Arnold Schwarzenegger
Governor

MAINTAIN, ENHANCE AND IMPROVE RELIABILITY OF CALIFORNIA'S ELECTRIC SYSTEM UNDER RESTRUCTURING

APPENDIX VIII

Advanced Topology Estimator Project Summary

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:

Lawrence Berkeley National Laboratory

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Advanced Topology Estimator Project Summary

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PRODUCT DESCRIPTION

Today's online power system applications rely on state estimators to calculate accurate network models. However, since current estimators have little ability to detect and identify incorrect switch statuses, these models frequently contain connectivity (topology) errors. The consequences are potentially very severe, ranging from loss of system operational security to market inefficiency and disruption. EPRI's Advanced Topology Estimator Project developed TOPAZ, which represents a breakthrough in real time modeling of power system networks. TOPAZ analyzes network breaker/isolator switch status errors using the very powerful 'combinatorial' approach, which until now was computationally prohibitive. This document provides a Final Report on the EPRI Advanced Topology Estimator Project.

Results and Findings

The Advanced Topology Estimator provides an essential foundation for implementing a number of applications that can significantly improve the safety, reliability and economy of operating power systems. TOPAZ performs rigorous combinatorial bad data analysis in which each combination can be a mix of suspected bad switch and analog measurements. This analysis is fast enough for real time use on very large networks, and is ideal for detecting and identifying switch status errors. TOPAZ is therefore able to overcome the key weaknesses of conventional estimators and topology error analyzers.

Challenges and Objectives

Commissioning of full AC State Estimators with traditional EMS tools has been a challenging assignment for even the largest electric utilities with a dedicated team of specialized database, display and power applications support staff. The goal of EPRI's Advanced Topology Estimator Project is to build an Advanced Topology Estimator that is simple for power systems engineers and operators to configure and install. With this degree of simplicity, even the smallest utilities will be able install and maintain the package.

Applications, Values and Uses

The correct modeling of network topology is essential to the safe, reliable operation of the power system. Every operator undertaking a switching procedure, from the largest to the smallest utility, must keep a model of the network topology in their head at each step of the procedure. An operator's incorrect assumptions about network topology can result in sustained outages affecting millions of customers, damage to equipment costing millions of dollars to repair and, worst of all, electrocution of crews working on lines and in substations. With an Advanced Topology Estimator, the computer can maintain an accurate model of the network topology to provide safety checks in the event that the operator may select erroneous switching actions.

The reliable and secure operation of power systems now requires the continuous and reliable operation of real-time network security applications. These include Topology Processor, State

Estimator, Contingency Analysis, Operator Power Flow and Optimal Power Flow. The foundation for successful operation of the real-time network applications is a reliable and accurate estimate of the network topology. A topology estimator forms a good base for automated and adaptive system islanding, adaptive load shedding, fast on-line voltage stability controls and automated and fast restoration controls.

EPRI Perspective

With open access, the U.S. interconnected systems are experiencing much greater levels of regional transfers as marketers strike deals between remote producers and consumers, resulting in new flow patterns from lower cost to higher cost regions. When the network topology is incorrect, the results of the remaining applications can be significantly in error, and may cause the operator to overlook an important overload or contingency violation, resulting in a blackout. The Topology Estimator can provide accurate information on switch and breaker status and reduce the risk of major problems on the electric power grid.

Approach

The project team developed the Advanced Topology Estimator Engine in two phases. Phase I successfully identified single status errors and validated the feasibility of using the simplified MW angle formulation for identification of topology errors. Phase II was extended to handle multiple interacting bad data due to breaker/switch status errors and MW measurement errors by using combinatorial search methods to determine the most probable combination of status and analog measurement errors. The project team also designed enhancements for the Power Application Computing Environment (PACE), to support integration, testing and demonstration of the Advanced Topology Estimator.

Keywords

Network topology
Real time modeling
Switch status errors

ABSTRACT

The nation's electricity grid requires continuous, reliable operation of computer-based topology analysis, state estimation and contingency analysis programs for uninterrupted operation. This document presents the final report of the Advanced Topology Estimator Project, which developed TOPAZ to calculate the best estimate of the electrical connectivity of a power system network.

Like a state estimator, the program will statistically process an Energy Management System (EMS) 'snap shot' of network analog measurements and switch (breaker, interrupt) status. However, unlike a state estimator, it will perform extensive 'combinatorial' bad data analysis to detect and identify network topology errors.

Combinatorial bad data analysis is powerful, but requires an amount of computation considered prohibitive within a conventional state estimator. However, the combinatorial effort can be reduced enormously by extending the unique "localized" bad data analysis features of the existing Nexant GEN-SE state estimation package, which itself performs an efficient but less powerful form of topology error analysis. The main output of the Topology Estimator will be a list of topology corrections that will be invaluable to any state estimator or other EMS application that builds a power system network model from real-time data.

The Advanced Topology Estimator and companion MW/Angle estimator require less commissioning and maintenance effort compared to a conventional state estimator since they are not affected by errors in shunt reactor/capacitor status and MVAR sign reversals. The project team has integrated the Advanced Topology Estimator with a CIM database and packaged it with simple to use graphical tools for maintaining the model and for displaying measured and estimated data on one-line diagrams.

Based upon the results obtained to date, it appears technically feasible to commission and maintain Topology Estimators and MW/Angle State Estimators from very small networks all the way up to large-scale networks that span entire Interconnections.

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1 INTRODUCTION

Advanced Topology Estimator Project Objectives

The objective of this document is to provide a Final Report on the EPRI Advanced Topology Estimator Project.

The Advanced Topology Estimator, named TOPAZ, represents a breakthrough in the real time modeling of power system networks. It analyzes network breaker / isolator switch status errors using the very powerful "combinatorial" approach, which until now was computationally prohibitive. Today's online power system applications rely on state estimators to calculate accurate network models. However, these models frequently have connectivity (topology) errors, because current estimators have little ability to detect and identify incorrect switch statuses. The consequences are potentially very severe, ranging from loss of system operational security to market inefficiency and disruption. TOPAZ responds to this very important problem.

Why a topology estimator is needed?

A conventional state estimator uses its switch status input data to construct the network topology. It then performs the main estimation process, whose primary sub-function is bad data analysis to detect, identify, and rectify any gross measurement errors. Unfortunately, conventional bad data analysis algorithms are fundamentally designed to find only analog measurement errors, on the assumption that the network topology is correct. When this assumption is false, these algorithms typically malfunction and produce either no state estimate or an estimated model with an incorrect and potentially dangerous topology. Effective bad data analysis must fully recognize and exploit the fact that switch and analog measurement errors interact with each other. For example, a topology error tends to be camouflaged as multiple spurious analog measurement errors. Many state estimators include ad hoc tests that can identify obvious topology anomalies—for instance, open circuits with measured non-zero flows. However, these kinds of tests have low success rates when dealing with non-trivial situations. They become completely useless when one or more topology errors interact with one or more analog measurement errors.

Program Summary

TOPAZ performs rigorous combinatorial bad data analysis, in which each combination can be a mix of suspected switch and analog bad measurements. This analysis captures the intimate interaction between the two types of measurements, and is ideal for detecting and identifying switch status errors. At the end, TOPAZ reports the most probable set of erroneous switch statuses and analog measurements.

Importantly and uniquely, the combinatorial analysis in TOPAZ is fast enough for real time use on very large networks. It is designed to run every few state estimator cycles, to clean any persistent switch status errors (recognizing that most status errors are due to manual reporting or database discrepancies).

TOPAZ analyzes the interaction between MW and switch status measurements. That is, it estimates the series topology of the network—the modeling that affects MW flows that is critical for most power system security and market operation functions.

By individually modeling switch statuses, TOPAZ is able to perform simultaneous bad data analysis on switch and analog measurements, thus overcoming the key weaknesses of conventional estimators and topology error analyzers.

Bad data tends to affect the state estimates only in its own electrical vicinity. In a large power system, this affected region is a very small proportion of the network. TOPAZ utilizes very sophisticated techniques to perform bad data analysis calculations only on the relevant small network subset(s). As a result, TOPAZ's computational effort becomes almost independent of network size.

Efficient combinatorial search is achieved via a special branch-and-bound technique. Knowledge of the electric power network is exploited to limit the range of search possibilities, thereby substantially reducing the number of combinations tested.

Obviously, the success of bad data analysis depends on measurement redundancy. In low-redundancy situations (often complex substations), TOPAZ may identify several equally likely candidate sets of in-correct switch statuses. Mostly, these correspond to the same electrical network topology.

Industry Applications

Commissioning of full AC State Estimators with traditional EMS tools has been a challenging assignment for even the largest electric utilities with a dedicated team of specialized database, display and power applications support staff.

The goal is to build an Advanced Topology Estimator and a companion MW/Angle estimator that is simple for power systems engineers and operators to configure and install. With this degree of simplicity even the smallest utilities will be able install and maintain the package. This project covers only Topology Estimator; its extension to MW/Angle estimator is not addressed.

The Advanced Topology Estimator will provide an essential foundation for implementing a number of applications that can significantly improve the safety, reliability and economy of operating power systems. These different applications are discussed in the following sections.

Basic Monitoring and Switching Applications

The correct modeling of network topology should be the essential foundation to safe and reliable operation of the power system. Every operator that undertakes a switching procedure from the largest to the smallest utility needs to keep a model of the network topology in his head at each step of the switching procedure. The results of the operator making incorrect assumptions about network topology can result in sustained outages affecting millions of customers, damage to equipment costing millions of dollars to repair and, worst of all, electrocution of crews working on lines and in substations.

With an Advanced Topology Estimator an accurate model of the network topology can be maintained by the computer and this can provide safety checks in the event that the operator may select erroneous switching actions.

The basic applications that can benefit from an accurate and robust Topology Estimator include:

- Projection map-board systems and system overview displays with line colorization
- Safe Switching Validation Procedures
- On-line Power System Simulator

Foundation for Security Analysis Applications

With open access the U.S. interconnected systems are experiencing much greater levels of regional transfers as marketers strike more and more deals between remote producers and consumers. New flow patterns are occurring as the marketer wheel power from lower cost to higher cost regions.

The reliable and secure operation of power systems now requires the continuous and reliable operation of real-time network security applications. These include Topology Processor, State Estimator, Contingency Analysis, Operator Power Flow and Optimal Power Flow. The foundation for successful operation of the real-time network applications is a reliable and accurate estimate of the network topology.

When the network topology is incorrect the results of the remaining applications can be significantly in error. Incorrect results may cause the operator to overlook an important overload or contingency violation and result in a blackout.

As an example, the U.S.-Canada Power System Outage Task Force Interim Report: Causes of the August 14th 2003 Blackout in the United States and Canada highlighted the need for the following tools which are all dependent on accurate knowledge of the network topology:

- Continuous operation of state estimators to monitor system problems.
- Use of effective contingency analysis tools on a routine basis.
- Monitoring tools for high-level visualization of the status of transmission facilities.

Foundation for Standard Market Design

The Advanced Topology Estimator and a companion MW/Angle Estimator can be an important foundation for the implementation of a Standard Market Design as mandated by FERC. The overall goal of the SMD has been stated by FERC to be:

1. "The objective of standard market design for wholesale electric markets is to establish a common market framework that promotes economic efficiency and lowers delivered energy costs, maintains power system reliability, mitigates significant market power and increases the choices offered to wholesale market participants. All customers should benefit from an efficient competitive wholesale energy market, whether or not they are in states that have elected to adopt retail access."

The management of congestion will be handled with spot markets that are based on clearing bids using Location Marginal Prices (LMP).

1. "Standard market design should create price signals that reflect the time and locational value of electricity. The price signal – here, created by LMP – should encourage short-term efficiency in the provision of wholesale energy and long-term efficiency by locating generation, demand response and/or transmission at the proper locations and times."

2. "To complement Network Access Service and implement the Standard Market Design, Independent Transmission Providers will manage congestion using LMP. Management of transmission grid congestion is difficult to do through bilateral transactions alone; thus a spot market is required to manage congestion efficiently. We believe that congestion management, balancing of load and generation in real time, and the provision of ancillary services can be accomplished most reliably and efficiently by a bid-based, security-constrained spot market."

One of the themes that repeatedly occurs in the FERC meetings and documents on RTOs and the Standard Market Design (SMD) are the "seams" issues.

1. "Even where market designs appear to be very similar in contiguous regions, "seams" problems have persisted. A seams problem occurs when differences in business practices, market design, reliability rules, or software platforms between regions impedes trade between the regions. When these seams problems prevent the economic exchange of energy, they increase transactions costs."

The accurate and reliable calculation of LMP depends on maintaining an accurate model of the network topology. LMPs and congestion can be quite sensitive to the status of the transmission circuits. The Advanced Topology Estimator has been designed with the objective to handle very large networks.

NERC has established an Inter-regional security network (ISN) so that the participants can exchange a vast amount of real-time data and scheduling information. ISN data is available with all major flows and voltages throughout the Eastern Interconnection.

