Advanced Substation Data Collecting and Processing for State Estimation Enhancement

Sasa Jakovljevic, *Student Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*--Many functions within a substation can be performed more efficiently if all the substation data is collected from and shared among Intelligent Electronic Devices (IEDs). Gathered measurements and apparatus statuses can be processed by (local) substation computer(s). Processing includes data consistency checking, switching sequence monitoring, predicting switching outcomes, etc. Processed data may be used locally and/or communicated to remote sites (neighboring substations and/or control centers). Substation data integration is facilitated by existence and appropriate connection of IEDs. The paper presents an approach to implementation of substation data integration and information exchange. The emphasis is on the utilization of local data redundancy to enhance power system state estimation, especially topology error detection.**

***Index Terms*--Data Processing, Intelligent Electronic Devices, Measurements, Monitoring, State Estimation, Substations**

I. Introduction

CONVENTIONAL Power System State Estimation relies on measurement data obtained from substations and on topological model that is stored centrally [1], [2]. Measurements that are communicated to the power system state estimator do not contain all the data that exist in one substation. The reasons for this are manifold. One can be that a legacy configuration of Remote Terminal Units (RTUs) is kept the same even after the addition of new Intelligent Electronic Devices (IEDs). Other may involve incompatible outputs from various substation devices and inability to utilize all the data in a rather simple manner.

Topological data that resides in the topology processor, which is an important part of the estimator, is usually updated manually. It is very common that this data does not reflect the real switching status of power apparatus in the field. Although the discrepancy may not be significant, it can cause a presence of bad data in the measurements even when the measurements themselves are accurate.

Another problem with topological data is that the model that describes the power system has only rough representation of substations. Even if all the existing topological data would be instantaneously available, still the detailed topology of substations would be unknown.

In an ideal case, utilization of all available measurements in the substation, not only analog but also digital (status) measurements, is desirable. In order to achieve this objective, additional level of data collecting and processing at the substation level needs to be inserted in the conventional state estimation.

Implementation of an integrated system that would collect measurement data from all the IEDs in a substation and be capable of processing them enhances the overall system state estimation significantly. However this would not be the only application of such a system. Several other functions within the substation or in neighboring substations may be enhanced utilizing the outcome of the substation data integration.

This paper presents possible implementation of a system that simulates collecting and processing of data at the substation level. The name given to such a system is the Substation State Estimator (SSE).

II. Data Availability

The advent of modern IEDs and their implementation in power substations facilitates enhanced data acquisition [3], [4]. The amount of data is increased, now offering much better monitoring of the loading and switching status within the substations. Both analog and digital (status) data can be collected from various locations within the substation and processed in one location.

Typically, more data is available than it is utilized for state estimation purpose. The idea of integrated substations is that all available data, once collected, can be processed and information obtained can be shared among all applications that may have interest in such information.

There are several problems facing the implementation of substation data integration. First and most obvious problem is great variety of devices that perform measurement tasks or data acquisition tasks. Different hardware records data differently and very broad spectrum of possible outputs is produced. The best case would be if all analog data is digitized and provided by IEDs in a consistent data format with similar accuracy. In reality, many instruments are completely analog and it is hard to fit them in the picture of modern integrated substation, although their performance is outstanding. It is also not cost effective to replace them. In such cases, additional devices can be implemented in parallel just for the purpose of redundant data acquisition or some other already installed devices can provide the acquisition of necessary data.

This work was supported in part by PSerc consortium, an NSF I/UCRC, and in part by Texas A&M University.

Dr. M. Kezunovic and S. Jakovljevic are with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77840 USA.

E-mails: kezunov@ee.tamu.edu and sasa@tamu.edu respectively.

Another problem that emerges is variety in the type of data collected from various devices. For example some meters provide rms values, other provide peak values, or measurements arrive as phasors (both magnitude and phase angle), or magnitudes only. Conventional instruments provide preprocessed values for the measured quantity whereas some IEDs provide signal samples. Since the data is available in different formats, it needs to be converted appropriately before processing. Frequency of data arrival can be different as well, which introduces the need for synchronizing the data. All conversions and preprocessing needs to be accomplished in real time which can be a problem if the amount of data is significant and/or the centralized processor is not powerful enough. This issue is becoming less and less important with steady enhancement in the performance of computers and associated equipment.

