DATA COLLECTING AND PROCESSING FOR SUBSTATION INTEGRATION ENHANCEMENT

A Thesis

by

SASA JAKOVLJEVIC

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

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May 2003

Major Subject: Electrical Engineering

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ABSTRACT

Data Collecting and Processing for Substation Integration Enhancement. (May 2003)

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The issue of substation integration is recognized as a very important one ever since the process of technological development brought a multitude of new computer-based devices and functions into substation operation. During the relatively short time period after the first microprocessors were invented, a myriad of computer-based devices found their application in power engineering. Those devices had a variety of input and output data formats, which hampered exchange of data among different devices.

Recent initiatives for standardization of substation data formats and communication protocols have progressed to facilitate production of devices with standardized data formats and data exchange capabilities. Central substation computers now have an opportunity to collect and process data from such computer-based devices.

An advanced data collecting and processing solution is developed and implemented as Integrated Substation Software in an effort to enhance substation integration. This report describes a solution that comprises data generation using a substation model, data collecting from modeled apparatus and instruments and finally application of data processing and consistency checking algorithms for creating outputs. The process of data collecting and processing is automated and repeated in equidistant time intervals. Results of processing and related reports are concisely displayed on the user interface screen and exported through data files.

The Substation Integration Software was tested through the set of scenarios where each scenario is used to test one of the processing and consistency checking algorithms. The results show that measurements are improved and applicable for usage by other substation and system-wide applications.

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CHAPTER I

INTRODUCTION

Problem Definition

Electric Power Systems (EPS) consist of three parts in the most general case: generation, transmission and distribution [1]. They play important role in providing electrical power to customers over a power network. The electricity that is delivered constitutes an integral part of everyday life for families and businesses. The dependence of daily activities on electricity makes it very important for the electrical utilities to maintain continuous service to their customers.

Electric power systems include variety of elements such as generators, transformers, transmission lines etc. They are all connected in a certain manner to achieve power flow from the generation point to the end user. Engineering theory and practice impose that power system apparatus operate in different regimes and at different voltage levels. Substations are inevitable components in all power networks. Substation operation facilitates maintaining quality service to the customers.

In electrical circuit connotation, substations are referred to as nodes where certain number of branches join. Their role is to facilitate connection of transmission lines and provide for large number of auxiliary purposes [2]. Generation plants and large users are directly connected to the power system through substations.

Connectivity of substation is determined by the current operating state of the power system as well as the needs for economically and technologically justified power flow [3]. One of the most important tasks accomplished within a substation is switching or connecting transmission lines and other elements as the present conditions demand. Substation topology ranges from very simple to complex, depending on number of transmission lines and the substation importance within the power system [2]. Majority of substations operate at two or more voltage levels, thus having power transformers

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This thesis follows the style and format of *IEEE Transactions on Power Delivery*.

connecting them. Their structure gets more complex both topologically and functionally as the voltage level increases.

Having an important role within the power system, substations are equipped with great variety of monitoring and control devices [4]. Number of different functions are implemented, such as revenue metering, protective relaying, apparatus monitoring, automated switching etc. Reliability and security of operation are achieved with rather complex monitoring, control and protection systems developed and improved over the years.

Existing Substation Operation Practice

Development of power systems has been going on for more than a century already. It was influenced in part by steady increase in electric energy consumption over the years and in part by advancements in technology. Development brought about many changes in the substation operation practice. As the power system was growing, new substations were built and the power networks became rather complex. That required new techniques to be devised and implemented to support required substation operations. New technical systems and solutions were constantly added to improve the operation of existing ones. Development took of in several directions. Functions that were emphasized through the development became more-less independent. They were concentrating on particular substation functions that needed to be handled.

An example is protective relaying function. Relays detect faults on the system and initiate disconnecting of a faulted element or a section from the rest of the system. Their role is to remove a faulted section as quickly as possible because a fault typically creates high levels of current that can damage or destroy equipment and endanger lives. Protective relays rely on information obtained from measurement system that is independent from other substation functions. This is in part due to enhanced reliability and in part to specific requirements applied in protective relaying practice. Latest developments introduced digital relays, devices with great processing power and versatile usage also utilized out of the area of protective relaying.

Other substation devices, like certain automation modules remained focused on the designated operation. One of the consequences is that automation function usually operates locally, without being controlled from remote locations or without communicating valuable outcomes to the remote sites.

Areas Which Need Improvement

Ordinary substation system setup usually comprises extensive number of devices designed for and dedicated to particular substation function. Yet, complex operations are commonly assisted by operators to achieve good performance. One of the examples is state estimation. Since only limited number of substation switching element statuses is reported to a power control center on a regular basis, detailed substation topology cannot be reconstructed when needed. Separate issue is that power system topology processor relies on information manually updated by operators. Practice like this is not only prone to increased likelihood of error, but also delayed reporting can cause inaccurate conclusions generated by the state estimators. On the other hand, time that operator spends updating the system data can be used better for other activities.

It is not uncommon that information required by one function may be obtainable from other function but it is not shared. In above-mentioned case, an automated system that would collect statuses from protective relaying function and monitoring and control functions needs to be implemented in substation. This implies exchanging data among different substation functions.

Another shortcoming of independent substation functions operation is in case when erroneous data occurs in the system. Due to a function relying on a single data acquisition device for particular measurement, malfunction of that device can cause malfunction of the whole function. In other words, redundancy of measurements that exist in substations is not utilized. Redundancy not only helps when certain measurement is lost, but it can also be used on a regular basis as a means of enhancing reliability of information and filtering out bad data.

Functions that rely on human input depend on their experience and intuition. This may not be the best way to handle the problem in operations that require complex quantitative assessment. Operator’s actions at least should be monitored by automated functions as in case of substation topology transition processes that require strictly followed switching sequences. Repetitious operations are performed the best by machines and should be automated in the highest possible extent.

Status of the Solution

The advent of Intelligent Electronic Devices (IEDs) enhanced the quality of operation of many substation functions. Although still new, digital equipment is being increasingly installed, thus replacing old mechanical and analog devices. High processing power of modern devices helped overcome many problems associated with complexity of certain functions. Large number of combinations faced in switching sequence procedures was overcome by complex algorithms conveniently performed on substation computers.

Ideas about sharing data among different substation devices existed from the early substation developments. Two problems were faced that delayed applicable solution. First, analog devices produced data that was stored, processed and compared with great difficulties. Benefits from shared data operation were hardly comparable with associated expenses and effort that were to be invested. Second issue was incompatibility of devices and non-existence of relevant standard that would unify forms of data produced by devices supplied by variety of vendors. Data conversion solutions were either not applicable or their price range was too high.

Technological advancements brought new generation of devices into operation. So called intelligent electronic devices offered solution for many problems. For the first time, “integration” option was discussed with promising results. Integration of substation monitoring, control and protection equipment suddenly became very attractive [4]. Great opportunity to enhance the operation of substations and the power system in whole appeared to be inherent to the digital equipment flexibility. Any piece of data, ones became digital, was convenient to be processed, stored and/or communicated.

Integrated Substation Solution

A breakthrough in substation operation is made with digital technology that facilitates communication among different Intelligent Electronic Devices (IEDs). Data can be collected around the substation from variety of IEDs. This facilitates local processing and enables enhancements of substation functions.

Integrated substation system is capable of collecting measurement data from all the IEDs in a substation. It performs processing of data, which proves to be beneficial for overall system state estimation purposes and also enhances local applications. Several other functions within the substation or in neighboring substations may be enhanced utilizing the outcome of the substation data integration. The amount of collected data is increased thanks to data integration and exchange capabilities. Monitoring of the loading and switching status within substations can be improved significantly. Both analog and digital (status) data can be collected from various locations within the substation and processed in one location. The idea of integrated substations is that all available data, once collected by different IEDs, can be processed and information obtained can be shared among all applications that may have need for 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 [4]. In the best case, all analog data is digitized and provided by IEDs in a consistent data format with similar accuracy. Reality indicates that 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.

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 loss of 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 due to bad communication connection.

Once all the data is collected and preprocessed to form a consistent database, 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.

Thesis explores the current state of the substation instrumentation technology, analyzes possible trends in integration of intelligent electronic devices installed in substations and finally enhances the substation integration by implementing advanced data collecting and processing. One of the important facets is to show that utilization of redundant data within substation improves several functions and enhances substation operation in general. Redundancy of data is based on exploiting the capability of intelligent electronic devices to communicate with each other and with central substation computer, thus sharing the information that was not be available in the earlier designs.

The remaining text describes the substation integration solution in detail as well as the relevant theory and developed software. Results are given for a set of test scenarios that are simulated by the software. It will be shown that this solution improves reliability of data that is generated as an output of an integrated system. Another important thing that will be shown is filtering out bad topology data that occurs as a consequence of bad status reporting.

CHAPTER II

INTEGRATED SUBSTATION BACKGROUND

Introduction

Before proceeding with solution for advanced substation data collecting and processing for enhanced substation integration, a background of integrated substation will be discussed. This review analyzes equipment, their relationships and ability to exchange data as a foundation for the integration process. Different types of intelligent electronic devices are presented along with their common features. Recently proposed communication standard is addressed as a prerequisite for successful data exchange among equipment produced by different vendors.

A great variety of instruments and other devices that coexist in a substation is producing different accuracy of measurements depending on the sources of the measurements. With that in mind, different standard accuracy classes of instruments are discussed.

The importance of digital (contact status) measurements is not less than any other measurement in the substation. Majority of local substation and system-wide applications use status data as necessary information in the decision-making process. Dependability on correct topology determination increases with complexity of particular function. A survey of existing bad data detection and identification methods is given to introduce this issue.

The integration of substation devices and measurements assumes consideration of at least three factors. Intelligent electronic devices are very important element in the integration process due to the ability of providing multitude of measurements in digital form. Availability and application of a standard that regulates consistency of data formats and communication protocols is a necessity. Redundancy of measurements is used to provide a consistent set of measurements available for different substation and system applications.

Intelligent Electronic Devices (IEDs)

Intelligent electronic devices are introduced to the world of substation equipment in the late nineties. Thanks to developments in microprocessor technology, a new generation of devices is created that brings new features with improved performance. Processing algorithms are incorporated even at the lowest level of instruments installed in substations. Processing power of digital electronic devices is one of the main reasons to replace old analog devices. Ease of digital data exchange is another very important reason to substitute traditional analog instruments.

Versatility of intelligent electronic devices in modern substations is great [4]. Many factors contributed to installation of such a variety of measuring, processing and recording equipment. Some of them include the history of substation developments and upgrades, operating practice of specific utility or location and importance of particular substation. Intelligent electronic devices can be sorted in several categories:

- Digital Protective Relays (DPRs)
- Digital Fault Recorders (DFRs)
- Sequence of Event Recorders (SERs)
- Remote Terminal Units (RTUs)
- Fault Locators (FLs)
- Other Intelligent Electronic Devices (IEDs) used for variety of monitoring and control applications

All these categories will be described in more details next.

Digital Protective Relays (DPRs)

The latest generation of protective relays is fully digital and equipped with decision-making algorithms. They are complex recording, monitoring and measurement devices capable of performing many new functions comparing to earlier generations of protective relays.

Thanks to their digital electronic nature, modern protective relays are capable of interfacing with outside world through communication channels. This allows them to be monitored and controlled from remote locations. Variety of relay settings can be accessed and changed from the control center. Internally computed measurements and logic signals could be communicated and used for variety of purposes.

Digital relays use analog current and voltage signals acquired by instrument transformers and digitize them by A/D converts. Process of digitizing assumes sampling analog signals with certain sampling rate and representing the created samples by certain number of binary digits. Protective relaying function requires fast operation and therefore digitization process must not be a bottleneck of the operation. In order to speed up A/D conversion, relatively low sampling rate is implemented. Obtained signal phasors are enough for protective relaying purposes and the content of higher harmonics is limited. When better frequency representation is needed for recording function, then digital fault recorders are utilized. However, developments in microprocessor technology increased the processing power of DPRs and made them capable of sampling signals with much faster rate. This allows even DPRs to capture broad bandwidth of input signals and represent those correctly.

Besides providing protective relaying function, modern DPRs are also equipped with different measuring functions and can be used as complex measuring instruments. In the process of substation integration, this fact is extensively used and relays are seen serving other purposes beside the main one. Protective relays have specialized data formats and communication protocols, which makes their measurements difficult to use for other applications.

Digital Fault Recorders (DFRs)

This type of intelligent electronic devices is primarily used for recording waveforms with high accuracy. They do not perform real time processing of obtained waveforms, as a difference from DPRs. This allows them to use the whole processing power for converting and storing samples, which in turn enables using very high sampling frequency. Therefore, monitored signals are recorded with great precision in both the magnitude and higher frequency harmonics.

Sampled waveforms of input signals and contact data are used in variety of monitoring applications. DFRs are usually connected in parallel with DPRs. They do not continuously store the waveforms, but start upon being triggered by relay trip signals. They provide detailed information about transient waveforms of monitored quantities during the fault. Triggering may also be accomplished through a separate function within DFR. Capability of triggering function to detect desired disturbance reflects on DFR's ability to capture relevant waveform.

Availability of DFRs in substations is closely related to their price. It is common that only most important signals are recorded. That means that not all the desired quantities will be recorded.

Sequence of Event Recorders (SERs)

These devices play an important role in recording status of switching elements. Triggered by certain change in the monitored signal, they are capable of capturing the whole switching sequences. The precision of captured events depends on data sampling rate, which is usually very high. Appropriate time tagging of recorded events provides for storing the time series measurement. Thus, it can be successfully analyzed later and additional information can be recovered.

SERs can be combined with analog signal measurements to provide for status change of variety of controllers. In addition, most of the SERs can be used to provide control functions through their control outputs.

Remote Terminal Units (RTUs)

RTUs are part of the Supervisory Control and Data Acquisition (SCADA) system. These devices are extensively used for monitoring substation quantities and communicating recorded data to SCADA database. Performance of modern RTUs is outstanding although they are one of the oldest IEDs. They can have many functions and some of them overlap with certain functions of previously described devices. They also possess moderate data preprocessing capabilities. Potential problem with RTUs is limited opportunity for usage of their outputs at the substation level due to nonexistence of appropriate interfacing module. This is a consequence of their design to primarily communicate outputs to the SCADA.

Fault Locators (FLs)

The primary function of these devices is very accurate determination of fault location. For that purpose, FLs monitor transmission line currents and voltages. Exchange of these quantities with other devices can significantly enhance substation monitoring function. Unfortunately, price range for dedicated FLs is very high and usually it cannot be justified since other devices within the substation are capable of providing similar function.

Other Intelligent Electronic Devices (IEDs)

The rest of the IEDs are used for variety of monitoring and control applications. They include various Programmable Logic Controllers (PLCs) and other power equipment controllers, position monitors, interposing relays, instruments for load survey and/or operation indication, revenue meters etc. They are designed to perform various tasks from simple operations to extensive processing combining monitoring and control functions. Their outputs usually comply with particular function needs and differ from device to device. This may be the main obstacle for their use in substation integration.

Substation integration idea is based on utilization of redundancy in analog and status measurements. Outputs of substation monitoring, control and protection equipment contain large number of redundant data that can be used to improve accuracy and tolerance to errors. Exchange of information creates redundancy since similar measurements can be compared. Consistency in measurements confirms their values while discrepancy indicates existence of erroneous data caused by either instrument malfunction or some communication problem.

Substation Communications

Digital data is much more convenient to be communicated then analog data. Convenience is not the only advantage. Reliability as well as the overall quality of transmission is significantly increased. Communication errors are easier to correct and data can be compressed in order to make the transfer faster [5]. One of the disadvantages is A/D conversion time used to convert analog signal into digital word. This is not a significant drawback, especially with modern fast multi channel converters.

Exchange of information is a crucial aspect in substation integration. First analog devices that were implemented had very limited communication abilities. Local displaying was prevailing form of their output. Reading such outputs was tedious and required operators to physically move around the substation. Later improvements of those devices and their communication abilities offered expanded remote control and monitoring. The real progress was made with installation of intelligent electronic devices (IEDs).

Various intelligent electronic devices perform monitoring, control and protective functions. They all generate outputs in certain formats understandable to applications they belong to. Capability of communicating outputs and collecting data at the centralized location within substation is one of the prerequisites for successful substation integration. However, variety of IEDs introduced incompatible data formats, which constrains the opportunity for system wide data exchange. Great advantages of digital devices were hampered due to nonexistence of appropriate standardized data formats and communication protocols.

Standardization of data formats and communication protocols plays an important role due to variety of vendors producing different types of IEDs. For that reason, an initiative to create the standard for substation digital equipment communication is under way. Utility Communication Architecture (UCA) concept was initiated and yielded several documents that are to be included in the future IEC 61850 standard [6], [7], [8]. One of the main goals is to produce and allow implementation of IEC 61850 standard.

This standard serves the need of assuring that interoperability of various substation IEDs is feasible.

The most important document is called “Generic Object Models for Substation and Feeder Equipment” (GOMSFE), version 0.91 [7]. It “provides the standard interface definition for the outside world to communicate with field device controllers, and the representation of the field devices”.

The substation communication standard is the base for enhanced substation integration. It gives necessary tools and definitions for successful data exchange among intelligent electronic devices. Practical setups already proved the validity of the concept. Since the majority of work regarding definitions of the standard is already finished, this thesis discusses some practical application issues.

The standard defines appropriate classes, objects and object models for various intelligent electronic devices. It also gives standard data types that are used throughout the system. All inputs and outputs are standardized which allows peer-to-peer communication (data exchange among different substation devices, including the local computer). Software applications that are based on the substation hardware are structured in several layers depending on their complexity. Each layer is interfaced with the vertically adjacent ones, from the physical devices at the bottom to humans at the top, and vice versa. The system is defined as a set of basic building modules (bricks) that are utilized to create arbitrary functional structure and complexity.

Measurements

The most important issue in substation monitoring is improved metering of various electrical quantities. One group of measurements is referred to as analog quantities such as currents, voltages and powers, whereas the other group represents contact statuses of substation switching devices. Knowing the values of relevant digital and analog quantities yields the picture of both substation topology and associated power flows. This in turn either keeps the current substation loading within the predefined limits or initiates corrective actions through appropriate substation functions.

The most common devices that are used in the process of measuring analog quantities are instrument transformers and transducers. Quality of measurements depends on the ability to accurately scale the quantity from the power system level on the primary side to a low level of the secondary side where IEDs are interfaced. Extensive survey of standard accuracy classes of instrument transformers is given in the IEEE standard C57.13-1997 [9], [10]. IEDs designed for protection function have one accuracy class. They accurately measure fault currents but the load regimes are followed by much less accurate measurements. On the other hand, devices whose measuring is part of a control function may lack the accuracy in the overloaded regimes.