Security Coordinators (SCs), Independent System Operators (ISOs) and RTOs have now built operational models for their own systems. In accordance with the NERC data exchange requirements, these models can now be exported in a standardized CIM XML format. These models could be combined to form an operational model for the entire Eastern or Western Interconnection When these models are available, the Topology Estimator and MW/Angle Estimator will be usable on the entire Eastern or Western interconnection.

Next Generation Emergency Control Applications

The North American Electric Power Systems have been designed with the philosophy that they should continuously operate as large synchronous interconnections and that they should be able to withstand the worst credible contingencies.

The systems are designed to deal with all types of contingencies, including acts of nature, equipment failures and accidents. Fires, ice storms, lightning strikes and wind storms are common causes for transmission outages. Mechanical problems are common causes for generator outages.

On August 10, 1996, a major electricity outage in the Western United States grid left 12 million customers without electricity for up to 8 hours and cost an estimated $2 billion. This outage was due to untrimmed trees causing a transmission circuit flash over. This showed the difficulty of designing the system to handle contingencies due to natural causes.

On August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. The outage affected an area with an estimated 50 million people and 61,800 megawatts (MW) of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, and New Jersey and the Canadian province of Ontario. The blackout began a few minutes after 4:00 pm Eastern Daylight Time (16:00 EDT), and power was not restored for 2 days in some parts of the United States. This outage showed the vulnerability for a large portion of the interconnection to collapse even when the instigating events can be quite localized.

New technological solutions are needed so that power systems can more robustly handle severe outages from both natural events and acts of terrorists. Power systems need to be designed to shut down more gracefully with minimal loss of load when severe contingencies occur, and customer service needs to restored a lot faster after major customer outages. The safe and reliable operation of an interconnected system requires that several different types of stability be maintained as shown in the following table.

Angle Stability	1-2 seconds
Frequency Stability	Few seconds - minutes
Voltage Stability	Few seconds - minutes
Small signal stability	Few seconds - minutes
Thermal Stability	Few minutes

The time intervals indicate the typical period following the contingency that will be used to determine whether stability will be maintained or lost. Loss of stability in each case will result in further cascading outages.

The philosophy of operating power systems has changed little in the last 25 years. The same steady state Energy Management System functions are performed today as were performed in the mid 1970s. These functions are now performed on very low cost Intel PCs instead of large multi-million dollar main-frame computers. These functions are designed to run at periodicities of several minutes and for the most part are only useful in a Preventative Mode. In this mode, the security software recommends and the operator implements Preventative Actions.

The idea of Preventative Action is that we conservatively use the transmission system so that the flows following any credible contingency will not cause Angle, Frequency, Voltage, Small Signal or Thermal instability. Preventative actions can be quite costly since they require us to constrain the ongoing normal operation of the power system to handle all the harmful contingencies even when these have not occurred or may have a low probability of occurrence.

In contrast, Remedial Actions are taken only following the actual occurrence of a particular contingency. The idea of Remedial Action is to quickly assess the new state that exists immediately following an actual event and to take specific actions for alleviating the effects of the event that actually occurred. Remedial actions are not very costly or very limiting since they are implemented only for a short period following the event. To date, Generalized Remedial Action software is only used for maintaining Thermal Stability with its extended time frame. Specialized pre-programmed Remedial Action schemes have been implemented for maintaining angle, frequency and voltage stability but these are implemented with their own dedicated and highly customized control and communication schemes.

With the definition of a credible event now being broadened to include acts of terror possibly causing the simultaneous outages at ten or more substations the industry can no longer afford to operate with such a heavy dependence on Preventative Actions. The industry needs to develop fast, general purpose, robust Remedial Actions Schemes that can handle all the different types of stability phenomena under all types of possible contingencies and system operating conditions. The computational capacity and the communications technologies are available to support these schemes. For the most part, we need a new generation of robust control algorithms to be designed, tested and implemented.

A fast robust real-time Topology Estimator and companion MW/Angle Estimator will be an essential part of the foundation to support advanced Emergency Control Functions with Adaptive and Generalized Remedial Action Schemes. These schemes must be fully automated and the current approach of having an engineer involved to manually find status errors will not work. As examples, a Topology Estimator will form a good base for:

- Automated and adaptive system islanding.
- Adaptive load shedding
- Fast on-line Voltage Stability Controls
- Automated and Fast Restoration Controls

Approach

This Topology Estimator is very similar to a state estimator, except that it is dedicated to estimating the connectivity rather than the state of a power system network. It uses the same information available to a conventional state estimator, but solves a simplified network model and performs extensive "combinatorial" bad data analysis. In the following, we will discuss the specific problem of topology errors in state estimation, and the combinatorial approach to be employed.

The Problem

State estimation is a function that solves an over-determined power flow problem with more measurements than states. It uses a set of redundant analog measurements and a set of switching device (breaker, interrupter) status measurements, together with network and device parameters. Generally, the measurements are a mix of telemetered real-time quantities and otherwise assigned (pseudo) values. The state estimator performs statistical analysis, including bad data analysis, on these quantities to determine the operating state of the network.

Bad data analysis in conventional state estimation attempts to identify erroneous analog measurements, assuming known switch statuses (network topology). However, any errors in topology can have a profound effect on the estimated network states. To the bad data analysis process, they manifest themselves as analog measurement errors (usually multiple). It is then very difficult to know whether these apparent analog errors are due to topology errors, and if so to work backwards to detect and identify such errors.

Successful topology error analysis can only be performed simultaneously with analog measurement error analysis. That is, both types of measurements must be processed together in the state estimation solution and in the bad data analysis. This is precisely the principle adopted in the existing Nexant GEN-SE package.

The difficult problems arise when there is more than one simultaneous topology and/or analog measurement error. Moreover, certain measurement errors are "interactive", meaning that an error in one measurement is coupled to an error in another. Conventional analog bad data analysis theory based on Weighted Least Squares normalized residuals is inadequate on its own to handle these situations. This project has developed and implemented a more powerful combinatorial bad data analysis methodology, within a software package to be termed a Topology Estimator.

Combinatorial Analysis - General

Combinatorial analysis is a systematic search for errors among multiple combinations of measurements. It is an approach that has been researched for identifying multiple bad analog measurements. In principle, when the search hits the correct set of bad measurements and removes them from the problem, the manifestations of bad data disappear.

Combinatorial analysis is inherently much more powerful than the conventional non-combinatorial methods. However, since it relies on repeated state estimation and bad data analysis, it can be computationally very time consuming.

The combinatorial approach has never been implemented in a large-scale industrial state estimator package, for the following reasons:

1. Development of the combinatorial approach can only be justified if it is comprehensive enough to address multiple interacting data of whatever type (both analog and status measurements).

2. Combinatorial analysis is too time consuming to be performed routinely within a conventional state estimator being run with a typical real-time solution cycle (1 – 5 minutes) on a large power system.

3. Conventional state estimators are not designed to perform simultaneous bad data analysis for status and analog measurements. This makes them unable to accommodate a combinatorial approach that caters for both types of bad data.

Combinatorial Analysis in this Project

In this project, the combinatorial approach has been extended to simultaneous bad status and analog measurements. This has been the first practical large-scale application of the combinatorial approach in general, and for topology errors in particular.

General Design Considerations for the Topology Estimator Program

The existing GEN-SE package contains many highly evolved special features needed for efficient state estimation and bad data analysis, including the analysis of switch status errors. This software is the basis for the Topology Estimator program.

A key characteristic of the TOPAZ design is that it preserves the existing GEN-SE architectural structure, its general features and capabilities, and its flexibility for future enhancement. As an example, a full-featured MW/Angle estimator could be developed from the Topology Estimator.

The program is available for use in different ways, as:

1. A stand-alone tool running under a command-line interface on any platform.
2. A calculation engine, with a modern API that makes it easy to "plug in" to other software systems (such as energy management systems or web-based environments).
3. Integrated with the EPRI CIM using the PACE Power Application Computing Environment.

Exactly like the present GEN-SE package, Topology Estimator will accept:

1. "EMS-style" data, in which the network is described at bus-section/breaker level.
2. "Planning-style" data described at bus and branch level.
3. Any mixture of the two.

However, topology estimation is only fully effective with "EMS-style" data.

Summary of Results

The Advanced Topology Estimator Engine was released in two phases. The Phase I engine was able to successfully identify single status errors. The Phase I program validated the feasibility of using the simplified MW angle formulation for identification of topology errors.

The Phase II Advanced Topology Estimator Engine was extended to handle multiple interacting bad data due to breaker/switch status errors and MW measurement errors. The Phase II engine uses combinatorial search methods for determining the most probable combination of status and analog measurement errors.

Tests to date have also confirmed that the MW measurement redundancy is vital to the success of the Advanced Topology Estimator. In the absence of independent sources of information, it is very difficult to detect and identify errors – be they analog measurements or switch statuses. The Topology Estimator is no exception and requires reasonable measurement redundancy to insure proper identification of bad data.

Power Application Computing Environment (PACE)

PACE was released with the following enhancements for supporting integration, testing and demonstration of the Advanced Topology Estimator:

- A graphical Data Engineering feature has been included so that users can easily change the power system model and displays. The Data Engineering feature has been tested with the models that are used to support the EPRI OTS and Topology Estimator.
- A new scheme has been included for automatically keeping the database topological model and the schematic display model in synchronism.
- The EPRI Topology Estimator has been integrated to run with measurement data generated by either the EPRI OTS or a real-time data link to a SCADA system.
- A CIM XML file Importer and Exporter were built. This will be a very valuable facility for demonstrating the Advanced Topology Estimator on other utility and RTO systems.

The Advanced Topology Estimator has been integrated with the EPRI Common Information Model and released with the PACE Power Application Computing Environment.

The PACE/PowerVisuals station one-line diagrams and system map displays allow the results of the Topology Estimator to be shown very clearly to system operators. Line coloring and symbols can be used to show energized/de-energized components, line end open/closed status, line MVA loading, bus splits and electrical islands.

The station and one-line diagrams are generated from the network topological model. This means that errors in the topology model can be readily identified and corrected. Linkages between the symbols for power system objects on displays and the database objects are generated automatically. The opportunity for errors in linkages between database and display objects is eliminated.

By using topology based station one-line diagrams and system map diagrams along with an accurate assessment of the network topology from the Topology Estimator, the opportunity for presenting misleading or inadequate information to the operators is minimized.

The Topology Estimator can now be tested on large scale models of Transmission Owners and RTOs by importing models in the CIM XML format. Testing can be performed with measurements that are simulated using EPRI OTS or measurements from data links to existing Energy Management Systems.

Project Team

The Advanced Topology Estimator Project has been performed with contributions and support from a number of organizations. Incremental Systems Corporation is the Prime Contractor. PowerData Corporation provided the PACE Power Application Computing Environment and Software Integration and Support. Nexant, Inc. is provided its base GEN-SE product as background software and developed the Advanced Topology Estimator engine. Metso Automation assisted with integration of the Nexant applications with CIM and PACE. Decision Systems International supported the EPRI OTS Power System Model.

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2
FUNCTIONAL REQUIREMENTS

Overview

The Advanced Topology Estimator (TOPAZ) was developed based upon the following functional requirements specification. TOPAZ forms the foundation for meeting these requirements by detecting errors in switch statuses. Some of the output or post-processing requirements are met by complementing the TOPAZ package with a Topology Processor, State Estimator or MW/Angle Estimator.

The Topology Estimator is an on-line application responsible for establishing the database used by both real-time and study functions.

The status of the switching devices, flow measurements and voltage/angle measurements shall be used to derive the power system connectivity information. The user shall be able to make changes to any telemetered and manually entered quantities.

The Topology Estimator shall process changes in the system configuration resulting from a change of state of any switching device.

Configurations handled shall include bus splits, bus outages, ring bus models, individual generators and loads, open-ended lines and transformers, and transmission line and transformer outages.

Topology Estimator Inputs

Input data sources for the Topology Estimator in the real-time mode include the following:

- Real-time measurement data for breaker and switch status points retrieved from an existing SCADA system or an ICCP link.
- Real-time measurement data for line flows, bus voltages and bus angles.

In the version integrated with CIM, the Topology Estimator will register to receive an event whenever the CIM measurement table is updated. The Topology Estimator will process the analog and status points in the CIM measurement table and determine if there is a need to recalculate the network topology.

Topology Estimator Outputs

Connectivity nodes are points where terminals of conducting equipment are connected together with zero impedance. A Topological Node is a set of Connectivity Nodes that are connected together through closed switches. A Topological Node has a unique voltage and angle which is represented and solved by the power flow solution.

The Topology Estimator Program output will include:

- Relationships between Connectivity Nodes and Topological Nodes (Electrical Buses)
- Relationship between Topological Islands and Topological Nodes
- Energization state of conducting equipment terminals.
- Identification of bad status measurements.

Bad Data Analysis

Bad data processing comprises the correct detection and identification of measurements with gross errors, followed by the elimination of all such measurements from the problem. It is equally important to identify measurements that were wrongly classified as bad data, or were previously identified as bad data but have become good data in the meantime.