Major achievement of data integration in substations is high redundancy of data. Many devices collect the same or similar data for different purposes. This data can be made available for all purposes and it is up to the particular application to select the data it needs to accomplish its function. Redundancy also means higher chance that the task, which utilizes certain data, will be performed successfully. The tolerance over loss of data or the whole instrument/device is increased.

Another great advantage of the data being gathered in the local computer is possibility to continuously store the data. This allows the history to be known for any quantity that is being monitored or measured. If the application needs data from previous times, it is easily pulled out from the memory. This is important when the function relies on the historical data. It also helps when the IED is lost either due to its malfunction or bad communication connection.

Once all the data is collected and preprocessed to form a consistent set, various application algorithms can be applied. Possible errors can be filtered out, inconsistencies can be brought to an acceptable level, additional information can be extracted and many other functions can be performed without much additional effort or processing time.

III. Data Collecting Simulator

First task of substation data integration is collecting the data from the switchyard. The data is usually in a row form and must be preprocessed before it is further utilized.

Data can be received from neighboring substations as well, however this type of data flow is not taken into consideration at this stage of research. It is assumed that the data from all substations is transmitted to the overall system state estimator. If necessary, already processed data can be received from the control center. Disadvantage of such an indirect path is the time delay that is introduced and therefore data may become useless for some time-critical functions such as transmission line relaying [5].

SIMULINK software is utilized to implement the model of substation data collection in a virtual substation computer [6]. The model is built to represent one typical substation layout that comprises breaker-and-a half setup with a transformer, three connecting transmission lines and a local power injection device (reactor, load or similar). The substation one-line diagram layout with measurement device allocation is shown in Fig. 1. The substation model layout as it appears in SIMULINK user interface is shown in Fig. 2.

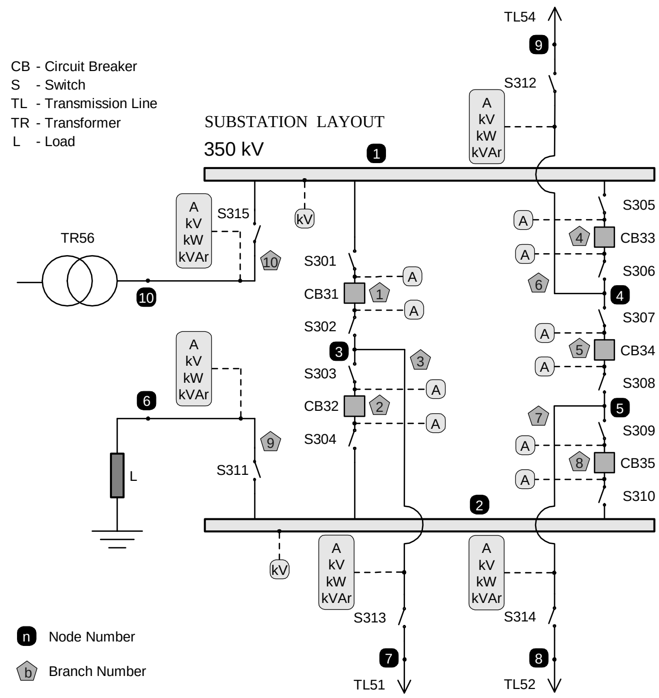

Fig. 1. One-line diagram of a typical substation layout with measurement device allocation

The substation model represents a part of the real substation that comprises apparatus at the same voltage level. Representation is much more detailed than one used for conventional state estimation purposes. The instruments whose analog measurements are collected throughout the simulation are indicated on the layout. The idea is to present only a certain level of redundancy, while in the real setup the redundancy may be much higher.

Since the model represents only a part of a larger network (in this case IEEE 14 bus system), the rest of the power system is equivalenced through boundary conditions obtained by the system admittance matrix reduction. Therefore the model contains certain terminating impedances that do not exist in an actual substation. The developed model is a three-phase model that allows unbalanced network conditions to be simulated when necessary.

