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Enhanced Reliability of Power System Operation Using Advanced Algorithms and IEDs for On-Line Monitoring

Part I of Final Project Report

Power Systems Engineering Research Center

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Enhanced Reliability of Power System Operation Using Advanced Algorithms and IEDs for On-Line Monitoring

Final Project Report

Part I : Substation Automation

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Power Systems Engineering Research Center

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Several graduate students and research staff at Texas A&M University participated in this project and contributed to the final report: Goran Latisko (glatisko@ee.tamu.edu) (research staff), Nitin Ved (nitinved@tamu.edu) (student), Yang Wu (wuyang@ee.tamu.edu) (student), and Xu Luo (xuluo@ee.tamu.edu) (student).

Executive Summary

This report is Part I of a study aimed at demonstrating how the reliability of substation operation may be enhanced using data collected by Intelligent Electronic Devices (IEDs). To achieve major operational reliability benefits, data collected by IEDs can be processed in real time to extract information to improve reliability. This report (Part I) discusses the applications that may be executed locally, while Part II talks about applications that are related to the overall power system operation and that may be located at the Energy Management System (EMS) level.

The report first identifies the applications and then discuses how they may be implemented in a substation automation system. Several automated analysis applications are included. While some applications were developed during this project, others were developed in other PSerc projects (T-9 and T-10), as well as some project funded by external sources. The automated analysis functions process data from the following IEDs: Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), and Circuit Breaker Monitors (CBMs). In addition, some applications were developed based on the data from the substation database; they include: Verification of Substation Switching Sequences (VSSS), Verification of Substation Database (VSDB), and Overall Analysis of Disturbances that includes Fault Analysis and Fault Location (FAFL).

Following benefits can be drawn from the proposed approach:

- Measurement Redundancy. The substation Intelligent Electronic devices (IEDs) quite often measure the same signals from the substation switchyard. If one collects the signal samples in the substation database, one can then use the redundant measurements to improve accuracy and robustness of the measured signals.
- Cause-effect Relationship. Since several IEDs may be involved in tracking substation operation, having data from different IEDs integrated, it is possible to capture various stages of the operation. This enables one to establish a cause-effect relationship in the changes of the measured signals. The ability to track cause-effect relationships in a control sequence, such as clearing of a fault, enhanced ability to determine any problems or deviations from the expected.
- Time series analysis. Being able to track IED measurements for longer periods of time and stored for future time series analysis allows implementation of function that will be able to tell if performance of a given function or peace of equipment is deteriorating. The ability to identify deteriorating performance and have a subsequent maintenance or design action that will restore the performance requirements, provides an improvement in the reliability of substation and power system operation.

This study paves the way for future change in substation automation practices aimed at improving operational reliability of substations, and, consequently, the entire power system. Software is developed for demonstration purposes and can be accessed from following password protected URL: http://eent1.tamu.edu/epri/temp/download.html.

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1. Introduction

1.1 Project Information

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Project Period	June 1, 2002 to June 30, 2005

1.2 Organization of the Report

The first section of the document provides basic information about the project.

The second section contains Statement of work, describing what are project objectives, tasks and final project outcomes.

The third section focuses on functional requirements of the applications developed for the project. First, the research framework of the project is given, describing the substation topology and IEDs configuration. Afterwards, block diagram of software architecture is given. At the end of this section, functional requirements for Graphical User Interface (GUI), Verification of Substation Database (VSDB), Substation Switching Sequences Verification (SSSV) and Digital Protective Relay Analysis (DPRA) are given.

The fourth section elaborates on implementation details of individual software modules.

The fifth section focuses on testing. The description of the IED data simulation process is given. The tested substation scenarios are briefly presented.

The last section of the document contains the conclusion and the references.

2. Statement of Work

2.1 Project Objective

Develop substation automation system which enables:

- Integration of data from multiple IEDs
- Processing of data at substation level by implementing novel applications
- Sharing of results with other substations and remote control centers.

2.2 Project Tasks

In order to successfully develop and implement the substation automation system featuring the functions listed in the project objectives, following project tasks have been identified:

- Data integration:
  - Research interfacing between IEC 61850 and IEC 61970 [1][2]
  - Enable importing data from multiple substation IEDs
  - Create description of substation topology in Substation Configuration Language (SCL) file [1]

- Implementation of substation tracking system:
  - Develop advanced application and user interface supporting information exchange

- Data simulation:
  - Create substation data model in Alternative Transients Program (ATP) [3] based on an arbitrary substation layout. Substation topology described in SCL file has been used.
  - Create Digital Protective Relay model in C++ and integrate it into the substation data model [10]
  - Enable conversion of simulated IED data from PL4 (native ATP) into standard COMTRADE file format [4]

- Implementation and integration of novel applications for automated analysis and verification:
  - Applications based on specific devices:
    - for Digital Protective Relay (DPR) device - Digital Protective Relay Analysis application (DPRA), [6][7][8]
  - Applications based on integrated data:
    - Verification of Substation Database (VSDB)
    - Substation Switching Sequences Verification (SSSV)

2.3 Project Outcomes

The project outcomes can be summarized as software deliverables and published papers. For list of published papers, please see the References section.

During the project, the following software applications and modules were designed, implemented and integrated into the Substation Automation software solution:

- **VSDB – Verification of Substation Database**

The application verifies the correctness of the substation IED data before they are stored into the substation database. The IED data can be analog (currents, voltages) and/or digital (statuses of contacts of circuit breakers).

- **SSSV – Substation Switching Sequences Verification**

The application monitors and extracts the switching sequences of circuit breakers in the substation. Additionally, it traces and finds the reasons for an extensive switching of large numbers of circuit breakers.

- **DPRA – Digital Protective Relay Analysis**

The application analyzes the protection (relay and circuit breaker) operations. Additionally it verifies data consistency between relay event report and oscillography files.

- **GUI – Graphical User Interface**

The user interface integrates the analysis applications, enables the simulation and displays IED data in graphical and consistent way.

- **Substation Data Model [13]**

Designed and implemented in ATP application package, used for simulation of substation IED data

- **Substation Topology Description in SCL file**

Designed and implemented using new SCL (Substation Configuration Language) as specified in new IEC 61850 standard.

- **Digital Protective Relay model**

Designed and implemented in C++ and MODELS language of the ATP application package.

- **File converter from PL4 to COMTRADE file format**

Designed and implemented as a separate application, capable of converting single PL4 file, generated by ATP application package, into multiple COMTRADE files

2.4 General Benefits

- Automated data extraction and verification, which enables fast and consistent analysis of data measured by multiple IED.
- Integrated archiving of IED data and analysis reports on a consistent basis
- System wide dissemination of IED data and analysis reports
- Universal user interface
- Elimination of IED measurement errors using measurement redundancy

2.5 Application Specific Benefits

- VSDB – enhances the reliability and correctness of the substation database by verifying the accuracy of IED data based on the redundancy and fundamental electricity laws.
- SSSV - verifies substation switching sequence automatically by gathering information from IED measurements and provides fast and accurate analysis to assist substation operators.
- DPRA – automatically analyzes protection operation based on reports and files generated by large number of digital relays under complex event conditions.

3. Functional Requirements

3.1 Research Framework

Substation automation software solution consists of the following software modules:

- substation tracking system (integrated GUI)
- module for simulation of substation IED data
- applications for automated analysis and verification of substation data.

All listed modules are integrated via common graphical user interface (GUI), as shown in Figure 3.1

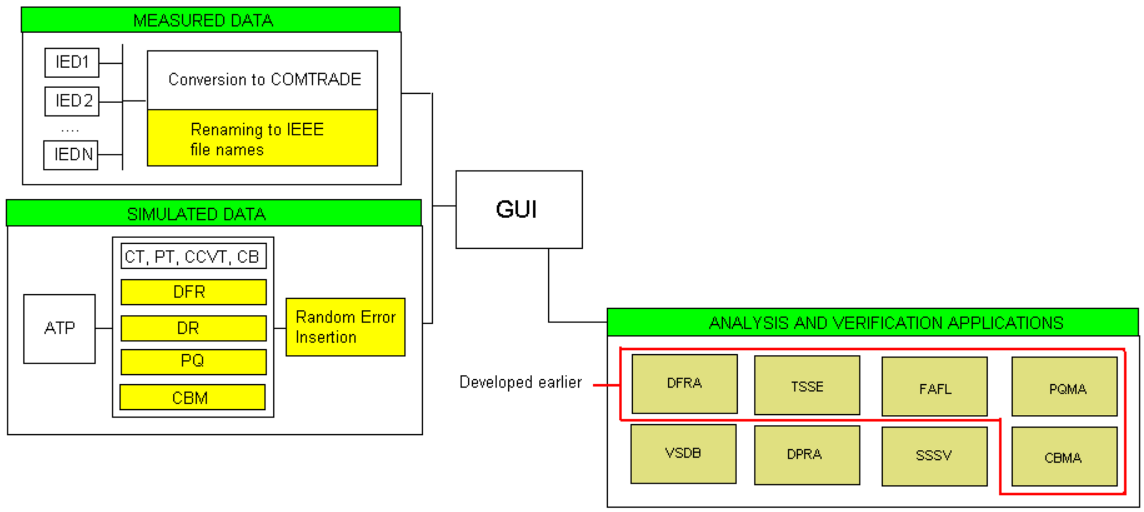


Figure 3.1 Substation Automation application architecture

The one-line diagram of the substation used for demonstration and testing of the analysis algorithms is displayed in Figure 3.2.