The level of trust in certain measurement is qualified by the standard deviation. The theory developed to treat this issue is the state estimation [11], [12]. Other substation functions also depend on this information. This is especially important in the process of mixing redundant measurements obtained from different types of measurement devices (for example metering and protection devices). Standard accuracy classes review for instrument transformers based on IEEE standard C57.13-1997 [9] will be given next. It is closely related to the issue of standard deviations.

Standard Accuracy Classes

Accuracy classes for revenue metering are based on the requirement that the transformer correction factor (TCF) of the current transformer or of the voltage transformer should be within specified limits when the power factor (lagging) of the metered load has any value from 0.6 to 1.0. The specified conditions under what we consider the previous are as follows:

a) For current transformers, at the specified standard burden at 10% and 100% of rated primary current. The accuracy class at a lower standard burden is not necessarily the same as at the specified standard burden.

b) For voltage transformers, for any burden in volt-amperes from zero to the specified standard burden, at the specified standard burden power factor and at any voltage from 90% to 110% of the rated voltage. The accuracy class at a lower standard burden of different power factor is not necessarily the same as at the specified standard burden.

The limits of transformer correction factor in standard accuracy classes should be within the ranges given in Tables I and II. The 100% rated current limit also applies to the current corresponding to the continuous thermal current rating factor. An accuracy rating should be given for each standard burden for which it is rated.

Table I. Transformer correction factor limits for current instrument transformers

Metering accuracy class	At 100% rated current		At 10% rated current	
	minimum	maximum	minimum	maximum
0.3	0.997	1.003	0.994	1.006
0.6	0.994	1.006	0.988	1.012
1.2	0.988	1.012	0.976	1.024

Table II. Transformer correction factor limits for voltage instrument transformers

Metering accuracy class	At 90% to 110% rated voltage	
	minimum	maximum
0.3	0.997	1.003
0.6	0.984	1.006
1.2	0.988	1.012

For relaying accuracy ratings, the ratio correction should not exceed 10%. Relaying accuracy ratings should be designated by a classification and a secondary terminal voltage rating as follows:

a) *C, K or T classification*. C or K classification covers current transformers in which the leakage flux in the core of the transformer does not have an appreciable effect on the ratio or ratios within the limits of current and outlined burden, so that the ratio can be calculated. Current transformers with K classification should have knee-point voltage at least 70% of the secondary terminal voltage rating. T classification covers current transformers in which the leakage flux in the core of the transformer has an effect on the ratio within the limits specified in item b.

b) *Secondary terminal voltage rating*. This is the voltage the transformer will deliver to a standard burden at 20 times rated secondary current without exceeding 10% ratio correction. Furthermore, the ratio correction should be limited to 10% at any current from 1 to 20 times rated secondary current at the standard burden or any lower standard burden used for secondary terminal voltage ratings.

Secondary terminal voltage ratings are based on a rated secondary current of 5A (100A at 20 times rated) and standard burdens. The voltage ratings and their associated burdens are given in Table III.

Table III. The secondary terminal voltage ratings and associated standard burdens

Secondary terminal voltage	10	20	50	100	200	400	800
Standard burden	B-0.1	B-0.2	B-0.5	B-1	B-2	B-4	B-8

If a current transformer secondary winding is rated at other than 5A, appropriate voltage rating values should be derived by multiplying the standard voltage rating values by coefficient 5/(amperes rating).

Definitions of some earlier mentioned terms

TCF is the ratio of the true watts or watt-hours to the measured secondary watts or watt-hours, divided by the marked ratio. Marked ratio is the ratio of the rated primary value to the rated secondary value as stated on the nameplate.

The transformer correction factor for instrument transformer is the ratio correction factor multiplied by the phase angle correction factor for a specific primary circuit power factor. Ratio correction factor is the ratio of the true ratio to the marked ratio. The primary current or voltage is equal to the secondary current or voltage multiplied by the marked ratio times the ratio correction factor. Phase angle correction factor is the ratio of the true power factor to the measured power factor. It is function of both the phase angles of the instrument transformers and the power factor of the primary circuit being measured.

Standard burdens

Burden of an instrument transformer is that property of the circuit connected to the secondary winding that determines the active and reactive power at the secondary terminals. Standard burdens for current transformers with 5A rated secondary current should have resistance and inductance according to Table IV.

Table IV. Standard burdens for current transformers with 5A rated secondary current

Burdens	Designation	Resistance	Inductance	Impedance	Voltamperes	Power factor
Metering burdens	B-0.1	0.09 Ohm	0.116 mH	0.1 Ohm	2.5	0.9
	B-0.2	0.18 Ohm	0.232 mH	0.2 Ohm	5.0	0.9
	B-0.5	0.45 Ohm	0.580 mH	0.5 Ohm	12.5	0.9
	B-0.9	0.81 Ohm	1.040 mH	0.9 Ohm	22.5	0.9
	B-1.8	1.62 Ohm	2.080 mH	1.8 Ohm	45.0	0.9
Relaying burdens	B-1	0.50 Ohm	2.300 mH	1.0 Ohm	25.0	0.5
	B-2	1.00 Ohm	4.600 mH	2.0 Ohm	50.0	0.5
	B-4	2.00 Ohm	9.200 mH	4.0 Ohm	100.0	0.5
	B-8	4.00 Ohm	18.400 mH	8.0 Ohm	200.0	0.5

Two Typical Bus Arrangements

Bus arrangements in high voltage substations vary depending on many factors such as flexibility of operation, available equipment, investment and operational costs etc. There are roughly ten different bus arrangements. They all have advantages and disadvantages regarding particular implementation but two bus arrangements that are most commonly found in the United States are breaker-and-a-half and two-bus-two-breaker type. They will be discussed next.

If more than six to eight circuits are connected to the bus, it needs to be split by circuit breaker due to fault protection reasons [2]. This breaker is called bus tie breaker and, if installed, has important role in determination of substation topology. Likewise, the circuit breakers employed for connecting generators, transmission lines, power transformers, motors etc, participate with equal importance in the determination of the substation topology. Correct status of all switching elements gives the overall picture of possible paths in the power network.

Two-bus-two-breaker type (also known as double bus – double breaker type) of bus arrangement is very flexible. The price for flexibility is paid through installation of two circuit breakers for each connecting element. The connection can be done to each bus independently by closing appropriate circuit breaker. In addition, two buses can be connected if both circuit breakers are closed.

Breaker-and-a-half type of bus arrangement also provides good operating flexibility. It is used to provide connection for two elements and it employs three circuit breakers. Since one of the circuit breakers serves both elements, it is in average “breaker-and-a-half” per element. The advantage is lower cost since fewer breakers are employed.

The analysis conducted in further chapters will refer to the two bus arrangements discussed here and the figures will be shown.

Bad Data Detection and Identification

Very important issue in substation integration process is enhancement of bad data detection and identification. Large number of local and remote power system functions rely on correct substation topology. Status of various switching elements within the substation (disconnect switches, ground switches and circuit breakers) is usually not reported in detail to the control center. Due to the frequent switching operations in the substation (reasons can be maintenance, fault clearance, load distribution etc), topology may be reported erroneously. Such a discrepancy reflects negatively on power system state estimation [12]. Currently, state estimators rely on a periodically updated topology information (in most cases the process of updating is manual). During the state estimation calculation process, estimators assume that the topology information they have is correct. Topology errors reflect as analog measurement errors at the end, which may cause some erroneous conclusions.

The interpretation of analog measurements in a substation is closely connected to topology. On the other hand knowing topology is equivalent to knowing correct and up-to-date status measurements. Integration of substation devices is a way of creating redundant measurements that leads to enhancement of overall substation measurements, where all or at least most of the bad data will be detected, identified and corrected.

Methods for treating topology error detection and identification can be classified through analysis of the research work described in literature and papers. Different approaches have been proposed to deal with topology assessment. Some of them relate to power system state estimation function while other give general aspect of the bad data handling problem.

Both measurement errors and network topology errors reduce accuracy of the measurement database used for power system operation and control. Detection and identification of topology errors is equally important and has to be analyzed properly. *Detection* refers to detection of the presence of topology error in the system, while *identification* refers to identification of location of the error. Status of circuit breakers and disconnect switches determine topology of the network. Analog measurements determine loading of transmission lines and transformers as well as system voltage profile.

Normalized Residuals Approach

Topology errors in electric power networks can be detected by methods that treat measurement residuals caused by such errors. Some of the methods utilize geometric interpretation of the residuals [13], [14], while other use conventional normalized residuals from the results of state estimation procedure [15].

Test for single topology error detection and identification is presented in the reference [13] and further generalized to multiple topology errors. In the presence of a single bad measurement, residual vector must be collinear with a column of residual sensitivity matrix, the column corresponding to the faulty measurement. Usual search for the largest normalized residual can be replaced by a search through the columns of the residual sensitivity matrix for the vector most nearly collinear with the residual vector. Analogous approach is utilized for single topology error, i.e. a test of collinearity between the topology error residual vector and the column of appropriate matrix (product of the residual sensitivity matrix with the measurement-to-branch incidence matrix) associated with the suspect branch. Test is similar to the normalized residual test for measurement errors. This method cannot detect topology errors on critical network branches (whose removal renders the network unobservable). An equation is developed for a matrix whose column linear dependencies determine whether the topology error is detectable and identifiable.

The approach given in [14] utilizes degree of collinearity of the columns of the sensitivity matrix to the calculated normalized residuals (but for the significant measurements in the external system) for the purpose of topology error detection. The focus is an issue of external system modeling and detection of topology errors in the external system. Proposed method facilitates decision on the most significant measurements and topology data from the external system in order to maintain an accurate network model. Detection of the topology error in the selected external system branches is further analyzed based on the sensitivity analysis and implementation of cosine test program.

Three types of topology errors are considered in the reference [15]: branch (transmission line or transformer) outage, bus split and shunt capacitor/reactor switching. Presented are conditions for detectability and non-detectability of topology errors, as well as topology error identification. Expected value of the residual is equal to zero when there is no topology error. Method utilizes expression for residual expected value in all three topology error types when determining errors, i.e. when the expression is not equal to zero.

Rule Based Approach

This approach implies a rule-based (knowledge-based) algorithm [16], [17]. It represents a completely different view to a topology detection problem then other conventional computational post-processing methods. Many advantages are recognized that characterize the implementation of expert systems: the method is simple, fast, reliable, flexible and does not have convergence problems nor does it depend on the type of the network.

The algorithm presented in reference [16] validates the changes in switch position utilizing the information available in the energy management system (EMS). It also uses the temporal consistency of the analog measurements and switch positions. It is not the post-processing method that requires a successful state estimation execution in spite of the presence of bad topology. Actually, the proposed method attempts to emulate a power system engineer. Knowledge is stored in a knowledge base in the form of rules which are applied logically to the given situation and the method infers whether the given switch condition is true or false. This algorithm does not perform a time consuming, extensive numerical solution and therefore it is very effective in an online implementation.

Practical experience gained in the integration of the rule-based online topology error detection is described in reference [17]. Integration objective was to embed the topology error detection module in the existing state estimation processing chain, without disturbing the actual operation of the system. Results showed to be very encouraging and promising. This fast and reliable method is expected to have a great use in real energy management systems.

LAV State Estimation Approach

Topology errors can be very well identified by implementation of Least Absolute Value (LAV) State Estimation [18], [19]. The use of LAV estimator enables identification of unknown breaker status in the presence of analog measurement errors. One of the advantages of using LAV based estimator for topology error identification is that it will converge to a solution even when the system model is severely in error and/or measurements have quite disparate weights.

Reference [18] describes an approach by which status of the circuit breakers, which is not directly monitored, can be monitored. The approach combines circuit breaker model [20], [21], [22] with the least absolute value state estimation method. The ability of the LAV estimators to reject inconsistent measurements is exploited in order to decide whether a circuit breaker is closed or opened. It also identifies unknown status of breakers in the presence of some analog measurement error. Regular state variables as well as the circuit breaker flow variables are considered and zero pseudomeasurements are used for the breaker flows and terminal voltage drops as redundant measurements. Statuses of breakers are identified based on the LAV estimator's rejection or acceptance of these redundant measurements.

Two-stage method that is able to differentiate between circuit breaker statuses and analog measurement errors is presented in reference [19]. The first stage estimation uses a bus level network model as in the conventional LAV estimators. Results of stage 1 are used to draw a set of suspect buses whose substation configurations may be erroneous. In the second stage, the identified buses are modeled in detail using the bus sections and the circuit breaker models (substation level), while keeping the bus level network for the rest of the system. The LAV estimation is repeated for the expanded system model and any remaining significant normalized residuals are flagged as bad analog measurements, while the correct topology is determined based on the estimated flows through the circuit breaker models in the substation.

Other Approaches

An algorithm for determining a correlation index between symptoms of anomalies in the estimation process and measurements related to the network elements suspected of being wrongly configured is proposed in reference [23]. A method based on such an algorithm enables one to recognize the occurrence of topology errors in the real time modeling process and to identify bad topological configuration.

Procedure that combines numerical computation and various consistency checks to detect topology errors in the state estimation model is proposed in reference [24]. Method can be used to detect branch inclusion, exclusion and bus configuration errors. Measurement data is classified using consistency checks. Network search based on a set of accurate measurements is used to calculate the bus voltage angles. Calculated and measured data is employed in detection of possible topology errors and validation of measurement data.

Method for topology error identification based on the use of normalized Lagrange multipliers is introduced in reference [25]. The proposed methodology models circuit breakers as network switching branches whose status is treated as operational constraint in the state estimation problem. The corresponding Lagrange multipliers are then normalized and used as a tool for topology error identification, in the same fashion as measurement of normalized residuals are conventionally employed for analog bad data processing. The largest normalized Lagrange multiplier corresponds to the bad data point.

A pre-processing method that identifies both multiple topology errors and bad measurement is described in reference [26]. The method determines branch status by testing the real and reactive power flow estimates of all branches of the network, irrespective of their assumed status. The procedure is not prone to divergence problems, which is of great importance in real-time computations.

Conclusion

Proposed methods are valuable tools in topology error detection and identification problem. Different approaches offer various ways to deal with this important issue, which confirms the complexity of the matter. Elaborate computational methodologies that are proposed correspond to the large power system models and number of possibilities encountered in handling the topology assessment. While some algorithms have many advantages, none of them is without disadvantages.

The integration of bad data detection and identification methods with real-time substation monitoring greatly enhances the topology data accuracy. Preprocessing of substation data and filtering out topology errors at the substation level improves operation of local and system-wide control and monitoring functions [27].

Conclusion

This chapter addressed some background aspects of substation integration issue. Most of the assumptions acquired in the thesis will be based on the material given in this chapter. Modeling issues will reflect mentioned analog and digital device features. The data generating and collecting procedures will follow the pattern of substation intelligent electronic devices and established communication protocol assumptions.

CHAPTER III

DATA COLLECTING AND PROCESSING

Introduction

Substation integration needs to be achieved through handling two very important issues. The first one is collecting data from all the devices installed in the substation and the other one is processing the collected data and creating desired output. Those two issues can be analyzed separately. It should be noted that data processing depends greatly on the amount and form of data that is collected.

Data collecting assumes interaction between the main substation computer and measurement devices located in the switchyard. Measurement device term is used here to describe a device that can convey any piece of information, no matter if it is analog or digital, preprocessed or not. Interconnection of Intelligent Electronic Devices implemented in the substation is also assumed.

Virtual data collecting system has been devised to analyze possible implementation of this process within the substation. It is part of the Integrated Substation Software (ISS) that will be described in detail in the following sections. ISS is designed as a standalone unit capable of simulating substation operation along with data generation, collecting and processing features. It will be used in the analysis of integrated substation operation.

ISS performs both the simulation of switchyard apparatus and measurement devices as well as the operation of central substation computer that is processing collected data. Simulation comprises substation modeling and running virtual substation system that makes up for the actual input to the main substation computer. Processing part performs various consistency check algorithms and utilizes the benefits of integrated substation systems. It provides more accurate and reliable data applicable in various substation as well as power system functions for the purpose of the enhancement.

Integrated Substation Modeling

Simulation of an integrated substation operation is achieved by running its computer model. Simulink modeling tools are used for its creation [28]. The computer model represents a significant part of the Integrated Substation Software (ISS).

Detailed single-phase substation model is developed using standard power blockset elements [29]. The model is invoked and controlled by the software. It is executed in the background and there is no need for user to make any actions directly on the model. Flow of simulated data from the model to the rest of the software is accomplished automatically and, since ISS offers comprehensive Graphical User Interface (GUI), parameters and topology changes are performed indirectly through the user interface.

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. Model represents one typical implementation of substation layout both graphically and functionally [11], [12]. Several major blocks are created in order to model important elements and functions of the substation.

Schematic of the chosen substation layout is shown in Fig. 1. It consists of two busbars with breaker-and-a-half type connection with the transmission lines and double-bus-double-breaker type connection to the load. All implemented substation apparatus and devices are represented as single-phase models.

Four main Simulink blocks are developed for the substation model to describe different elements: equivalent source block, switching element block, measuring unit block and triggering block. All of them will be described in detail further in this chapter.

Type and placement of analog measurement devices within the model are also shown in Fig. 1. Digital (status) measurements are assumed to be associated with circuit breakers and switches. Designation of nodes, branches and power apparatus in Fig. 1 is consistent throughout the software.

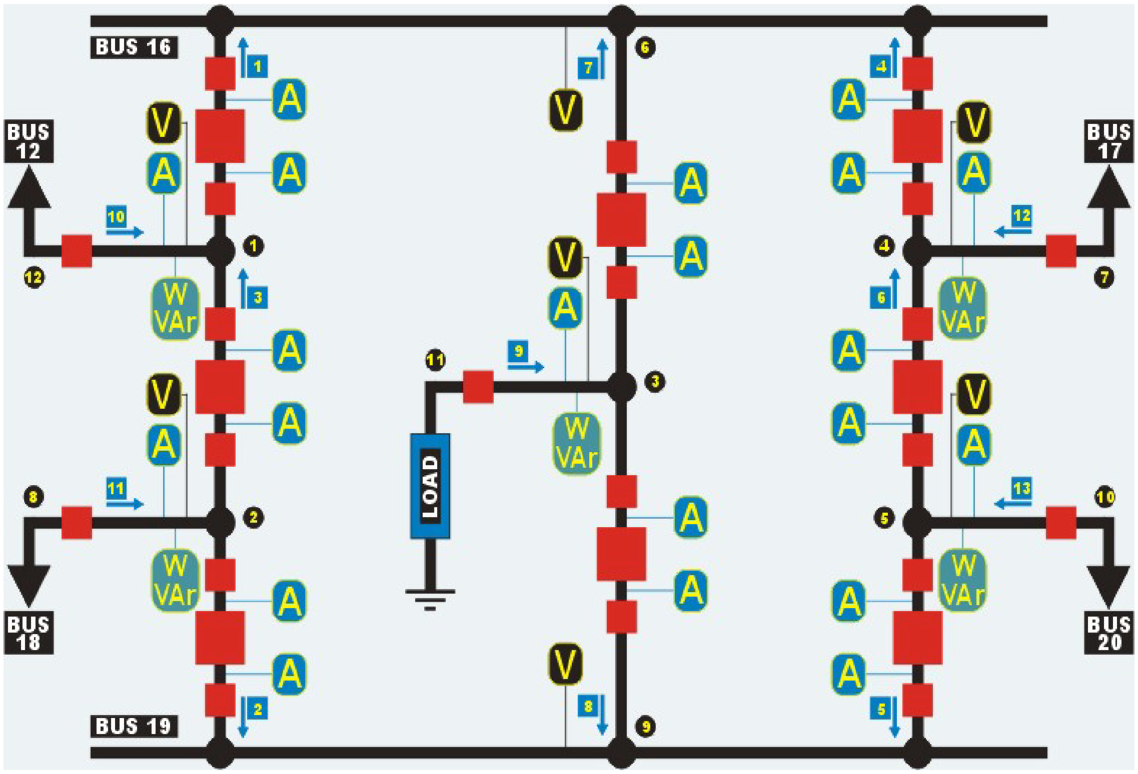

Fig. 1. One-line diagram of a substation layout with measurement device placement

Equivalent Source

The model of electrical sources that generate power flows through the substation is accomplished as the equivalent source block. The structure of this block is shown in Fig. 2. It consists of an equivalent ideal generator and corresponding equivalent impedances toward neighboring substations in the network.

