Software for Enhanced Monitoring in Integrated Substations

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***Abstract*--Substation data integration is facilitated by existence and appropriate connection of Intelligent Electronic Devices (IEDs). Collecting data from IEDs and its processing facilitates performing data consistency checks, filtering out erroneous measurements, monitoring of switching sequences and substation topology transitions etc. Processed data may be used locally and/or communicated to remote sites (neighboring substations and/or control centers). The paper presents software that implements substation data integration and performs processing and monitoring functions. Generated output is made available for exchange with other applications. The emphasis of data processing is on utilization of redundancy in local measurements to enhance reliability of the monitoring functions in integrated substations.**

***Index Terms*--Data Processing, Intelligent Electronic Devices, Measurements, Monitoring, Substation Integration**

I. Introduction

MAJOR achievement of data integration in substations is utilization of high redundancy of data. Many devices collect the same or similar data for different purposes [1,2,3]. This data can be made available for enhancing the monitoring functions in substations. Redundancy also means higher chance that the task, which utilizes certain data, will be performed successfully even when the data is lost [4,5]. The tolerance over loss of data or the whole instrument/device is increased. Another great advantage is a continuous storage of data. This allows the history to be known for any quantity that is being monitored or measured. This is important when a function relies on the historical data. The integration also helps when the Intelligent Electronic Device (IED) is lost either due to its malfunction or due to bad communication connection [6]. Another problem that emerges in integrated substation systems is variety in the type of data collected from different IEDs [7]. For example, some meters provide rms values, others provide peak values, or measurements arrive as phasors (both magnitude and phase angle) or magnitudes only. Frequency of data sampling can be different as well, which introduces the need for synchronizing the data. All of these problems can be resolved and consistent data can be presented by the substation monitoring function.

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II. Substation Modeling

In order to perform enhanced monitoring, the software first allows the user to configure the substation equipment connection and data acquisition system layout. All the IEDs are placed at the appropriate locations in the model by selecting the type of measurements available from the IEDs and connecting them to the particular branch and/or bus. An example of the outcome of this process is shown in Figure 1 where the substation model representing a breaker-and-a-half scheme is implemented [8].

Since the model represents only a part of a larger network, 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.

Substation modeling assumes creating interaction between the main substation computer and measurement devices located in the switchyard. Measurement device term is used here to describe Intelligent Electronic Device (IED) or an instrument that can convey any piece of information, no matter if it is analog or digital, preprocessed or not. Interconnection of IEDs implemented in the substation is also assumed [9].

The model can be executed using simulated data or the real data can be brought from the filed located IEDs [10]. Integrated substation model is designed to constantly generate raw substation data that would otherwise be obtained from a physical substation. Data is communicated in predetermined time intervals to other software components for further processing. Once the model is established, then the processing implemented in the software for the purpose of enhancing the monitoring function can be initiated.

Simulink software and standard power blockset elements are utilized to implement the model of substation data collection [11]. Several major blocks are particularly designed to model important elements and functions of the substation. Among them are equivalent source block, switching element block, measuring unit block (instrument or IED) and triggering block.

Triggering is an important step in the process of providing captured measurements to the software. Its purpose is to control data exchange rate between the model and the software and to call processing subroutine that manages measurements. The triggering synchronizes data collecting, which facilitates data comparison and related data processing.