As indicated on the figure, some of the analysis applications, such are DFR Assistant (DFRA), Two Stage State Estimation (TSEE), Fault Analysis and Fault Location (FAFL), Power Quality Monitoring and Analysis (PQMA) and Circuit Breaker Monitoring and Analysis (CBMA) were developed for some earlier projects and included in substation automation solution.

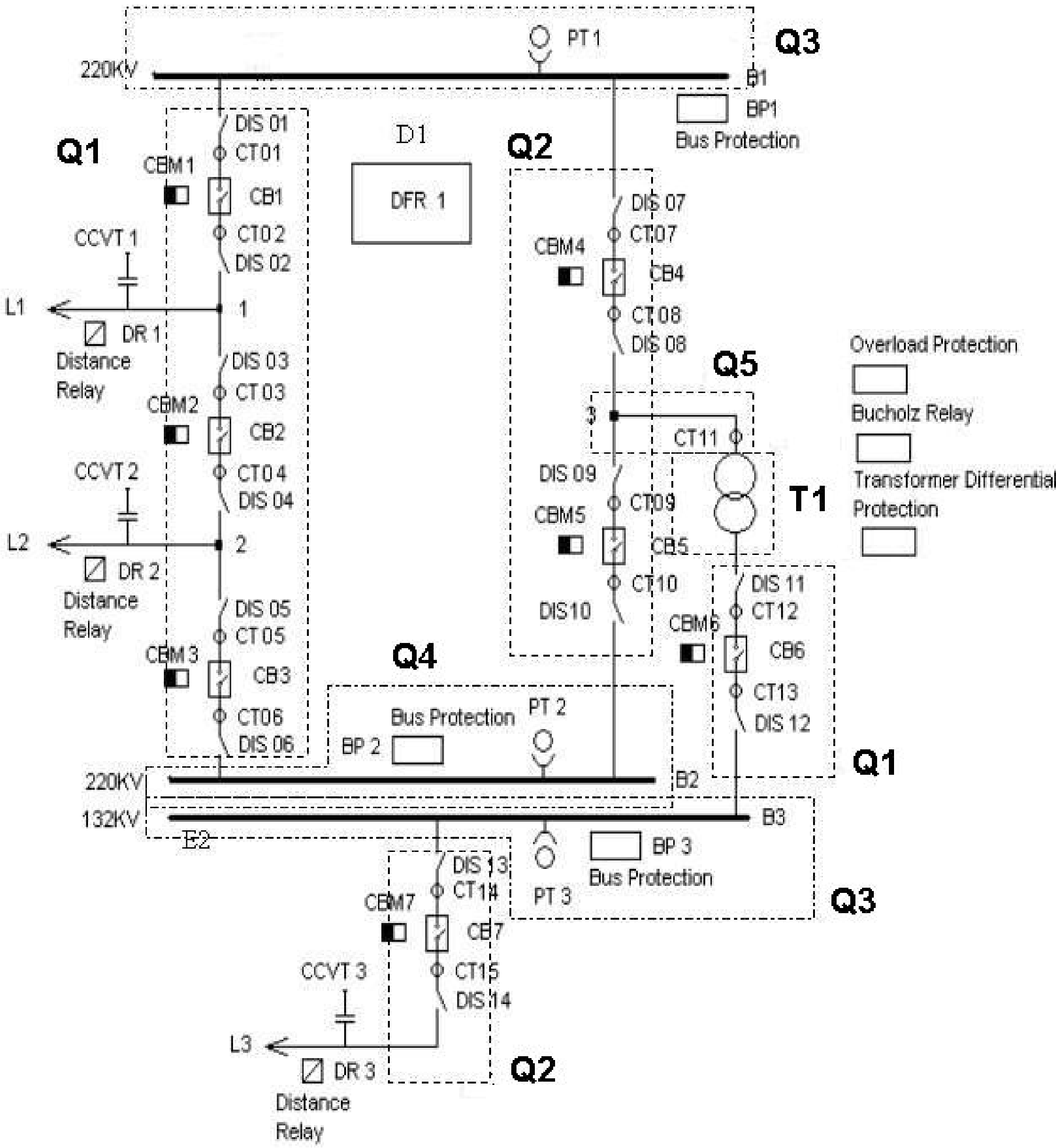


Figure 3.2 One-line diagram of modeled substation

The topology of the modeled substation is described using new Substation Configuration Language (SCL) which is defined in the latest version of substation communication standard IEC 61850. In the figure below, the excerpt from the topology file is given.

```
<?xml version="1.0" ?>
- <tns:SCL xmlns:sxy="file://c:/schema.xsd"
     xmlns:tns="file://c:/schema.xsd">
  <Header Ref="" NameStructure="IEDName" />
- <Substation Name="S1">
- <VoltageLevel Name="D1" Voltage="220kV">
- <Bay Name="Q1">
- <Device Name="DIS01" Type="DIS" sxy:x="2" sxy:y="1">
  <Connection CNodeName="L1" />
  <Connection CNodeName="B1" BayName="Q3" />
  </Device>
- <Device Name="CT01" Type="CTR" sxy:x="2" sxy:y="2">
  <Connection CNodeName="L1" />
  <Connection CNodeName="L2" />
  </Device>
- <Device Name="CB1" Type="CBR" sxy:x="2" sxy:y="3">
  <Connection CNodeName="L2" />
  <Connection CNodeName="L3" />
  </Device>
- <Device Name="CT02" Type="CTR" sxy:x="2" sxy:y="4">
  <Connection CNodeName="L3" />
  <Connection CNodeName="L4" />
  </Device>
- <Device Name="DIS02" Type="DIS" sxy:x="2" sxy:y="5">
  <Connection CNodeName="L4" />
  <Connection CNodeName="C5" BayName="Q6" />
</Device>
- <Device Name="DIS03" Type="DIS" sxy:x="2" sxy:y="7">
  <Connection CNodeName="C5" BayName="Q6" />
  <Connection CNodeName="L6" />
  </Device>
- <Device Name="CT03" Type="CTR" sxy:x="2" sxy:y="8">
  <Connection CNodeName="L6" />
  <Connection CNodeName="L7" />
  </Device>
- <Device Name="CB2" Type="CBR" sxy:x="2" sxy:y="9">
  <Connection CNodeName="L7" />
  <Connection CNodeName="L8" />
```

Figure 3.3 SCL topology description of modeled substation

3.2 Graphical User Interface (GUI)

3.2.1 Introduction

This section of the document contains descriptions of the functions of the common graphical user interface developed for support of the substation data analysis and verification applications.

Functions can be divided in three main groups:

- data displaying,
- data simulation
- interfacing the analysis and verification applications \

Each of these functions is explained in following subsections.

3.2.2 Functions for Data Displaying

This section describes design and implementation of functions for data displaying of integrated GUI. These functions are classified based on the type of information they are rendering to the user and are listed below:

- Functions for displaying measured and simulated data. In order to be displayed, data does not have to be assigned to the substation IEDs. Types of data displayed this way are signal waveforms in COMTRADE file format, event logs and various device specific reports in plain ASCII textual file format.
- Functions for substation topology displaying. The information displayed using these functions are the one line diagram of substation layout and the designations of buses, lines, equipment and IEDs used for monitoring, protection and control in the substation.
- Functions for displaying of device statuses. These are reflecting the statuses of substation equipment and IEDs such as circuit breakers (CBs), circuit breaker monitors (CBMs), digital protective relays (DPRs), Current Transformers (CTs) and Voltage Transformers (PTs). Different device statuses, such as "open"/"closed" circuit breaker, "data assigned", digital relay "tripped", "inconsistent data", are indicated in different colors of device symbol in topology window. Some of the device statuses can be set by user, and others can be set by the analysis and verification applications.
- Functions for displaying the instantaneous measurements. These functions are displaying instantaneous values of currents and voltages measured by substation CTs, PTs and CCVTs. Measured values are displayed for each phase, at specific time instances by the label next to the device symbol.

More details about each of the functions for data display is given in the rest of this section.