Generator and impedance values are obtained through the reduction of power network admittance matrix. They are calculated by the main software routine based on the network equivalent data. Generator block receives values for voltage magnitude and phase angle parameters whereas its frequency is set to 60 Hz. The values for impedances (resistances and inductances) are also obtained from the main software routine. Substation model also contains some additional connections between the equivalent source blocks, which model closed loops in the rest of the power network.

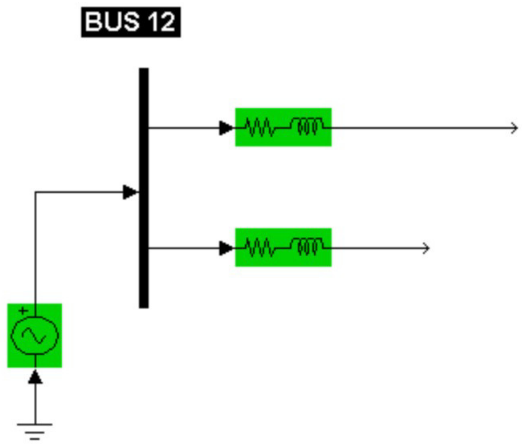

Fig. 2. Layout of an equivalent source

Switching Element

Circuit breakers and disconnect switches installed in substation are both modeled with the switching element block (grounding switches are not represented). The structure of this block is shown in Fig. 3. Switching elements are modeled as controllable switches. They can be opened or closed by the user through the GUI. Their status can be changed at any time during the simulation. Discrete pulse generator controlled by the main software determines the times when the switch element status is captured and transferred for processing. Switch element model also contains one resistor (with high value of resistance) in parallel and one inductor (with low value of inductance) in series. Those additional elements are necessary in the Simulink software environment to run the model properly (switch elements are modeled as current generators and their series connection is not allowed if they are stand-alone elements). Values for the parallel resistance and series inductance are obtained from the main software.

Contact status (digital measurement) of all switching elements is captured through the appropriate control blocks. Separately written subroutines take care that status of each switch is being properly reported to the software. This information is later used in substation topology determination. The status can only have two different values: “1” for closed and “0” for opened position.

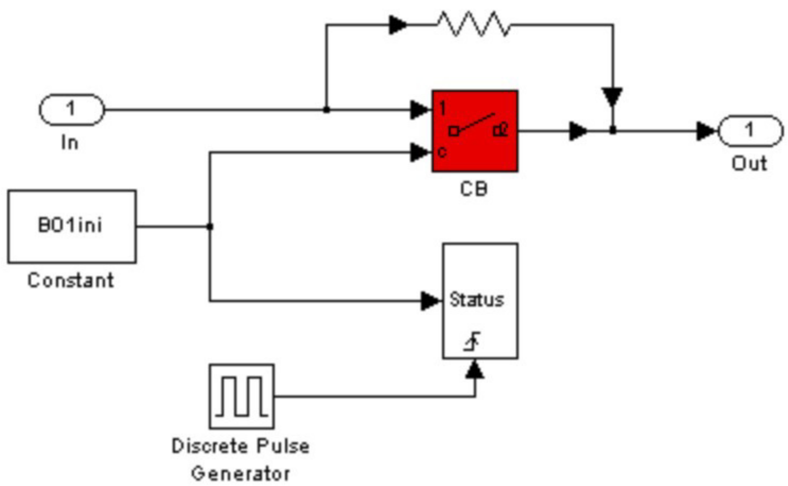

Fig. 3. Layout of a switching element

Analog Measurements

There are two types of analog measurements: current and voltage. Their layout is shown in Fig. 4 and Fig. 5 respectively. The corresponding blocks are structurally the same, except that voltage measurement has only an input (due to parallel connection) whereas current measurement has both input and output (due to series connection).

The distribution (location) of analog measurements in the substation model is determined based on the following rules:

- Each circuit breaker has two current measurements (one at each side)
- Each transmission line has one current measurement, one voltage measurement and calculated active and reactive power measurements
- Busbars have one voltage measurement

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 [31], [32]. Those two parameters completely determine phasors of measured electrical quantities.

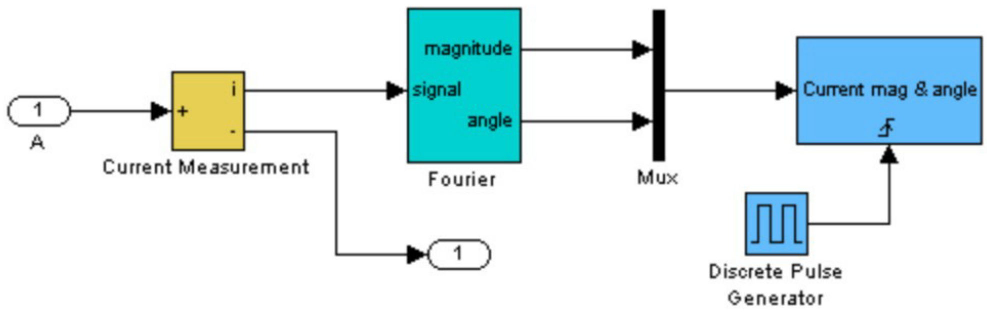

Fig. 4. Layout of current measurement

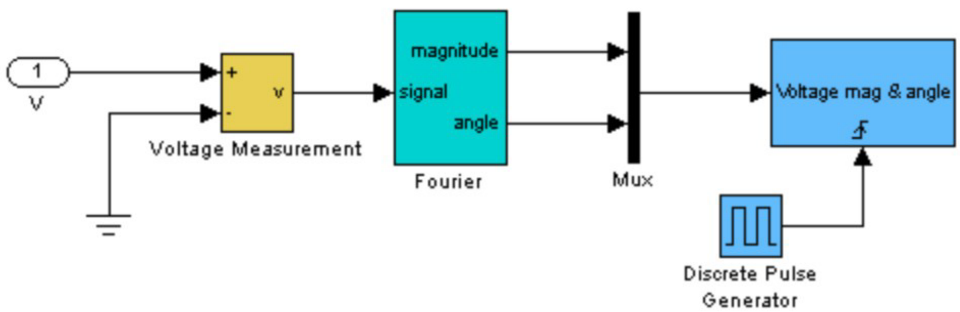

Fig. 5. Layout of voltage measurement

The same as with the switching element status, discrete pulse generators control transfers of current and voltage phasor. Since all the discrete pulse generators within the substation model are controlled by the main software, their operation is synchronized. Thus, all the analog and status measurements throughout the model are captured in the same time instances. This is very important since it facilitates operations with phasors. It is assumed that the actual substation setup would provide means to achieve the same outcome as with actual field phasor measurements.

Triggering of Processing

The triggering is an important step in the process of providing captured measurements to the main software routine. Its purpose is to control data exchange rate between software components and to call processing subroutine that manages utilization of measurements from the Simulink model. Major idea is implemented through the simple structure shown in Fig. 6.

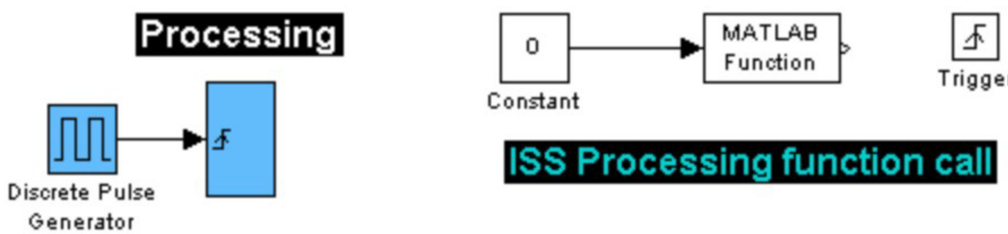

Fig. 6. Layout of triggering element

The triggering of processing models the main substation computer clock. Its function is reflected through synchronization of collected data, which facilitates data comparison and related data processing.

The processing is triggered by discrete pulse generator that determines time instants of the function call. This way, the software performs processing of simulated substation data while the substation model simulation is running. Discrete pulse generators connected to all the measurements trigger at the same time and the substation data snapshot is memorized. After short delay, discrete pulse generator connected to the processing block triggers execution of processing subroutine. Thus, data snapshot is being processed shortly after being generated.

Data Collecting and Preprocessing

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.

Several software routines take care of the data snapshots created by the integrated substation model. Preprocessing routine retrieves data of the latest snapshot and performs data preprocessing. Processing routine is invoked next and it applies data consistency check algorithms and generates outputs. Both preprocessing and processing routines are written in Matlab programming language [30].

All above-mentioned routines actually simulate the substation computer, which controls collecting data from the switchyard, performs data processing and generates desired outputs. Their role is to filter collected data and yield processed information in the form understandable to other substation and/or system applications. This sort of data processing is feasible thanks to the integration of substation devices and their ability to communicate and exchange measurements.

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

Data Preparation

First task of the preprocessing routine is to prepare data for further processing. Integrated substation model generates data snapshots with analog and status measurements. In addition, some measurements that do not originate from physical instruments can be computed and supplemented to the snapshot. This is usually the case with active and reactive power. It can be obtained by multiplying corresponding voltage and current phasor measurements. In an actual substation implementation, the power data may be obtained either directly from the transducer or through calculation. Substation model can be modified to generate power measurements as well, but in order to avoid simulation complexity it is accomplished through preprocessing rather than through simulation.

As it was mentioned earlier, each measurement has its own subroutine that takes care of storing corresponding values that belong to the data snapshot. Those subroutines also perform part of the preprocessing task before the value is stored. First, the phasor angles are converted from degrees into radians and phasors are calculated as complex numbers from their polar components.

It is very important to emphasize that after preprocessing, the data is converted into consistent format. Although different measurements around substation are acquired in different formats, eventually it is adjusted so the measurements can be compared with each other. Substation model generates all analog measurements in phasor format. It may not be the case in an actual setup. It is common that most of the analog instruments measure only rms values of electrical quantities. If this is the case, a provision in the software needs to be incorporated to create a “full” phasor representation.

Description of the Measurement Placement and Topology

In order to perform processing of data, the topology of modeled substation as well as placement of measurements (analog and digital) need to be described.

Topology is described by the list of node numbers (consecutive numbers starting from 1) and their corresponding classifications. Nodes can be busbars (classification 1), external nodes (classification 2) or internal nodes (classification 3). In addition, branches are described in a separate list that contains branch number, “from” and “to” node of each branch. Branch orientation is also determined by the sequence of terminal nodes and branch current is later expressed regarding this orientation.

All branches are zero impedance branches except branches that connect neighboring substations (transmission lines or transformer branches) whose impedance is taken into account in calculating an equivalent source impedances. Transmission lines and transformer branches are terminated in corresponding substation external nodes. All other nodes are classified as internal nodes (except busbars).

Lists with node and branch descriptions reflect part of the data that does not change in time, i.e. data in the lists is constant for the modeled substation.

The rest of the data that can change from snapshot to snapshot is also prepared by the preprocessing routine. Preprocessing routine is called after each data snapshot has been generated and performs this task for each new set of data. Integrated substation model provides branch current measurements, voltage measurements for some nodes and status of all switch elements. Preprocessing routine needs to know what are the available measurements, what is the value of a particular measurement and where the associated instruments are located within the substation. Therefore, four lists are defined for this purpose: branches with current measurements, nodes with voltage measurements, branches with calculated power flows and branches with switch elements and their status. All these lists are updated for each new snapshot of data since the values for all the quantities can differ in time. Previous lists are stored in the memory for the purpose of later retrieval when data history is needed.

List that describes status of switching elements is created differently depending on the mode the software is operating in. Modes of software operation will be discussed later, but it can be mentioned now that status can be obtained either from the substation model (which corresponds to data obtained from the switchyard in reality) or from the user interface (when the software is in a “bad data” mode that simulates erroneous status acquisition).

Processing and Consistency Checking

After the snapshot data is preprocessed, it is further handled by various processing routines. The routines make the core of the integrated substation software. Processing and 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 and it 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.

Several different processing and consistency check algorithms are implemented in the processing routine. All of them will be described next. In addition, substation transitions reporting algorithm will be discussed at the end.

Double Current Measurements

Some branches have two measurements of current (branches with circuit breakers having two current transformers in their bushings). One redundant measurement of current can also be obtained from a digital relay or some other intelligent electronic device (IED) that is monitoring the branch [33], [34]. In these cases, the value for current in the branch needs to be decided. This is easy if both measurements agree but becomes a little more difficult when discrepancy exists.

This 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. 7.

Algorithm treats all the branches. It determines first if there is a redundant measurement of current in the branch. In the case when there is only one measurement of current and redundancy does not exist, that measurement is assigned for the branch current and the rest of the logic is skipped. Additionally, this branch current can be marked and possibly rejected or corrected later if some of the algorithms discover inconsistency. It is mainly up to First Kirchhoff's Law and time series algorithms to recheck the value of current in such branches.

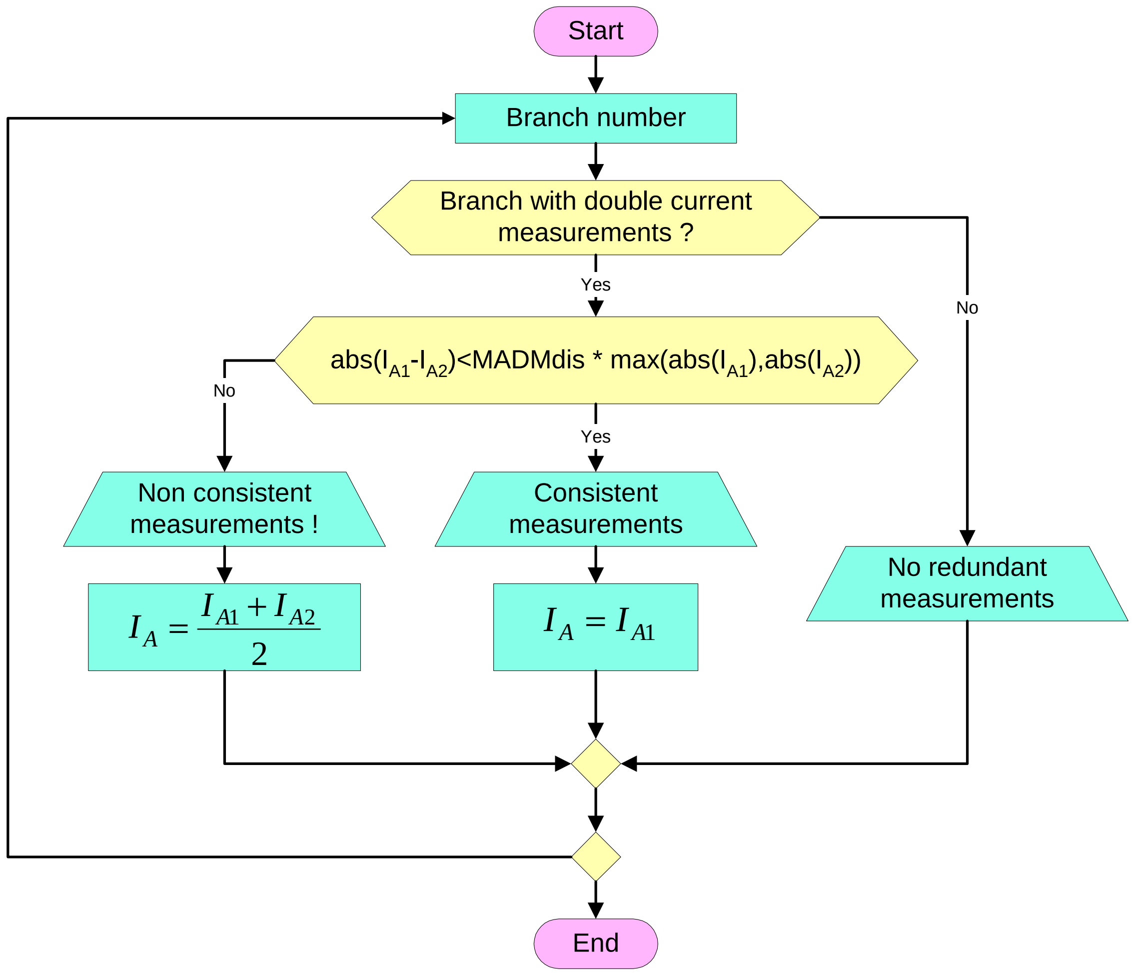

Fig. 7. Flowchart of the algorithm for branch currents consistency check

In branches where redundant measurement of current exists, consistency check is performed. Criterion is that the absolute value of the difference between the measured phasors should be less than certain percent of the absolute value of the larger measurement. Percent is determined by the variable MADMdiss (Maximum Allowable Double Measurement Discrepancy), which is initialized in the software (default value is 0.0001) and can be changed through the user interface. The assumption is that there will be no discrepancy in phase angle without discrepancy in magnitude. This way, algorithm is also applicable in cases when only current rms is being measured and the phasor angle is not available.

If the criterion is satisfied, the icon between two A-meter symbols (on the GUI) is set to vertical position ("||" icon on the blue background). The current in the branch is assigned to be one of the current measurements (since they are the same to the level of precision determined by MADMdiss variable).

In case when the current criterion is not satisfied, the icon between two A-meter symbols (on the GUI) is set ("X" icon on the red background). The GUI processing report is also generated and it gives the information about the snapshot and branch number where "currents are NOT consistent". The current in the branch is determined as an average value of two current measurements. The same logic of temporary marking the branch and current value can be applied here as well. The measurement can be rejected or corrected later upon additional checks if the consistency is not fulfilled.