The difficult problems arise when there is more than one simultaneous topology and/or analog measurement error. Moreover, certain measurement errors are "interactive", meaning that the error in one measurement is coupled to the error in another. To handle these situations, a more powerful combinatorial methodology is needed and shall be developed.

User Interface

The Topology Estimator has been integrated with a Graphical User Interface that supports a variety of user defined displays types that are typically found in modern Energy Management, SCADA and process control systems including:

- World map one-line diagram displays with multiple layers.
- Substation one-line displays
- Repeat tabular (spreadsheet) displays.

Displays contain any combination of static and dynamic graphical objects. Dynamic objects are connected to “live” data in a databases. The form, color and values displayed with dynamic objects will typically change with the value in the databases. This change can occur on a periodic, event driven or user requested basis.

The GUI provides an environment for accessing and maintaining information on topological models by means of schematic diagrams. In Viewer mode the GUI shall manage commands, events, and data between users, and the applications. In Viewer mode, information on displays updates dynamically as data in its supporting databases changes. The result is a live graphical display that is updated in real time. In Editor mode, the existence and appearance of various pieces of information about the topological model can be controlled and changed.

An automatic display builder is available to build the one-line diagrams for a number of substations. The Topology Estimator can be tested by manually changing the status of breakers on the diagrams and running the program. The program is tested for a variety of single and multiple contingencies that involve generation outages, transmission outages and bus splits.

The GUI supports network coloring. Based on a topology analysis, the user is able to select between a number of coloring modes with the results as described below:

- Select Coloring Mode by energize/de-energize: The operator investigates if every thing is being fed and if not he can find out the cause.
- Select Coloring Mode by voltage levels: The operator investigates if anything is different, not normal with the voltage levels (what should very rare, almost impossible)

The following displays are provided:

- Topology Estimator Parameters: Tuning parameters include the ability to set the solution tolerance, maximum number of iterations allowed, and parameters to control the removal of bad data.
- Topology Estimator Input: Allows the operator to review and change the measurement parameters used to drive the Advanced Topology Estimator. For each substation in the system, the display includes the station name and type, the component name and type, the measurement value in either KV or MW, the MVAR value, the meter full-scale and meter error and the measurement usage status.
- Topology Estimator Output: This display shows a summary of the status errors that have been detected by the Advanced Topology Estimator. As a result of the hypothesis testing there may be multiple solutions. The Advanced Topology Estimator will present the results of multiple solutions in these cases.
- Rejected Measurement Parameters: This display allows the user to review the history of the measurements that have been rejected. For each measurement, the measurement name and type, substation name, measurement value in KV, MW or MVAr or status, the data and time are provided.

3
STATE ESTIMATION PRINCIPLES

Introduction

The Topology Estimator is based on the Weighted Least Squares (WLS) formulation, which is the approach thus far universally applied to practical power system state estimation. The state estimator determines the network state, given:

- a set of redundant measurements (telemetered and/or pseudo-measurements comprising analog and digital quantities)
- the network topology (connectivity based on status measurements)
- device models and parameters (based on the mathematical representation of the physical system)

The state variables comprise all the unknown independent quantities to be determined by the estimator. Once the state variables are known, all other power system quantities can be calculated directly.

The measurements are uncertain, in that they may contain random and/or gross errors. The variances of the errors reflect the uncertainty of the measurements. Unless otherwise specified, the device models and their parameters used by the state estimator are assumed to be known.

The most modern technique for the solution of the WLS problem is the orthogonal transformation method. Its main attraction is its guaranteed superior numerical robustness in the central estimation solution, which avoids solution failure in those (not infrequent) cases where earlier methods such as the normal equations approach and its variants suffer acute ill-conditioning.

Unconstrained WLS Formulation

Power system state estimation is traditionally formulated as an unconstrained WLS problem based on the electrical relationships between the state variables and the measurements. Let $\mathbf{x}$ denote the (nx1) vector of state variables, and $\mathbf{z}$ the (mx1) measurement vector, where m > n. Then the relation between these quantities may be expressed as:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \boldsymbol{\upsilon} \qquad \text{Equation 2-1}$$

where $\mathbf{h}$ is the (mx1) vector of non-linear equations expressing the measurements in terms of the state variables, and $\boldsymbol{\upsilon}$ is the (mx1) vector of random measurement errors.

Normally, the measurement errors are assumed to be independent of each other, and have Gaussian distribution with zero mean. When available, their variances indicate the accuracy of the measurements: the larger the variance σ_i^2, the less accurate the measurement z_i.

The estimate $\hat{\mathbf{x}}$ of the state vector is obtained by minimizing the unconstrained WLS function:

$$J(\mathbf{x}) = [\mathbf{z} - \mathbf{h}(\mathbf{x})]^t . \mathbf{W} . [\mathbf{z} - \mathbf{h}(\mathbf{x})]$$ **Equation 2-2**

where **W** is a (mxm) diagonal matrix of measurement weights. The elements of **W** can be chosen based upon available information on instrument accuracy or reliability, or upon engineering judgement. They are usually based on accuracy as expressed by the reciprocals of the measurement error variances:

$$W = \begin{bmatrix} 1/\sigma_1^2 & & & \\ & \cdot & & \\ & & \cdot & \\ & & & 1/\sigma_m^2 \end{bmatrix} = R_v^{-1}$$

Equation 2-3

where $\mathbf{R}_\upsilon$ is the measurement error covariance matrix.

Linearized WLS Problem

Linearization of equation (2-2) around a specified point gives the incremental WLS function:

$$J(\Delta\mathbf{x}) = [\Delta\mathbf{z} - \mathbf{H}(\mathbf{x}) . \Delta\mathbf{x}]^t . \mathbf{W} . [\Delta\mathbf{z} - \mathbf{H}(\mathbf{x}) . \Delta\mathbf{x}]$$ **Equation 2-4**

where $\Delta\mathbf{x}$ is the state change vector, $\Delta\mathbf{z}$ is the measurement mismatch or residual vector:

$$\Delta\mathbf{z} = \mathbf{z} - \mathbf{h}(\mathbf{x})$$ **Equation 2-5**

and **H** is the (mxn) measurement Jacobian matrix:

$$\mathbf{H}(\mathbf{x}) = \partial\mathbf{h}(\mathbf{x}) / \partial\mathbf{x}$$ **Equation 2-6**

all expressed around the point of linearization. It can be shown that, solving a sequence of linearized problems in the form (2-4) is equivalent to solving the non-linear WLS problem (2-2) by Newton's method.

Orthogonal Transformation Approach

The WLS estimation approach with least tendency to numerical ill-conditioning is the orthogonal transformation approach using fast Givens rotations. Re-expressing (2-4) as:

$$J(\Delta\mathbf{x}) = [\mathbf{W}^{½}.\ \Delta\mathbf{z} - \mathbf{W}^{½}.\ \mathbf{H}(\mathbf{x}).\ \Delta\mathbf{x}]^{t}\ .\ [\mathbf{W}^{½}.\ \Delta\mathbf{z} - \mathbf{W}^{½}.\ \mathbf{H}(\mathbf{x}).\ \Delta\mathbf{x}]$$ **Equation 2-7**

and introducing an (mxm) orthogonal transformation matrix $\mathbf{Q}$, i.e. $\mathbf{Q}^{t}.\ \mathbf{Q} = \mathbf{I}$, (2-7) now becomes:

$$J(\Delta\mathbf{x}) = [\mathbf{Q}.\ \mathbf{W}^{½}.\ \Delta\mathbf{z} - \mathbf{Q}.\ \mathbf{W}^{½}.\ \mathbf{H}(\mathbf{x}).\ \Delta\mathbf{x}]^{t}\ .\ [\mathbf{Q}.\ \mathbf{W}^{½}.\ \Delta\mathbf{z} - \mathbf{Q}.\ \mathbf{W}^{½}.\ \mathbf{H}.(\mathbf{x})\ \Delta\mathbf{x}]$$ **Equation 2-8**

Defining $\mathbf{Q}$ such that:

$$Q\,.\,W^{1/2}\,.\,H(x) \;=\; \begin{bmatrix} D_1^{-1/2}\,.\,U(x) \\ 0 \end{bmatrix}$$ **Equation 2-9**

and

$$Q\,.\,W^{1/2}\,.\,\Delta z \;=\; \begin{bmatrix} D_1^{-1/2}\,.\,\Delta z_1 \\ D_2^{-1/2}\,.\,\Delta z_2 \end{bmatrix}$$ **Equation 2-10**

where $\mathbf{U}$ is an (nxn) upper triangular matrix, and $\mathbf{D}_1$ and $\mathbf{D}_2$ are (nxn) and (m-n)x(m-n) diagonal matrices respectively, (2-8) reduces to:

$$J(\Delta\mathbf{x}) = [\Delta\mathbf{z}_1 - \mathbf{U}(\mathbf{x}).\ \Delta\mathbf{x}]^{t}.\ \mathbf{D}_1^{-1}.\ [\Delta\mathbf{z}_1 - \mathbf{U}(\mathbf{x}).\ \Delta\mathbf{x}] + \Delta\mathbf{z}_2^{t}.\ \mathbf{D}_2^{-1}.\ \Delta\mathbf{z}_2$$ **Equation 2-11**

Solving the necessary condition equations for the minimum of (2-11) yields:

$$\partial\mathbf{J}(\Delta\mathbf{x}) / \partial(\Delta\mathbf{x}) = \mathbf{U}(\mathbf{x}).\ \Delta\mathbf{x} - \Delta\mathbf{z}_1 \equiv 0$$ **Equation 2-12**

which is solved for $\Delta\mathbf{x}$. Equation (2-12) has to be solved iteratively for non-linear problems. For a given set of measurements and an initial state vector, the basic steps of this algorithm can be expressed as:

1. Form and orthogonalize the Jacobian matrix $\mathbf{H}(\mathbf{x})$ to obtain the gain matrix factor $\mathbf{U}(\mathbf{x})$
2. Form the measurement mismatch vector $\Delta\mathbf{z} = \mathbf{z} - \mathbf{h}(\mathbf{x})$, and compute the right hand side vectors $\Delta\mathbf{z}_1$ and $\Delta\mathbf{z}_2$ using the transformation matrix $\mathbf{Q}$
3. Solve: $\mathbf{U}(\mathbf{x}).\ \Delta\mathbf{x} = \Delta\mathbf{z}_1$, for $\Delta\mathbf{x}$, and exit if converged ($|\Delta\mathbf{x}| \le \boldsymbol{\varepsilon}$)
4. Update state variables $\mathbf{x} = \mathbf{x} + \Delta\mathbf{x}$, and go to step (a) if the Jacobian matrix is to be re-calculated, else go to step (b)

Observability Analysis

An electrical network is said to be observable if the available measurements, including the pseudo-measurements representing the imposed network constraints, are sufficient to estimate all the state variables uniquely. For a given network, this depends on the network topology as well as the numbers, types and locations of these measurements.

In general, the state estimation problem is "solvable" only for the observable parts (groups or islands of buses) of the network. The unobservable parts have to be either removed from the state estimation calculation, or made observable by adding pseudo-measurements. Hence, the observability analysis is concerned with the determination of these observable islands.

Observability algorithms can be classified into two distinct groups: topological and numerical algorithms, as shown in Table 3-1.

Table 3-1
Classification of Observability Algorithms

Observability Algorithms		
Topological	Numerical	
	Topological Mode	Numerical Mode

Topological observability algorithms are based on the information about the measurement system and network topology only. They tend to be combinatorial and use advanced graph theory concepts.

Numerical observability algorithms are based on the triangular factors of the gain matrix that may be calculated by direct factorization or orthogonalization of the Jacobian matrix. Because they utilize already existing software used for the state estimation calculation, they can handle all types of measurements and state variables.

Bad Data Analysis

Implicit in the WLS formulation is that the measurement errors are small. Occasionally, large errors or bad data occur due to various reasons such as meter or communication system failures. In order to avoid the corruption of the state estimation results, it is critical that

- the presence of bad data is correctly **detected**, and
- the measurements with bad data are correctly **identified**, and
- all such measurements are **eliminated** from the problem.

Bad data analysis is made possible by measurement redundancy in the observable portion of the network. The local redundancy, where the measurements and unknown states are counted only in the neighborhood of bad data, play an important role in this analysis. Measurement redundancy is usually linked with observability by various definitions of "critical" measurements:

- A measurement is critical if its deletion from the measurement set causes loss of observability
- A pair of individually non-critical measurements is critical if its deletion from the measurement set causes loss of observability

Just as observability is a prerequisite for state estimation solution, "detectability" is a prerequisite for bad data detection, and "identifiability" is a prerequisite for bad data identification. A measurement error is detectable if the measurement is not critical. A detectable error is identifiable if the measurement is not part of any critical pair.