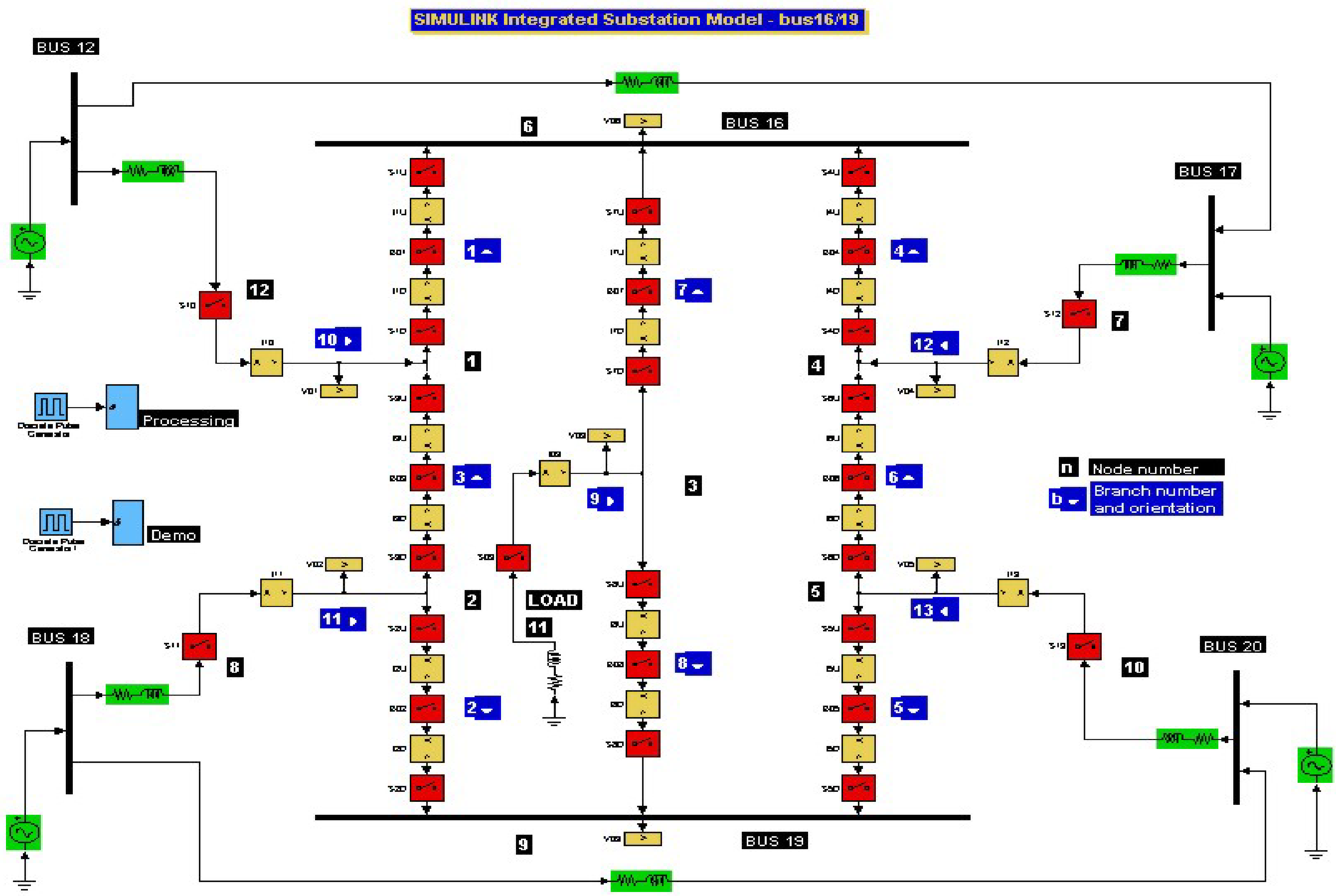

Fig. 1. Substation model representing a breaker-and-a-half scheme implemented in Simulink

III. DATA PROCESSING ENGINE

A separate part of the software is developed in Matlab [12]. It performs data preprocessing and application implementation.

As a part of data preprocessing, continuous (time domain) signals obtained from current and voltage measurement blocks are fed to the Fourier analyzer. Fourier transform is performed over a running window of one cycle of fundamental frequency. That way the magnitude and phase angle are extracted from the continuous signal being measured [13], [14]. Those two parameters completely determine phasors of measured electrical quantities.

Separate routines associated with each analog and digital measurement take care of data collecting. Their role is to acquire phasor or status measurement at the given time instants. They store those values for further processing. Phasor measurements are complex values (consisting of phasor magnitude and phase angle) while status measurements are binary scalars. Set of collected analog and digital measurements that belong to the same time instant is called data snapshot.

The adjustment of measurements originating from different IEDs needs to be accomplished prior to introducing them to the preprocessing part of the application engine. It is to be noted that preprocessing routines conduct final adjustment of signal formats, which implies certain data format conversions. Substation model extracts phasor values from sampled currents and voltages but the rest of the adjustment task is assumed to be already completed by IEDs.