First Kirchhoff's Law

This type of consistency check can be performed for all nodes where three or more branches meet and the measurements of current exist in all those branches. The algorithm flowchart is shown in Fig. 8.

Algorithm treats all nodes and checks the node classification first. Only busbars and 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. Current measurement at the remote part of the branch is usually not accessible. The other reason is that external nodes are incident with only two branch parts, which is not enough to perform the check.

For nodes with classification 1 (busbars) or 3 (internal nodes), incident branches need to be determined and they have to be checked if all of them are equipped with the current measuring instruments. If this is not the case, the rest of the logic is skipped for this node since the First Kirchhoff's Law cannot be performed (some branch current measurements are missing). Internal nodes are successfully treated most of the time since all the branches connected to these nodes have some information about their current values (due to existed redundancy).

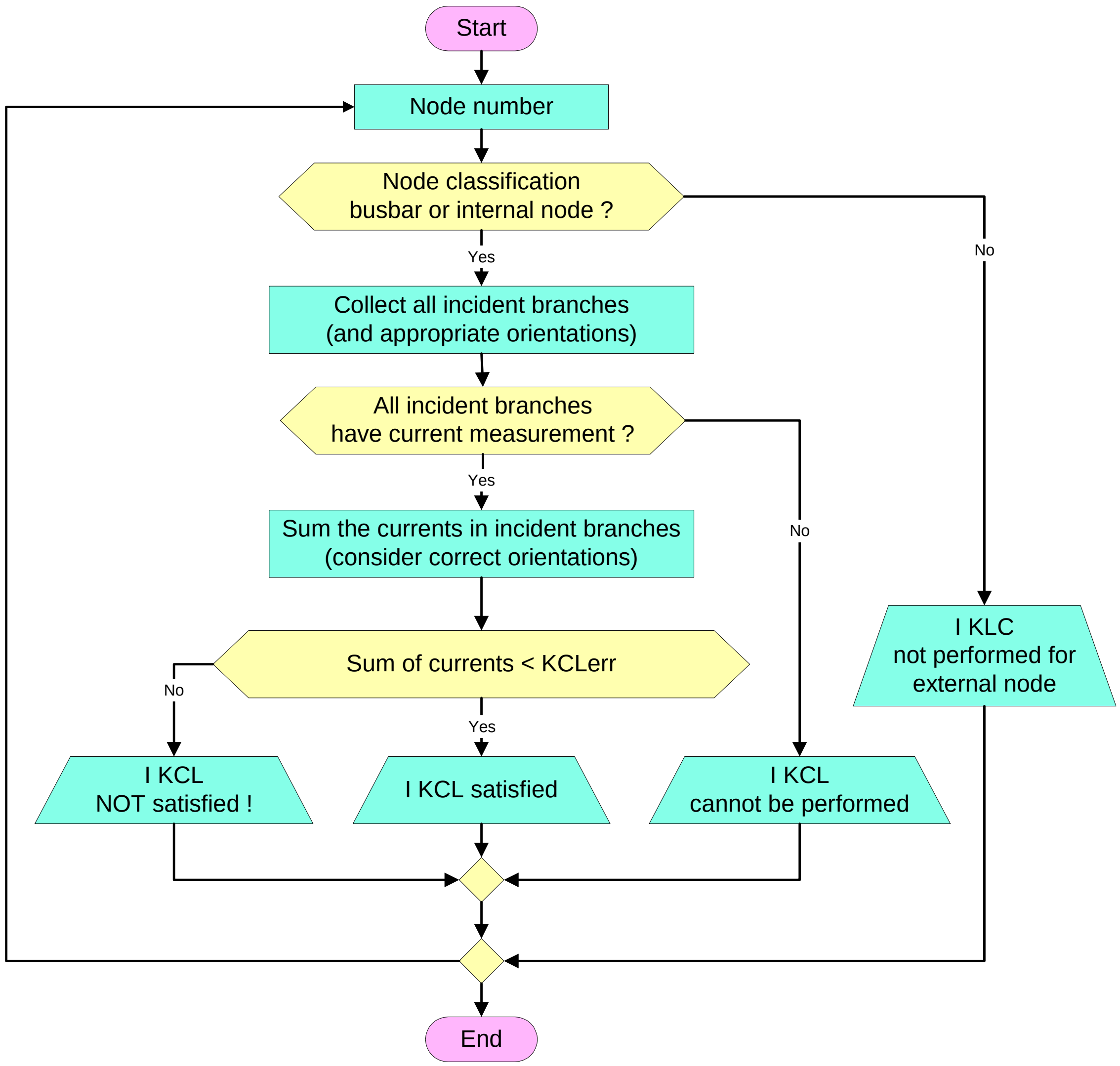

Fig. 8. Flowchart of the consistency check based on the 1st Kirchhoff's Law

For the internal nodes, there is enough information to check Kirchhoff's Current Law (KCL). Currents in the node incident branches are summed up considering each current's orientation (leaving or entering the node). Then the First Kirchhoff's Law condition is checked. Ideally, the sum of currents should be zero, but the processing routine allows existence of certain error (tolerance). This error is defined with variable KCLerr, whose value is initialized in the software (default value is 0.0001) and can be changed through the user interface.

If the KCL condition is satisfied, the icon next to the node (on the GUI) is set to “kcl” to note consistency (“kcl” icon on the black background). In the opposite case, the icon is set to alert sign to note inconsistency (“>!<” icon on the red background). In addition, the GUI processing report is generated, and it gives the information about the snapshot number and says “KCL NOT satisfied for the node” and the node number. After reporting inconsistency no further investigation is conducted as to why the sum of currents deviates from zero. The exception is the case when one of the previously marked branches is incident with this node. Then the current value for that branch may be re-examined or even rejected.

Branch Status Determination

Determination of a branch status is accomplished considering all the switching elements in particular branches. The configuration of switch elements for a chosen substation layout is either one disconnect switch, or one circuit breaker and two disconnect switches in the branch. The flowchart of the algorithm is shown in Fig. 9. All the branches are treated and first it is determined if there is one or three switching elements in each new branch.

If the branch has only one switching element, that one is a disconnect switch. Branch status is determined based on the status of that switch, i.e. the branch status is same as the disconnect switch status.

For branches with three switching elements, status is determined to be “1” (closed) only if all switching elements in the branch are “1”. In other words, if only one element in the branch is “0” (opened) the branch status will be determined as “0”.

This algorithm determines only the branch status. No check is done and therefore no processing report is generated at this time. The algorithm takes care of setting each switch element icon (on the GUI) to the appropriate value that will reflect its status: zero for opened or one for closed (both “0” and “1” icons are on the black background). As it will be described next, the branch status determined here is not definite since consistency check algorithm, that is applied later, can alter the branch status after it takes into account more comprehensive data.

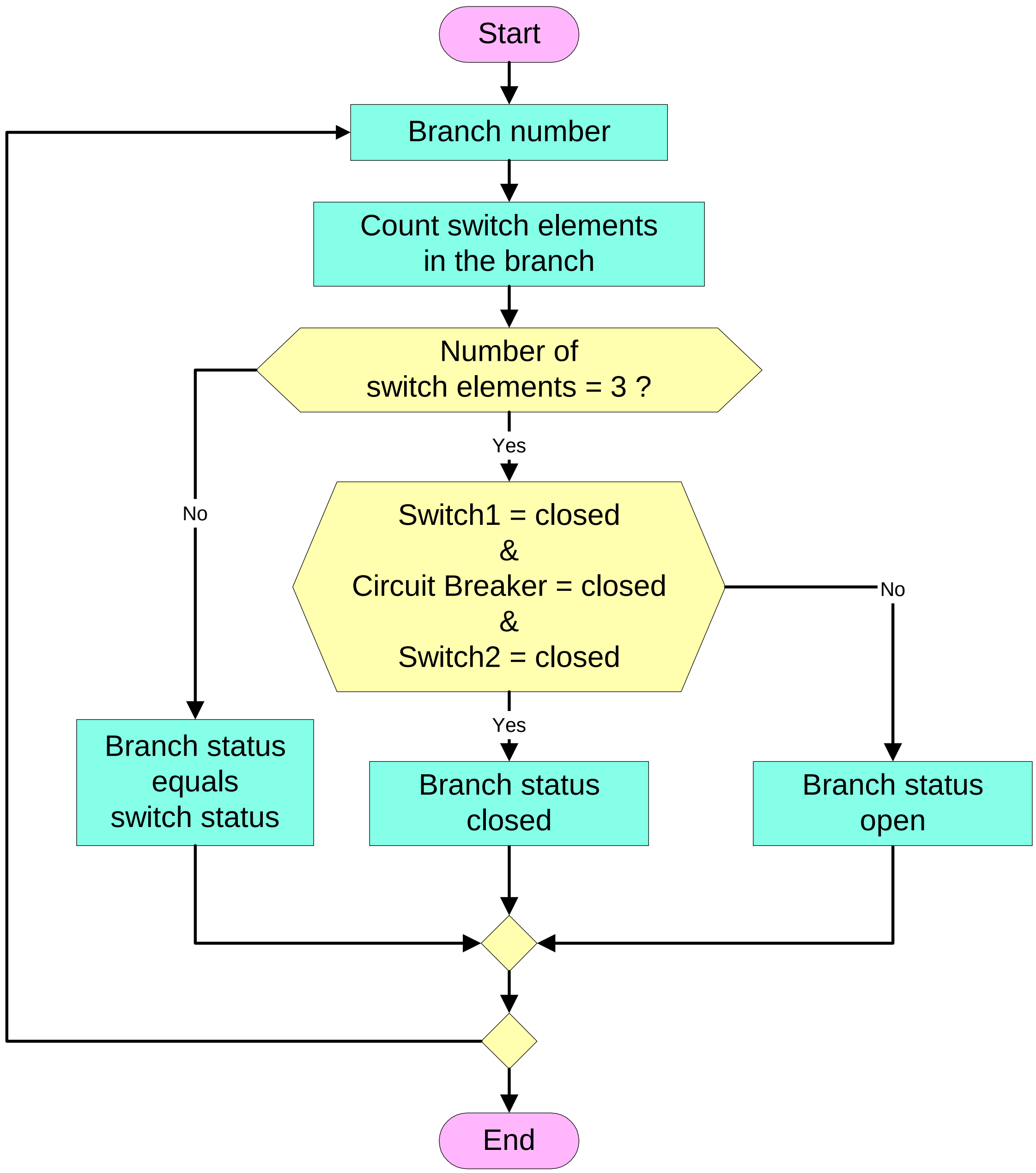

Fig. 9. Flowchart of the algorithm for branch status determination

The substation model does not contain representation of ground switches. Those can be added and branch status algorithm can be expanded appropriately to include their status as the additional data for consistency checks and improved topology determination. Status of ground switch elements is usually not of significance for the power system level functions. However, their status is valuable information for local applications (at the level of substation).

Ground switching element that is closed can be used to infer about the node voltage it is connected to, i.e. that voltage should be zero. In addition, no branch should be in status “1” if it connects such node with another one that is at the rated voltage. Ground switches are usually closed when some maintenance work is in progress. Their status can guide the switching sequence control applications to follow corresponding path in analyzing and predicting topology of the substation.

Branch Current Value and Status

Following algorithm is developed to perform consistency check between branch current values and branch status (topology data). It determines correct switching element status based on additional information about the branch current. It is the most complex algorithm applied in the processing routine due to many possible combinations of branch current values and branch status. Those combinations reflect different situations and have distinct impact on the conclusion. Flowchart of the algorithm is shown in Fig. 10.

Algorithm treats all branches that have current measurement and retrieves corresponding branch current value and branch status determined by the previous algorithms.

The first thing that is checked is whether there is a current flow through the treated branch. In order to consider current as a zero flow, certain threshold is introduced through variable ZCV (Zero Current Value). In other words, current needs to be less then ZCV to be considered as zero flow. This threshold was necessary since there is always a small leakage current despite an opened switching device.

Variable ZCV defines acceptable zero value tolerance and it is initialized in the software main routine (default value is 0.0002). It can be changed at any time through the user interface. Fine tuning of this variable can make the algorithm more or less sensitive when determining the branch status depending on the branch current value.

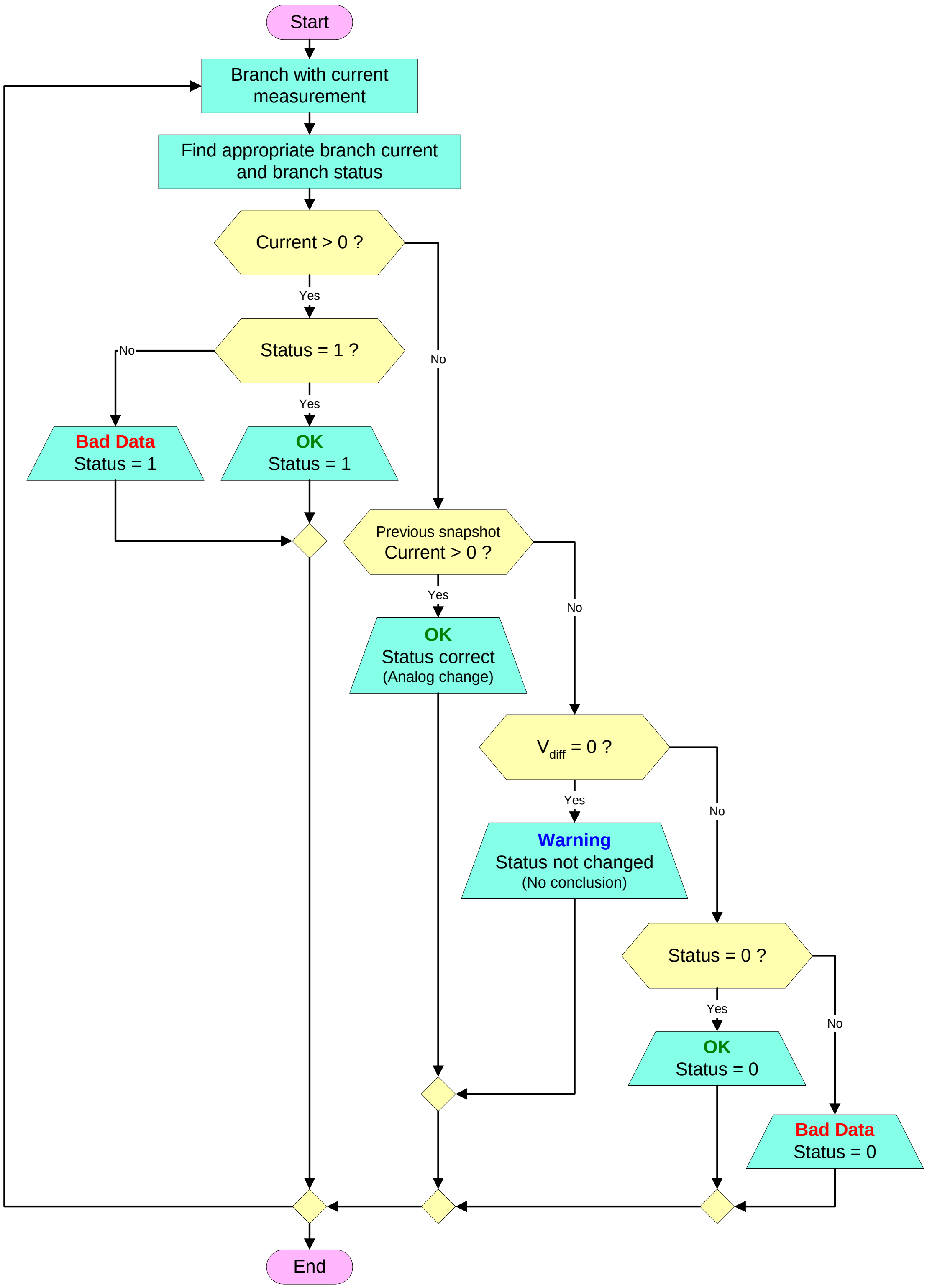

Fig. 10. Flowchart of the algorithm for consistency check of branch current and status

If there is a non-zero current through the branch, the branch status is considered to be “1”. If it has already been determined as “1”, it is not changed, i.e. it is only confirmed by the existence of the branch current. Therefore, consistency is fulfilled. In an opposite case, branch status is corrected from “0” to “1”. Appropriate processing report is generated and displayed on the GUI. It gives the information about the snapshot number and the branch where bad status was corrected to “1”.

This is the case when bad data is detected and eliminated. Since it is less likely that an analog measurement would become non-zero than the status measurement to be flipped, an analog measurement is trusted more. This kind of compromise is inevitable in case of two data sources. With more redundancy, better decisions can be made.

The case when there is no current flow through the branch is more difficult. It entails more checks before any conclusion can be reached. The first thing that is checked in this case is the value of branch current in the previous snapshot. This is to allow temporary loss of analog measurement, i.e. the branch status will be preserved as is and it will not be influenced by erroneous analog measurement. Another thing is assumption that bad data will not be introduced in the moment of analog change (one snapshot is left as a reserve before any corrective action is taken).

When the current persists at zero level for at least two snapshots in a row, more data needs to be introduced before the branch status can be decided upon. At this time, voltage difference between branch terminals is calculated (algorithm also scans if appropriate voltage measurements exist in the substation).

Calculated voltage difference (absolute value of phasor voltage difference) is compared with variable NVD - Necessary Voltage Difference for current existence. NVD is initialized in the software main routine (default value is 0.0001) and it can be changed at any time through the user interface. It determines minimum voltage that would create non-zero current through the branch. By decreasing the value of NVD, greater sensitivity can be achieved.

If there is no voltage difference between branch terminals and since the branch current is zero, no conclusion can be made. The status can be either “0” or “1”.

Informative processing report is generated in this case and it gives snapshot number together with branch number where “I=0, Vdiff=0”. Status of the branch is left as is. Actually it really does not matter in this case whether the status is “0” or “1” since it would make no difference even if it is erroneous.

In the case when enough voltage difference exists to create the current but the branch flow is still zero, status is determined to be “0”. If it has already been “0”, it is not changed, i.e. it is only confirmed by the existence of sufficient voltage difference while the current is zero. Therefore, the consistency is fulfilled. In case when the status has previously been determined as “1”, it is corrected. Bad data is detected and eliminated by flipping the branch status. Similar processing report is generated as in the previous bad data case, except now bad status was corrected to “0”.

This algorithm also generates an informative processing report in case when the branch status is “1” but there is no current flow through the branch. It states the snapshot number and “NO flow through closed switch in Br” and the branch number. Since this report is not even a warning, it can be ignored. It is generated only to inform the user that there is a transmission line connected to the bus, which most likely is not connected to any other transmission line.

Time Series Changes

This algorithm performs consistency check of changes from the previous state. Analog set of measurements (both currents and voltages) and topology data are examined. Their values are compared between the current and the previous snapshot.