Linear Sensitivity Analysis of Residuals

The first order sensitivity between the changes in estimated states $\hat{x}$ and the changes in measurements z can be obtained as:

$$\Delta\hat{\mathbf{x}} = \mathbf{G}^{-1}.\ \mathbf{H}^{t}.\ \mathbf{W}.\ \Delta\mathbf{z} \qquad \textbf{Equation 2-13}$$

where the inverse of the gain matrix $\mathbf{G} = \mathbf{H}^{t}.\ \mathbf{W}.\ \mathbf{H}$ is sometimes referred to as the state covariance matrix. The corresponding changes in the estimated measurements $\hat{\mathbf{z}}$ may now be expressed as:

$$\Delta\hat{\mathbf{z}} = \mathbf{H}.\ \Delta\hat{\mathbf{x}} = \mathbf{H}.\ \mathbf{G}^{-1}.\ \mathbf{H}^{t}.\ \mathbf{W}.\ \Delta\mathbf{z} = \mathbf{R}_{z}.\ \mathbf{W}.\ \Delta\mathbf{z} \qquad \textbf{Equation 2-14}$$

where $\mathbf{R}_{z} = \mathbf{H}.\ \mathbf{G}^{-1}.\ \mathbf{H}^{t}$, is the (mxm) measurement covariance matrix. The measurement residual vector at the estimated state is given by:

$$\mathbf{r} = \mathbf{z} - \mathbf{h}(\hat{\mathbf{x}}) \qquad \textbf{Equation 2-15}$$

For a change $\Delta\mathbf{z}$ in measurements, the first order change $\Delta\mathbf{r}$ in the estimated residuals $\mathbf{r}$ becomes:

$$\Delta\mathbf{r} = \Delta\mathbf{z} - \Delta\hat{\mathbf{z}} = \Delta\mathbf{z} - \mathbf{H}.\ \Delta\hat{\mathbf{x}} \qquad \textbf{Equation 2-16}$$

It follows from (2-13) and (2-16) that:

$$\Delta \mathbf{r} = \mathbf{R}_r . \mathbf{W} . \Delta \mathbf{z} = \mathbf{S} . \Delta \mathbf{z}$$ **Equation 2-17**

where **S** is the (mxm) residual sensitivity matrix, which transforms the measurement change vector into the residual change vector, and $\mathbf{R}_r$ is the (mxm) residual covariance matrix given by:

$$\mathbf{R}_r = \mathbf{W}^{-1} - \mathbf{H} . \mathbf{G}^{-1} . \mathbf{H}^t = \mathbf{R}_\upsilon - \mathbf{R}_z$$ **Equation 2-18**

Although the measurement error covariance matrix $\mathbf{R}_\upsilon$ is diagonal, the residual covariance matrix $\mathbf{R}_r$ is generally full, indicating that the residuals are correlated. In order for a bad measurement to be detectable, the corresponding column of $\mathbf{R}_r$ should be non-zero; and for the bad data to be identifiable, this column should be linearly independent of other columns. For critical measurements, the corresponding columns of the residual covariance matrix are zero, indicating that the associated bad data cannot be detected.

Bad Data Detection and Identification

The (mx1) weighted and normalized residual vectors are defined as:

$$\mathbf{r}^W = \mathbf{R}_\upsilon^{-1/2} . \mathbf{r}$$ **Equation 2-19**

and

$$\mathbf{r}^N = [\ \mathrm{diag}\ \{ \mathbf{R}_r \}\ ]^{-1/2} . \mathbf{r}$$ **Equation 2-20**

where diag{.} indicates the matrix formed by the diagonal elements. The weighted or normalized residual tests are used for bad data detection and identification at various stages of analysis. Bad data is detected if for any measurement i in the trusted measurement set:

$$|\mathbf{r}_i^{w}| = |\mathbf{r}_i / \mathbf{R}_{\upsilon_{ii}}^{1/2}| > \beta$$ **Equation 2-21**

or

$$|\mathbf{r}_i^{N}| = |\mathbf{r}_i / \mathbf{R}_{r_{ii}}^{1/2}| > \gamma$$ **Equation 2-22**

where β and γ are the corresponding detection thresholds. The weighted residual test (2-21) is sometimes preferred to avoid the computational burden of calculating the residual covariance matrix diagonals. However, its identification properties are not as good as the normalized residual test (2-22).

Status Estimation

Conventional state estimation programs process the analog data assuming that the network model is known. That is, the topology processor processes the switching device statuses and converts the "bus-section/switching-device" model into the network "bus/branch model". The state estimator then solves and analyzes this bus/branch model.

The segregation of bus-section/switching-device and bus/branch models and the associated processes is not always favorable, and can lead to various difficulties, particularly those in bad data analysis when topology errors are present. A superior approach for handling topology errors and for utilizing measurements on switching devices is to process both analog measurements and switching device statuses simultaneously. The Generalized State Estimation approach uses the generalized network model with explicit representation of switching devices. Switching devices whose statuses are "open", "closed" or "unknown" can be handled as a part of the model.

The basic principles behind the explicit modeling of switching devices are:

- to include the power flow of the device as a state variable, and
- to add pseudo-measurements representing the status of the device

The first principle avoids the explicit use of unknown (zero or infinite) device impedance as a part of the network model, and the second principle defines the specific constraints associated with "open" or "closed" device statuses.

The explicit representation of a "closed" switching device requires the voltage angle and magnitude differences to be added as zero-valued pseudo-measurements. Similarly, an explicitly represented "open" switching device requires active and reactive power flows to be introduced as zero-valued pseudo-measurements. Switching devices with "unknown" statuses do not have additional pseudo-measurements.

Topology Errors

Topology errors arise when one or more network elements are misconfigured as a consequence of wrong switching device statuses introduced into the network topology processor. The resulting electrical network connectivity may involve single or multiple network elements erroneously excluded, included or misconfigured. Topology error detection and identification comprise various stages in the overall estimation process:

- Consistency and validation tests performed by the network topology processor and state estimator pre- and post-processing steps (measurement confidence rating assessment)
- Determination of suspected switching devices for explicit representation by using the generalized network model (zooming)
- Subsequent analysis carried out for estimating the switching device statuses within the state estimator (status estimation)

Although in certain cases topology errors can be identified only by the consistency and validation tests, many situations require the use of more reliable and sophisticated tools. The generalized network model permits parts of the network to be represented by the bus-section/switching-device model, and the rest by the usual bus/branch model.

4
TOPOLOGY ESTIMATION METHODOLOGY

Topology Errors

Topology errors are the bane of most state estimators. When presented with an erroneous bus/branch model, conventional state estimators encounter difficulties and frequently fail to converge. In those instances when a solution is obtained, the inconsistency between the measurements and model causes a different estimation result. Bad data processing, after a conventional state estimation solution, using a bus/branch network model, will rate good analog measurements in the vicinity of the topology error as bad, and will eliminate them from the measurement set. Usually, the elimination process will continue until no further inconsistencies are detected, frequently due to the loss of local redundancy. The quality of the resulting system state is poor and in all likelihood will cause errors in succeeding network applications like contingency analysis.

The Largest Normalized Residual (LNR) method works very well for single and multiple non-interacting bad data. It loses its reliability for multiple interacting bad data where the net effect of the interaction is such that the largest normalized residual corresponds to a good measurement, or a bad measurement has a small normalized residual (i.e. conforming multiple bad data). The major cause of conforming bad data in practice is topology errors. To handle such cases, more powerful and time consuming methods, such as combinatorial search techniques need to be employed. The principles of the technique and its application to power system state estimation is described below.

Decision Theory Approach to Bad Data Identification

At the heart of the state estimation solution is the assumption that there is no bad data in the system. The best estimate of the system state is obtained amidst the Gaussian noise superimposed on the true values of the analog measurements. Then, the detection of bad data can be formally represented as a hypothesis testing procedure:

H_0 (null hypothesis) : No bad data is present

H_1 (alternate hypothesis) : H_0 is not true (bad data is present)

The largest normalized residual method of testing these hypotheses is:

Accept H_0 : if $|r_i^N| < \gamma \quad \forall \quad i = 1..m$

Reject H_0 (accept H_1) : otherwise

where the threshold γ is chosen to reduce the "false alarm probability" of accepting H_0. Critical measurements are excluded from this assessment since their residuals, as well as the corresponding diagonal elements of the residual covariance matrix, are equal to zero. If the normalized residual of any of the measurements exceeds the defined threshold, this strongly suggests the presence of bad data in the system. For the purpose of explanation, this and the following section will build the foundation of the decision theory approach subjecting only the analog measurements to bad data analysis. The extension to status measurements is outlined in a subsequent section.

The next step is the identification of the bad measurements. Corresponding to the m measurements in the system, there are theoretically 2^m combinations of good and bad measurements that should be analyzed. Each combination corresponds to a decision vector

$$\mathbf{u} = (u_1, u_2, u_3, u_4, \ldots, u_m),$$

where u_i is the formal decision of determining whether a particular measurement i is bad and is denoted as:

$$u_i = 1 \quad \text{if measurement i is good}$$

$$= 0 \quad \text{if measurement i is bad}$$

The multitude of these combinations can be viewed in the form of a decision tree shown in Figure 4-1. The tree is composed of m+1 levels. At each level i +1, a decision has to be made as to whether measurement i is good or bad. Thus each node has two sub-trees associated with it. Also to be noted is the fact that at level k, decisions have been made on k -1 measurements.

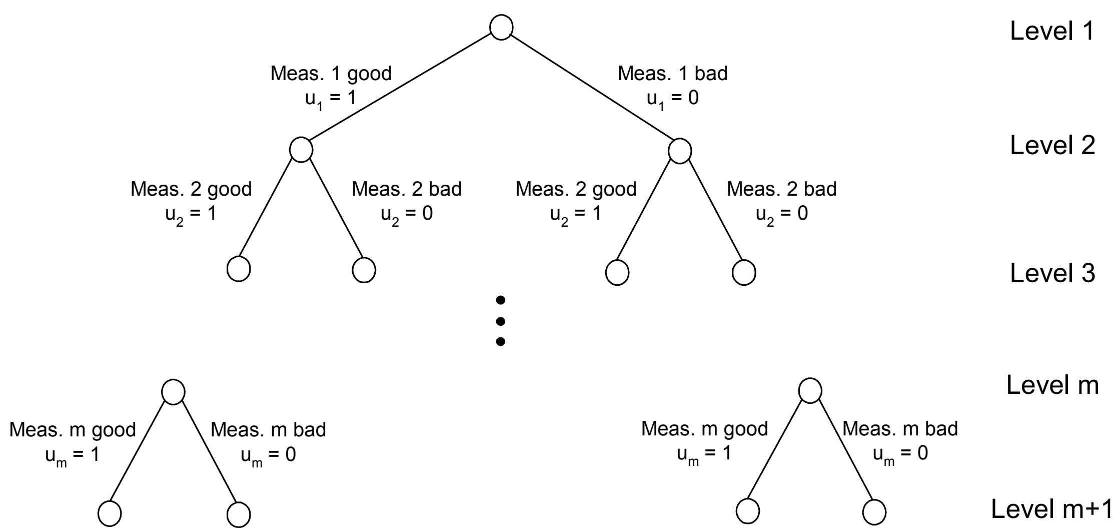

Figure 4-1
Decision Tree

Some of these combinations are simply not viable. For a combination to be feasible (after removal of all bad measurements defined in the decision), the following two conditions have to hold:

1. The network remains observable with same number of observable states, islands etc.

2. No more bad data is present in the system, i.e. normalized residuals of the remaining good measurements fall below the detection threshold.

There are many feasible combinations present in the system, with each combination corresponding to a particular choice of set of bad measurements. To pick between these alternatives, the concept of measurement reliability is brought into the formulation. The underlying premise is that measurements with lower reliability are prone to errors.

Let p_i be the probability that meter i is functioning properly, U be the set of meters that are functioning properly and D be the set of meters that are malfunctioning. Then the probability associated with a particular combination **u** is

$$P(\mathbf{u}) = \prod p_i \prod (1 - p_j) \qquad \text{where } i \in U \text{ and } j \in D$$

Applying the maximum likelihood criterion, the optimal decision **u** is the one that maximizes P(**u**) or alternatively, minimizes log P (**u**). Thus,

$$C(\mathbf{u}) = \log P(\mathbf{u}) = \sum \log p_i + \sum \log (1 - p_j) \qquad \text{where } i \in U \text{ and } j \in D$$

Under the assumptions that (i) p_i is close to 1.0 and (ii) the number of meters that are likely to be working properly are much larger than those that malfunction, the first term becomes a constant and the objective function can be rewritten as:

$$C(\mathbf{u}) = \sum \log (1 - p_j) \qquad \text{where } j \in D$$

With the simplifying assumption that all meters have the same reliability i.e. $(1 - p_j)$ = constant, the objective function reduces to:

$$C(\mathbf{u}) = \sum (1 - u_i) \qquad \text{where } i = 1..m$$

The optimal solution is the one wherein the least number of meters are malfunctioning, i.e. the minimum numbers of measurements are declared bad.

In summary, the bad data identification problem is formulated as a combinatorial optimization problem:

$$\min_{\mathbf{u}} C(\mathbf{u})$$

subject to:

1. The network remains observable with same number of states, islands etc.

2. No more bad data is present in the system, i.e. normalized residuals of the remaining good measurements fall below the detection threshold.

