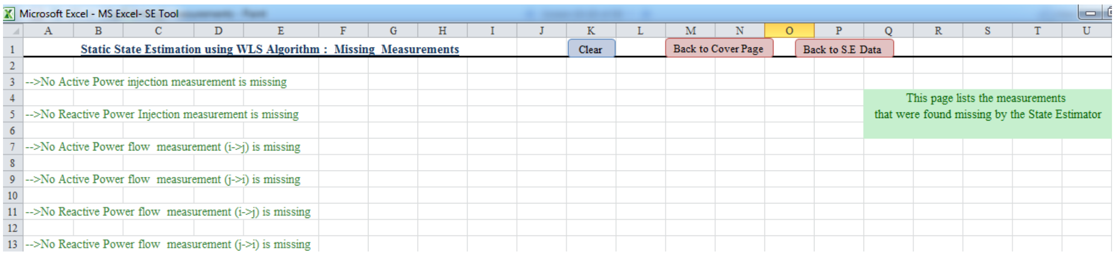
Measurements taken : 122

Measurements identified as bad data in Chi-square test : 1

Figure 4: Results of State Estimation of IEEE-14 Bus

The estimates of the missing measurements if any, are displayed on the "Missing_Data" sheet. Measurements identified as 'Bad Data' in the Chi-Squares test are displayed on the "Delete_List" sheet. Figure 5 and Figure 6 show screenshots of the "Missing_Data" sheet and "Delete_List" sheet respectively for the IEEE 14 bus state estimation with full measurement set and active power flow from bus 1 to 2 corrupted

The variation of the condition number of the Gain Matrix with every iteration and after removal of each identified bad data is shown the sheet "cond_num_G"(Figure 7). It should be noted that BDR denotes Bad Data Removed. To understand the intermediate calculations, the Gain Matrix and Jacobian Matrix obtained in the final iteration after all bad data is removed are provided in separate sheets of this tool.



Static State Estimation using WLS Algorithm : Missing Measurements

-->No Active Power injection measurement is missing

-->No Reactive Power Injection measurement is missing

-->No Active Power flow measurement (i->j) is missing

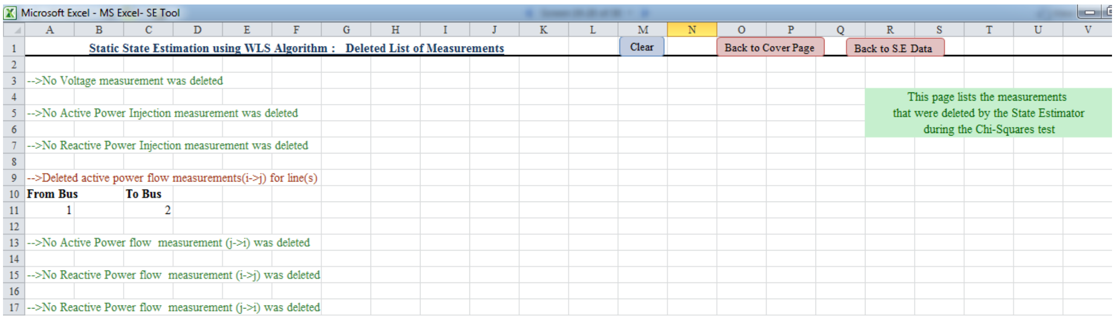
-->No Active Power flow measurement (j->i) is missing

-->No Reactive Power flow measurement (i->j) is missing

-->No Reactive Power flow measurement (j->i) is missing

This page lists the measurements that were found missing by the State Estimator

Figure 5: Missing Data Sheet



Static State Estimation using WLS Algorithm : Deleted List of Measurements

-->No Voltage measurement was deleted

-->No Active Power Injection measurement was deleted

-->No Reactive Power Injection measurement was deleted

-->Deleted active power flow measurements(i->j) for line(s)