The assumption is that only a change in topology can cause change in analog measurements. What is a change of an analog measurement should be taken conditionally. Since there is always a fluctuation in the power flow even in normal operation of power network, variable MTAMC is introduced (default value is 0.01 p.u.). It determines the Maximal Tolerable Analog Measurement Change. Any change in analog measurement less then MTAMC is actually not considered as a change. This way, algorithm can be made insensitive to analog changes in normal operation.

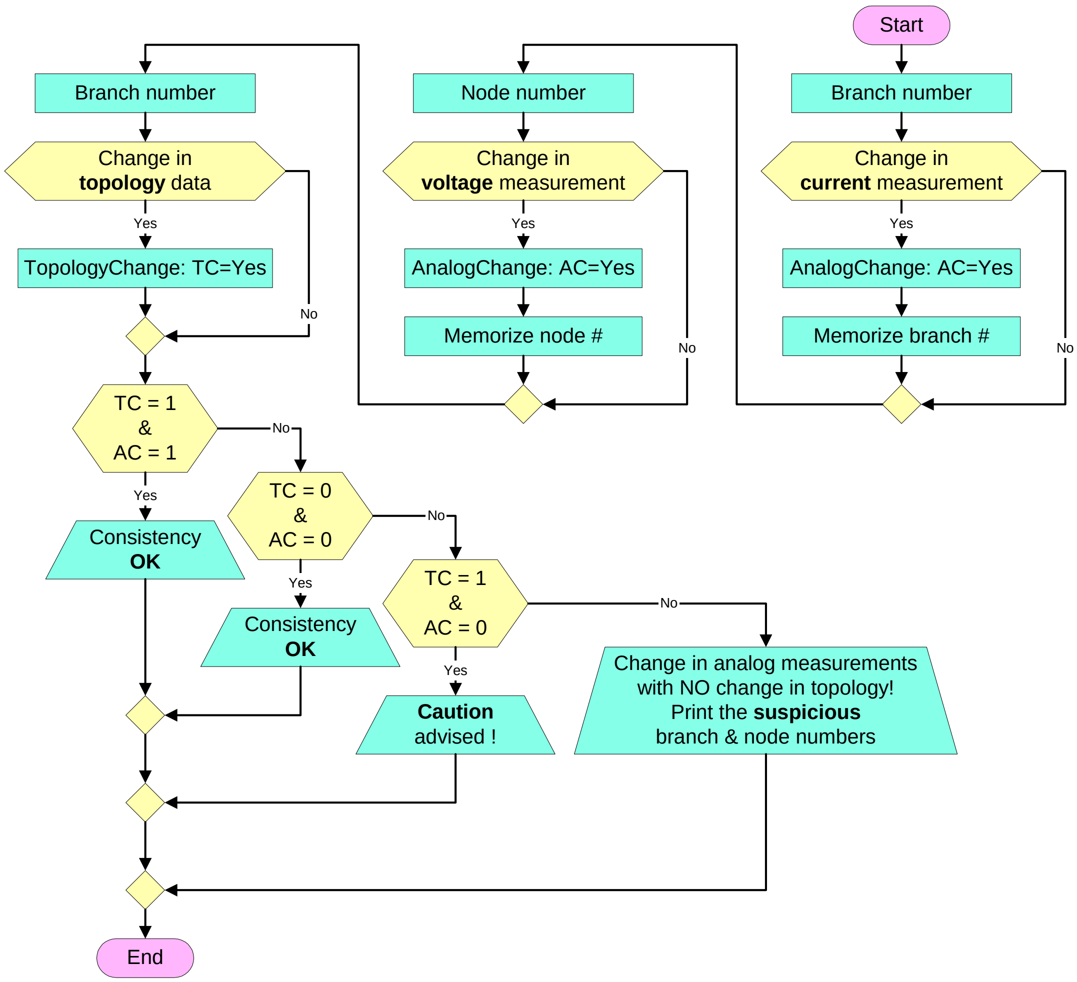

Fig. 11. Flowchart of the algorithm for consistency check based on time series

Flowchart of the algorithm is shown in Fig. 11. Changes after the previous snapshot need to be detected first. All branches are examined for a change in current measurements while the nodes are examined for change in voltage measurements. Even one change will cause the variable AnalogChange to memorize that there was a change in some analog measurement. Branch numbers with changed current values and node numbers with changed voltage values are stored for later reporting. Next, all branches are examined for change in topology and even a change in the state of one switch element will cause the variable TopologyChange to memorize it.

Now, the algorithm is ready to examine the consistency of all four combinations of variables AnalogChange and TopologyChange. Two basic combinations yield the consistency:

- Change in topology and change in analog measurement values
- NO change in topology and NO change in analog measurements.

No action is performed in any of those two cases since consistency is fulfilled. No processing report is generated due to avoiding unnecessarily cluttering the screen.

Next case that is considered is when there is a change in topology (status) but no analog measurement has changed its value. This can happen in normal operation when for example the branch status changes from “1” to “0” and there was no current in the branch before it was opened. Therefore, this case does not necessarily means bad data. Only a single warning report is generated that states the snapshot number and “Status changed but NOT analogs”.

One more case exists when there is a change in some analog measurement with no change in topology. This is considered more serious case than the previous one since it is more likely that the bad data is causing it. Generated processing report is displayed on the GUI and it states the snapshot number and “Analogs changed but NOT status”. In addition, all branches where the current has changed are listed together with all nodes where the voltage has changed. They are considered as suspicious branches and nodes. It is possible that due to some remote fault, a sudden change in power flow caused change in analog measurements and no activity is necessary. On the other hand, rechecking the suspicious branches and nodes can discover some local instrument malfunction.

Independent routine overlooks all the algorithms and in case when no algorithm generated a processing report (either warning or alert), it confirms the successful completion of data acquisition and the fact that no error was found throughout processing. The report displayed on the GUI states the snapshot number and “Everything OK in this snapshot”. Most of the time while running the software these reports will be the only ones outputted. That makes other reports even more visible.

An actual substation processing computer can be equipped with an audio signal associated with alert reporting. This would draw additional attention of substation operators beside regular visual impression (alert reports are generated on a red color background).

Substation Transitions Reporting

Besides displaying processing reports, substation transition reports are also displayed on the GUI. Separate routine that takes care of this task was developed. It follows the algorithm whose flowchart is shown in Fig. 12.

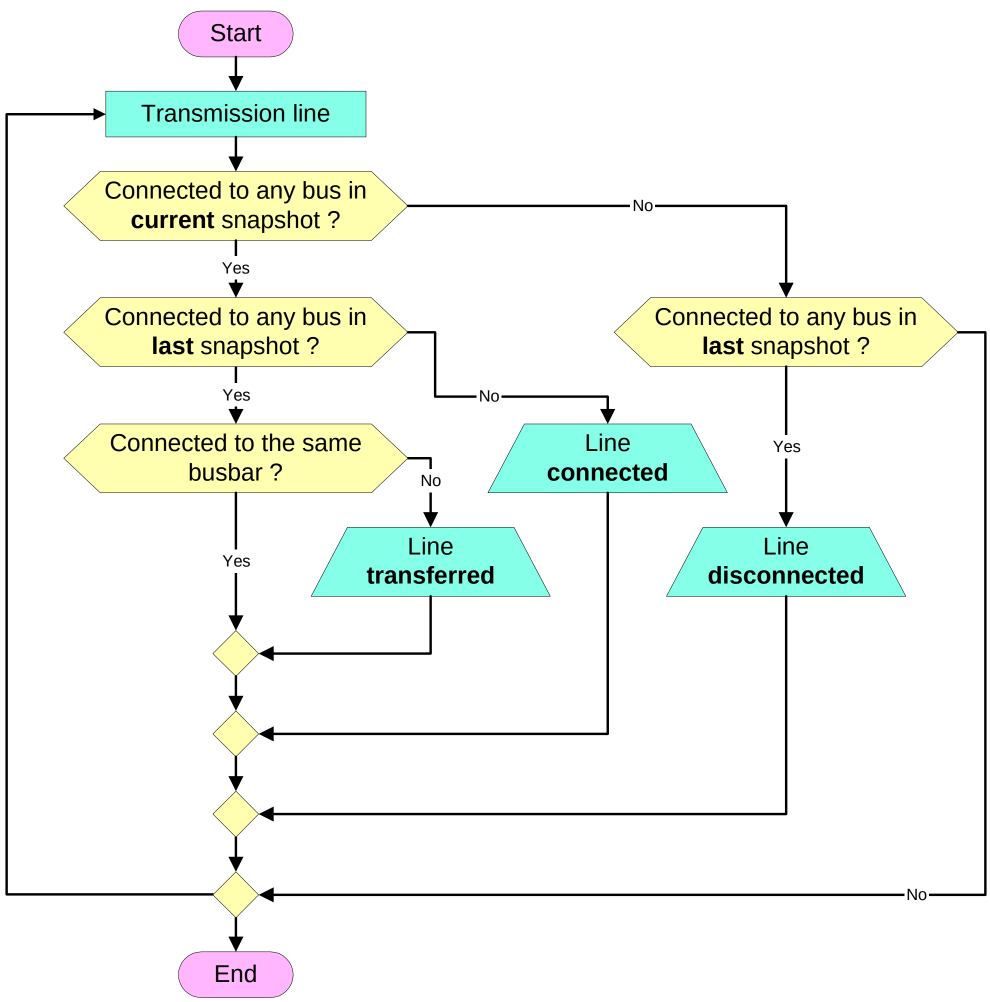

Fig. 12. Flowchart of the algorithm for transmission line transitions reporting

Transition reporting algorithm 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 cases when 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 reporting algorithm also detects changes in connection to any of the branches. The flowchart of this part of the algorithm is shown in Fig. 13.

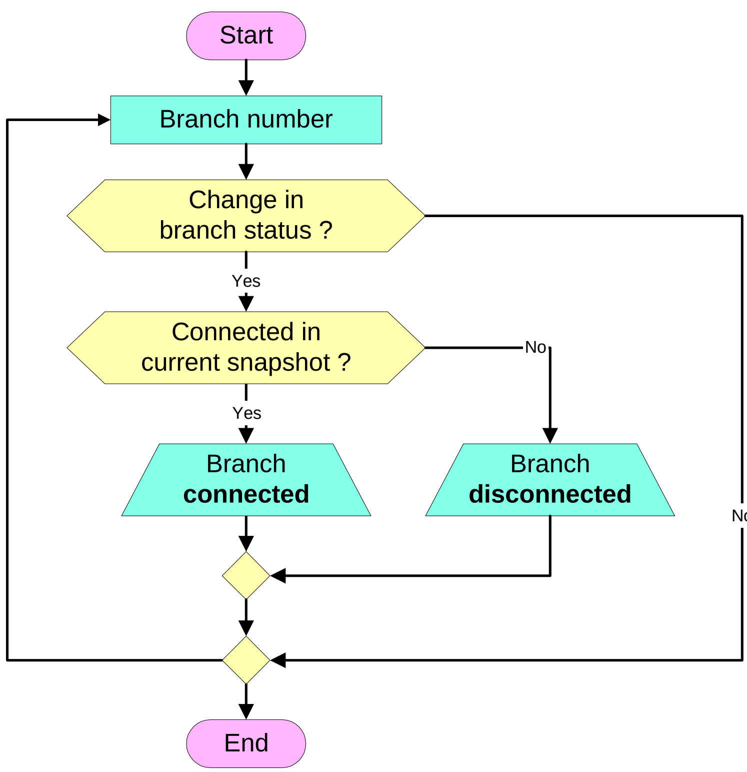

Fig. 13. Flowchart of the algorithm for branch transitions reporting

The algorithm treats all branches. Treated branch is checked for a change of status first. If the change is detected the current branch status is further checked. Closed branch means that the branch is just closed and the “branch connected” report is display. In the opposite case “branch disconnected” report is generated and displayed.

The difference between transmission line and branch algorithms is due to different switching elements that are involved. Transmission lines are connected to the busbars through one disconnect switch and a combination of circuit breaker and two disconnect switches. Status of all those switching elements needs to be examined to determine transmission line connection. In addition to that, transmission lines can be connected to one of two busbars (or both) and thus alternative paths need to be examined as well. Branch connection is simpler to examine since the output of status processing algorithms can be used and the number of combinations is fewer.

Conclusion

This chapter analyzed the process of integrated substation data collecting and processing. Substation simulation and processing software that is developed for this purpose is used to describe the steps from data generation to processed outputs. Virtual substation model is devised to make up for an actual substation system. Details of substation elements modeling have been presented. Data collecting and preprocessing are discussed as the necessary steps that need to be performed. Particular emphasis is given to the processing and consistency check algorithms. They were explained in more detail being the core of the integrated substation software. At the end, substation transitions reporting algorithm is presented.

CHAPTER IV

SOFTWARE OPERATION

Introduction

Integrated Substation Software (ISS) is developed as a processing and consistency check tool for data collected within the integrated substation. In addition to that primary function, software is capable of simulating substation operation and generating substation analog and digital measurements. Extensive Graphical User Interface (GUI) is developed for conveniently manipulating the substation switching elements as well as presenting processing and transition reports.

This chapter explains operation of the Integrated Substation Software. It also explains software features and other important issues relevant for successful software usage. The most recent software (Version 2.0) is presented and used throughout this chapter.

ISS is developed using Simulink modeling tools and Matlab programming language [28], [30]. Since Simulink is already a Matlab based application, the software performs as one coherent design. Software comprises two major parts: integrated substation model implemented in Simulink and data processing and consistency checks written in Matlab. All software components allow parallel execution of simulation and processing functions.

The background of integrated substation operation and the algorithms used for data processing and consistency checks are already explained in detail in previous chapters. This chapter will focus on remaining issues relevant for complete insight in the capabilities of developed software.

Graphical User Interface (GUI)

The software is started by typing "iss" or "ISS" at the prompt in the Matlab command window. This command opens the Graphical User Interface (GUI) screen. Major part of the first screen that is presented to the user is shown in Fig. 14.

The interface 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. ISS is designed to run on the main substation computer.

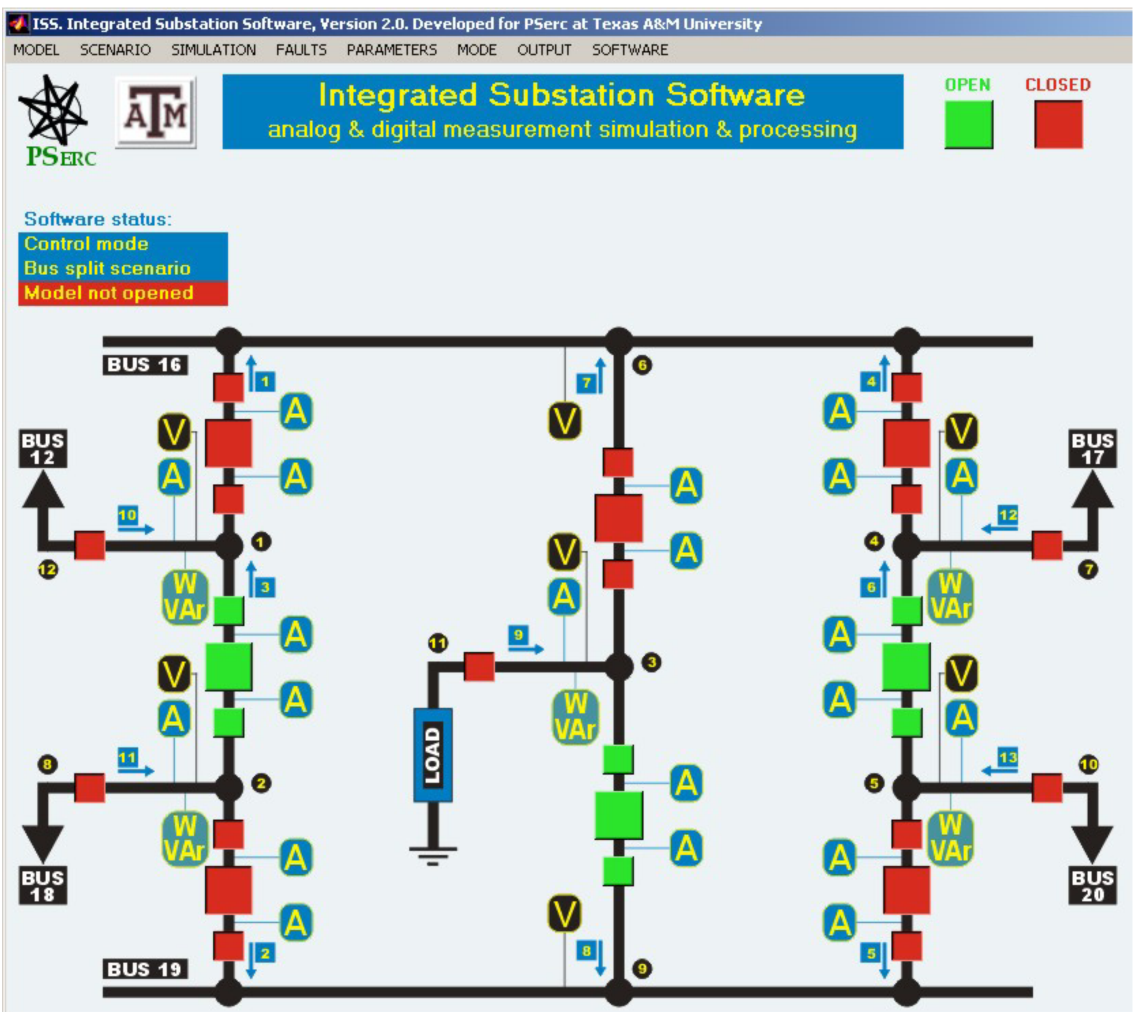

Fig. 14. ISS Graphical User Interface (GUI) after the software is started

Substation consists of two busbars (designated as BUS 16 and BUS 19) where four transmission lines and a load are connected. Transmission lines lead to other buses in the IEEE 30 bus power network (BUS 12, BUS 17, BUS 18 and BUS 20). Load is locally grounded. User can see the type of connections. Switching devices are presented as red and green squares. Larger ones are circuit breakers while smaller ones are disconnect switches. Their current operating state is reflected through their color: green ones are opened and red ones are closed. Switch element symbols are shown in Fig. 15.

Distribution of metering equipment around the substation is also shown on the GUI. Three types of symbols are used here, each representing different type of electrical instrument: the blue one is for A-meter (current measurement), black one represents V-meter (voltage measurement) while the green one is used for combination of W- and VAr-meter (active and reactive power measurement). Their symbols are also shown in Fig. 15.