Functions for displaying measured and simulated data

Those functions can display the data for the whole measurement/simulation interval. These function are used to display following measured and simulated data from IEDs data records:

- Signal waveforms – The displayed data has to be stored in COMTRADE file format
- Event files and device specific reports – The displayed data has to be stored in ASCII textual file format

Signal waveforms are displayed using custom developed software module "COMTRADE Viewer" for displaying of the ASCII COMTRADE files, as displayed in Figure 3.4. This module has features such as zoom in, zoom out, horizontal and vertical scrolling, reading of the current cursor position, window panning etc. User can also change the color used for drawing the waveform and additional details about selected signal such as max and min magnitude, unit, type of signal, channel, ratio etc. displays the screenshot of the "COMTRADE Viewer" main window, displaying the CT current waveform.

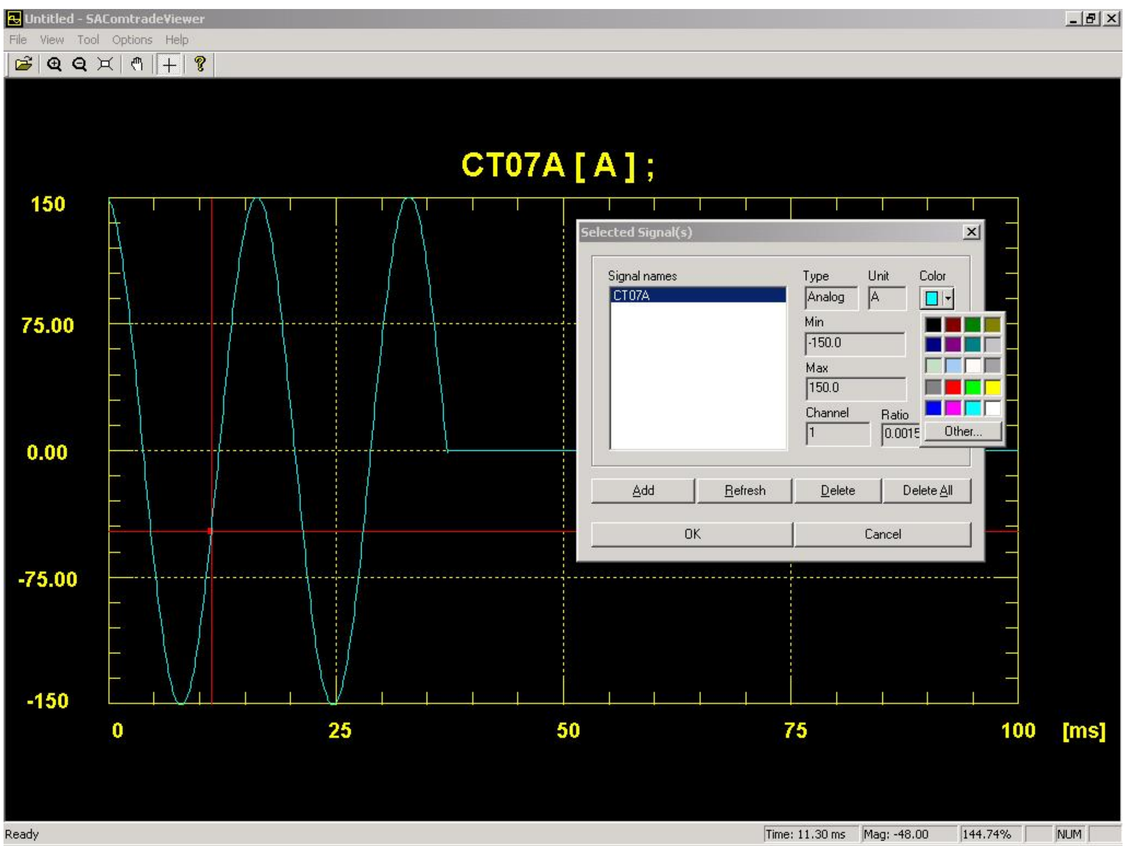


Figure 3.4 Main window of the "COMTRADE Viewer" application displaying the CT current waveform

Event files and device specific reports are displayed in common text editor.

GUI can display measured and simulated signal waveforms, events and reports from the following devices:

- Current and Voltage Measurement Transformers – CTs, PTs, CCVTs
- Circuit Breaker Monitors – CBMs
- Digital Fault Recorders – DFRs
- Digital Relays – DPRs

It is anticipated that all data will be in COMTRADE or plain ASCII text file format, as shown below:

Comtrade files:
CTs, PTs, CCVTs, CBMs, DFRs, DRs waveforms files

ASCII Textual files:
DPRs Event files, DPRs Fault files

User can display data by either:

- selecting a data record file using standard file selection dialog from the main application menu OR
- (if data is already assigned to the substation device) by clicking on the device symbol in the Topology window and selecting appropriate command from the context menu.

Functions for topology displaying

Those functions are used to display one line diagram of the substation layout and designations of buses, lines, and IEDs used for monitoring, protection and control in the substation.

Substation topology and designation of its devices and components are shown in the Topology window, as indicated in Figure 3.5. The following elements of the substation topology are displayed:

Devices:

- Current and Voltage Measurement Transformers – CTs, PTs, CCVTs
- Circuit Breaker Monitors – CBMs
- Digital Fault Recorders – DFRs
- Digital Relays – DRs

Components:

- buses
- lines
- circuit breakers – CBs

- switches
- power transformers

Events:

- faults

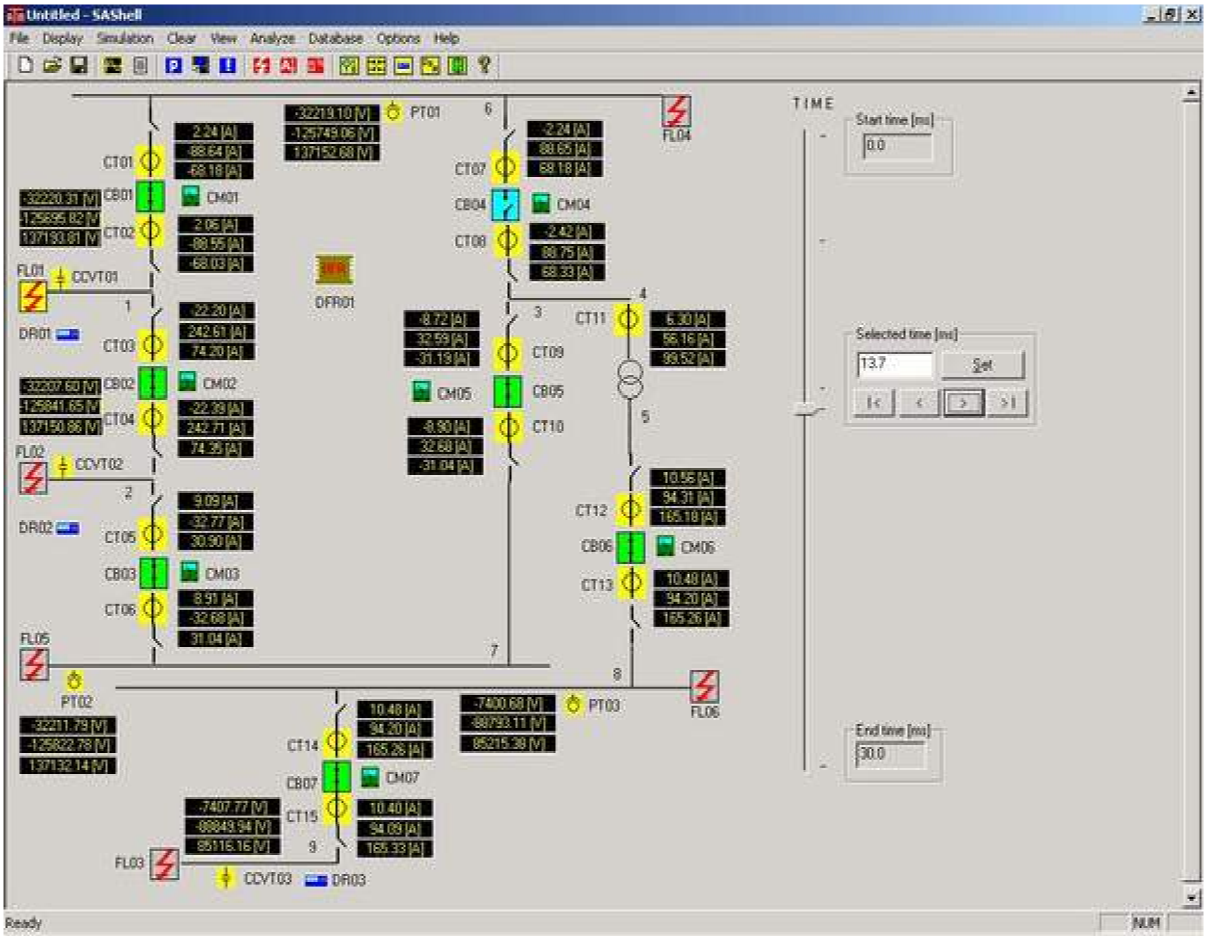


Figure 3.5 “Topology window” of the GUI

In current GUI implementation, substation topology is predefined and fixed. We selected an arbitrary substation layout, allocation and designation of the equipment in the substation and hardcoded it into the GUI. In the future implementations of the GUI, information about the substation layout will be stored in a single, IEC 61850 compliant, topology file. This file will follow the requirements defined in the Substation Configuration Language (SCL). The user will be able to modify the topology information displayed in the topology window by changing the contents of a XML file.