From Bus	To Bus
1	2

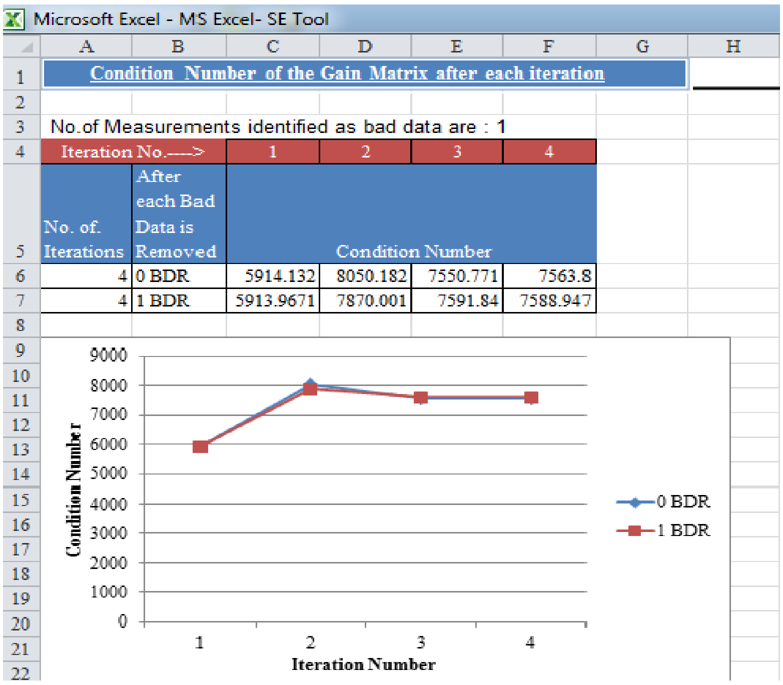
-->No Active Power flow measurement (j->i) was deleted

-->No Reactive Power flow measurement (i->j) was deleted

-->No Reactive Power flow measurement (j->i) was deleted

This page lists the measurements that were deleted by the State Estimator during the Chi-Squares test

Figure 6: Delete_List sheet



Condition Number of the Gain Matrix after each iteration

No.of Measurements identified as bad data are : 1

Iteration No.--->		1	2	3	4
No. of Iterations	After each Bad Data is Removed	Condition Number			
4	0 BDR	5914.132	8050.182	7550.771	7563.8
4	1 BDR	5913.9671	7870.001	7591.84	7588.947

Figure 7: Variation of Condition Number with iterations

4. Implementation of State Estimation using Visual Basic Application

4.1. User Forms

The built in Microsoft Visual Basic Editor is used to design the user forms. Twelve user forms were designed to facilitate the user enter the bus data, branch data, corrupt and delete one or more load flow data. Figure 8 shows the user form that allows the user to delete a measurement.