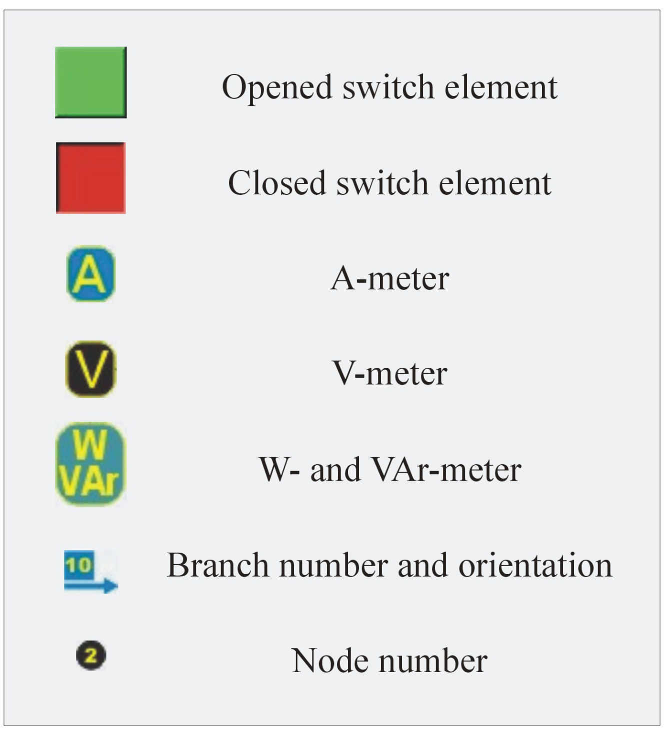

Fig. 15. Symbols used in the Graphical User Interface

Following color convention for measurements is used in the user interface:

- Blue color A-meters and current measurements (also branches)
- Black color V-meters and voltage measurements (also nodes)
- Green color W- and VAr-meters and power measurements

Other important elements on the GUI are symbols for nodes and branches. Since they are referred in most of the processing and transition reports, user needs to recognize these symbols. Branch number is inscribed in a blue square and associated branch orientation is given with a blue arrow next to the branch number. Node number is inscribed in a black circle. These symbols are also shown in Fig. 15.

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. Software status box can be seen in Fig. 14. Mentioned features will be explained in detail later in this chapter.

Very important part of the GUI is the user's menu. This drop down menu is used for most of the software control activities. By clicking anywhere on the menu, depending on the position of the mouse cursor, appropriate menu will drop down and offer list of associated activities. Top level menu options can be seen in Fig. 14. All the user menu options will be described in following sections.

Other parts of the user interface screen include several less important details. They can be seen in Fig. 14. ISS window title mentions PSerc (Power System Engineering Research Center), which is industry and university consortium that participated in the project funding [35]. Texas A&M University is mentioned as well and both TAMU and PSerc logos are displayed in the upper left corner of the user interface screen. ISS screen title is positioned above the substation diagram and gives general information about the software. To the right of the screen title, symbols for opened and closed switch element are displayed. User can always refer to these symbols if in doubt about the switch status color definitions.

Simulation of Integrated Substation Measurements

After the software is started and the initial user interface screen is displayed, user needs to perform several steps to start the simulation. At this point, all the functions on the initial user interface screen are disabled. There are only limited number of operations that can be done through the menu. This was done purposely since after software initialization, substation model is not automatically opened and there is not much left to do without having the model or associated measurements specified. Software status box displays the message “Model not opened” on the red background.

Normally, the first step after software initialization is opening the substation model. This is done through the user interface menu. Menu options are ordered from left to right in the sequence they are most commonly accessed. In that prospective, MODEL is the first menu option on the left hand side. User needs to click on MODEL → Open in order to open the substation model. New window with Simulink substation model will be opened, but the screen will automatically switch back to the GUI. Model will still be in the background and user is not supposed to perform any actions on the model directly in the model window. Model needs to be controlled strictly through the GUI. Even manually closing the model window can permanently change the model settings, which would later cause certain software malfunctions.

When the substation model is opened, software status box displays the message “Model opened” on the blue background. The model can be closed through the user interface menu by selecting MODEL → Close. At this point, such operation would revert the software to the previous state, which is not something that we want to do. Actually, once opened, substation model does not need to be closed at all throughout the software operation. It is even simpler that at the end of the work, user closes both the model and the whole software by selecting SOFTWARE → Exit menu command.

There are two initial scenarios implemented in ISS: Line outage and Bus split scenario. Either one of them can be employed before the simulation is run. Scenarios actually determine initial substation switch device states and associated network equivalent that is used in the substation model. Difference between scenarios regarding the switch device states is shown in Fig. 16.

Bus split scenario is the default scenario upon software initialization. It can be kept or changed. It assumes independent operation of two substation buses. Line outage scenario additionally assumes transmission line 12-16 disconnected.

Initial scenario can be changed either when the substation model is opened or closed, but certainly before the simulation is run. Scenario change can be done through the user interface menu: SCENARIO → Line outage and appropriate substation switch devices will change their status. In addition, software status box will display "Line outage scenario". Similarly, scenario can be switched back to the default one by clicking SCENARIO → Bus split. It would also be accompanied by a change in the appropriate switching element status and the software status box will display "Bus split scenario".

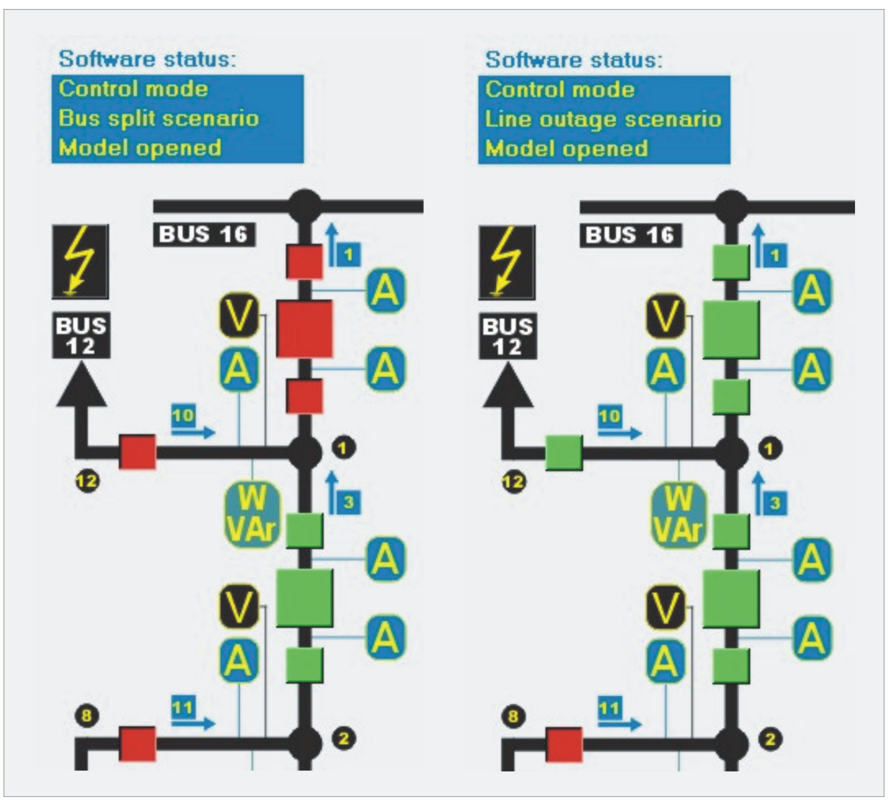

Fig. 16. Bus split and Line outage scenario and associated switch device status

When the substation model is opened, substation switching device control 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. Software modes of operation will be discussed in detail in the following section.

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. Breaking the rated current is associated with electric arc extinguishing and disconnect switches are not designed to extinguish arcs. 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 monitor functions are implemented in the software. They protect all disconnect switches in the substation from breaking the current. Figure 17 shows some of the possible warnings generated when inappropriate switching sequences are attempted.

Upper two warnings are generated when there is an attempt to use the branch disconnect switch or transmission line disconnect switch to break the current. Disconnect switch is not supposed to be opened before one or both circuit breakers in the current path are opened. When the warning is generated, action on the disconnect switch is cancelled and the user should apply correct switching sequence described in the warning.

Lower two warnings are generated when there is an attempt to use the branch disconnect switch or transmission line disconnect switch to switch on the current. Only circuit breaker can be the last switching element in the current path to be closed. Therefore, disconnect switches must be closed before circuit breakers.

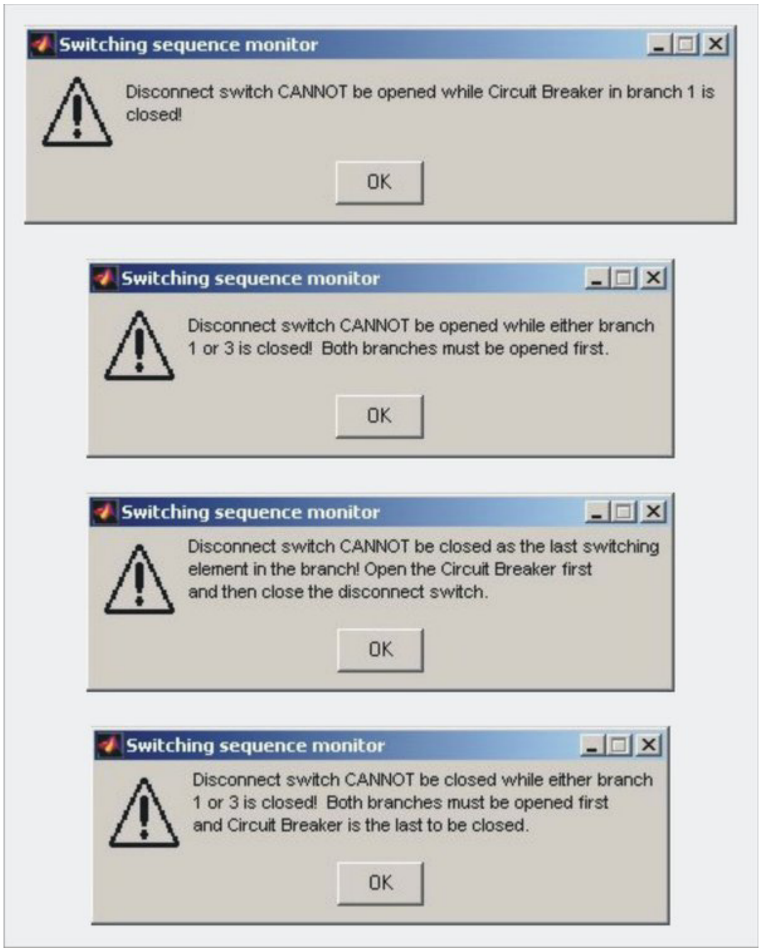

Fig. 17. Example of warnings resulting from monitoring of the switching sequence

One more object that appears on the user interface screen when the substation model is opened is fault pushbutton. As it can be seen on the GUI screen, seven fault pushbuttons in total are located next to transmission lines, load and busbars. Fault pushbutton is shown in Fig. 18.

Fig. 18. Fault pushbutton

The purpose of fault pushbuttons is to control opening of two or more circuit breakers at a time. When the fault is detected in the system, all circuit breakers closest to the fault need to be opened in order to clear the fault. Since the transmission lines in this substation layout are associated with two circuit breakers, they both have to be opened upon the fault occurrence (the opposite terminal of the transmission line is not considered here). Similar situation is with the load. Busbar faults are cleared in the same manner, except there are three circuit breakers associated with each busbar. They all have to be opened upon the bus fault. Fault pushbuttons can be used in the simulation of fault clearing.

By clicking on the fault pushbutton, all associated circuit breakers will be opened. If any of the circuit breakers is already opened, its status will not change. Instead of clicking on the fault pushbutton, the same effect can be obtained through the user interface menu: choosing the FAULTS option and then selecting the element where fault occurred (Line 12-16, Line 18-19, Line 17-16, Line 20-19, Load, Busbar 16 or Busbar 19).

Finally, the procedure for running the simulation will be described.

Simulation is started from the user interface menu: SIMULATION → Start. The first task before the simulation starts running is the substation model initialization. This inevitable part is performed by Simulink whenever the model is employed. It entails certain time to check the connections in the model and accomplish other important tasks before the model is run. In the case of the substation model, initialization process lasts up to one minute (depends also on the computer processing power). During that time, appropriate message is displayed on the screen: “Simulation initializing… Please wait. This process will take approximately one minute…”

When the initialization process is over, simulation starts running. New box objects appear on the user interface screen. They are used as a background to display snapshot processing results. As soon as the first snapshot of the measurements is processed, the boxes are filled with results. Various measurement boxes are constantly updated during the simulation as the new results are generated.

The snapshot counter appears in the lower right corner of the user interface. It starts counting from zero when the simulation is started and increases by one whenever new snapshot data is processed and results are displayed. It also alternates the color of the snapshot number (black and red) in order to emphasize each time results are generated. Examples of the snapshot counter are shown in Fig. 19.

Right above the snapshot counter is a pushbutton that can be used to control the simulation, i.e. to alternatively pause and continue simulation when clicked. Accordingly, the pushbutton will display: “RUNNING” or “PAUSED”. The simulation status is reflected through the software status box that displays appropriate simulation status message: “Simulation running” or “Simulation paused”. Red color background is chosen for GUI messages when the simulation is paused.

Full simulation control is achieved through SIMULATION user interface menu:

- When the simulation is running, it can be either paused (SIMULATION → Pause) or stopped (SIMULATION → Stop)
- When the simulation is paused, it can be either continued (SIMULATION → Continue) or stopped (SIMULATION → Stop)
- When the simulation is stopped it can be run (SIMULATION → Start)

Appropriate simulation status is always reflected through the software status box. After the simulation is stopped, it needs to go through an initialization process whenever it is to run again. Continuing the simulation after being paused does not require initialization.

Fig. 19. Example of simulation status and snapshot counter

The results of processing the data snapshots 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 transition reports.

Algorithm outcomes were described earlier when the processing and consistency check algorithms have been analyzed. Those are represented as icons or symbols next to the appropriate measurements, switch elements or nodes. All icons and symbols can be seen during software operation by selecting SOFTWARE → Legend from the user interface menu. Symbols are listed as consistency and inconsistency outputs in the software legend window. The legend is also shown in Fig. 20.

After each data snapshot is processed, all symbols are updated. Any change in consistency is immediately reflected through appropriate consistency check symbols.

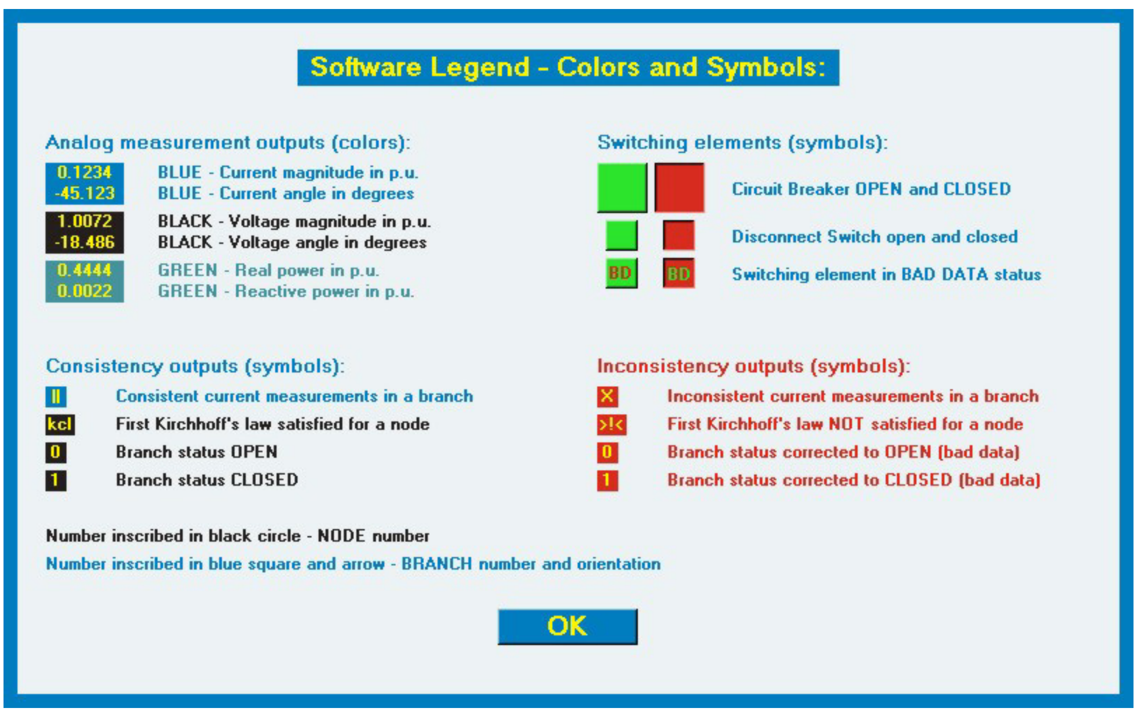

Fig. 20. ISS legend that describes software colors and symbols

The analog measurement values are displayed in corresponding measurement boxes after each data snapshot is being processed. Each type of instruments is associated with appropriately colored boxes: blue boxes are reserved for current measurements, black boxes for voltage measurements and green boxes are reserved for power flow and power injection measurements.

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 power flow and power injection measurements, upper value corresponds to real (active) power and the lower one represents reactive power. An example of measurement boxes filled with values is shown in software legend in Fig. 20 under the title “Analog measurement outputs”.

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). Switching elements can be operated (opened or closed) through the user interface during the simulation run. This will cause a change in the status and corresponding analog measurements immediately after the next data snapshot is being processed.

After each data snapshot processing is over, processing and transition reports are being displayed. Processing 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. 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. Discussion of different processing and transition reports was already given in the previous chapter.

Substation model and data processing parameters can be seen and/or modified through the user interface menu PARAMETERS. They can be accessed by selecting PARAMETERS → Model → Switch…. The dialog box that opens up is shown at the top of Fig. 21 and allows modification of the parameters of the switch element model.