The simulation is run for at least one second. This time is enough to obtain data for several data "snapshots". The term snapshot is used here to indicate data obtained from various locations around substation at the same time instant. Each snapshot is later processed separately and the output is prepared for communication to the overall state estimator.

Data is generated during the simulation and saved in a separate file. It is used later for off-line processing. In an actual application, it would be used in real-time processing. Analog data is collected from all instruments. The statuses of

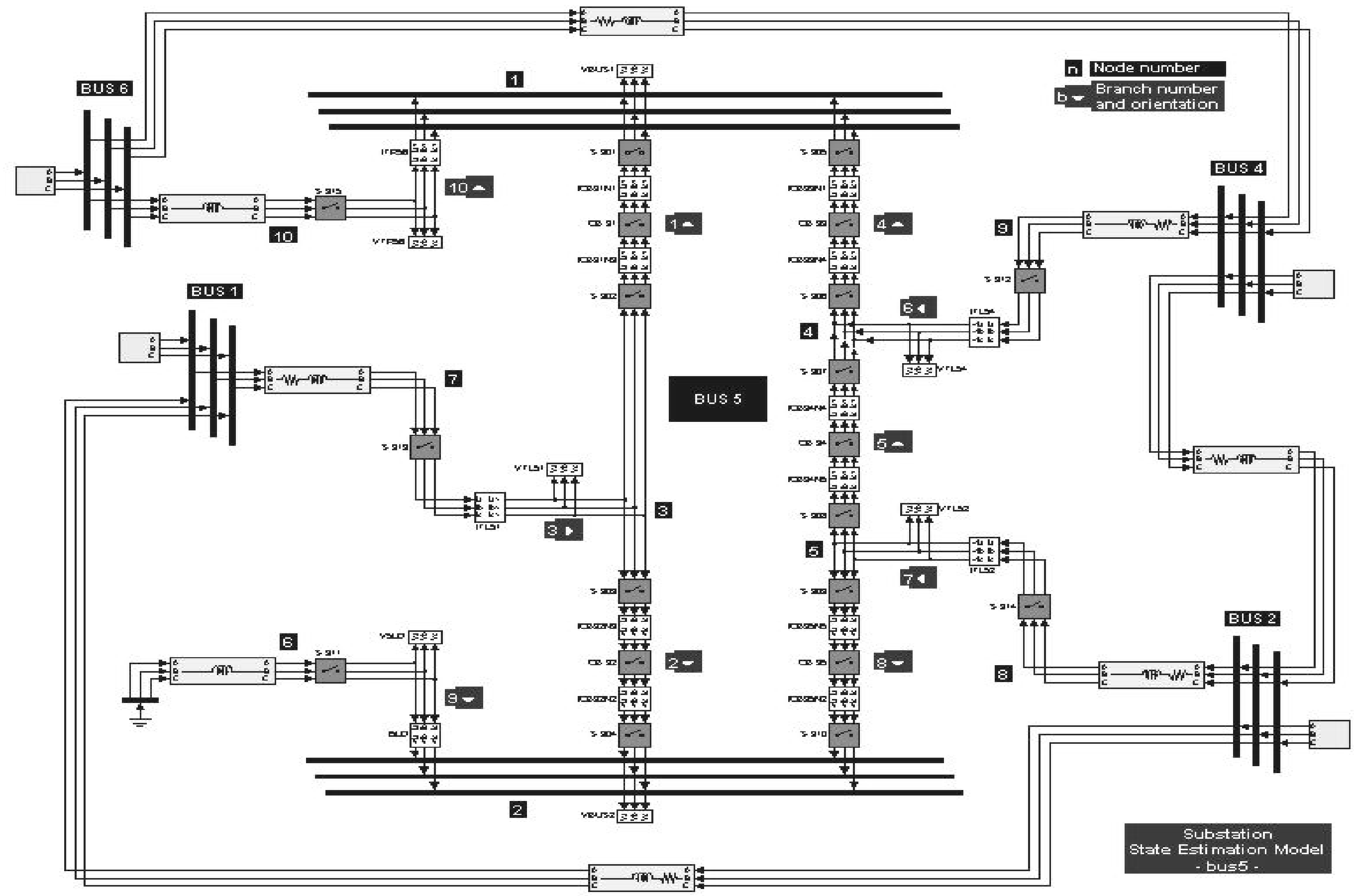

Fig. 2. Layout of the substation model as it appears in SIMULINK (comprising impedances that present boundary condition connections)

all switching elements (digital data) are also collected throughout the simulation. After completing the simulation, stored data is processed further for other applications.