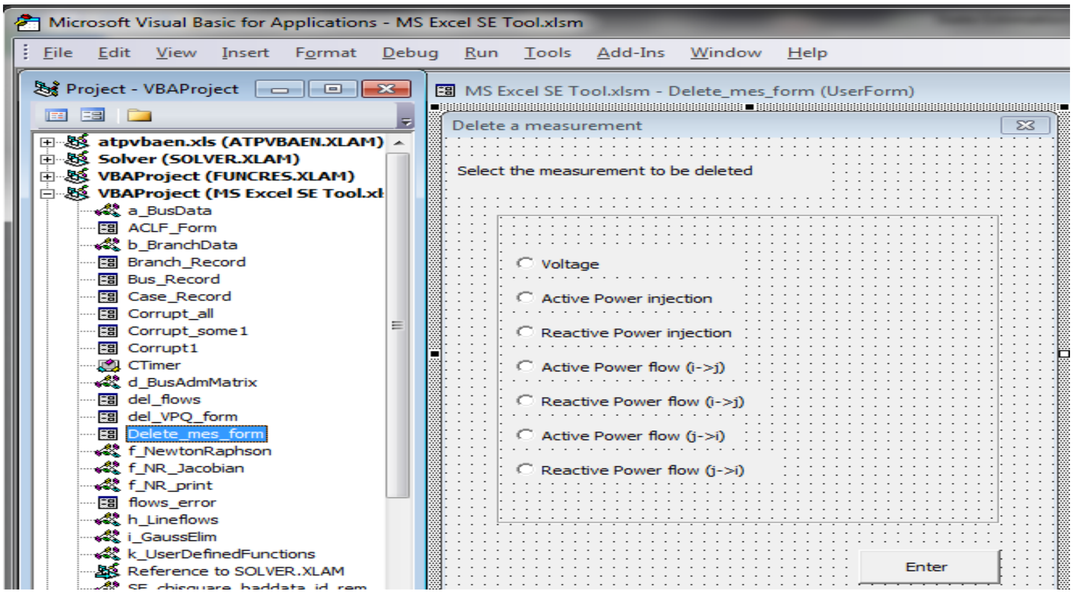

Microsoft Visual Basic for Applications - MS Excel SE Tool.xlsm
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Project - VBAProject
atpvbaen.xls (ATPVBAEN.XLAM)
Solver (SOLVER.XLAM)
VBAProject (FUNCRES.XLAM)
VBAProject (MS Excel SE Tool.xl
a_BusData
ACLF_Form
b_BranchData
Branch_Record
Bus_Record
Case_Record
Corrupt_all
Corrupt_some1
Corrupt1
CTimer
d_BusAdmMatrix
del_flows
del_VPQ_form
Delete_mes_form
f_NewtonRaphson
f_NR_Jacobian
f_NR_print
flows_error
h_Lineflows
i_GaussElim
k_UserDefinedFunctions
Reference to SOLVER.XLAM
MS Excel SE Tool.xlsm - Delete_mes_form (UserForm)
Delete a measurement
Select the measurement to be deleted
○ Voltage
○ Active Power injection
○ Reactive Power injection
○ Active Power flow (i->j)
○ Reactive Power flow (i->j)
○ Active Power flow (j->i)
○ Reactive Power flow (j->i)
Enter

Figure 8 : VBA User form and various functions used in State Estimation

4.2. Code Structure

The entire code is divided in to 20 modules (9 modules for the load flow analysis and 11 modules for state estimation analysis) and 2 class modules. Since the current tool is built up on our previous contribution (Sastry and Ramkhelawan, 2012), description of the modules related to load flow and the Ctimer class module are omitted in this paper to avoid duplicity. The 'svd' class module is used to obtain the singular value decomposition and thereby the pseudo inverse of the gain matrix.

4.3. Modules, Subroutines and Functions

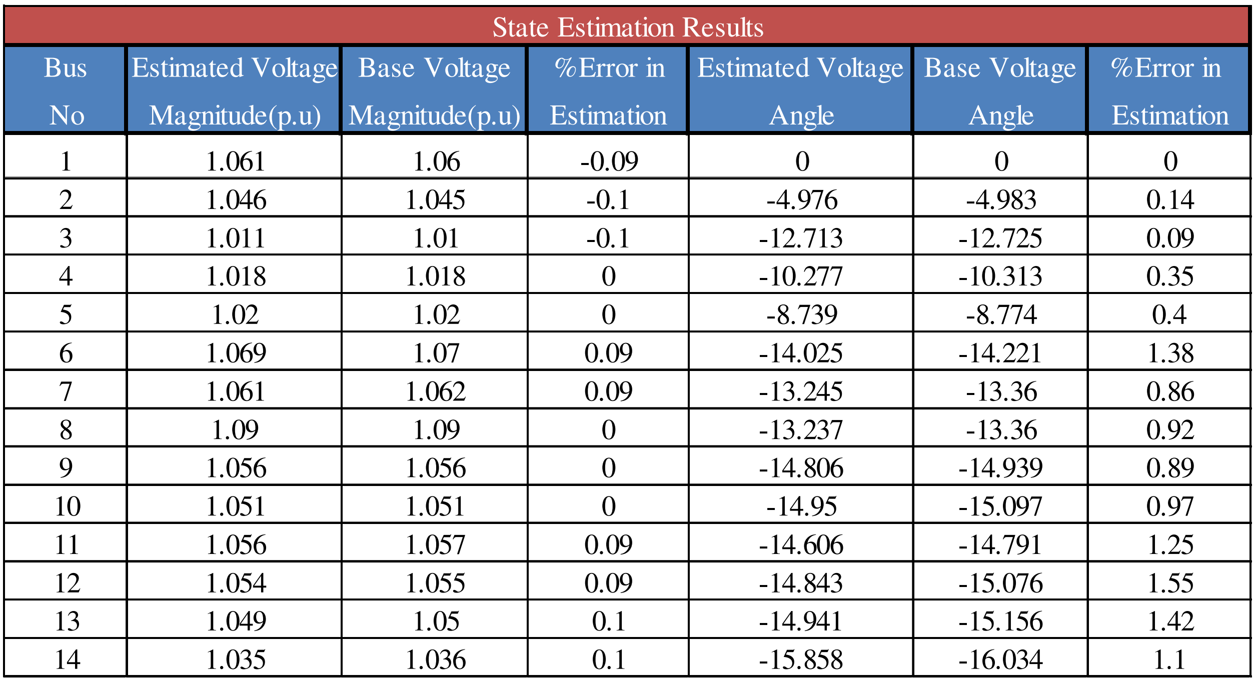
The module 'SE_misc_Functions' contain some matrix functions, subroutine 's_flatstart' to initiate a flat start to the state variables, subroutine 'Enter_case_data' that facilitates the user to enter the bus and branch data for the load flow,subroutines g_print and clear_g to print and clear the gain matrix on the sheet "Gain_Matrix" respectively , subroutines j_print, clear_j to print and clear the Jacobian matrix on the sheet "Jacobian_Matrix" respectively. The matrix functions include: 'MMYMULTIPLY(a, b) to multiply 2 matrices 'a' and 'b' ; 'MTRANSPOSE(a)' to transpose a matrix 'a' ; ' MYMATRIXINVERSE(a)' to find the inverse of matrix 'a' using SVD technique; 'MYMATRIXSUBTRACT(a, b)' to subtract matrix 'b' from matrix 'a'. Table 2 provides description for some of the modules with their subroutines.