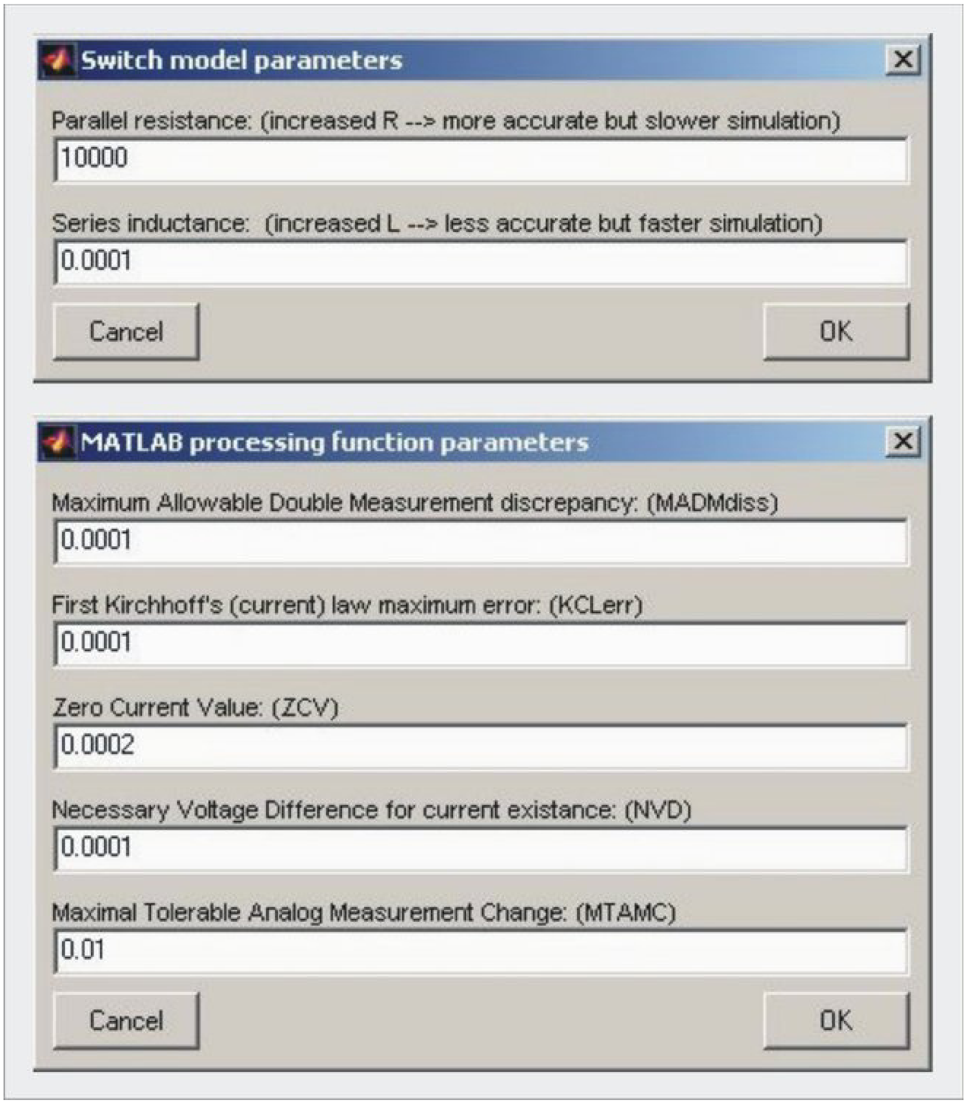

Fig. 21. Dialog boxes for parameter adjustment

As mentioned in the substation modeling section, the switching element model requires parallel resistance and series inductance to operate correctly. In an ideal case, those values should be an infinite resistance and zero inductance. Unfortunately, the Simulink model does not accept the ideal values. Therefore, resistance needs to be some finite value and inductance needs to be larger than zero.

Non-ideal values introduce errors in simulation. Actually, there is a trade-off between the simulation speed and accuracy. The closer the parameters are to the ideal values, the simulation runs slower. Default values are empirically chosen to make the best trade-off. User can increase the value for parallel resistance and/or decrease the value for series inductance and that will make the simulation more accurate but slower. On the contrary, it is possible to sacrifice accuracy in order to gain the simulation speed.

Processing routine parameters can be accessed through the user interface menu by selecting PARAMETERS → Processing…. The dialog box that opens is shown at the bottom of Fig. 21. It contains all the processing parameters in a single box. One or more of them can be changed before the OK button is pressed. All the processing parameters were explained earlier when the processing and consistency check algorithms have been discussed. If the dialog box is opened during the simulation, the execution of simulation is paused until the OK or CANCEL button is pressed.

Modifying the values of processing parameters will greatly influence the operation of 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.

Default values of all the parameters can be restored at any time. This can be accomplished through the user interface menu by selecting PARAMETERS → Default. Parameter values will be reset to their default values used to initialize the software.

Modes of Operation

Integrated Substation Software is designed to operate in two modes. The default mode of operation is the Control mode. Current mode of operation can be seen at any time by looking at the software status box in the GUI.

The Control mode enables user to change the status of switching devices. The user “controls” operation of substation by switching in and out certain transmission lines, load or performing the power flow transfers from one busbar to the other. Transmission line and busbar fault clearing can be simulated as well by click on the fault pushbuttons. During all these control operations, simulation is running. Measurements are acquired from the integrated substation model and processed corresponding to the implemented algorithms. The results of processing and consistency checks are readily displayed on the user interface screen. User can promptly see how certain control action influences the power flow and other quantities in the substation.

The other mode of operation is developed to present behavior of the algorithms in the presence of erroneous status measurements. It is named “Bad data” mode. User can switch to the Bad data mode through the user interface menu by selecting MODE → Bad data. The software status box will reflect this change through the message “Bad data mode”.

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 corresponding switch element in the model does not change, but only its reported status. In other words, when user changes the 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.

Erroneous status of a switching element that is reported to the processing routine is designated by the bad data symbol “BD” on the switching element toggle button. Switching element that is closed, but due to bad data appears like opened is represented with green square and red “BD” text on it. In an opposite case, the switch element that is opened, but due to bad data appears like closed is represented with red square and green “BD” text on it. These symbols were shown earlier in the software legend in Fig. 20.

When the processing and consistency check algorithms detect bad data, corrected status is displayed next to the appropriate switching element. The background of corrected status turns to red to notify of a previous existence of bad data. In addition, corresponding processing report is generated for each eliminated bad data. It states either “Bad data in branch corrected to 1” or “Bad data in branch corrected to 0”. It also notifies both the snapshot and branch number.

User can switch back to the Control mode at any time by selecting MODE → Control from the user interface menu. The software automatically eliminates all bad data that were introduced during the Bad data mode. In other words, status of all switching elements reverts to the correct value. Switching element symbols on the user interface display appropriate color of each element as it was shown before the bad data has been introduced.

Software Outputs

The results of processing and consistency checks are displayed on the user interface screen for each snapshot of data. User can see the values of processed measurements and recent history of processing and transition reports. Displaying results on the screen is just an auxiliary way to output the results.

Integrated Substation Software is designed to operate on computers in the substation control room. One of the important software features is communication of processing results to other substation or power system applications. This task is accomplished through the exchange of data files that contain list of processed analog and digital measurements. Data files can be communicated on a regular basis after processing of each data snapshot. An alternative is to allow other applications to demand data files whenever they have a need for additional data. This is even more convenient way of operation.

There are two types of data files: constant topology and measurements. Constant topology data file contains list of nodes with their classification and list of branches with their “from” and “to” nodes. This file describes constant topology data, i.e. data that does not change in time and does not depend on simulation execution.

Software creates constant topology data file on user’s request at any time. Since this file does not depend on simulation, it can be created even before the simulation is run. To request this output file, user needs to select OUTPUT → Topology from the user interface menu. The message that is displayed is shown at the top of Fig. 22.

Constant topology data file is named Sub1619.top. It is created and saved in the Matlab work directory. It can be opened by any text editor (e.g. notepad). An example of constant topology data file content is shown on the left-hand side of Fig. 23.

The other data file contains analog and status measurements. Data in this file contains the latest snapshot of results. Its contents will change depending on when the snapshot is created. The file can be created on user’s request by selecting OUTPUT → Measurements from the menu. An example of a message that is displayed is shown in the middle of Fig. 22. Since measurement data is generated only during substation model simulation, measurement data files are available only when the simulation is running. Therefore, user can request a measurement data file to be created only when at least one snapshot is being processed. Premature request would result in a warning shown at the bottom of Fig. 22.

The name of measurement data file consists of a string “Sub1619shot” and the snapshot number appended at the end. The extension is “.sub”. An example of measurement data file name is Sub1619shot5.sub. The file is also created and saved in the Matlab work directory and it can be opened by any text editor. An example of measurement data file content is shown on the right-hand side of Fig. 23.

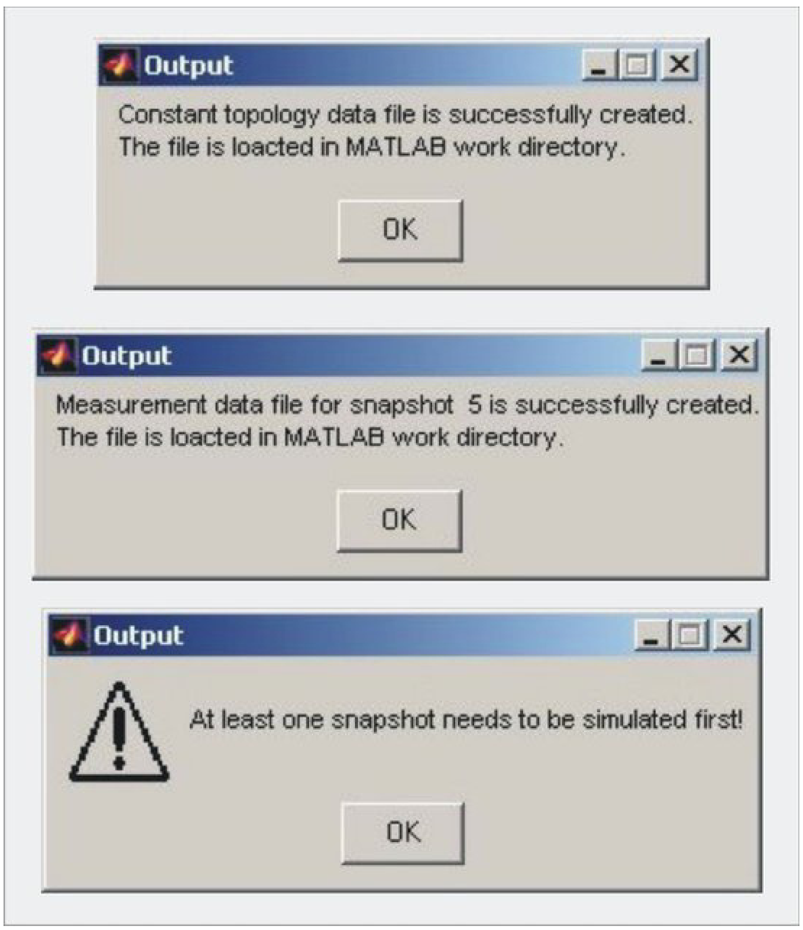

Fig. 22. Dialog boxes when topology or measurement data files are outputted

```
12
 1  3
 2  3
 3  3
 4  3
 5  3
 6  1
 7  2
 8  2
 9  1
10  2
11  2
12  2
13
 1  6
 2  9
 2  1
 4  6
 5  9
 5  4
 3  6
 3  9
11  3
12  1
 8  2
 7  4
10  5
```

```
Sub1619.top
   17  99
   18  99
   20  99
    0  99
   12  99
1        0.001
1        0.001
0        0.001
1        0.001
1        0.001
0        0.001
1        0.001
0        0.001
1        0.001
1        0.001
1        0.001
1        0.001
1        0.001
  7
  1    1.03759    -15.9248      0.0010
  2    1.03947    -15.9767      0.0010
  3    1.02591    -17.2664      0.0010
  4    1.03374    -16.2863      0.0010
  5    1.04035    -15.9180      0.0010
  6    1.03236    -16.4898      0.0010
  9    1.03991    -15.9473      0.0010
  0
  5
  9    -0.1270     -0.0573      0.0050
 10     0.0934      0.0481      0.0050
 11    -0.0049     -0.0040      0.0050
 12     0.0335      0.0126      0.0050
 13     0.0049      0.0040      0.0050
```

Fig. 23. Example of output data files: sub1619.top and Sub1619shot5.sub

First line in the measurement data file is actually the name of the corresponding constant topology data file. It is followed by the list of neighboring substation numbers. Next is a list of processed status (digital) measurements, i.e. variable topology data – list of branch statuses. Processed analog measurements are listed below in the following order: voltages, power flows and power injections. Each section contains the number of measurement, measurement values and corresponding standard deviations.

Integrated Substation Software operates with more data then it is communicated through the measurement files. Sometimes redundant data or data that is used temporarily may be of interest for other substation applications. In that case, it is possible to adjust output files to the format understandable to certain application. In addition, content of the file could be changed as well to fit the need of that particular application.

The last thing to be mentioned is the “about software” box. It opens up when the user selects SOFTWARE → About from the menu. The box is shown in Fig. 24.

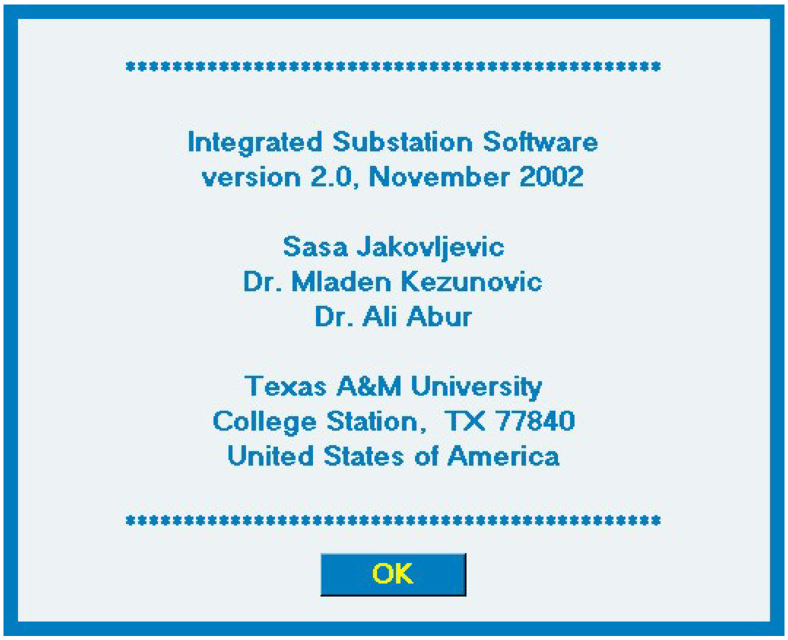

Fig. 24. The “about software” box

Conclusion

The Integrated Substation Software is developed to present the abilities of different processing and consistency check routines executed over redundant measurements acquired from the substation. Extensive Graphical User Interface accompanies substation model implemented in Simulink and Matlab processing routines. User has the ability to control the substation switching elements and observe the outcome through the change of different electrical quantities. Different modes of operation are implemented were the sensitivity of algorithms can be checked against bad (erroneous) data. Software outputs are readily displayed on the screen and can be exported through data files to other applications.

Data files that are obtained as a result of software processing can be used to serve both local and remote applications. Local (substation) monitoring and control functions make use of both analog and status information contained in data files. The set of utilized information depends on particular application needs. Remote applications mainly use contact data information for determining the power system topology. Analog measurements are useful for particular applications such as two-stage state estimation or system-wide power flow monitoring.

CHAPTER V

SIMULATIONS AND RESULTS

Introduction

This chapter demonstrates simulation of different scenarios in an integrated substation. It concentrates on the operation of consistency check algorithms and analysis of obtained results. Benefits of redundant measurements obtained by data exchange among intelligent electronic devices are shown.

Software components and installation will be explained first as a necessary step towards running successful simulation. All other facets of software operation were described in previous chapters.

Different scenarios can be created in both the Control mode and Bad data mode. The process of switching the transmission lines in and out will be used. Parameters will be changed to increase or reduce sensitivity of consistency check algorithms. This feature will be exploited to create inconsistencies and demonstrate their handling by algorithms. In addition, erroneous digital measurements will be introduced to test bad data detection and elimination. Improved sets of measurements will be discussed as well as their benefit to other substation and system applications.

All obtained results will be listed in appropriate tables. Additional tables that further clarify certain algorithms will be given. Output obtained by the software will be compared with unprocessed output or raw value directly obtained from the simulation model.

Software Installation

Integrated Substation Software is delivered as a single zip file (IS_Software.zip). The software consists of 120 files distributed in 5 folders and the zipping facilitates convenient storing, transferring and handling of all the files as a single file. This way, possibility of loosing any single file is reduced to a minimum. In addition, software files are compressed and the size of the zip file is more than 10 times smaller.

Part of the software installation requires extracting files from the software zip file. It can be done by double-clicking the zip file icon (with assumption that WinZip or similar software is previously installed on the computer). Extraction will be completed with the original folder structure preserved. In other words, after the software files are extracted, new folders will be created and each will contain appropriate software files.

The main software folder is named IS_Software and it contains four subfolders and three files. Two files are Matlab files and the third one is Simulink model file. The content of this folder is shown in Fig. 25.

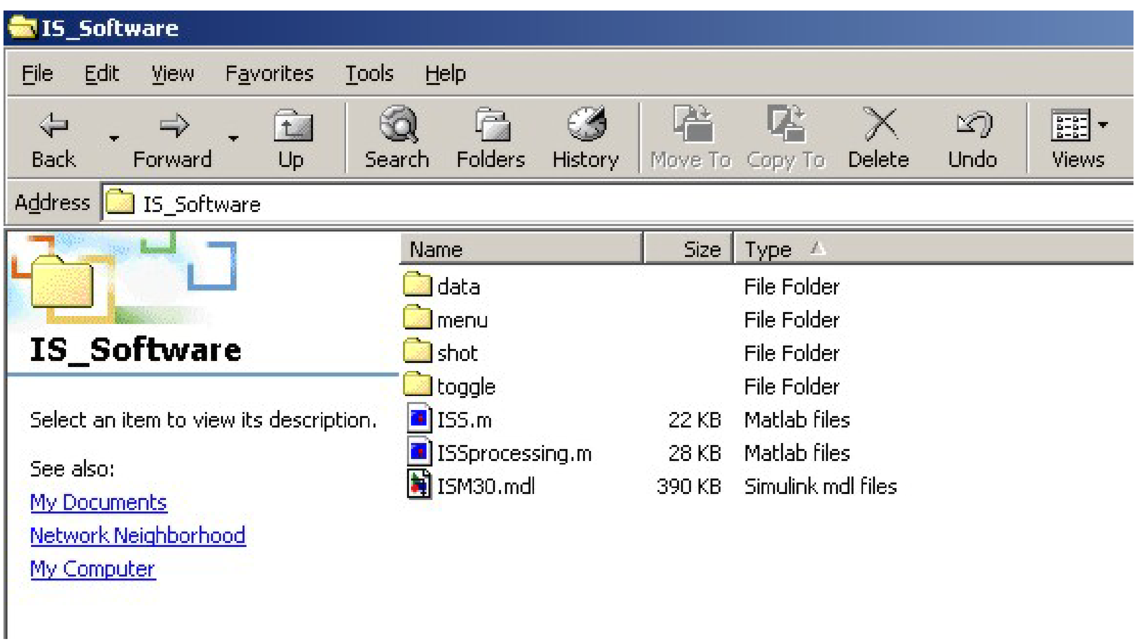

Fig. 25. The content of IS_Software folder

The software files in the main folder:

ISS.m	Main software routine
ISSprocessing.m	Main processing and consistency checking routine
ISM30.mdl	Integrated substation model file

Subfolders are:

data	Contains 5 mat files with GUI images and network equivalents
menu	Contains 26 m files that contain the user interface menu
shot	Contains 57 m files that collect substation measurements
toggle	Contains 29 m files that control switch element toggle buttons

Since the ISS is a Matlab based application, processing computer needs to have Matlab software installed. Matlab version 5.3 (release 11) and associated Simulink tools with Power blockset are required. After the software files are extracted, user should start the Matlab first. As a part of the software installation, all five newly created folders need to be added to the Matlab path browser list.