By selecting commands from the context menu assigned to each substation device symbol in the Topology window, user will be able to:

- assign measurement/simulated data to the devices (CTs, PTs, CCVTs, CBMs, DRs)
- view assigned measurement/simulated data
- set switching sequences of the circuit breakers (CBs)
- set faults and values of related fault parameters
- call analysis and verification applications for particular device (if data is assigned to device).

Functions for IED status displaying

Those functions are rendering the statuses of substation equipment and IEDs. Devices that are reporting different statuses are circuit breakers (CBs), circuit breaker monitors (CBMs), digital protective relays (DPRs), Current Measurement Transformers (CTs) and Voltage Measurement Transformers (PTs and CCVTs).

Different statuses of the substation IEDs are distinguished by different colors of their symbols in the topology window. Some of the device statuses can be set by user, and others can be set only by the analysis and verification applications. Table below lists the relations between substation devices, statuses and their colors.

There is a slider control with navigation buttons, which enables the users to view statuses of the CBs, DPRs and CTs, PTs, CCVTs, at different time instances. Each time the time instance is changed using slider control, information displayed within the topology window is updated with the new set of data describing substation state at the selected moment. Smallest resolution of the slider is 0.0001 sec.

Time instances at which the statuses of the devices are displayed are defined by the user, ATP model parameters and analysis and verification applications. User defines the instances at which the switching sequences of the circuit breakers or faults occur. ATP model and predefined circuit breaker failure ratios influence the actual switching times of the breakers. Results of analysis and verifications applications affect the time instances at which the statuses of the analyzed devices should be reported.

Table 3-1 List of substation devices, statuses and corresponding colors

Reporting application	Device	Status	Color
SSSV	Circuit Breaker – CB	Closed by user	Dark Green
		Actually closed	Light Green
		Opened by user	Dark Blue
		Actually opened	Light Blue
		Breaker miss operated or delayed	Red
DPRA	Digital Protective Relay - DPR	Data not assigned	Gray
		Data assigned	Yellow
		Data inconsistent, relay failed to trip or delayed	Red
VSDB	Current and Voltage measurement transformers: - CTs, PTs, CCVTs	Data not assigned	Gray
		Data assigned	Yellow
		Data inconsistent with related data	Red
CBMA	Circuit Breaker Monitor – CBM	Data not assigned	Gray
		Data assigned	Yellow
		There is a problem in CB operation	Red

Functions for instantaneous data displaying

Functions for instantaneous data displaying are showing the instantaneous values of the currents and voltages measured by the substation current and voltage measurement transformers (CTs, PTs and CCVTs) or obtained by simulation of the ATP model.

Values are extracted from the COMTRADE format files. Sample values of the signal waveforms are extracted from the DAT files and multiplied with the ratios read from the CFG files. Only values at predefined time instances are displayed. Measured values for each phase are displayed next to the device symbol in the topology window together with the units (volts or amperes).

3.2.3 Functions Supporting Data Simulation

This section will describe design and implementation of the user interface functions supporting simulation of the substation data.

Simulation of the data is based on the Alternative Transients Program (ATP) and the substation data model defined in the ATP compatible input file. ATP software is invoked from the user interface shell and provided with the following information: simulation parameters (such as length of the simulation interval and simulation step), circuit breaker switching sequences, backup schema and failure ratios, faults and related parameters, substation layout and equipment designations etc.

As a result of a simulation, COMTRADE format files containing the simulated signal waveforms of currents and voltages of the CTs, PTs and CCVTs defined in the ATP data model are created. Figure 3.6 illustrates the simulation process. The details about the data model and how the ATP is simulating the data are given in separate section of this document.

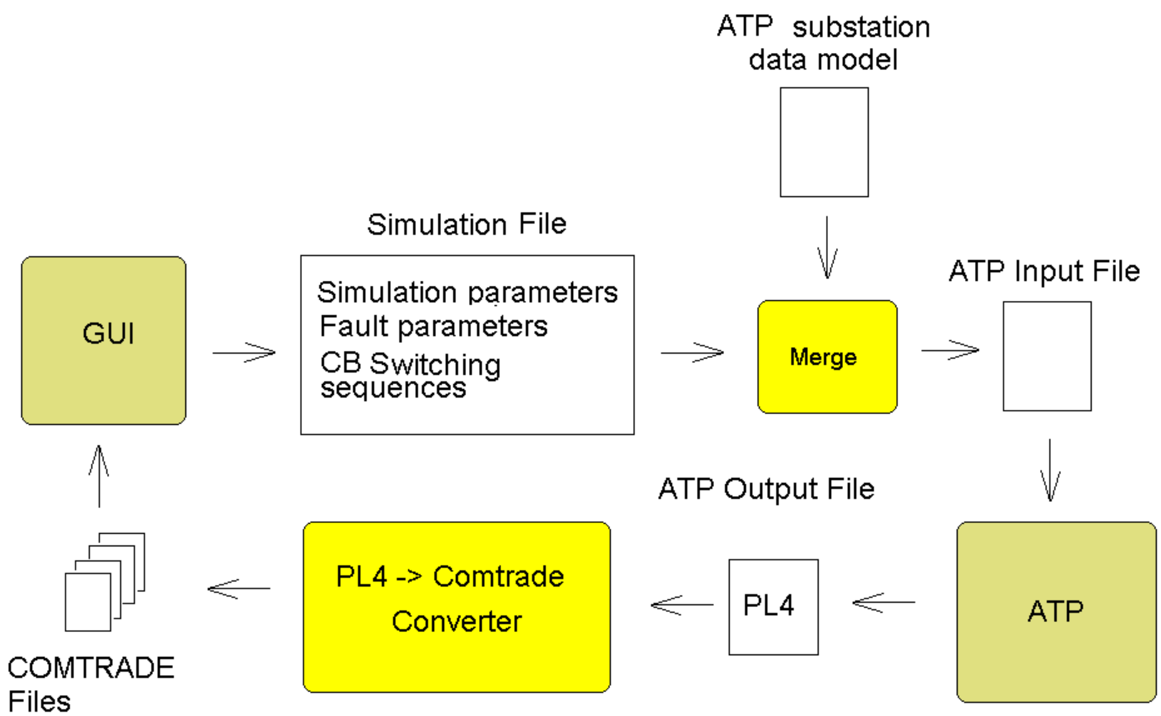


Figure 3.6 Substation data simulation with GUI and ATP

The operation of digital protective relays are defined by the waveform, event and fault files and are also simulated by the ATP program, using precompiled IED device models. The details of this procedure are described in separate section of this document.

The circuit breaker monitor IED is also simulated by the ATP program using precompiled IED device models. The details of this procedure are described in separate section of this document.

In this section, the following user interface functions supporting data simulation are described in the order they are used to enable the simulation of data:

- Setting the simulation parameters
- Setting the circuit breaker switching sequences
- Setting the circuit breaker failure ratios
- Setting the faults and related parameters
- Substation data assignment

Functions for setting the simulation parameters

Those functions provide support to the custom "Simulation parameters" dialog in which users can set parameters required for the simulation of IED data. Parameters that need to be provided are length of the simulation interval, simulation step, name of the input simulation file (default value is info.txt) and parameters identifying the simulations such as time and location of the substation data simulation.