With the defined objective function, it is possible that there may be more than one optimal solution and all of them have to be identified.

Branch and Bound Method

As the number of measurements increase, the number of combinations to be analyzed grows exponentially. Effective techniques are required to limit the number of combinations to be analyzed. A factor in favor of the combinatorial method is that relatively few measurements are actually bad in a power system. Therefore, if at any decision node, the measurement being analyzed passes the normalized residual test, the sub-trees do not have to be visited – all undeclared measurements in the sub-tree are designated as good. This halves the number of combinations to be analyzed under this decision node.

Ideally, if the list of bad measurements were known, the decision nodes related to them would be placed at the top of the tree. In the absence of such insight, the largest normalized residual test is used to guide the search. This selection process is not precise but offers the perfect alternative. The measurements can be ordered dynamically so that the next candidate measurement is the one with the largest normalized residual among the undeclared measurements. As a result of proclaiming the measurement to be bad, two new decision nodes are created: g-successor and b-successor. The g-successor corresponds to the decision to consider the measurement as good while the b-successor corresponds to the decision to consider the measurement as bad, as shown in Figure 4-2.

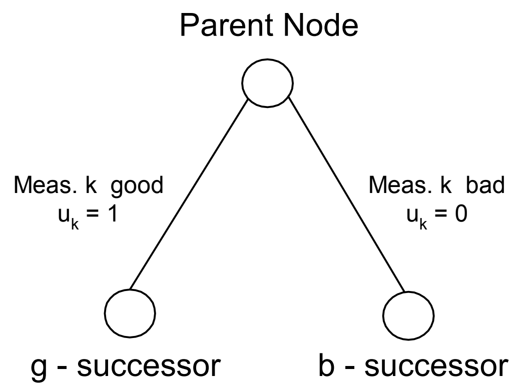

Figure 4-2
Successors of a Decision Tree

In Figure 4-1, the extreme left of the decision tree corresponds to the solution wherein all measurements are regarded as good while at the extreme right all measurements are declared as bad. Due to the lack of observability, several of the nodes towards the right are not feasible and the search technique should incorporate a strategy to automatically eliminate several of these combinations.

The overall scheme consists of finding a feasible solution as far to the right as possible and then testing other combinations with the intent of further reducing the objective function. Since the largest normalized residual test is the primary detection tool in the search, special consideration has to be given to interacting data. In such cases, the measurement with the largest normalized residual does not necessarily correspond to the erroneous one but is effective in pinpointing the location of the error. The offending measurement is in all likelihood within a small neighborhood of the measurement. Accordingly, the search algorithm has to accommodate this special type of bad data.

Extension of Combinatorial Analysis to Status Measurements

Breaker statuses are represented as measurements in the state estimation solution. This formulation permits them to be subjected to bad data analysis in the same manner as analog measurements. The combinatorial analysis algorithm does not undergo any changes and is equally applicable to the case when switch pseudo-measurements are being analyzed for errors.

Switch pseudo-measurements differ from analog measurements in one respect. Removal of an analog measurement is equivalent to its absence from the measurement set. However, elimination of switch pseudo-measurements does not toggle the switch position but merely makes the switch position "unknown". For example, if pseudo-measurements of zero voltage/angle difference representing a closed switch are eliminated from the system, the switch position becomes "unknown". Ideally, pseudo-measurements of zero active/reactive power can be introduced to represent the toggled position of an "open" switch, but this is rarely practiced.

Computational Hurdles

As each combination of good and bad measurements represents a separate state estimation problem, the solution time for the above combinatorial analysis could be considerable. Every known heuristic will be employed to reduce the problem space.

Recalling that the effects of bad data are observed locally, it is unwise to test all four combinations when two non-interacting bad data are in play. It is preferable to delineate the regions of influence of these two measurements and to analyze measurements in the relevant neighborhood.

Limitations of the Topology Estimator

The Topology Estimator will not be capable of uniquely determining errors on certain circuit breaker configurations due to lack of measurement redundancy. Similarly, erroneous statuses of circuit breakers connected to transmission lines with low MW loading, cannot be detected. This lack of detectability and error identifiability are not deficiencies of the proposed program but are problem formulations with insufficient information. Under these circumstances, it is impossible for any algorithm to correctly identify the wrong analog measurement or switch status.

Topology errors do not necessarily have detrimental effects on the state estimation process. For instance, if a misconfigured network element is not related to any measurement, then it will not affect the estimated results and may not be identified. Similarly, when a network element associated only with flow measurements is erroneously excluded from the model, these flow measurements are also excluded from the estimation process, changing the number of measurements used but introducing no gross errors. These measurements, however, can still be used in the consistency and validation tests for topology error identification.

5
TESTS WITH TOPOLOGY ESTIMATOR ENGINE

Introduction

This Chapter describes the tests with Topology Estimator Software program. The Tests were performed in two Phases:

- Phase I involved the delivery and testing of a program that could detect simple topology errors
- Phase II involved the delivery and testing of a program that could detect complex topology errors.

The Phase I Topology Estimator was based on the existing GEN-SE product and inherited the bad data analysis techniques from that package. The more comprehensive "combinatorial" methods were developed during Phase II of the project.

Test systems

While the program was internally tested using several large customer networks, the results on two test systems are summarized here – a 102 bus system and a 562 bus system. These networks were carved out of typical North American systems. Table 5-1 reports the system statistics for these two networks. The measurements (MW flows and injections, transformer taps and phase angles, and bus section voltages) associated with each network are listed in Table 5-2.

Table 5-1
Network Characteristics

System	Bus sections	Breakers	Branches		Loads	Generators
			Transmission Lines	Transformers		
102 bus	602	585	63	67	67	32
562 bus	3446	3254	529	324	339	159

Table 5-2
Measurement Characteristics

System	Measurements					
	Bus section voltage	Generator active power	Load active power	Branch active power	Transformer	
					Tap	Phase shift
102 bus	54	32	60	67	23	0
562 bus	265	126	247	550	122	12

Test Results

Phase I Test Scenarios

To show the capability of the program, three Phase I scenarios are considered. In all cases, the program successfully identified the topology error. The salient characteristics of the three scenarios are shown in Table 5-3. The substation diagrams of the topology errors in the neighborhood of the three scenarios are given in Figures 5-1, 5-2 and 5-3.

Table 5-3
Phase I Solution Characteristics

Scenario	Test system	Observable buses	Incorrect status	Execution time of topology estimator
Scenario 1	102 bus	102	Breaker ID 1866	0.06 seconds
Scenario 2	562 bus	432	Breaker ID 639	0.17 seconds
Scenario 3	562 bus	432	Breaker ID 702	0.15 seconds