The software is started by typing “iss” or “ISS” at the prompt in the Matlab command window. This command invokes the main software routine ISS.m. It is the only routine that user needs to run the program. Complete software control is further achieved through the graphical user interface. For the best viewing results, it is recommended that user sets the screen resolution to 1024 x 768 pixels.

Simulation Scenarios and Results

Several different scenarios were created to demonstrate behavior of each data processing and consistency checking algorithm. Results of the quantities treated by the algorithm are shown in separate tables. Discussion makes a comparison between the two cases. In one case, default parameter values are employed. In the other, parameters have different values, suitable for demonstration desires algorithm feature.

Double Current Measurements

Suitable scenario will be selected to demonstrate the branch current calculation results done by a double current measurements algorithm. Branches 1-8 in the integrated substation model contain two current measurements. Simulation precision is very high and expected values for all current pairs are to be very similar. Ideally, since no shunt elements are modeled in any of those branches, current values should be identical.

This scenario assumes bus split scenario. Table V gives the results for MADMdiss=0.0001 (default value) and results for very strict consistency criterion MADMdiss=1e-12 are given Table VI. Any data snapshot could be taken in this case, but in this scenario, the results of snapshots 3 and 5 will be listed in Tables V and VI respectively. The MADMdiss variable was changed during simulation of snapshot 4.

Table V. Results of double current measurements algorithm (snapshot 3)

Branch	Current I [p.u.]	Current II [p.u.]	Output current [p.u.]	Consistency
1	0.10128732979158	0.10128732979169	0.10128732979158	OK
2	0.00610758752173	0.00610758752175	0.00610758752173	OK
3	0.00000007026783	0.00000007026783	0	OK
4	0.03463473251587	0.03463473251596	0.03463473251587	OK
5	0.00610745538474	0.00610745538473	0.00610745538474	OK
6	0.00000031317417	0.00000031317418	0	OK
7	0.13576289376887	0.13576289376880	0.13576289376887	OK
8	0.00000092009646	0.00000092009653	0	OK

Table VI. Results of double current measurements algorithm (snapshot 5)

Branch	Current I [p.u.]	Current II [p.u.]	Output current [p.u.]	Consistency
1	0.10130903991885	0.10130903991893	0.10130903991889	NO
2	0.00610923818302	0.00610923818305	0.00610923818304	NO
3	0.00000007029254	0.00000007029255	0	OK
4	0.03463980822324	0.03463980822334	0.03463980822329	NO
5	0.00610910581085	0.00610910581084	0.00610910581085	OK
6	0.00000031306191	0.00000031306191	0	OK
7	0.13578979159149	0.13578979159143	0.13578979159146	NO
8	0.00000091981054	0.00000091981061	0	OK

As it can be seen from Table V, consistency is fulfilled for all branch current measurements. The value of current I is taken as an output in those cases. Currents below ZCV=0.0002 threshold are considered as zero current measurements.

Table VI presents the case when inconsistencies occur in branches 1, 2, 4 and 7. Actually, those inconsistencies are artificially induced with very low MADMdiss value. Since the algorithm realizes those values as inconsistent, it applies average value calculation and such results are outputted.

The double current measurements algorithm generates reasonable outputs even when measurements are not consistent. Current values are averaged and very low values are considered as zero thus making the rest of calculations less complicated.

First Kirchhoff's Law

Another scenario shows how the First Kirchhoff's Law consistency check algorithm treats different current summation values. As it was described earlier, this algorithm sums up currents in branches that meet at the same node. Several nodes in the integrated substation model fulfill the criteria for Kirchhoff's Current Law. The value of variable KCLerr has an important role in this process. It is used to decide whether the summation can be considered consistent or not.

Table VII. Results of First Kirchhoff's Law algorithm

Node	Current summation [p.u.]	KCLerr [p.u.]	Consistency	KCLerr [p.u.]	Consistency
1	0.00000007026797	0.0001	OK	1e-07	OK
2	0.00000007026786	0.0001	OK	1e-07	OK
3	0.00000092009623	0.0001	OK	1e-07	NO
4	0.00000031317421	0.0001	OK	1e-07	NO
5	0.00000031317417	0.0001	OK	1e-07	NO
6	0.00000000000043	0.0001	OK	1e-07	OK
9	0.00000092009651	0.0001	OK	1e-07	NO

Since the simulation precision is very high, it is expected that all current summation values will be very small. Theoretically, summation of currents should be zero, but due to measurement errors, it appears as non-zero number. KCLerr variable determines if this number is below the satisfactory threshold.

Scenario assumes an initial switching element status and bus split scenario. Any data snapshot could be taken in this case, but this scenario takes current summations from snapshot 3. Table VII gives the results for current summations in nodes where more than two branches meet. First value for KCLerr=0.0001 (default value) designates all measurements as consistent. Second value for KCLerr=1e-07 is chosen as lower tolerance threshold and four measurements appear as inconsistent.

Simulation is run twice with different values of KCLerr. For lower value of KCLerr, current summations in nodes 3, 4, 5 and 9 are considered inconsistent. Again, those inconsistencies are artificially induced with low KCLerr value. Since the algorithm realizes those summations as inconsistent, it displays corresponding inconsistency reports on the user interface screen.

Branch Status Determination

During the integrated substation simulation, status of all switch elements is collected. In branches where there are more than one switch element, status is determined based on the status of all switching elements.

Table VIII presents all possible combinations of the status of three switching elements and temporary branch status determined by the algorithm. As it was described earlier, a final branch status is determined after another algorithm that takes into account branch current and other useful information is executed.

Table VIII. Status of switching elements and temporary branch status determination

Combination	Status of DS I	Status of CB	Status of DS II	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

During the simulation, switching elements change status as the user clicks on their symbols. In the Control mode, status is changed in the substation model, whereas in Bad data mode, only status relevant for processing is changed. In any case, temporary branch status is determined based on Table VIII.

Branch Current Value and Status

This algorithm determines final branch status. The operation of this algorithm is best demonstrated through the Bad data mode. Since this is the most important algorithm, Bad data mode was developed to test it with erroneous status data. Bad status reporting can be created for any switching element in the substation.

In the process of final branch status determination, algorithm considers four variables. It looks at the value of branch current in the current and previous snapshot. It calculates branch terminal voltage difference when necessary. At the end, it retrieves temporary determined branch status and either confirms it or changes it based on the values of other variables. The logic of this algorithm was explained earlier through the flowchart shown in Fig. 10. Now, Table IX can be observed for further clarification. It gives all possible combinations of four relevant variables and shows how the final branch status is determined.

Table IX. Final branch status determination

Current snapshot	Previous snapshot	Temporary status	Voltage difference	Algorithm conclusion	Final status
$I_{CURRENT} > 0$	irrelevant	1	irrelevant	consistent	1
		0		bad data	1
$I_{CURRENT} = 0$	$I_{PREVIOUS} > 0$	1	irrelevant	consistent	1
		0		consistent	0
	$I_{PREVIOUS} = 0$	1	$V_{DIFF} = 0$	warning	1
		0		warning	0
		1	$V_{DIFF} > 0$	bad data	0
		0		consistent	0

During the integrated substation simulation, all of the cases shown in Table IX can occur. It is not convenient to list status of all the switching elements and analog measurements for all the cases. Therefore, only two most important scenarios when bad data is corrected will be selected.

Both scenarios assume Bad data mode of software operation, bus split scenario and initial status of all switching elements in the substation model (branch 1 is closed and branch 3 is opened). Threshold for the zero current value is determined by the variable ZCV=0.0002. Threshold for the necessary voltage difference for current existence is determined by the variable NVD=0.0001.

In the first scenario, bad data is created on the circuit breaker in branch 1. Now, reported status of two disconnect switches in the branch are “1” and the circuit breaker status is “0”. Algorithm calculates temporary branch status as “0”. However, the current in the branch is $I_{CURRENT}$ = 0.1013 p.u., which is greater than zero (ZCV). Algorithm detects bad status data and determines the final branch status as “1”. Therefore, the algorithm operates correctly and bad data is successfully eliminated.

In the second scenario, bad data is created on all switching devices in branch 3. Now, reported status of all three switching elements in the branch is “1”. Algorithm calculates temporary branch status as “1”. The current in the branch in both the current and previous snapshot is $I_{CURRENT}$ = $I_{PREVIOUS}$ = 0 p.u. In order to determine correct branch status, algorithm calculates voltage difference between two branch terminals as V_{DIFF} = 0.0021 p.u., which is greater than zero (NVD). Algorithm detects bad status data and determines the final branch status as “0”. Therefore, the algorithm operates correctly again and bad data is successfully eliminated.

Application of this algorithm detects a correct status of switching elements in an integrated substation. Benefits of the implementation of this algorithm are significant due to great importance of correct topology determination. Algorithm is robust and handles very well erroneous reporting of the status for switching elements. It detects bad data, identifies the location of bad data and eventually corrects the status. It also exploits advantages of integrated substations, data exchange features and ability to retrieve historical data from computer’s memory.

Time Series Changes

The operation of this algorithm is based on Table X. A change from previous snapshot is determined in each next snapshot. Both analog (current and voltage) and digital (status) measurements are checked. It is expected that analog measurement values change when the substation topology changes. This is an example of a consistency. Another consistency case is when no change occurs in both analog and status data. Remaining two combinations create inconsistencies.

In ordinary substation operation, no inconsistencies should occur. However, sometimes remote switching can change the analog measurements in a substation even when no local switching was performed. In such case, inconsistency report may be generated if the level of change is greater than the variable MTAMC that defines algorithm sensitivity. Inconsistency report draws attention of substation operators so they can check the reason of the change in analog data.

In the case of a sudden failure of an instrument or a communication link from the switchyard, the likelihood of inconsistency report generation is increased since the cause would be an abrupt change in measured value. This case can be simulated by the software and response of the algorithm can be tested.

Table X. Operating logic of time series algorithm

Analog Change	Topology Change	Conclusion
NO	NO	Consistency OK
YES	YES	Consistency OK
NO	YES	Caution advised
YES	NO	Alert: print suspicious branches and nodes

A small modification is made in the processing routine so the voltage measurement on the busbar 16 is blocked after third snapshot. Thus, everything should be consistent in the first three snapshots. In the fourth snapshot, voltage measurement will be lost. This should immediately create inconsistency alarm.

The simulation was run and for the first three snapshots, processing routine was displaying reports “Everything OK in this snapshot”. After the fourth snapshot was processed, the following report was displayed on the user interface screen: “Analogs changed but NOT status. Check Nd: 6”. The algorithm determined that busbar 16 voltage measurement was lost (its node number is 6).

Voltage measurement at busbar 16 was V_6 = 1.0325 p.u. before it was lost. The change in the value was greater than variable MTAMC = 0.01. Therefore, change in analog data was detected. Since no switch element changed its status, the inconsistency report was produced.

Similar scenario can be created for the opposite case as well. Instead of losing analog measurement, status measurement can be prevented from reporting. This would produce similar inconsistency report.

The time series consistency check algorithm worked as expected. Although this algorithm does not alter output values, its importance is significant due to generation of inconsistency alerts.

Reporting of Substation Transitions

This algorithm treats all transmission lines and load to detect and report their transitions between the two latest snapshots. The logic of operation (transmission line part) is presented in Table XI.

Table XI. The logic of operation of transitions algorithm (transmission line part)

<table>
<tr><th colspan="3">Current snapshot</th><th colspan="3">Previous snapshot</th><th rowspan="2">Transition</th></tr>
<tr><th>Branch to Busbar 16</th><th>DS</th><th>Branch to Busbar 19</th><th>Branch to Busbar 16</th><th>DS</th><th>Branch to Busbar 19</th></tr>
<tr><td>1</td><td rowspan="3">1</td><td>0</td><td rowspan="3">Irrelev.</td><td rowspan="3">0</td><td rowspan="3">Irrelev.</td><td rowspan="6">Transmission line CONNECTED</td></tr>
<tr><td>0</td><td>1</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td>1</td><td rowspan="3">1</td><td>0</td><td rowspan="3">0</td><td rowspan="3">1</td><td rowspan="3">0</td></tr>
<tr><td>0</td><td>1</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td>1</td><td rowspan="2">1</td><td>0</td><td>0</td><td rowspan="2">1</td><td>1</td><td rowspan="2">Transmission line TRANSFERRED</td></tr>
<tr><td>0</td><td>1</td><td>1</td><td>0</td></tr>
<tr><td rowspan="3">Irrelev.</td><td rowspan="3">0</td><td rowspan="3">Irrelev.</td><td>1</td><td rowspan="3">1</td><td>0</td><td rowspan="6">Transmission line DISCONNECTED</td></tr>
<tr><td>0</td><td>1</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td rowspan="3">0</td><td rowspan="3">1</td><td rowspan="3">0</td><td>1</td><td rowspan="3">1</td><td>0</td></tr>
<tr><td>0</td><td>1</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td colspan="6">All other combinations</td><td>No transition</td></tr>
</table>

Algorithm checks combinations of the status of corresponding switching elements in the current and previous snapshot and decides what type of transition occurred (if the transition occurred at all). Each transmission line or load can be connected to Busbar 16 or Busbar 19 or both. Relevant switching elements are transmission line disconnect switch (DS) and circuit breakers (CBs) in connecting branches (branch to Busbar 16 and branch to Busbar 19). Table XI gives all the combinations of statuses that produce transition.

The algorithm also treats all branches in the substation model to detect and report their transitions between the two latest snapshots. The logic of operation (branch part) is presented in Table XII. This part of the algorithm is simpler since fewer combinations need to be examined.

Table XII. The logic of operation of transitions algorithm (branch part)

Status in current snapshot	Status in previous snapshot	Branch transition
0	0	No transition
0	1	DISCONNECTED
1	0	CONNECTED
1	1	No transition

Reports created by substation transitions algorithm are displayed after each transition in the substation. Algorithm checks for transitions in every data snapshot. Transition reports enable substation operator to get better picture of changes in the substation. The algorithm automates analysis of status changes and outputs conclusion. The history of transition reports can be saved in the case a further analysis needs to be conducted later.

Conclusion

Results obtained by Integrated Substation Software were presented through analysis of each data processing and consistency check algorithm separately. Different scenarios are simulated to demonstrate proper operation of algorithms and software as a whole. The improvement of collected data is made by using redundancy of measurements, checking consistency of corresponding measurements, filtering out bad data and generating various reports relevant for substation operation. All these features unified in one simulation and processing software enhance the completeness of available data within substation. This is a benefit to substation and system applications that are in need of such a consistent set of data.

CHAPTER VI

CONCLUSION

Summary

The process of technological development brought multitude of new devices and functions into substation operation. During relatively short time period after first microprocessors were implemented, a myriad of electronic devices found their application in power engineering. Although pretty conservative, this field of electrical engineering suddenly began expanding. New devices allowed for new implementations. In addition, old functions were improved due to new device installation.

The implementation of new devices and fast development of substation functions was not followed by appropriate development of standards. Newly developed electronic devices operated in an outstanding manner for the function they were designed. Different vendors had freedom to implement the best solution according to their design criteria. Such a practice created variety of input and output signal formats, which hampered exchange of data among different devices.

Substation integration was recognized from the beginning as inherent value of electronic device application. Since data communication and exchange of data were limited, collecting data centrally and its processing could not give full benefits. Redundancy created by measurements done in parallel by several devices could not be utilized. Recent initiative for standardization of substation data formats and communication protocols made a progress on a standard that facilitates production of devices capable of "talking" one to each other [6]. Substation computers finally have an opportunity to collect substation data centrally and perform its processing.

In an effort to enhance substation integration, advanced data collecting and processing solutions are developed and implemented in an integrated substation software. The process of software operation comprises data generation, the exchange of data and finally application of processing and consistency check algorithms for creating outputs. Measurements are acquired from the substation device models and sent to be preprocessed and eventually checked for inconsistencies by processing routine. Several algorithms are applied to treat measurements of both analog and digital (contact) signals. Measurement data format is adjusted so the comparisons can be made. Redundant analog measurements are processed for consistency, topology of the substation is determined and measurements of analog and digital signals are further analyzed together. Bad topology data is filtered out. Changes in time of substation measurements as well as transmission line connection and branch status transitions are reported.

All the conclusions and processing outputs are either displayed on the user interface screen or exported through data files. The Substation Integration Software was tested through the set of scenarios where each scenario is used to test one of the processing and consistency check algorithms. Obtained results showed that the measurements can be improved and contained in a consistent set of analog and digital values applicable for usage by other substation and system-wide applications.

Contribution

There are six major benefits to this solution that include the following:

- Online system: By having the software installed on the main substation computer which communicates with substation apparatus, instruments and electronic devices, an operator is capable of performing substation control activities and obtaining processed measurements and reports on the computer screen.
- Automated analysis: The software operates continuously. All the substation measurements are automatically acquired and processed. This eliminates the need for a substation technician to manually perform measurement analysis and consistency checks.
- Consistent analysis: By automating the analysis, it ensures that all future measurement sets will be processed in a consistent manner defined by the user. This will reduce the possibility that two different substation technicians arrive at two different conclusions for the same inconsistency.
- Redundancy: Redundant measurements are created by collecting measurements from variety of instruments and IEDs around the substation. Utilization of

redundant measurements facilitated data consistency checks. Consistent set of measurements is generated for application by local and/or remote functions, bad status data is filtered out, alarm signals are generated upon detected inconsistencies and suspicious measurements are either rejected or averaged.

- Concise reporting: The outputs of the Substation Integration Software are concise reports that are easy to understand. They display any type of inconsistency found, warn or alert upon measurement abnormalities and inform about substation topology transitions. If applicable, corrective actions are suggested. This is done for every snapshot of collected data.
- Saves man-hours and money: The automated integrated substation software operation frees up the time of the substation personnel to work on other projects and ultimately saves the utility money.

It is also expected that this research and development effort contributes the following to the area of power systems engineering:

- Summarizes substation intelligent electronic devices and their function as well as the existing bad data detection and identification methods
- Provides the substation apparatus modeling and simulation requirements
- Proposes an advanced data collecting and processing approach for integrated substation enhancement
- Describes a solution for processing of measurement and consistency checks through algorithms
- Implements Graphical User Interface for substation switchyard presentation, switch element status control and processing and transition reports displaying
- Gives results for a set of test scenarios that can help in evaluating developed algorithms and consistency check procedures

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