IV. Data Processing Simulator

A separate program developed in MATLAB is performing processing of data [7]. This program simulates operation of substation computer that communicates the output of processing to the power system state estimator.

Data preprocessing extracts the data snapshots from the raw simulated data. It also normalizes (converts to per-unit values) the measurements for a known voltage and power base. Power flow values along certain branches are obtained where both voltage and current phasors are known. Program stores the lists of all measurement devices as well as exact topology of the substation (location of meters and switching elements).

After initial data preparation, the program performs several consistency check algorithms.

A. Consistency Check Using Redundant Current Measurements

Some branches have two measurements of current (branches containing circuit breakers with two current transformers in their bushings). The redundant measurements of current are obtained from a digital relay or some other IED monitoring the branch. In these cases, it needs to be decided what is the value for current in the branch. This is easy if both measurements agree but becomes a little more difficult when a discrepancy exists.

Algorithm calculates one value for the branch current based on both measurements and performs consistency check at the same time (ideally, both values should be almost equal). Algorithm flowchart is shown in Fig. 3.

Algorithm treats all the branches in the model. It determines first if there is a redundant measurement of current in the branch. In the branches where redundant measurement exists, consistency check is performed. The criterion is that the absolute value of the difference between the phasor currents should be less than certain percent of the absolute value of the larger current. The percent is determined by variable *MADMdis* (Maximum Allowable Double Measurement Discrepancy). This criterion needs to be satisfied for all three phases. The assumption is that there will be no discrepancy in the phase angle without a discrepancy in the magnitude.

If the criterion is satisfied, the current in the branch will be assigned one of the measurements (since they are the same to the precision determined by *MADMdis* variable).

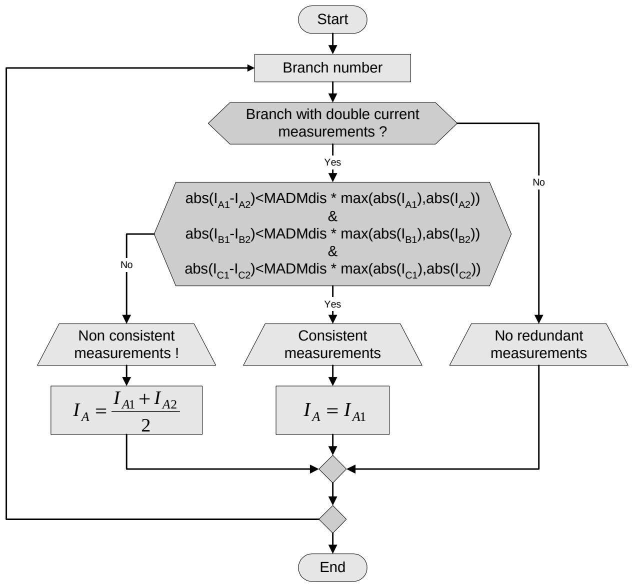

Fig. 3. Algorithm for checking the branch current consistency

In the case when any of the phase current criteria is not satisfied, alarm is generated. The current in a branch is determined as an average value of the two current measurements. Alternative to this conclusion would be to mark the current in this branch, and upon additional checks, to reject one of the measurements (if it is bad data).

B. Consistency Check Using Kirchoff's Current Law

This type of check can be performed for all the nodes where three or more branches meet and the measurements of current exist in all those branches. The algorithm is shown in Fig. 4.