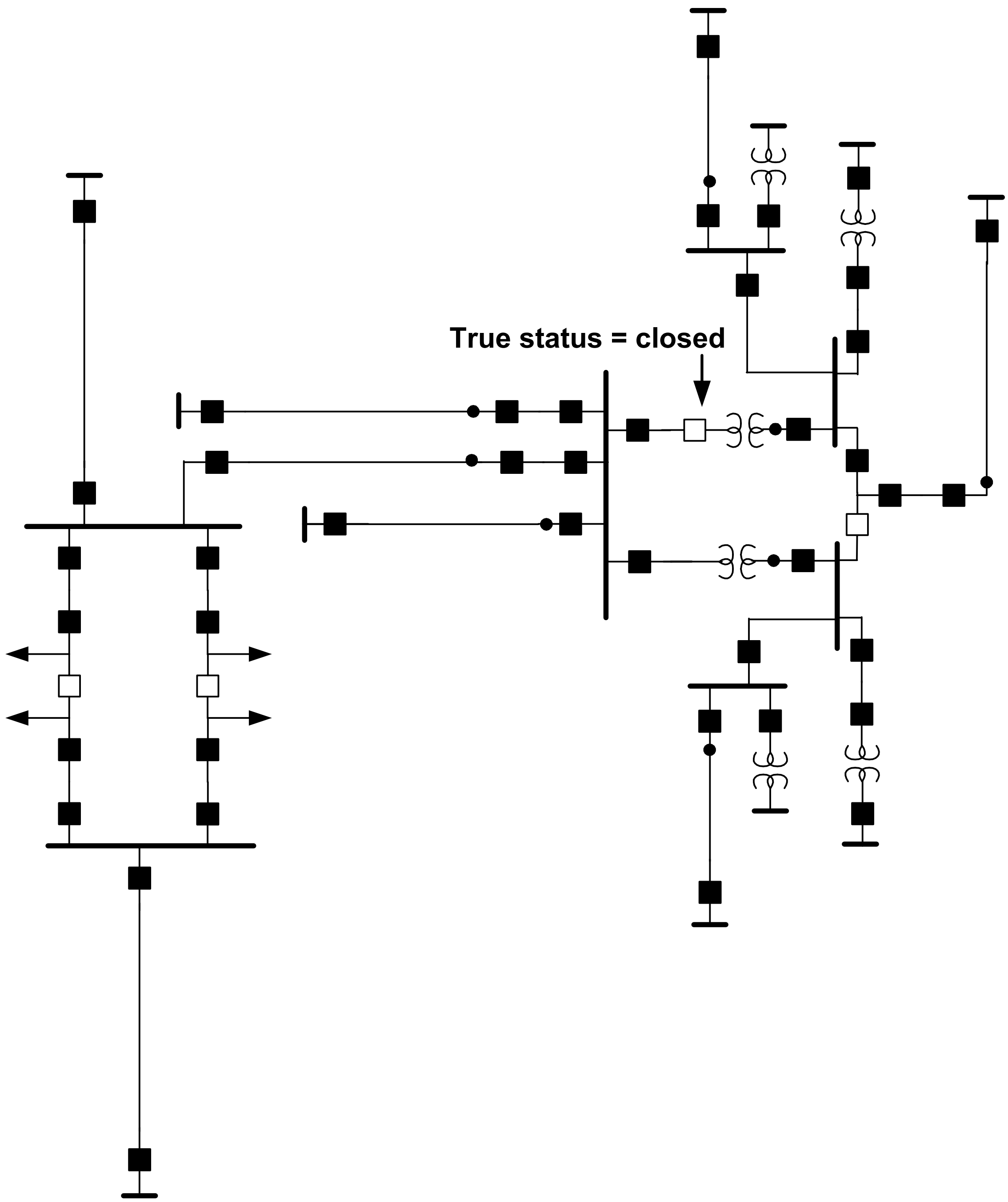

Figure 5-1
Scenario 1 - Station Diagram in the neighborhood of topology error

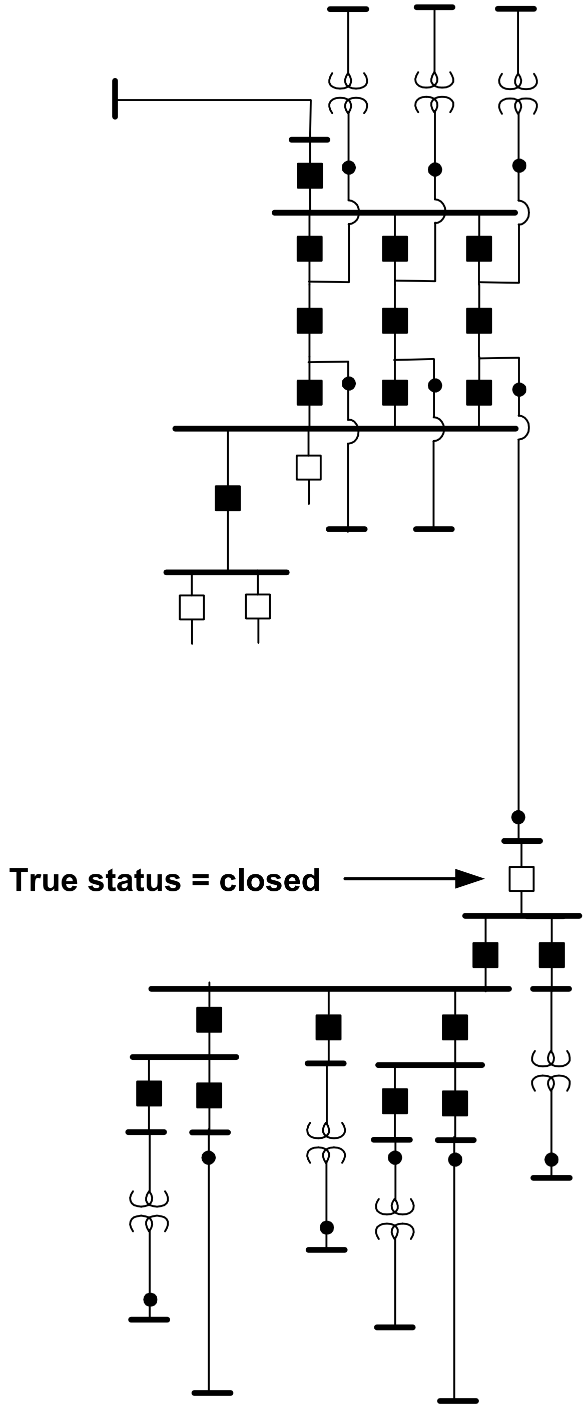

Figure 5-2
Scenario 2 - Station Diagram in the neighborhood of topology error

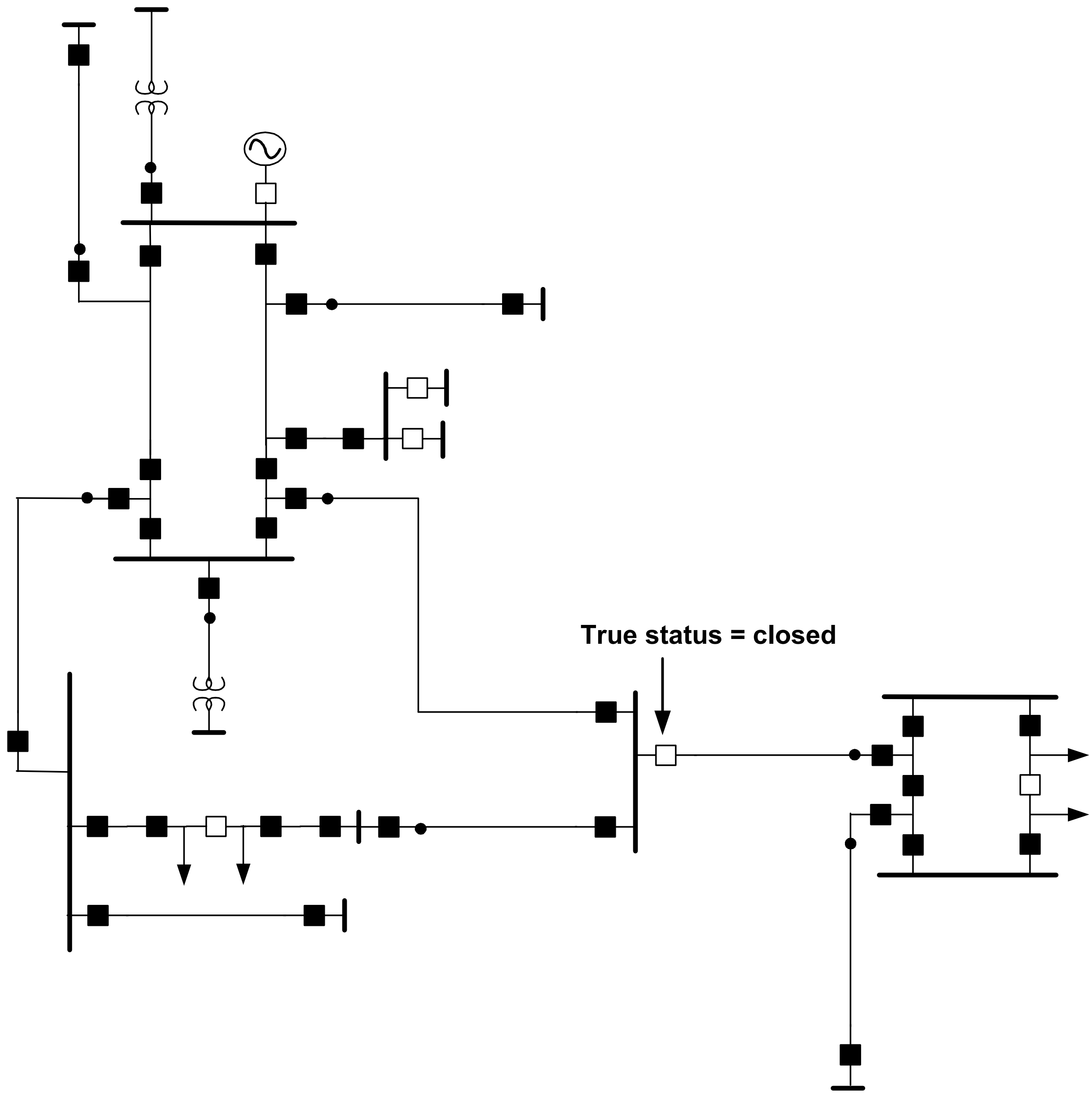

Figure 5-3
Scenario 3 - Station Diagram in the neighborhood of topology error

Phase II Test Scenarios

To show the capability of the program to handle more complex error cases, three additional scenarios are described. In all cases, the program successfully identified the topology error. The salient characteristics of the three scenarios are shown in Table 5-4.

Table 5-4
Phase II Solution Characteristics

System	Test system	Observable buses	Incorrect status	Execution time of topology estimator
Scenario 4	102 bus	102	Breaker ID 1760 Breaker ID 1841 Breaker ID 1880 Breaker ID 2018 Breaker ID 2138	0.55 seconds
Scenario 5	562 bus	432	Breaker ID 1099 Breaker ID 1293 Breaker ID 1382 Breaker ID 1565 Breaker ID 2082 Analog MW 34897 Analog MW 35948	1.92 seconds
Scenario 6	562 bus	432	Breaker ID 1099 Breaker ID 1147 Breaker ID 1293 Breaker ID 1806	6.86 seconds

The Phase II scenarios show the different flavors of the algorithm. The pertinent substation diagrams are shown in Figures 5-4, 5-5 and 5-6.

Figure 5-4 depicts a substation of the 562-bus system representing scenario 5. In this case an analog error is included in the proximity of a breaker error. The algorithm correctly identifies the position of the breaker and the MW flow to be bad data, assigning the best possible estimate to the flow.

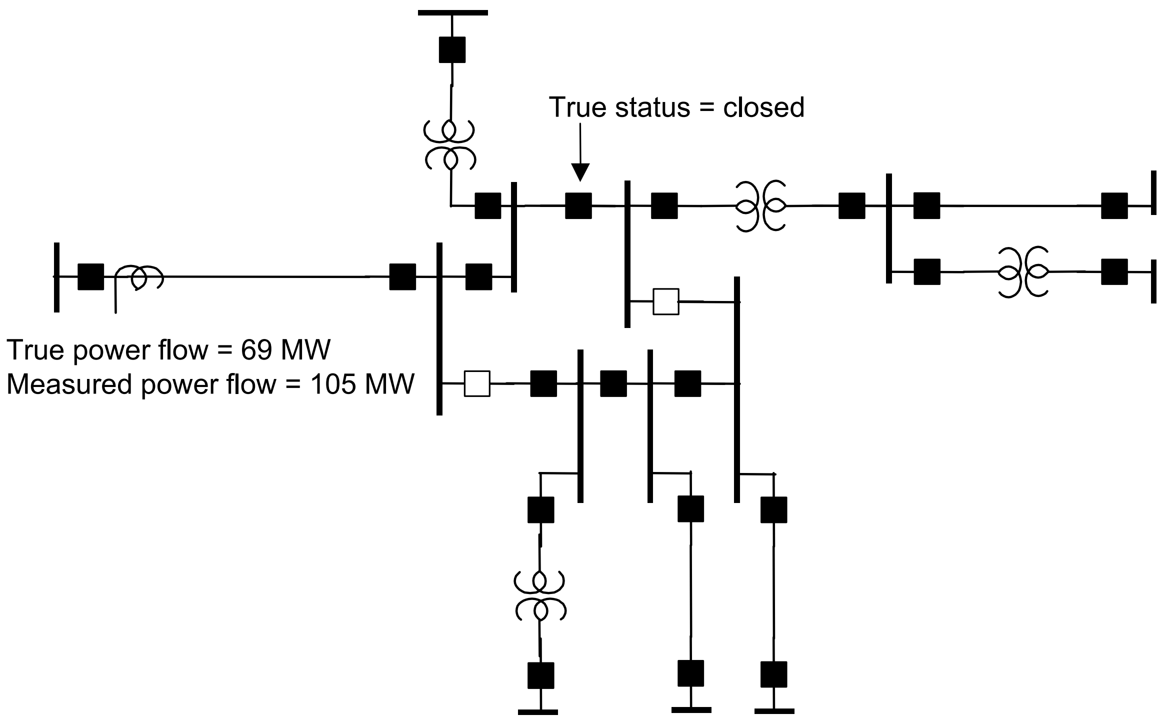

Figure 5-4
Scenario 5 - Station Diagram in the neighborhood one analog and one topology error

Figure 5-5 shows a group of three substations from the 562-bus system and the event from scenario 6. In this case one of the breaker errors triggers the detection of five possible solutions. Each of these solutions is valid and fits the model correctly. All possible solutions are identified, but only one of them is implemented, and the remaining sets are shown as alternate combinations. Note that all the breakers (or logical groups of breakers) are in series spanning three substations.

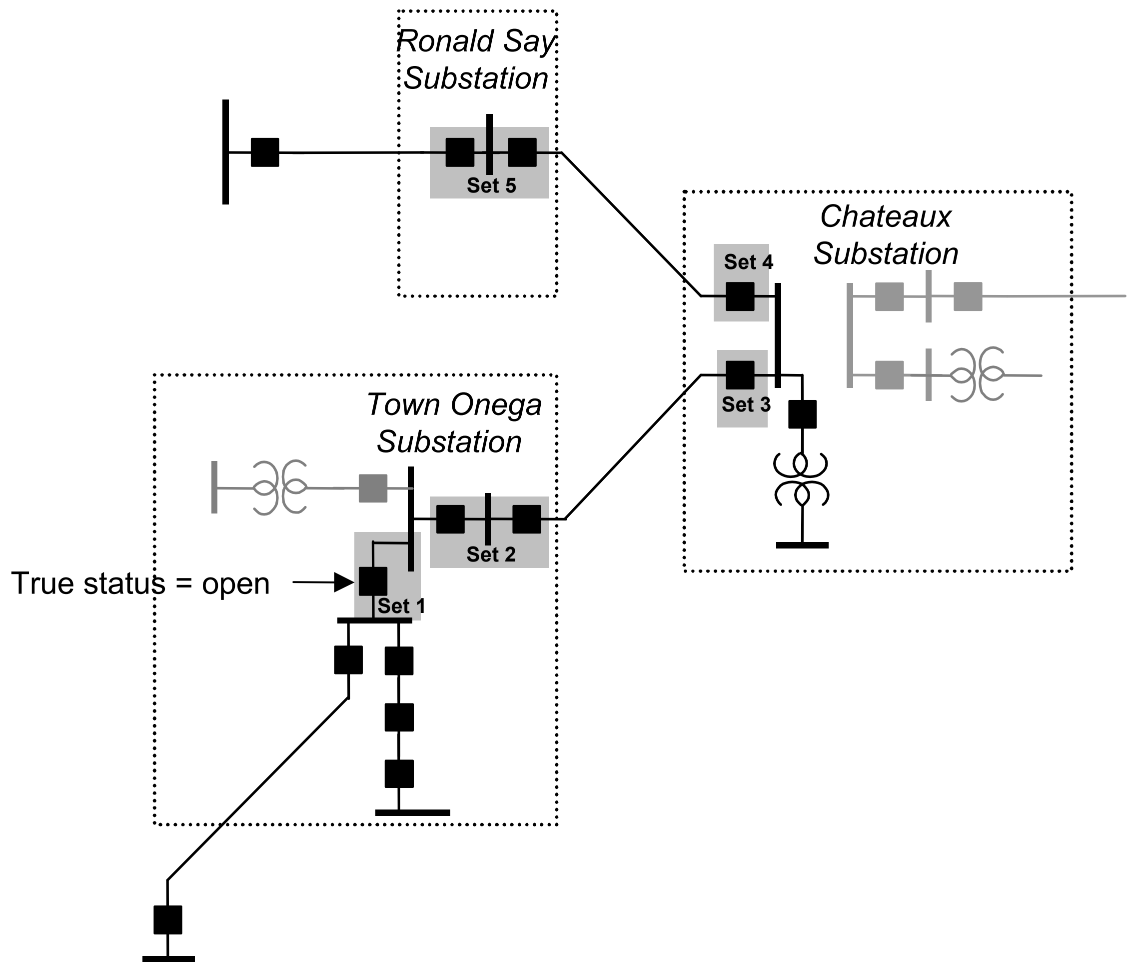

Figure 5-5
Scenario 6 – Multiple Station Diagram of a topology error with multiple solutions

Figure 5-6 shows a substation from the 562-bus system and the event from scenario 6. In this case one of the breaker errors triggers the detection of two possible solutions. Each of these solutions is valid and fits the model correctly. Both solutions are identified, but only one of them is implemented, and the alternative is available at the output. Note that both breakers are in parallel causing the same effect in the substation.