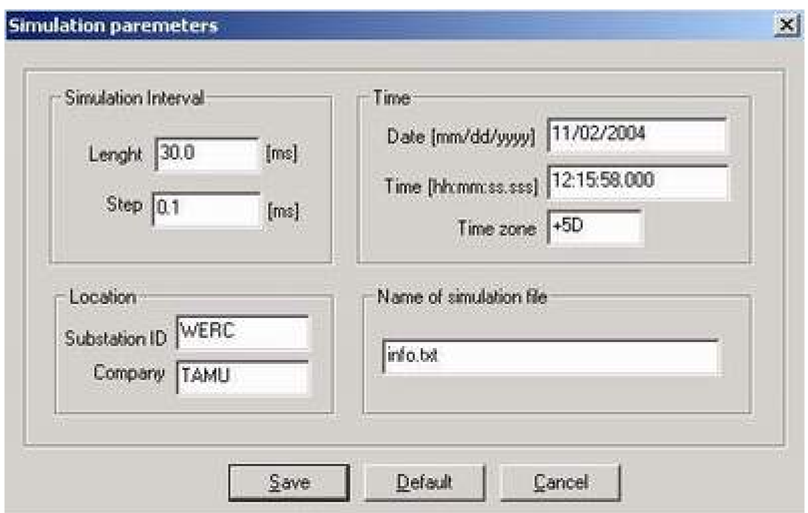


Figure 3.7 Dialog for setting the simulation parameters

Additional information required for the ATP simulation, such as path of the ATP substation data model file and path of the ATP program used for simulation is provided as well.

Selected simulation parameters are saved to the “Simulation File” in ASCII text file format. Figure 3.7 shows the dialog for setting the simulation parameters.

Functions for setting the circuit breaker switching sequences

They enable users to set the switching sequences for one or more substation circuit breakers. Sequences can be set within the whole simulation interval. Before saving the new open/close operation in the switching sequence of the circuit breaker, software verifies the new status by comparing it with the previously set status of the breaker within the sequence and informs the user if any discrepancies are detected.

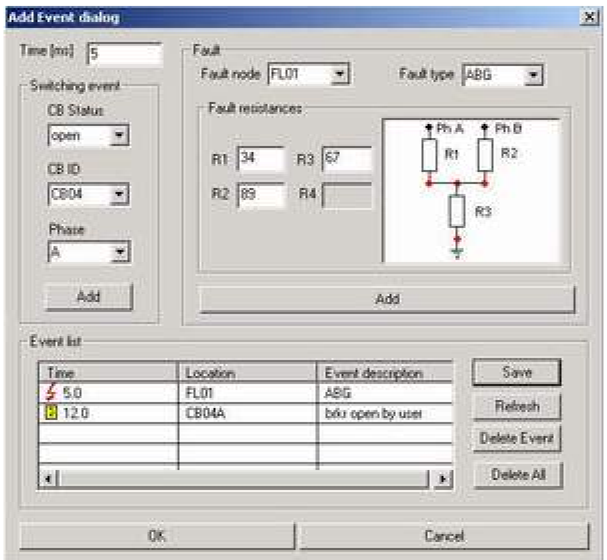


Figure 3.8 Dialog for setting circuit breaker switching sequences and faults

These functions can be invoked by clicking on the circuit breaker device symbol in the Topology window of the GUI or by calling the command from the main menu. Figure below displays the dialog used for setting the circuit breaker switching sequences and faults.

The statuses of the circuit breakers could be set to the values OPEN or CLOSED. Sequences for each phase circuit breaker can be set. By default, all circuit breakers in the substation are initially CLOSED.

Each time the user changes the circuit breaker status, new status is saved to the substation status file. After that, color of device symbol representing the relevant circuit breaker in the Topology window changes according to the set operation – status.

Functions for setting the circuit breaker failure ratios

These functions enable users to set the circuit breaker failure ratios. Circuit breaker failure ratio is used by the ATP model to define the probability that the circuit breaker will fail to perform its operation. Failure ratios can be any number from the interval between 0 and 1, and can be different for open and close operation. Once set, circuit breaker failure ratio is valid for the whole simulation interval. Figure 3.9 below displays the screenshot of the dialog for setting the circuit breaker failure ratios.

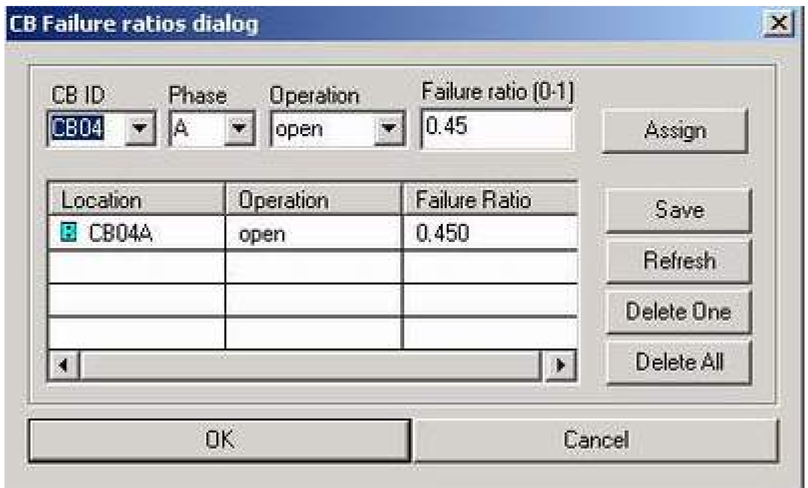


Figure 3.9 Dialog for setting circuit breaker failure ratios

Functions for setting the faults and related parameters

These functions are providing support for setting the faults in the substation simulation scenario. They can be invoked by clicking on the symbol for the fault in the "Topology" window or from the user interface main menu. Figure 3.8 illustrates the dialog used for setting faults and related parameters.

In current implementation, user can set the following fault parameters:

- Time of fault occurrence within the simulation interval
- Location of the fault. Faults can be set on all lines and buses in the substation layout
- Type of fault (phase to ground, phase to phase, 3 phase, 3 phase to ground). For each selected type of faults, an image is displayed illustrating the fault and related parameters
- Fault resistances (R1-R4)

Each time user changes any of the fault parameters, changes are saved to the substation status file and color of the fault symbol in topology window changes from gray to yellow.

Functions for substation data assignment

Functions for substation data assignment are used after the simulation to enable assignment of simulated or measured data to the substation devices represented by the symbols in the topology window. In order to be assigned, data for each device have to be stored in a single COMTRADE or ASCII textual file. Names of the files assigned should follow IEEE file naming convention for time sequence data [4]. Figure 3.10 below illustrates the dialog for substation data assignment.

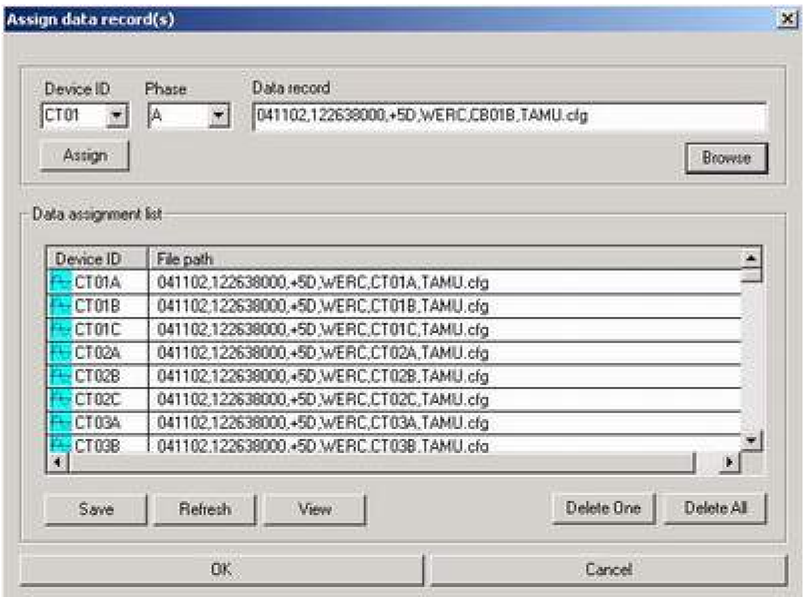


Figure 3.10 Dialog for substation data assignment

This dialog can be invoked by clicking on the device symbol in "Topology" window or from the GUI main menu.

If simulation is performed successfully, software automatically assigns simulated data from the current and voltage measurement transformers to the substation devices. If simulation or automated assignment fail, user can manually assign the CT, PT or CCVT data using the dialog shown above.

The list of devices to which data can be manually assigned is given below:
CT - Data file: ASCII Comtrade file
PT - Data file: ASCII Comtrade file
CBM - Data file: ASCII Comtrade file
DFR - Data file: ASCII Comtrade file
DPR - Data files:
- Oscillography file - ASCII Comtrade file
- Event file - ASCII Textual file
- Fault file - ASCII Textual file

After the data is successfully assigned to the device, the color of its symbol in "Topology" window changes to yellow.

Functions for insertion of IED data errors

Functions for insertion of IED errors are supported by the dialog displayed in Figure 3.11 below.