Table 2: Description of State Estimation Modules

Modules/Subroutines	Description
SE_WLS_start Subroutine: State_Estimation_WLS	Calls the subroutines, functions to get the state estimates, detect/identify and eliminate the bad data within an loop structure until the Chi-Squares test is passed
SE_WLS Subroutines: WLS_SE, chi_test, print_SERESULTS	Contains a subroutine to call the 'form_jacobian' subroutine, form the gain matrix and iteratively implement the WLS algorithm to get the state estimates. The 2nd subroutine tests the redundancy of the measurement set before calling the subroutine to perform the Chi-Squares test. The 3rd subroutine prints the state estimates after successful estimation.
SE_measurements Subroutine: z_measurements	Formulates the measurement set to the state estimator from the S.E input. Also identifies possible missing measurements.
SE_Jacobian Subroutine: form_jacobian	This module contains a subroutine to form the state estimation Jacobian matrix.
SE_hmatrix Subroutines: S_buspwr, flows,h_matrix	This module is used to form the measurement matrix *H(x)* from the state variables in every iteration. The 1st and 2nd subroutines are used to calculate the power injections and flows respectively using the state variables. The 3rd subroutine forms the matrix *H(x)*
SE_baddata Subroutines: chi_sq, id_bad, update_variables Function: update_matrix(x)	This module is used to perform the bad data detection, identification and elimination. The 1st subroutine tests if the Chi-Squares test is passed. If the test fails then the bad data in the measurement set is identified and removed using the subroutine 'id_bad', update_variables and the function 'update_ matrix (x)' respectively. The argument of the function 'update_ matrix (x)' is the matrix corresponding to the type of measurement(V, P, Q, P_{ij}, Q_{ij}) which has the bad data.
SE_missing_mes Function: missing_mes(worksheet)	This function is used to get an estimate of the missing measurements and print them. The argument of the function used is the worksheet where the missing data estimates are to be printed.
SE_delete_list Function: del_list(worksheet)	This module contains a function to print the measurement type and index that is deleted from the measurement set during the Chi-Squares test. The argument of the function used is the worksheet where the deleted list is to be printed.

5. Illustrative Example of State Estimation

IEEE 14 bus system is considered for illustration. A Microsoft windows machine (Intel core i3-370M processor at 2.4GHz, 3GB RAM, Windows 7 Professional 64 bit operating system; MS office 2010) is used to develop this application. IEEE 14 bus state estimates are shown in figure 9 after the execution of the program. The input measurement set to the state estimator is full and uncorrupted. The standard deviation of all the measurement is assumed to be the same and is equal to 0.01.