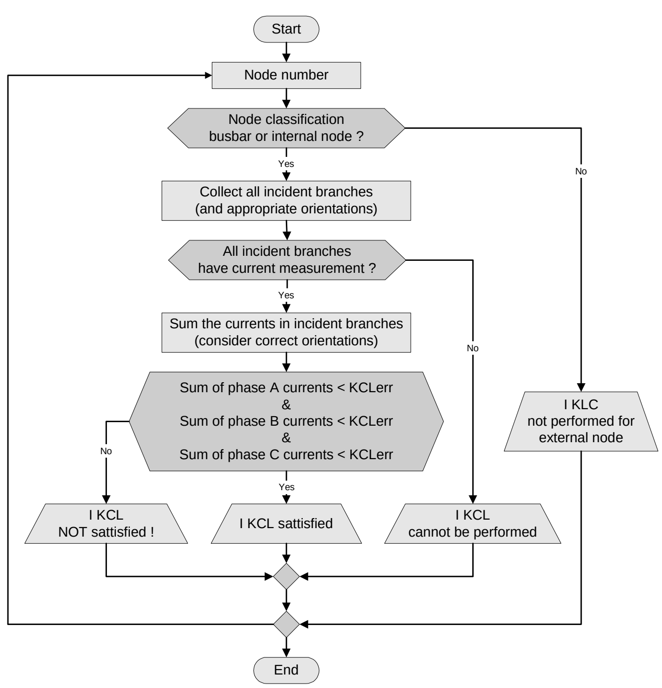

Fig. 4. Algorithm for the check of Kirchoff's Current Law

Algorithm treats all the nodes and first checks the node classification. Only the busbars and substation internal nodes are taken into consideration. First Kirchoff's law is not performed for external nodes since they split one branch (that connects two substations) into two parts and usually there is no current measurement available at least on one side.

For busbars or internal nodes, the incident branches need to be determined and a check is performed to see if all of them are equipped with IEDs measuring the currents.

For the internal nodes, there is enough information to check Kirchoff's Current Law (KCL). Currents in the node incident branches are summed considering orientation of each current (leaving or entering the node). Then the First Kirchoff's law condition is checked for each phase separately. Ideally the sum of currents should be zero, but in the program, certain error is allowable. This is defined with the variable *KCLerr*.

Appropriate messages are printed depending whether the KCL condition is satisfied or not.

C. Check of Symmetrical Components and Balanced Voltages

This algorithm also treats all the nodes. It determines first if the voltage measurement exists at a given node. The task is to calculate symmetrical components and check relative value of the zero and negative component with respect to the positive component.

Calculation of the symmetrical components for the voltage is performed applying Fortescue transform. Two variables are defined: ratio of the zero sequence component and positive sequence component (*ZOP*) and ratio of the negative sequence component and positive sequence component (*NOP*). They are used to check the balance of voltages. In order for voltages to be considered balanced, both *ZOP* and *NOP* need to be less than *MAUT* (Maximum Allowable Unbalance Tolerance). Appropriate messages are generated depending on the balance condition satisfaction.

D. Check of the Branch Status

Determination of branch switching statuses is accomplished considering all the switch elements in particular branches. Typical substation layout has either one disconnect switch or one circuit breaker with two disconnect switches in a branch. If the branch has only one switch element, that one is a disconnect switch. Branch status is determined based on the status of that switch, i.e. the branch status is the same as the switch status. For branches with three switch elements, applied logic is shown in the Table I.

TABLE I
APPLIED LOGIC FOR CHECK OF THE BRANCH STATUS IN THE CASE OF TWO CIRCUIT BREAKERS (CB) AND ONE DISCONNECT SWITCH (DS)

DS1 status	0	0	0	1	1	0	1	1
CB status	0	1	1	1	0	0	0	1
DS2 status	0	0	1	0	0	1	1	1
Branch status	0	2	2	2	0	0	0	1

Status: 0 - open, 1 - closed, 2 - unknown

Algorithm shown in Fig. 5 treats all branches and counts if there is one or three switch elements in any branch.