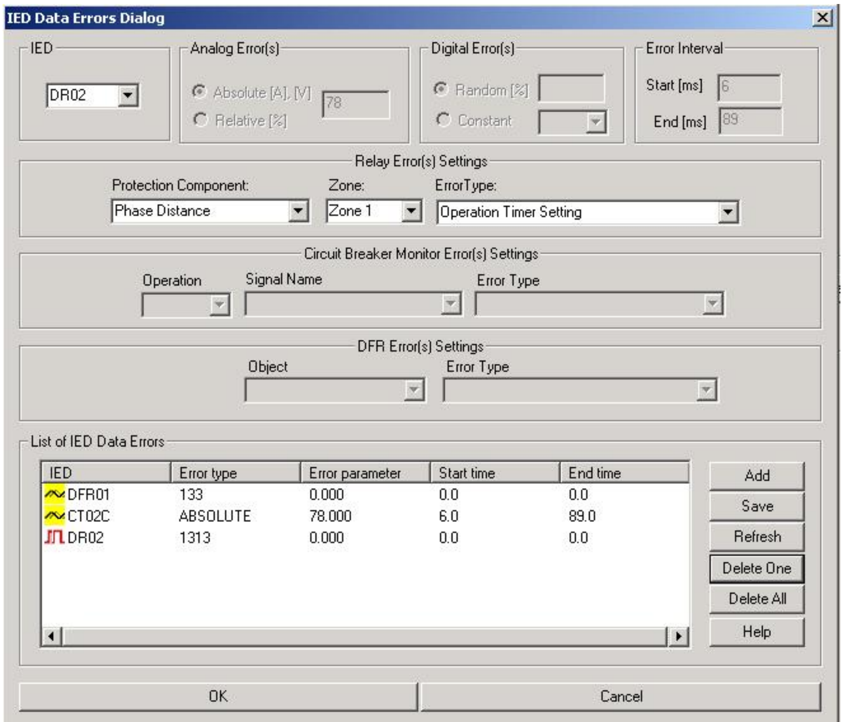


Figure 3.11 Dialog for insertion of IED errors

The dialog enables inserting the errors into the simulated data of the following IEDs:

- CT, PT, CCVT. Their errors can be relative or absolute (DC offset).
- CB status. The errors can be random or deterministic.
- CBM, DPR, DFR. For these devices, the errors are defined based on the specific functionality that they are representing.

See tables given below for more detailed explanation of errors.

Table 3-2 List of DPR errors

Element	Zone	Error Type	Error Code
Phase IOC		Pickup Setting Incorrect	1102
		Operation Timer Setting Incorrect	1103
		Operation Block Logic Incorrect	1104
Ground IOC		Pickup Setting Incorrect	1202
		Operation Timer Setting Incorrect	1203
		Operation Block Logic Incorrect	1204
Phase Distance	Zone 1	Supervision Current Level Setting Incorrect	1311
	Zone 2	Supervision Current Level Setting Incorrect	1321
	Zone 3	Supervision Current Level Setting Incorrect	1331
	Zone 4	Supervision Current Level Setting Incorrect	1341
	Zone 1	Pickup Setting Incorrect	1312
	Zone 2	Pickup Setting Incorrect	1322
	Zone 3	Pickup Setting Incorrect	1332
	Zone 4	Pickup Setting Incorrect	1342
	Zone 1	Operation Timer Setting Incorrect	1313
	Zone 2	Operation Timer Setting Incorrect	1323
	Zone 3	Operation Timer Setting Incorrect	1333
	Zone 4	Operation Timer Setting Incorrect	1343
	Zone 1	Operation Block Logic Incorrect	1314
	Zone 2	Operation Block Logic Incorrect	1324
	Zone 3	Operation Block Logic Incorrect	1334
	Zone 4	Operation Block Logic Incorrect	1344
Ground Distance	Zone 1	Supervision Current Level Setting Incorrect	1411
	Zone 2	Supervision Current Level Setting Incorrect	1421
	Zone 3	Supervision Current Level Setting Incorrect	1431
	Zone 4	Supervision Current Level Setting Incorrect	1441
	Zone 1	Pickup Setting Incorrect	1412
	Zone 2	Pickup Setting Incorrect	1422
	Zone 3	Pickup Setting Incorrect	1432
	Zone 4	Pickup Setting Incorrect	1442
	Zone 1	Operation Timer Setting Incorrect	1413
	Zone 2	Operation Timer Setting Incorrect	1423
	Zone 3	Operation Timer Setting Incorrect	1433
	Zone 4	Operation Timer Setting Incorrect	1443
	Zone 1	Operation Block Logic Incorrect	1414
	Zone 2	Operation Block Logic Incorrect	1424
	Zone 3	Operation Block Logic Incorrect	1434
	Zone 4	Operation Block Logic Incorrect	1444

Table 3-3 List of DPR errors (continued)

Element	Zone	Error Type	Error Code
Circuit Breaker 1		Trip Logic Incorrect	1501
		Trip Wire Connection Broken	1502
		Close Logic Incorrect	1503
		Close Wire Connection Broken	1504
		Reclosing Fault Detection Function Incorrect	1505
		Trip Signal Recording Incorrect	1506
		Close Signal Recording Incorrect	1507
		“a” Contact Recording Incorrect	1508
		“b” Contact Recording Incorrect	1509
Circuit Breaker 2		Trip Logic Incorrect	1601
		Trip Wire Connection Broken	1602
		Close Logic Incorrect	603
		Close Wire Connection Broken	1604
		Reclosing Fault Detection Function Incorrect	1605
		Trip Signal Recording Incorrect	1606
		Close Signal Recording Incorrect	1607
		“a” Contact Recording Incorrect	1608
		“b” Contact Recording Incorrect	1609
Fault Type		Fault Detection Incorrect	1701
Fault Location		Fault Detection Incorrect	1801

Table 3-4 List of CBM errors

Process	Signal	Error Type	Error Code
Trip	Trip Initiate	Flat	1111
	Trip Initiate	Reset Premature	1112
	Trip Current	Flat	1121
	Trip Current	Pickup Delayed	1122
	Trip Current	No Drop	1123
	“a” Contact	Flat	1131
	“a” Contact	Change Premature	1132
	“a” Contact	Change Delayed	1133
	“b” Contact	Flat	1141
	“b” Contact	Change Premature	1142
	“b” Contact	Change Delayed	1143
	Phase Currents	No Drop	1151
	Phase Currents	Interruption Slow	1152
Close	Close Initiate	Flat	1211
	Close Initiate	Reset Premature	1212
	X Coil	Flat	1221
	X Coil	Activation Delayed	1222
	X Coil	Deactivation Premature	1223
	Close Current	Flat	1231
	Close Current	Pickup Delayed	1232
	Close Current	No Drop	1233
	“a” Contact	Flat	1241
	“a” Contact	Change Premature	1242
	“a” Contact	Change Delayed	1243
	“b” Contact	Flat	1251
	“b” Contact	Change Premature	1252
	“b” Contact	Change Delayed	1253
	Y Coil	No Activation	1261
	Y Coil	Activation Premature	1262
	Y Coil	Activation Delayed	1263
	Phase Currents	No Rise	1271
	Phase Currents	Resume Slow	1272

Table 3-5 List of DFR errors

Object	Error Type	Error Code
Fault	Fault Detection Incorrect	111
Relay	Trip Signal Recording Incorrect	121
	Close Signal Recording Incorrect	122
Circuit Breaker 1	“a” Contact Recording Incorrect	131
	“b” Contact Recording Incorrect	132
	Current Interruption Detection Incorrect	133
	Current Resume Detection Incorrect	134
Circuit Breaker 2	“a” Contact Recording Incorrect	141
	“b” Contact Recording Incorrect	142
	Current Interruption Detection Incorrect	143
	Current Resume Detection Incorrect	144

3.2.4 Integration with Analysis and Verification Applications

This section describes design and implementation of the user interface functions supporting integration of the analysis and verification applications within the GUI. Analysis and verification applications are implemented as independent software modules.

Integration functions provide the applications with measured/simulated data and information about events and statuses of the devices (IEDs) in a substation. They enable users to launch the applications from the integrated shell and display the results of the analysis (such as reports and device statuses) within the “Topology” window.

There are two ways how the applications can be invoked from the GUI. First is from the main application menu. This is the only possible way if application is analyzing the data originating from several substations IEDs. If application is analyzing the data from only one IED (e.g., DPRA application for a single relay), then the application can be also invoked by clicking on the device symbol in topology window and selecting appropriate command from the context menu.

In general, GUI interfaces with the analysis and verification applications as shown in Figure 3.12. Substation status data contains the information about the statuses of the substation devices, assigned data, switching sequences and fault parameters. COMTRADE files contain the signal waveforms of the assigned data and “Application Reports” are the conclusions drawn on the data after analysis and verification.