After preprocessing, different measurements that are acquired around the substation are converted into consistent format. Substation model generates all analog measurements in the phasor format. If this is not the case in an actual substation IED setup, a provision in the software needs to be incorporated to create a “full” phasor representation (most of the analog instruments measure only rms values of electrical quantities).

After the snapshot data is preprocessed, it is further handled by various application routines. The routines make the core of the software. Data consistency checks are performed for each snapshot separately. In addition, each snapshot is completely processed before another one arrives. This is important due to the real time software operation, which corresponds to the way the data is processed by the main substation computer. Time series check is also feasible since data from previous snapshots is stored in computer memory and the snapshot history is readily available.

After initial data preparation, the program performs several consistency check algorithms as well as monitoring of substation topology transitions.

A. *Consistency Check of 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 also 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.

Algorithm calculates one value for the branch current based on multiple measurements and performs consistency check at the same time (ideally, all values should be almost equal). If all currents match within a preset tolerance, the output value is average of all collected values (considering measurement standard deviations). If there is a mismatch among values, branch is marked for further consideration by other algorithms. Once identified, erroneous current measurement is rejected from the set and consistency check is performed anew.

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

The sum of the currents needs to be around zero within preset tolerance. The outcome of the algorithm is displayed on the Graphical User Interface (GUI). The substation operator is alerted if the Kirchhoff's Current Law (KCL) is not satisfied for the node. Suspicious branch numbers are listed so the measurements can be additionally analyzed.

C. *Branch Status Determination*

Determination of the branch status is accomplished considering all the switch elements in particular branch and associated logic is shown in Table I. Typical substation layout has either one disconnect switch (DS) or one circuit breaker (CB) 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. Additional information is obtained from protective relays since they continuously monitor certain branches and directly influence the status of switching elements [8,15].

The algorithm determines branch status to be closed only if all switch element statuses are reported closed. This logic proved to be robust enough to allow successful detection of bad status measurements. It is to be noted here that status determined by this algorithm is temporary and the final status is determined after the consistency check performed by the next algorithm.

D. *Consistency Check of Branch Currents and Statuses*

This algorithm is developed to perform consistency check between branch current value and branch status (topology data). It determines correct switch element status based on additional information about the branch current and/or voltage difference at branch terminals. Several possible combinations of branch current values and branch statuses are given in Table II. Those combinations reflect different situations and have distinct impact on the conclusion.

Algorithm passes through all branches that have current measurement and retrieves the corresponding branch current value and branch status determined by the previous algorithm. The first thing that is checked is whether there is a current flow through the selected branch. Consistency is fulfilled when there is a current in the branch and the branch status is closed. Consistency is also fulfilled when there is no current in the branch and the branch status is opened.

In the case when there is no current in the branch and the branch status is closed, branch terminals voltage difference check is involved in the decision-making process. At last, when there is a current in the branch but the branch status is closed, status is corrected. Since it is less likely that an analog measurement would suddenly become non-zero than the status measurement suddenly be flipped, an analog measurement is trusted more. When the inconsistency is found, the alert is generated and branch status is corrected.

TABLE I
STATUS OF SWITCHING ELEMENTS AND TEMPORARY BRANCH STATUS DETERMINATION

No	DS I status	CB status	DS II status	Branch status	Comment
1	0	0	0	0	Opened
2	1	0	0	0	Opened
3	0	0	1	0	Opened
4	1	0	1	0	Opened
5	0	1	0	0	Opened
6	0	1	1	0	Opened
7	1	1	0	0	Opened
8	1	1	1	1	Closed

TABLE II
FINAL BRANCH STATUS DETERMINATION

Current snapshot	Previous snapshot	Temp. status	Voltage difference	Algorithm conclusion	Final status
$I_{CURR} > 0$	irrelevant	1	irrelevant	consistent	1
		0		**bad data**	1
$I_{CURR} = 0$	$I_{PREV} > 0$	1	irrelevant	consistent	1
		0		consistent	0
	$I_{PREV} = 0$	1	$V_{DIFF} = 0$	warning	1
		0		warning	0
		1	$V_{DIFF} > 0$	**bad data**	0
		0		consistent	0

E. Time-Series Consistency Check

This algorithm performs consistency check for a change from the previous to the current state. The analog and topology measurements may change in each new snapshot. The algorithm examines consistency of four possible combinations. The first combination is a change in both topology and analog measurement while the second one is when there is no change in those two. Such combinations yield consistency.