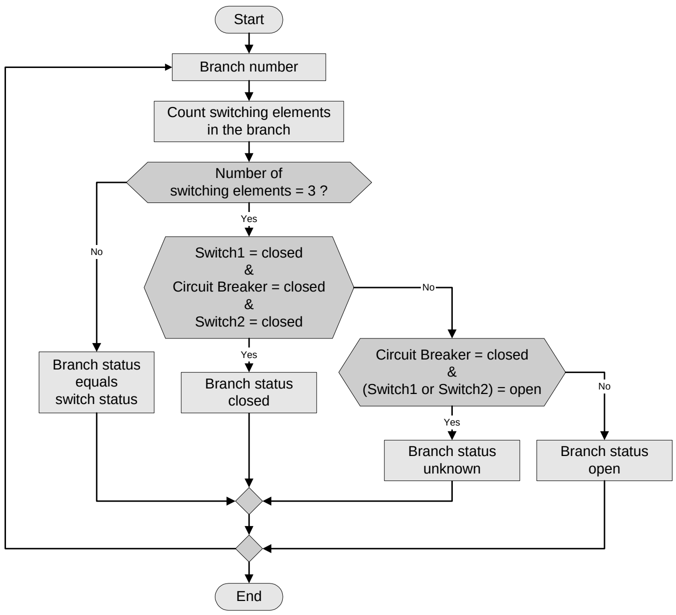

Fig. 5. Algorithm for branch status determination

Based on the status of all three switch elements, appropriate function checks the status of the branch. Function is implemented with two if-commands. First, the case when all statuses are "1" (closed) is eliminated by concluding that the branch status is also "1". Next, three cases when the branch status is "2" (unknown) are eliminated. At last, all (four) remaining cases are considered as the branch status "0" (open). This status check procedure is repeated for each phase separately. Therefore not necessarily all the phases in one branch will be in the same status. This feature allows treating non-symmetry in the phase topology when, for instance, some of the switch poles malfunction. The branch status check is not final since it can be modified later after performing the consistency checks.

The Substation State Estimation Model does not contain representation of ground switches. Those can be added and branch status check algorithm can be expanded appropriately to include their statuses in the additional consistency checks and improved topology determination. Statuses of ground switch elements are not reported to the system state estimation computer and they can be used only locally (at the level of substation).

E. Consistency Check of Branch Currents and Topology Data

This algorithm is developed to perform consistency check between branch current values and branch statuses (topology data). Checks are performed for each phase separately. There are several possible combinations of branch current values and branch statuses. Each possibility reflects different situation and has distinct impact on the conclusion.

Algorithm passes through all branches that have current measurement and finds corresponding branch current and branch status. Consistency is fulfilled for two basic cases:

- when the switch element is "1" and there is some current in the branch and
- when the switch element is "0" and there is no current in the branch.

In the case the switch element is open but there is some current in the branch, the branch status in the previous snapshot is examined since there are at least two reasons for this inconsistency. This is the first usage of the historical topology data for the purpose of determining the present state. Due to some transient processes in the circuit breaker, it is possible that current has some value greater then zero even after the "open" command is issued to the circuit breaker. By determining that the branch status has just changed in the present snapshot, it is concluded that the value of current should be zero and appropriate value is selected.

The case when switch element is "1" and there is no current in the branch is not necessarily inconsistent. If there is no voltage difference between branch terminals, branch current will be zero even if the switch element is "1". In order to investigate that, algorithm looks for the voltage measurements at the branch terminal nodes. When both branch terminals are equipped with voltage measurements, absolute value of the difference between voltage phasors is calculated. If the calculated voltage difference is greater then some already preset value, bad topology data most likely exists (correct branch status is probably "0"). Alarm is generated and the value of appropriate branch status is changed to "unknown" rather then to "0".

When the actual voltage difference is small, the situation is considered normal since the voltage difference is insufficient to create noticeable current through the branch even when the branch switching element status is "1". The consistency is fulfilled.

The last case is when the branch status is unknown. Consistency check can not yield meaningful result. Actually the branch current value can be checked and if it is greater then zero, it is possible that one of the disconnect switches in the branch had erroneous status "0" reported (which caused "unknown" branch status). The branch status could be corrected to "1".

F. Time-Series Consistency Check

This algorithm performs consistency check for a change from the previous to the current state. Analog set of measurements and topology data are examined. Their values are compared between the present and the last snapshot.