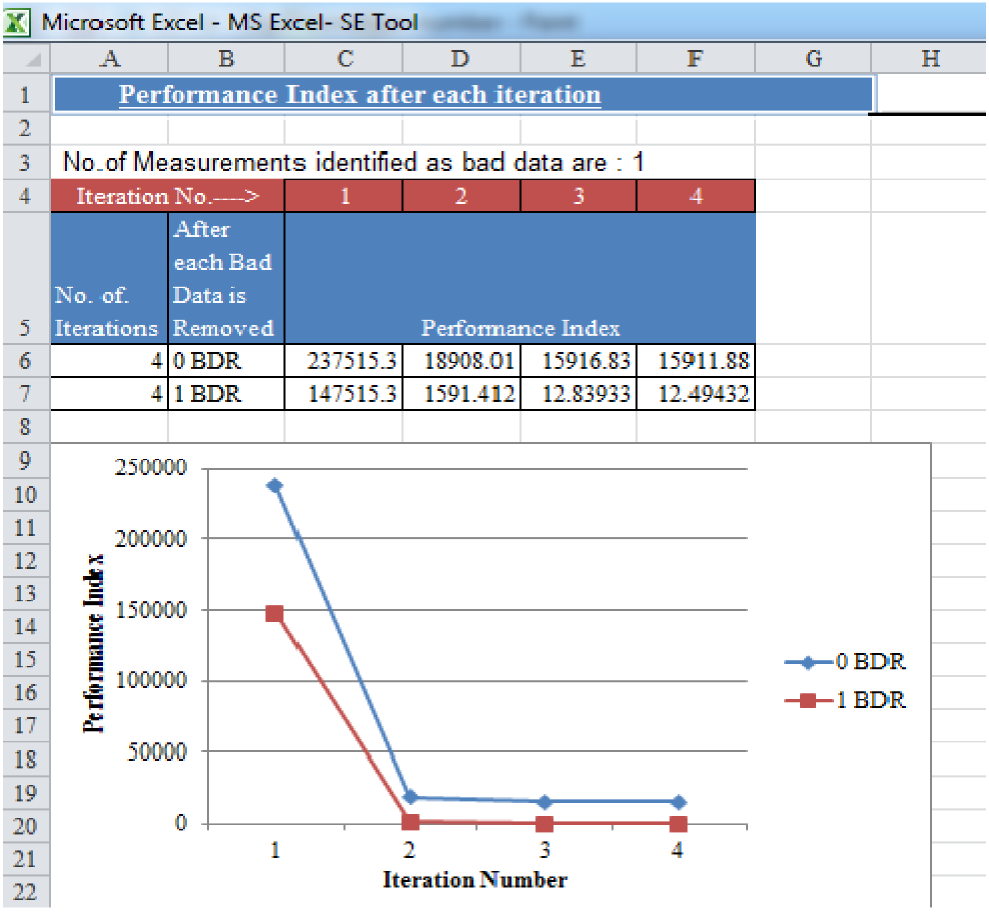
State Estimation Results

Bus No	Estimated Voltage Magnitude(p.u)	Base Voltage Magnitude(p.u)	%Error in Estimation	Estimated Voltage Angle	Base Voltage Angle	%Error in Estimation
1	1.061	1.06	-0.09	0	0	0
2	1.046	1.045	-0.1	-4.976	-4.983	0.14
3	1.011	1.01	-0.1	-12.713	-12.725	0.09
4	1.018	1.018	0	-10.277	-10.313	0.35
5	1.02	1.02	0	-8.739	-8.774	0.4
6	1.069	1.07	0.09	-14.025	-14.221	1.38
7	1.061	1.062	0.09	-13.245	-13.36	0.86
8	1.09	1.09	0	-13.237	-13.36	0.92
9	1.056	1.056	0	-14.806	-14.939	0.89
10	1.051	1.051	0	-14.95	-15.097	0.97
11	1.056	1.057	0.09	-14.606	-14.791	1.25
12	1.054	1.055	0.09	-14.843	-15.076	1.55
13	1.049	1.05	0.1	-14.941	-15.156	1.42
14	1.035	1.036	0.1	-15.858	-16.034	1.1

Figure 9 : IEEE 14 Bus State Estimation Results using WLS method

The number of input measurements to the state estimator are 122 and the total time taken by the state estimator to get the results is 2.1 seconds (this may vary from processor to processor). The Chi-Squares test was performed with 99 % confidence level and no data was identified as bad.

As the iterations proceed, the error in the estimation reduces thereby lowering the value of performance index with each iteration. This can be observed from the performance index plot. The value of performance index reduces to a very small value in the final iteration compared to that in the first iteration. From the plots shown in figure 10, it can be observed that the value of performance index reduces with the subsequent removal of bad data in the measurement set.