The assumption is that only a change in topology can cause change in analog measurements (a threshold is introduced to compensate for regular fluctuations in the power flow during normal operation of power network). Therefore, the third case is a change in some analog measurement without a change in topology and this is considered inconsistent. The last case is an inconsistency - a change in topology with no change in any analog measurement. This case actually generates only a warning message without any corrective activity.

F. Topology Transitions

The algorithm for reporting topology transitions is capable of detecting changes in the transmission line connection. It treats all transmission lines (load branch is also considered as a transmission line) and examines their connection in the current and previous snapshot. If the treated line is connected in both snapshots or it is not connected in both snapshots, no transition occurred. Only in the cases when the connection changed, corresponding transition report is generated and displayed. Line can either be connected or disconnected. Special case is when the transmission line is connected in both snapshots but to different busbars. This is called transmission line transfer and this is also detected by the transition algorithm. Transition algorithm flowchart is shown in Figure 2, while corresponding transition table is given in Table III.

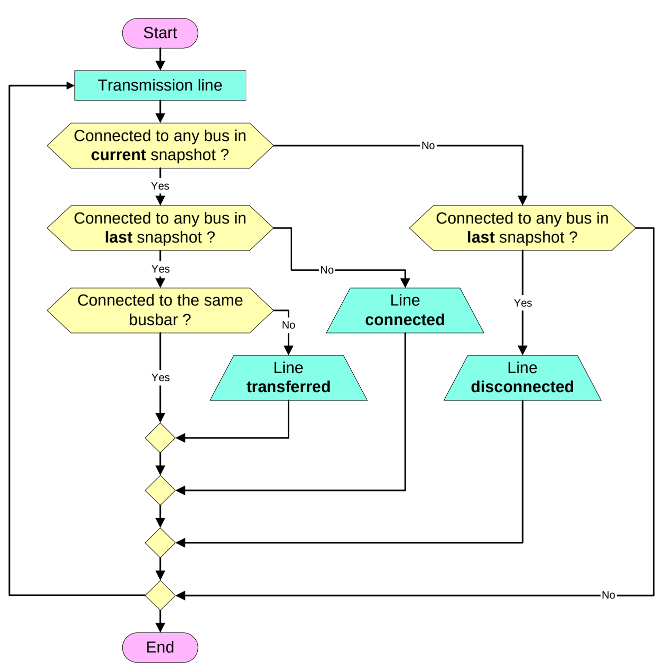

Fig. 2. Flowchart of the algorithm for reporting changes in line connections

TABLE III
TOPOLOGY TRANSITION ALGORITHM

Current snapshot			Previous snapshot			Transition
Bus I	DS	Bus II	Bus I	DS	Bus II	
1	1	0	Irrelev.	0	Irrelev.	CONNECTED
0		1				
1		1				
1	1	0	0	1	0	
0		1				
1		1				
1	1	0	0	1	1	TRANSFER
0		1	1		0	
Irrelev.	0	Irrelev.	1	1	0	DISCONNECTED
			0		1	
			1		1	
0	1	0	1	1	0	
			0		1	
			1		1	
All other combinations						No transition

IV. USER INTERFACING

User interfacing is implemented using Matlab [12]. An appearance of the user interface is shown in Figure 3. As the monitoring system “discovers” inconsistencies and bad data, it reports the results to the operator in real time. This software can be implemented either in substations or at a centralized location. The main requirement is that the substation data is brought to a database and the software executes monitoring of that substation. Interface offers selection of several modes of software operation. “Bad data” mode can be used for testing the algorithm sensitivities. “Demo” mode allows user to familiarize with typical switching sequences. “Topology transition” mode monitors changes in connection status of transmission lines and busbars. This type of interface is not presently available in commercial solutions. It is expected that implementing a system like this will give the operators much better assessment of what is going on in the system.

The Graphical User Interface (GUI), shown in Figure 3, presents one-line diagram of the integrated substation that is modeled and utilized throughout the software operation. This diagram can be realized as a visualization of the substation switchyard in the substation control room.