The assumption is that only a change in topology can cause a change in analog measurements. What is a change of an analog measurement should be taken conditionally since there is always fluctuation in the power flow even in the normal operation of power network. Any change in analog measurement less then some already preset value is actually not considered as a change.

The analog and topology changes since the last snapshot are detected. The algorithm examines the consistency of four possible combinations. One combination is when there is a change in both topology and analog measurement while the other one is when there is no change in those two. Both combinations yield consistency.

Third case is a change in topology without a change in analog measurement. This can happen for example when the branch status changes from "1" to "0" and there was no current in the branch before it was opened. Other example is a change in the status of a disconnect switch with circuit breaker in the branch in status "0". The topology can also change due to topology data error. Since the true reason for the topology change is unknown, it is advised to take caution due to possibly bad data.

Last case is a change in some analog measurement with no change in topology. This is more serious case than the previous one and it is more likely that the bad data is causing it. Branch numbers with changed currents as well as node numbers with changed voltages are printed as suspicious data to be further examined. It is possible that due to some remote fault, sudden change in the power flow caused a change in analog measurements and no activity is necessary. On the other hand, rechecking the suspicious data can discover some local instrument malfunction.

V. Simulation Results

Processed data is prepared to be communicated to the overall state estimator. Quantities that are of interest are node voltages and power injections and branch currents and power flows. Also topology data (switching element statuses) are sent after each snapshot. The data can be three-phase data or positive sequence data depending on the overall state estimator (currently state estimators deal with positive sequence data only, but the model gives an option for future realization of a three-phase state estimator).

Table II represents a part of the data passed to the state estimator for one of the cases that were simulated.

Table II
An example of data communicated after single snapshot to the power system control center

Node #	1	2	3	…
Voltage (mag)	0.99206	0.99206	0.99206	
Voltage (ang)	0.208	0.208	0.207	
Injection (act)	n/a	-0.0235	n/a	
Injection (react)	n/a	-0.9814	n/a	

Branch #	1	2	3	…
Current (mag)	1.62494	1.02758	2.59226	
Current (ang)	176.539	-158.331	-173.769	
Flow (act)	-	-	-2.55749	
Flow (react)	-	-	-0.26988	
Status	1	1	1	

VI. Conclusion

In order to accomplish a goal of providing accurate and detailed data to the overall state estimator, certain substation modeling tasks are performed. In addition, systematic analysis of the model behavior is realized through execution of many different simulations.

The model of integrated substation data collecting and processing application showed that a lot could be done with different data processing and checking procedures. They are all performed on raw data obtained from substation. SIMULINK part of the model simulates physical locations in the substation where measurements of different quantities originate. MATLAB part of the model simulates substation state estimation processing as a filtering stage before the data is transferred to the higher layer of the state estimation hierarchy.

VII. References

[1] A. Monticelli, “State Estimation in Electric Power Systems: A Generalized Approach”, *Kluwer Academic Publishers, Boston*, 1999

[2] A. Monticelli, “Electric Power System State Estimation”, *Proceedings of the IEEE*, Vol. 88, No. 2, February 2000

[3] A. T. Johns, S. K. Salman, "Digital Protection for Power Systems", *Peter Peregrims Ltd., London, United Kingdom*, 1995

[4] A. G. Phadke, J. S. Thorp, "Computer Relaying for Power Systems", *Research Studies Press*, 1988

[5] P. M. Anderson, "Power System Protection", *Power Math Associates, Inc., McGraw-Hill & IEEE Press, New York*, 1999

[6] SIMULINK Manual: "Using SIMULINK", The Math Works Inc., Version 4 (Release 12), November 2000

[7] Math Works, "Using MATLAB", fourth printing, revised for MATLAB 5.3., January 1999

VIII. Biographies

Sasa Jakovljevic (S'00) received his B.S. degree in electrical engineering from University of Belgrade in 1998, and currently is a M.S. candidate in electrical engineering at Texas A&M University. His research interests are power system monitoring, state estimation, protection and simulations.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of IEEE.