Performance Index after each iteration

No.of Measurements identified as bad data are : 1

Iteration No.--->		1	2	3	4
No. of Iterations	After each Bad Data is Removed	Performance Index			
4	0 BDR	237515.3	18908.01	15916.83	15911.88
4	1 BDR	147515.3	1591.412	12.83933	12.49432

Figure 10: Plot of Performance Index with iterations and Bad Data Removal

6. Learning State Estimation using MS Excel tool

Students who would like to use this tool should be familiar with the pre-requisite pockets of knowledge. This includes power system load flow; real time monitoring and control aspects of power system; SCADA based or PMU based data collection and relaying; various factors that affect the data quality and accuracy; and possible ways of bad data identification. Firstly, understanding the entire process of load flow of a typical power system from the beginning to the end is important. Specifically, understanding the usage of our load flow program (Sastry and Ramkhelawan, 2012) is essential as the current tool is built up on the same. Then, theoretical treatment of power system state estimation, its importance and application in real time control should be studied so that an appreciation for the state estimation process is developed. Then this tool can be used with the existing IEEE-14 bus data to experiment initially to understand its operation. As shown in figure 1, various stages of state estimation can be seen quickly. Different data corruption scenarios can be simulated either by deleting, over-writing the data or replacing with the data with zeros etc., to observe the operating performance of the tool. Then for solidifying the learning process, it is strongly recommended that students should take up a small system up to 5 buses and do the state estimation computations manually and then compare their values with those generated by the tool. This approach provides effective learning of the process. Researchers can use the tool for wide ranging real time control applications with different scenarios.

7. Conclusion

Microsoft Excel based tool for power system state estimation is developed. Details of the design, various modules and overall code implementation are presented. Data can be corrupted as needed to simulate different possible conditions to test the effectiveness of the state estimator. The results pertaining to Gain Matrix, Jacobian Matrix, Condition number of the gain matrix and performance index in every iteration are presented in the excel sheet. This MS Excel can be effectively used to teach or learn power system state estimation process.

References

[1]. M.K.S. Sastry and Ramkhelawan, Ricardo B. (2012) "Power System Load Flow Analysis using Microsoft Excel," Spreadsheets in Education (eJSiE): Vol. 6: Iss. 1, Article 1. http://epublications.bond.edu.au/ejsie/vol6/iss1/1/

[2]. M.K.S. Sastry, P.V. Balasubrahmanyam and Rajiv Ramrattan (2014) "Design and Development of Matlab Toolbox for State Estimation", Fourth International Conference on Communication Systems and Network Technologies (CSNT), http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6821548

[3]. C. Rakpenthai and S. Uatrongjit, "Rectangular coordinates state estimation of electrical power system using singular value decomposition," International Conference on Industrial Technology, 2009, 10-13 February 2009, pp.924 – 927

[4]. Abur and A. G. Exposito, Power System State Estimation: Theory and Implementation. New York: Marcel Dekker Inc. 2004.

[5]. Jiaxiong Chen, "Power System State Estimation using Phasor Measurement Units", Ph.D. dissertation, Dept. of Elect & Comp.Eng., Univ.Kentucky,2013.

[6]. Ellery A.Blood, "From Static to Dynamic Electric Power Network State Estimation: The Role of Bus Component Dynamics", Ph.D. dissertation, Dept. of Elect & Comp. Eng., Carnegie Mellon Univ., Pittsburg, PA, 2011.

[7]. Jyoti .S.Bhonsle and Anjali S. Junghare (2013), "Multiple Constraints Consideration in Power System State Estimation", IOSR Journal of Electrical and Electronics Engineering(IOSR-JEEE): Vol.5: Iss.4, pp .39-44.

[8]. Microsoft (2012), "System requirements for Office 2010", http://technet.microsoft.com/en-us/library/ee624351.aspx ; Last Accessed July 2014

[9]. Gomez-Exposito, A., Abur, A., de la Villa Jaen, A., C. (2011), "A Multilevel State Estimation Paradigm for Smart Grids", Proc of IEEE, Vol 99, No. 6, pp 952-976

[10]. Alam, S.M.S., Natarajan, B., Pahwa (2014), "A Distribution Grid State Estimation from Compressed Measurements", IEEE Trans on Smart Grid, Vol 5, No. 4, pp. 1631-1642

[11]. Jain, A., Shivakumar, N.R. (2009), "Power system tracking and dynamic state estimation" IEEE/PES Power Systems Conference and Exposition, PSCE '09, pp 1-8

[12]. Wenzhong Gao and Shaobu Wang (2010), "On-line dynamic state estimation of power systems", IEEE North American Symposium, September 26-28, Texas, USA, pp 1-6.