On the left hand side of user interface screen and above the substation diagram, the software status box displays the status of three software features: current mode of operation, initial topology scenario and status of the integrated substation model. Blue color is used to describe normal operation, while red color messages are designed to convey alert information. Important part of the GUI is the user’s menu. This drop down menu is used for most of the software control activities.

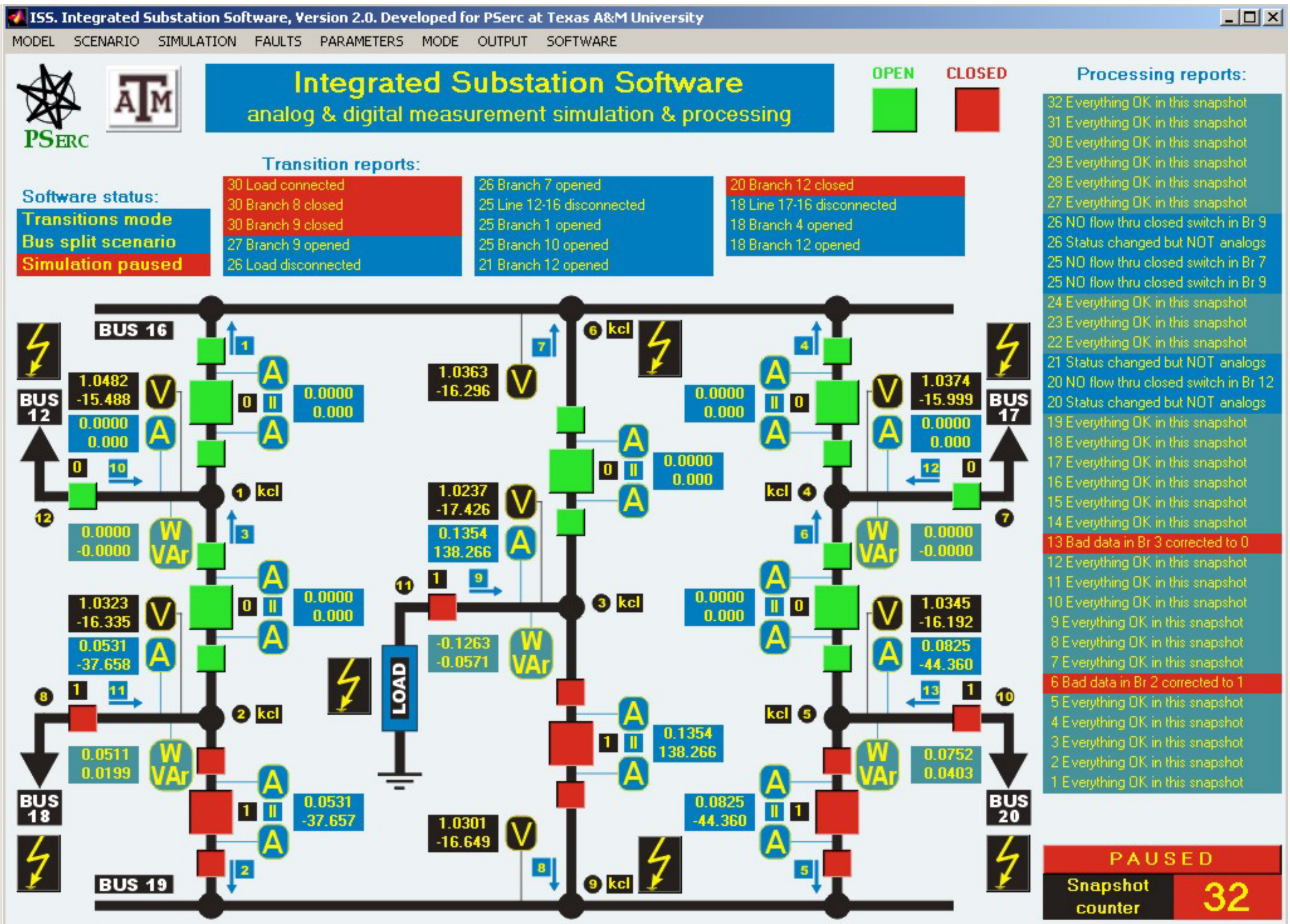

Fig. 3. Graphical User Interface screenshot with transition and processing reports

When the substation model is defined, control of substation switching device is enabled through the GUI. In other words, user can change the status of any switching element in the substation model by simply clicking on an appropriate switching element square on the user interface screen. The switch elements are presented as green or red squares depending whether they are opened or closed respectively. Clicking changes the status and color accordingly. Corresponding switching element in the substation model (that is opened in the background) will receive the new status information from the GUI. All this holds for the Control mode while Bad Data mode has slightly different logic.