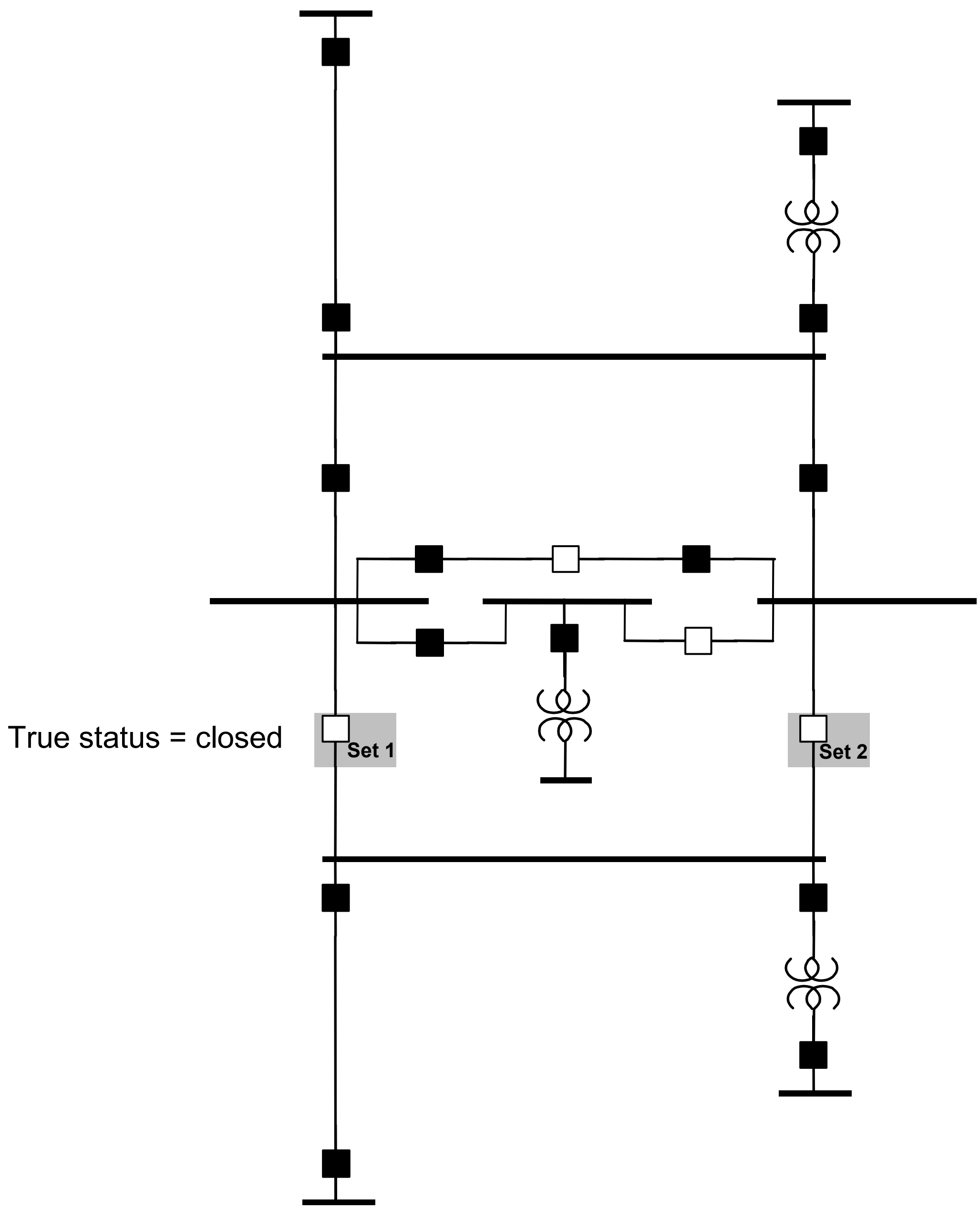

Figure 5-6
Scenario 6 – Multiple Station Diagram of a topology error with multiple solutions

Conclusions

To obtain an accurate representation of the losses, it is essential that the transformer taps and bus voltages be included (even if from a previous cycle). Telemetry of transformer taps should be readily available to an installation of the Topology estimator and should be used as surrogates for the "actual" tap positions. If the topology estimator is used in a control center wherein a conventional state estimator is already running, the bus voltages can be derived from that sub-system, and utilized to great advantage in this program.

The Phase I deliverable and tests showed the viability using a MW only solution for the Topology Estimator. The Phase I version of the program concentrated on detecting and identifying only one topology error.

The Phase II deliverable and tests showed the usefulness of the topology estimator. The topology error estimation systematically analyzes combinations of bad data (analog and topology) and reports them. The topology estimator obtains the set of possible alternate combinations that account for the bad data. Out of these combinations, only one is fully implemented, and the rest are given to the dispatcher as an output.

6 INTEGRATION WITH CIM

Background

There have been significant barriers and costs to demonstrating new power applications on host utility systems. Firstly, it is difficult to find a host utility that is prepared to deal with the disruption to a mission critical operational system. When a host utility is found, a lot of the time, effort and expense are spent on software integration issues such as:

- Building real-time data-links to legacy systems.
- Converting legacy system databases
- Building station displays to manage the applications
- Integrating application results with a legacy system user interface.

These complex software integration issues detract from the main objective of demonstrating and testing the new application. The problem is compounded by fact that the software developed for the demonstration may not be reused at other sites due to the special nature of the host utility system.

Overview

The EPRI Topology Estimator has been integrated with a Common Information Model (CIM) database using the PACE Power Application Computing Environment. It has been packaged with the EPRI Operator Training Simulator and the Nexant Generalized State Estimator (GEN-SE)[1]. The general software architecture for the PACE Power Application Computing Environment is shown in Figure 6-1.

[1] GEN-SE is not part of the Topology Estimator product.

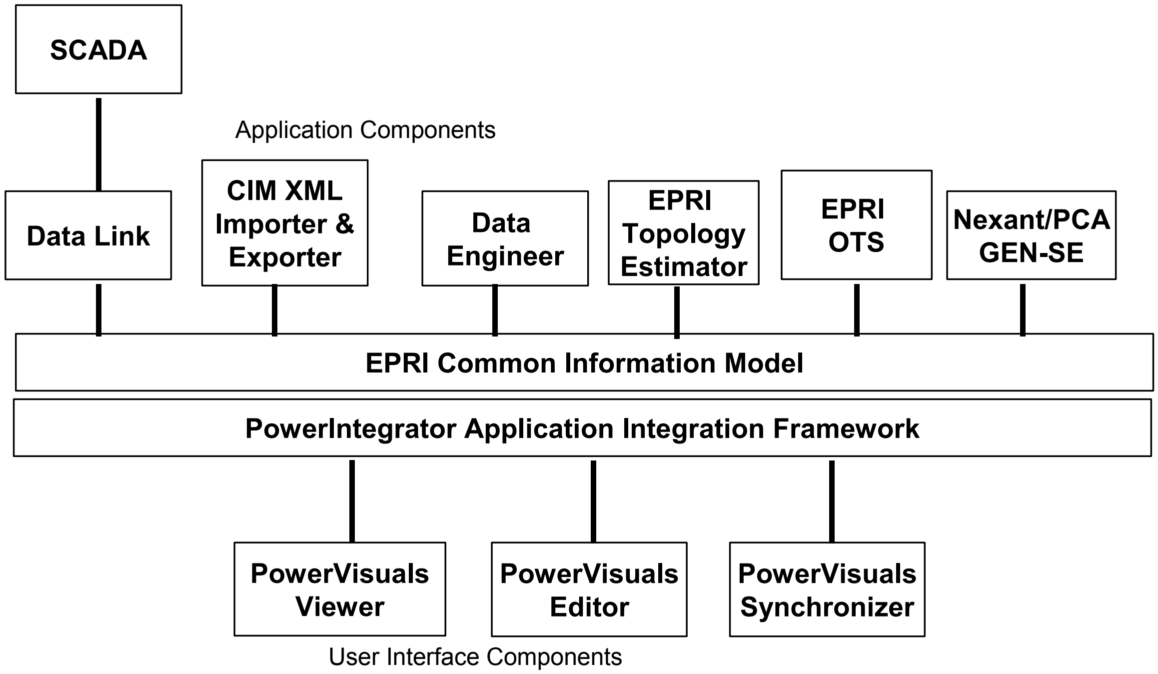

Figure 6-1
Software Architecture for Power Application Computing Environment.

The foundation of PACE includes the EPRI Common Information Model, the *PowerData* real time database, the *PowerIntegrator* real-time integration framework and the *PowerVisuals* JAVA based graphical user interface. PACE is based upon a component architecture where all the components are integrated using the PowerIntegrator real-time integration framework. The components can be database components, user interface components and application components.

The EPRI Common Information Model provides specific knowledge of the power system. The entities, attributes and relationships for the EPRI Common Information Model (CIM) are defined in the EPRI Control Center Application Program Interface Guidelines. The EPRI CIM is used to define the schema and persistent storage structure for a comprehensive database. The EPRI Common Information Model is implemented as an on-line real time application that not only stores the power system static model but it also stores the real time measurements, operator training simulator solutions, topology/state estimator solutions and power flow solutions. The data dictionaries are openly published and accessible to all interested third party developers.

The PowerIntegrator Application Integration Framework allows software applications written in a variety of languages, running on a variety of platforms, to successfully share information. By using the PowerIntegrator Application Integration Framework for exchanging information, multi-vendor systems and applications can be integrated in way that significantly reduces maintenance costs and enhances their usefulness. In the ideal situation, model data is entered once and all the other systems that use the data can be updated automatically in near real time. To the end user the systems appear to be seamlessly integrated and all the required information is immediately available at his/her fingertips. The components can be database components, user interface components and application components. Any component can act as both a consumer and provider for data, events and methods. All components communicate with each other using the EPRI Common Data Source (CDS) Application Program Interface (API). Components can provide and receive information using either asynchronous publish/subscribe or synchronous request/response mechanisms.

The PowerData Real-time Data Base (RTDB) is a high performance real-time relational database management system developed by PowerData Corporation to support real time processes and large scale mathematical models. In real-time applications it is not practical to continuously poll the database for changes to the data. PowerData supports asynchronous events and synchronous polling operations. The Event Server notifies an application of events for any database object for which the application has requested notification. These notifications indicate the operation that occurred and the time it occurred.

PowerVisuals is a family of Net-enabled graphical user interface products that can be used for monitoring and controlling real-time event driven processes as well as maintaining and accessing their underlying databases. PowerVisuals supports user defined displays types that are typically found in modern Energy Management, SCADA and process control systems including:

- System Overview Displays
- Substation one-line diagrams
- Tabular (spreadsheet) displays.
- Trend displays

With PowerVisuals diverse applications and databases can be integrated with a single universal user interface. PowerVisuals is based upon the Java programming language. PowerVisuals is designed to provide the developer with a high degree of flexibility on how dynamic objects change in relation to the applications data. PowerVisuals provides an environment for accessing and maintaining information on topological models by means of schematic diagrams.

The PowerVisuals family includes the following programs:

- PowerVisuals Viewer manages commands, events, and data between users, and the applications. In Viewer mode, information on PowerVisuals displays updates dynamically as data in its supporting data bases changes. The result is a live graphical display that is updated in real time.
- PowerVisuals Editor allows the user to define the format and layout on how objects are connected and presented to the user. Displays can consist of various combinations of schematics, trends, tables and menus.
- PowerVisuals Synchronizer is a program for keeping the network topology model in the CIM database and the schematic display model in the PowerVisuals database in synchronism.

PACE Data Engineer provides a simple, intuitive and unified approach to maintaining power system models and schematic displays. PowerVisuals Synchronizer is a key part of the PACE Data Engineer. If an object is defined in the CIM database, it automatically shows on its substation schematic display. If an object is added to a substation display, it is automatically added to the CIM database. The user is therefore always assured that what he/she sees on the schematic display is what is in the CIM database and vice versa.

The EPRI Operator Training Simulator (OTS) Power System Model simulates the long term dynamic response of the power system in real-time. The model is driven by daily load curves, a schedule of contingencies and real-time operator inputs. Every few seconds the power system model updates the power system states by running a system wide power flow solution. Every 1 second the power system model updates the dynamic equations for prime movers, governors and the system frequency. The result to the user is a realistic second by second simulation of the system conditions. When the results of the PSM are loaded into the CIM measurement value table, the applications and the user cannot distinguish whether the results came from the OTS or from actual field measurements. The EPRI OTS generates a real-time stream of simulated measurements and measurement errors for testing the Advanced Topology Estimator.

The CIM XML File Importer imports an IEC standard CIM XML network description file into the CIM relational database. The CIM XML File Exporter exports an IEC standard CIM XML network description file from the CIM relational database. Each time a power system model is imported into the CIM database, the PowerVisuals to CIM Synchronizer ensures that the schematic database is consistent with the CIM database. Any objects that have been deleted from the CIM database will also be deleted from their station displays. Any objects that have been added to the CIM database are added, with their connections in the top left corner of their station displays. The user just has to position these objects with a couple of mouse clicks.

Adapter for Topology Estimator Applications

The Topology Estimator has been integrated with the CIM database using PowerIntegrator. This has required the development of a PACE Adapter. Most of the logic is contained in the text files that are configured for the Join Engine. The actual amount of new compiled code that had to be developed was small. The overall structure of the PACE Adapter for the Topology Estimator is shown in Figure 6-2.