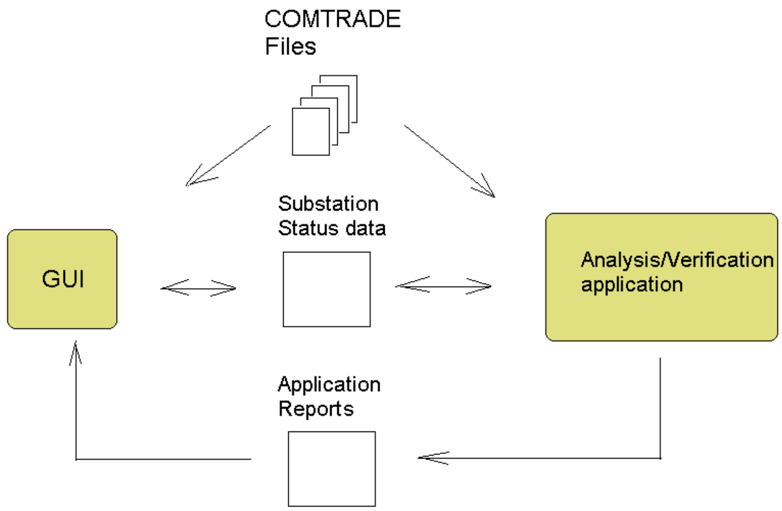


Figure 3.12 Integration of the GUI with the analysis and verification application

User interface functions for integration of the analysis and verification applications currently support three applications listed below:

- Verification of Substation Database - VSDB
- Substation Switching Sequences Verification - SSSV
- Digital Protective Relay Application - DPRA.

More details about their interfacing is provided in the remainder of this section.

Integration of Verification of Substation Database (VSDB) application

The VSDB application verifies the currents and voltages measured or simulated in the substation by the CTs, PTs or CCVTs. The GUI supports the integration of the VSDB application by providing input data and displaying the results of the analysis. VSDB can be invoked from the main application menu only.

Input data:

- GUI provides location of data records (in form of the IEEE filenames) assigned to all CT, PT and CCVT devices in the substation
- GUI provides statuses and switching times of all substation CBs

Output data:

- GUI displays statuses and time instances reported by VSDB when data assigned to CTs, PTs or CCVTs were inconsistent mutually or with reported CB statuses
- GUI displays report generated by VSDB

More details about the VSDB application can be found in separate section of this document.

Integration of Substation Switching Sequences Verification (SSSV) application

The SSSV application verifies switching sequences of circuit breakers in the substation in case of faults or operator initiated circuit breaker operations. The GUI supports the integration of the SSSV application by providing input data and displaying the results of the analysis. SSSV can be invoked from the main application menu only.

Input data:

- GUI provides the simulation file created before simulation, containing following parameters:
    1. Breaker initial statuses (OPEN/CLOSED)
    2. Fault information (location, type, parameters, time of occurrence)
    3. Statuses of the circuit breakers (CBs) at specific time instances (when CB status changes during switching sequence or fault occurrence)
    4. Topology information (switch and circuit breaker names, from/to node names, switch type, corresponding CT names, backup breaker names)
    5. ATP simulation parameters (simulation time, time step)

- GUI provides paths of data records assigned to all CTs in the substation

Output data:

- GUI displays statuses and time instances reported by SSSV when the data and statuses assigned to the CBs were inconsistent
- GUI displays the SSSV report.

More details about the SSSV application can be found in separate section of this document.

Integration of Digital Protective Relay Analysis (DPRA) Application

The DPRA application analyzes digital protective relay files acquired in the field or simulated by the ATP. The GUI supports the integration of the DPRA application by providing input data and displaying the results of the analysis. DPRA can be invoked from the main application menu or by clicking on the digital relay symbol in the topology window. Since the input data cannot be simulated by ATP, only measured data can be provided.

Input data:

- For each analyzed digital protective relay in the substation - the following files are assigned to the relay device symbol in the GUI: Comtrade oscillography files, event record file and fault report file assigned by the user.

Output data:

- GUI displays statuses of analyzed digital protective relays. Based on results of the analysis, the following statuses of the relays could be reported:
  - Relay tripped
  - Relay miss operated
  - Data within different relay reports are inconsistent
- GUI displays relay data consistency checking report
- GUI displays relay status validation report.

More details about the DPRA application can be found in separate section of this document.

3.3 Verification of Substation Database

3.3.1 Introduction

Verification of Substation Database (VSDB) performs data processing and consistency checking at the substation level. The detected errors are updated in the application GUI for their particular time stamps for user to view. The application is designed to run on the substation computer due to physical proximity of measurement points located in the substation control house.

The VSDB takes data input from files deposited into a directory/database by different IEDs and measurement devices. The application is designed to take input data in IEEE COMTRADE and IEC 61850 formats. The data is verified using redundancy in measurement based on certain basic electrical network theory laws. If there is an inconsistency in data, it is reported.

Bad data is eliminated if available redundancy makes is possible to determine accurate data, else the data is stored as is, but is labeled as inconsistent.

The application provides a graphical user interface for viewing error reports. A user can set tolerances for the consistency check algorithms, run the data consistency checks and view error reports using this interface. The interface is invoked from the main application GUI by clicking the appropriate button in the toolbar or through the Analyze menu.

3.3.2 Input Data Specification

The applications input data can be grouped into four categories

- Topology data
- Measurement data
- Configuration data
- User inputs

Topology data - The topology information required to process data using network laws is provided in the IEC 61850 SCL file format. Topology information is extracted from the

SCL configuration file for the substation and stored in a txt format file named ‘topology.dat’. This file must be placed in the SETTINGS directory of the application folder.

Measurement data - Measurement data from the substation is provided to the application in COMTRADE file format. The data includes:

- Voltage and current measurements from CTs and VTs.
- Switch and circuit breaker statuses from CBM
- Switch and circuit breaker statuses from the main application user interface.

The data is extracted from COMTRADE files with.dat extension. Each file has a record of data from a single measurement device or IED for a duration specified in the configuration file corresponding to that data file. The current software version supports data files in ASCII format only. The file name must be in the IEEE file naming standard format.

Configuration data - Configuration data here refers to the measurement device’s configuration settings. This data is extracted from the COMTRADE format from files with .cfg extension. The files are loaded in the applications installation directory and each file corresponds to a single device or IED. The file name must be in the IEEE file naming standard format.

The configuration files contain the following information:

- Station name, identification of the recording device, and COMTRADE Standard revision year;
- Number and type of channels;
- Channel names, units, and conversion factors;
- System frequency;
- Sample rate(s) and number of samples at each rate;
- Date and time of first data point;
- Date and time of trigger point;
- Data file type; and
- Time Stamp Multiplication Factor.

3.3.3 User Input

The user can set tolerance parameters for different consistency check algorithms used in the application. The following parameters can be set using the settings tab from the Options Menu in VSDB GUI:

- Maximum Allowable Double Measurement discrepancy (MADMdis)
- Maximum KCL first law error allowed. (KCLerr)
- Zero Current Value (ZCV)
- Necessary Voltage Difference for current existence (NVD)
- Maximum Tolerable Analog Measurement Change (MTAMC)

3.3.4 Data Generation

The measurement data is generated using the ATP software. The data is generated by setting parameters in the integrated GUI. The simulated data is stored by GUI into specific folders and then picked up by the VSDB software from these folders. The topology data comes from SCL file that is currently generated manually for the substation model to be used for demonstration.

3.3.5 Output Data Specification

The VSDB software generates two reports and updates main GUI after running consistency checks on the input data.

Summary Report: The summary report lists the timestamps during which any of the inconsistency errors has occurred for the entire set of input data. The order of reporting errors is

- Double current measurement errors
- Kirchoff's current law errors
- Branch status errors
- Time status change errors

The summary report file is named according to the IEEE file naming format specified in appendix with the only difference that the name is appended with 'VSDB_Summary'. The file format is ASCII text.

Detailed Report: The detailed report lists detailed error records for each timestamp in the input data. The format of each record is as follows:

- Timestamp: <timestamp>
- Double current Measurement errors: <branch><phase>……..
- KCL errors: <node><phase>………
- Branch Status error:<branch><phase><description>…
- Time Status error: <branch><phase>

The detailed report file is named according to the IEEE file naming format specified in appendix with the only difference that the name is appended with 'VSDB_report'. The file format is ASCII text.

Main GUI Update: The VSDB module after performing consistency check updates the main application GUI with branch status error data. If the status of circuit breakers is found to be incorrect in the input data the breakers are set to red color in the main GUI.

3.3.6 Functional Specification

Verification of Substation Database (VSDB) performs data processing and consistency checking on the input data obtained by ATP simulation and generates error reports. It also updates the man GUI to show data inconsistencies and circuit breaker status for particular timestamps. This section describes the functionality of the software in detail.