Changing the status is associated with executing switching sequences. Basic switching sequence rule is that a disconnect switch should never be exposed to the electric arc. Switching sequences prevent electric arc to appear anywhere else except in circuit breakers and therefore protect substation equipment from damage and substation personnel from injuries.

Several switching sequence monitoring functions are implemented in the software. They protect all disconnect switches in the substation from breaking the current. Warnings are generated when inappropriate switching sequence is attempted, and the software prevents switching operation.

Snapshots of processing results are displayed in the box objects next to the corresponding measurement devices. Values are constantly updated during the simulation as new results are generated. The processing results as well as substation transition reports are displayed on the user interface screen. There are several types of messages being displayed: algorithm outcomes, measurement values, processing reports and topology transition reports. After each data snapshot is processed, all symbols on GUI are updated. Any change in the consistency is immediately reflected through an appropriate consistency check symbol.

Each measurement box contains a column with two numbers. For current and voltage measurements, upper value corresponds to the phasor magnitude while the lower one represents the phase angle. For the power flow and power injection measurements, upper value corresponds to real (active) power and the lower one represents reactive power. Figure 2 also gives an example of measurement boxes filled with output values.

All analog measurement values are normalized and are given in relative units. Status (digital) measurements are displayed next to the branch switching devices (or groups of switching devices) in binary form.

After processing of each data snapshot is over, measurements and topology transition reports are being displayed. Measurement reports are scrolled along the right edge of the user interface screen. Most recent reports are always displayed on the top while the earlier ones are shifted downwards. Topology transition reports are displayed only for the snapshots when some transition was detected. They are formed in three columns located above the substation layout figure. Older transition reports are also scrolled down when new ones are generated. All reports begin with a corresponding snapshot number.

The values of processing parameters can be modified. They greatly influence the operation of the consistency check algorithms. Default parameter values are selected for the best algorithm performance. User can artificially create inconsistencies by changing parameter values. This is a good way to test the operation of algorithms.

A special mode of software operation is developed for bad topology (status) data testing. In the "Bad data" mode user can click on the switch element symbol to change its status. Big difference between the "Bad data" and the "Control" mode is that the change of status does not influence substation model, but only the processing. Status of the corresponding switch element in the model does not change, but only its reported status. In other words, when user changes status of certain switching element, erroneous (bad) data is introduced. Since no status change occurs within the substation model, analog measurements that are collected from the substation remain the same (and correct).

Processing and consistency check algorithms are designed to detect and eliminate bad data measurements. It is to be mentioned here that the algorithms applied in the "Bad data" mode are the same as the ones applied in "Control" mode, i.e. the algorithms "do not know" whether the software is in the "Control" or "Bad data" mode.

V. Conclusions

This software solution demonstrates how the use of integrated substation data can significantly improve the power system monitoring capabilities and enhances performance of substation functions relying on the local measurements. It presents the abilities of different data preprocessing and checking routines that are executed over redundant measurements acquired from the substation. Extensive Graphical User Interface accompanies Simulink substation model that is executed in the background while Matlab processing routines perform the number crunching activities. User has the ability to control the substation switch elements and observe the outcome through the change of different electrical quantities. Different modes of operation are implemented here and the sensitivity of algorithms can be checked against bad (erroneous) data. Software outputs are readily displayed on the screen and can be exported as data files for the power system control center or other applications.

VI. References

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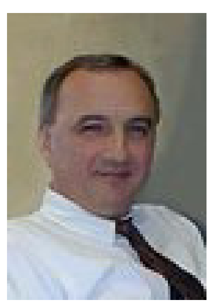
VII. Biographies

Sasa Jakovljevic (S'00) received his Dipl. Ing. degree from the University of Belgrade and M.S. degree from Texas A&M University, both in electrical engineering in 1998 and 2003, respectively. His research interests include power system monitoring, state estimation, protective relaying and simulations.



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