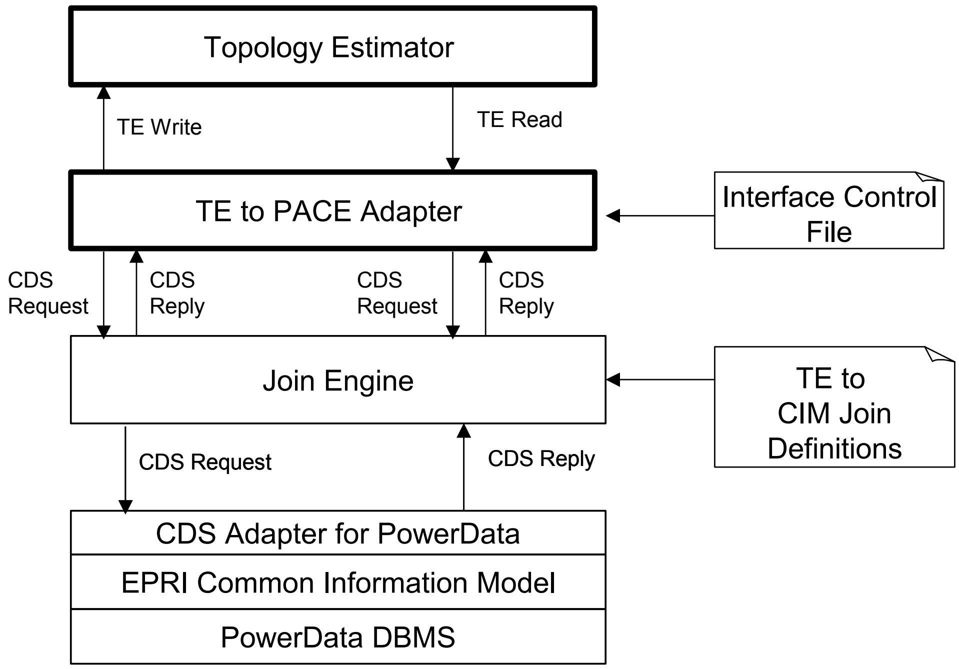

Figure 6-2
PACE Adapter for Topology Estimator

To initialize the Topology Estimator (TE) with the base power system model the TE to PACE Adapter performs the following operations:

1. Opens a CDS for a TE Object Class: Example Line

2. Read the required TE attributes from the CIM via a Join CDS. Example Line resistance, reactance, To Node and From Node

3. Makes successive calls to the Topology Estimator to write the attributes for each instance of the TE Object Class. E.g. for all of the Lines.

4. Return to Step 1 to process the next TE Object Class.

To update the Topology Estimator with a new set of analog and status measurements the TE to PACE Adapter performs the following operations:

1. Opens a CDS for the TE Measurement Class.

2. Makes a Bulk read of all of the required analog and status measurements from the CIM.

3. Makes successive calls to the Topology Estimator for all of the Measurement instances.

The following operations are used to read the results of the Topology Estimator after it has completed its cycle and load the results into the CIM database:

1. Open a CDS for a TE Object Class; For example Line.
2. Make successive calls to the Topology Estimator to read the results for all of the objects in the current TE Object Class. For example for the Line Object Class the TE to PACE Adapter will read the estimated MW and MVAR flow at the From End and To End of the line.
3. Make a Bulk Update of all the State Estimator attributes into the CIM. For example, for the TE Line Object Class all the estimated MW and MVAR values will be written via a Join to the CIM MeasurementValue Table.
4. Return to Step 1 for the next TE Object Class.

With this approach, the entire mapping between the CIM classes and CIM attributes and the TE Classes and TE attributes is performed in the TE to CIM Join Definition Files. For each TE application, separate TE to CIM Join Definition Files are required for each TE Object Class to handle; program initialization, load real-time data and read TE solution results. These are text configuration files. No code needs to be recompiled when these are changed. The actual amount of compiled code is quite small, around several thousand lines for the entire TE to PACE adapter.

Topology Estimator User Interface

The PACE PowerVisuals User Interface supports a combination of One-Line Displays, Tabular Displays and Trend Displays for showing the results of power system applications in general and the Topology Estimator in particular.

The Station One-Line displays and System Map displays can be generated from the network topology model. In the event that there are connection errors in the network topology model, these are made clearly visible. Figure 6-3 shows an example for the Doyle station in the Power and Light System Model. The ELLS-DOY Line should be connected to line breakers CB 5 and CB 6. Instead it is connected to line breakers CB 4 and CB 5 along with the DOY2-CRA Line. This error is immediately apparent to the viewer. In traditional systems, the one-line diagram is built separately from the network topology database. Errors can exist in the network topology model for many years without being discovered.

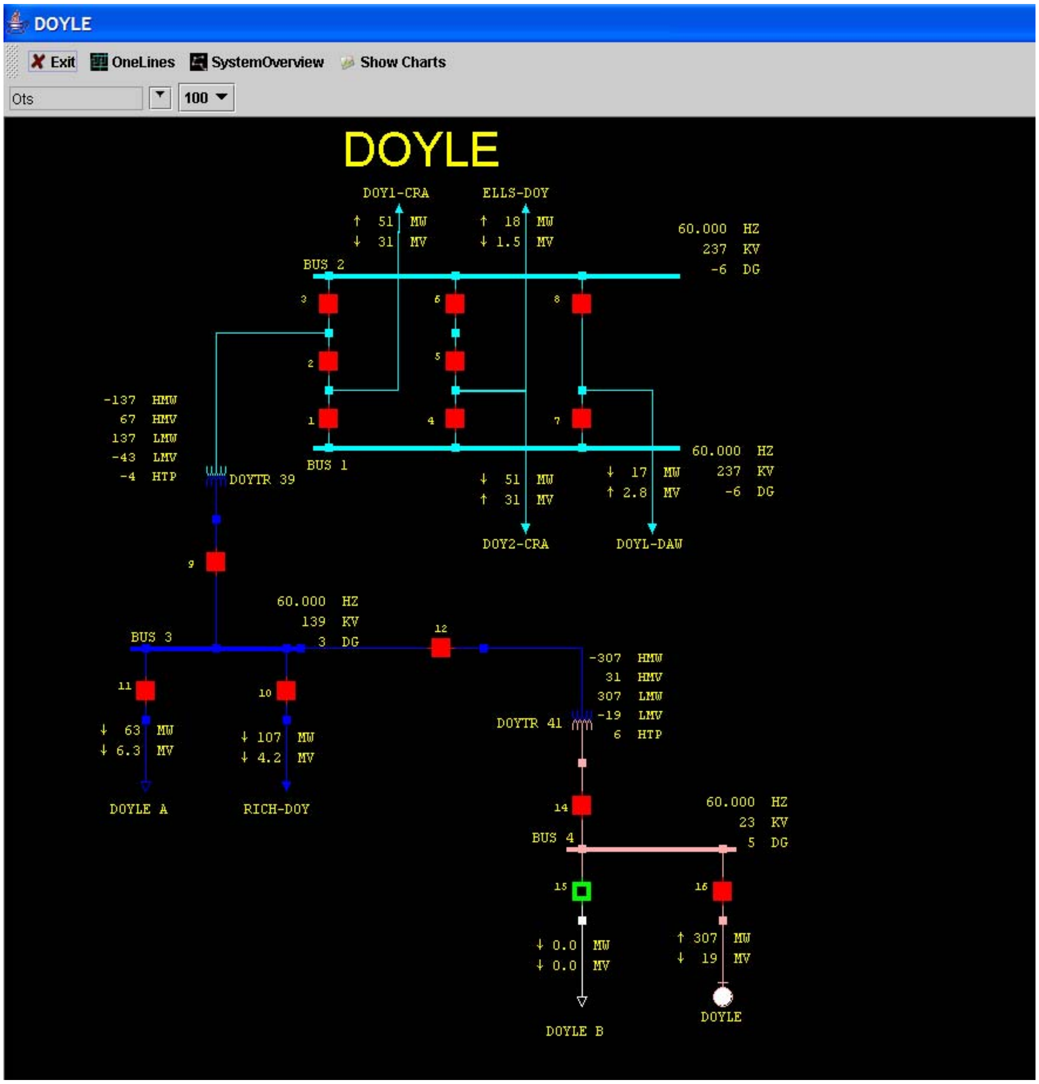

Figure 6-3
DOYLE Station Diagram with Topology Configuration Error.

Figure 6-4 shows the DOYLE Station with the ELLS-DOY line correctly connected to line breakers CB 5 and CB 6. The Topology Estimator requires that all network components should be connected to their correct Junctions and Bus Sections.

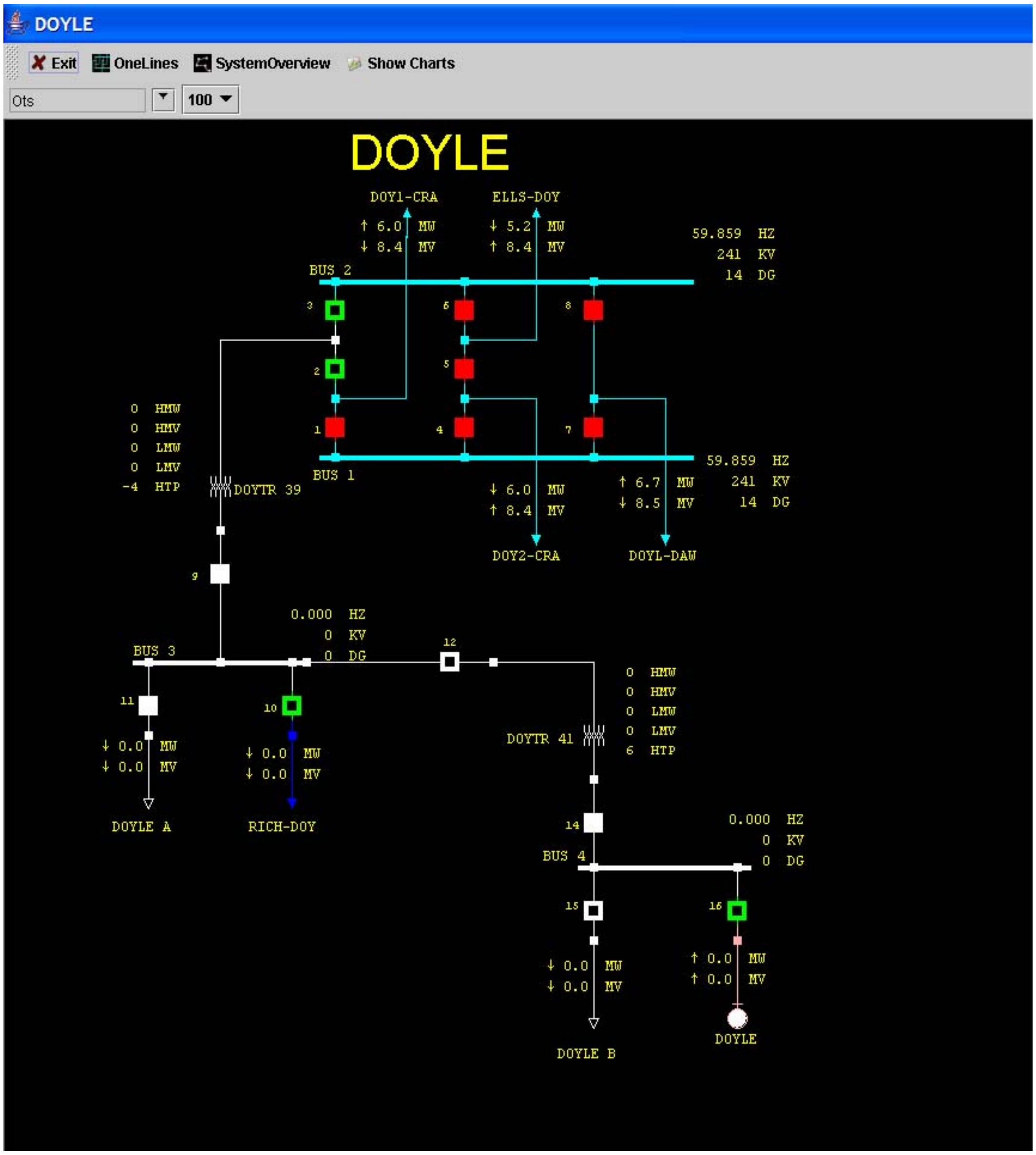

Figure 6-4
DOYLE Station with BUS 3 Cleared.

The PowerVisuals network colorization shows the energization status of the network components.

The example in Figure 6-4 shows an example of using line colorization under abnormal conditions. Loads are the symbols with the un-filled arrows. Line ends are the symbols with filled arrows.

If a component (non-switch) is energized it is colored according to its voltage level.

If a component is de-energized it is shown white.

Open breakers are open squares. Closed breakers are solid squares.

Breakers are:

- Red if closed and energized.
- Green if open with one or both terminals energized.
- White if open with both terminals de-energized.

With this line colorization scheme, the effects of various switching actions can be anticipated. For example, the RICH-DOY Line end is a live source. Therefore, closing Breaker 10 will energize the DOYTR 39 transformer through to the open CB 2 and CB 3 breakers. It will also energize the DOYLE A Load since CB 11 is closed.