The VSDB software loads input data and performs the following checks using the user set parameters:

- **Double Measurement check:** For all branches that have more than 1 current measurement available, the software checks the discrepancy between all measurements and sets the branch current to the average value. If the percentage discrepancy is higher than the maximum allowed value set by the user in parameter MADMdis the values are declared inconsistent. Inconsistent measurements detected are reported in the "Errors reported during current timestamp" window.
- **Kirchoff's Current Law check:** For all nodes that have all the incident branch currents known, the measured values are tested for consistency with Kirchoff's current law. If the total current at a node is greater than the user-set parameter KCLerror, the node is declared as inconsistent with KCL. Nodes at which KCL is not satisfied are reported in the "Errors reported during current timestamp" window.
- **Branch Status check:** The software verifies the circuit breaker statuses against the current flowing through them and voltage difference across the branch. The following decision table is used for verification. The squares in gray show the decisions taken for different cases.

|Measured current|	Switch	Voltage difference in required range	Voltage difference outside range
= 0	Open	Open (010)	Open(000)
	Closed	Open (Bad switch data detected and corrected)(011)	Previous status (Status doesn't matter)(001)
> 0	Open	Closed (Possible switch data inconsistency)(110)	Open (Current measurement error)(100)
	Closed	Closed(111)	Closed (Possible voltage measurement error)(101)

- **Time based Status check:** After every cycle, the software checks if there has been a change in the previous cycle's analog and digital measurements and those for the current cycle. Inconsistent changes are detected and reported according to the following decision table.

		Change in topology	
		Yes	No
Change in analog measurement	Yes	All ok	Inconsistency in analog measurement
	No	Possible inconsistency	All ok

The following two error reports can be viewed from the GUIs Run VSDB Menu screen:

Summary Report: This report lists the time stamps at which the following errors have occurred.

- Double measurement error
- KCL error
- Branch Status Check error
- Time status change error

Detailed Report: This report lists the detailed errors for each time stamp. It specifies the branch/node and the phase where the error originated.

3.3.7 Implementation

The VSDB software is implemented in Visual C++ 6.0 using Microsoft Foundation Classes (MFC) Library for the windows GUI. The software is implemented using single document multiple views architecture. This section describes the implementation of software in VC++. Figure 3.13 shows the flow diagram for the different modules of VSDB software.

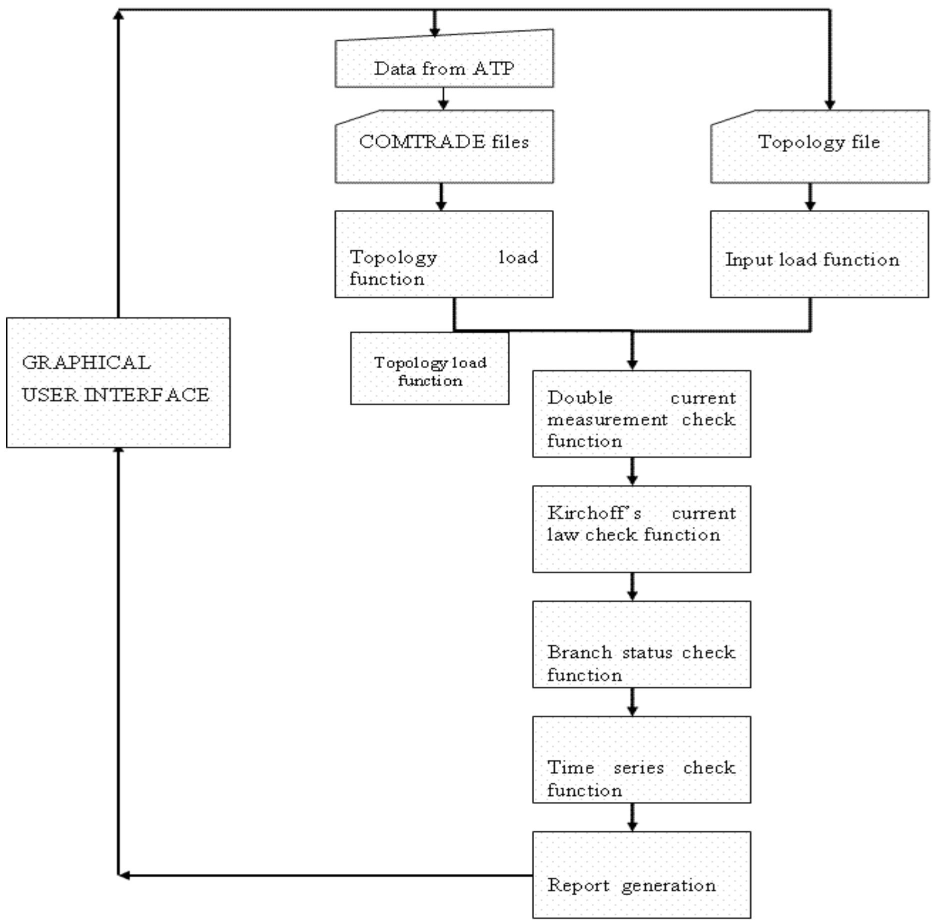


Figure 3.13 Flow diagram for VSDB application

The Main menu of VSDB software GUI lets the user interact with the software using the following options:

- **Topology:** This option opens the topology view which displays the topology information in terms of branches and nodes.

- Figure 3.14 shows a snapshot of the topology view.

- **Options - Settings:** This menu item opens a tabbed dialog for setting the consistency check parameters and the file paths for Data folder, topology file and report file. Figure 3.15 and Figure 3.16

- **Run VSDB:** This is the main view of the program. This view lets the user start the consistency check routine and stop it. After consistency check is completed the user can view the summary report or the detailed report by clicking the respective buttons at the bottom right corner of the view. The view displays assigned branch currents and statuses for each timestamp as the consistency check algorithm progresses. It also displays the data discrepancies encountered for the current time stamp. Figure 3.17 shows the Run VSDB view.

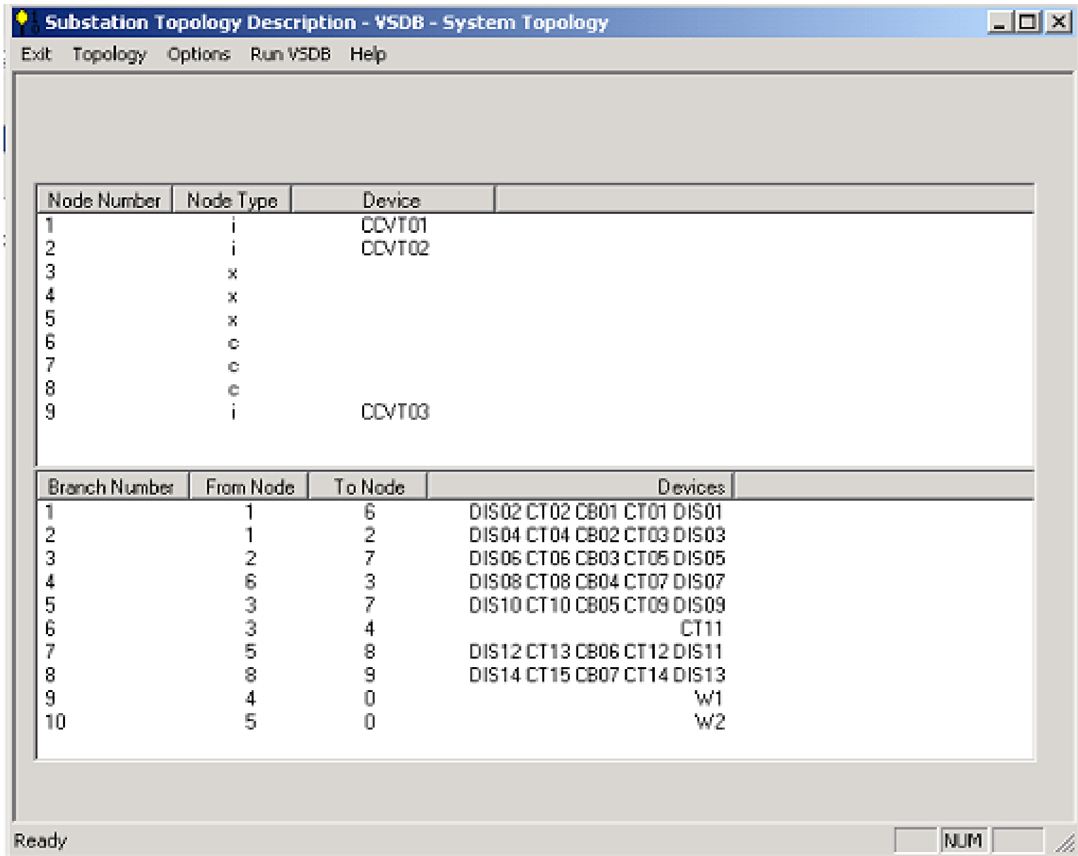


Figure 3.14 Topology View

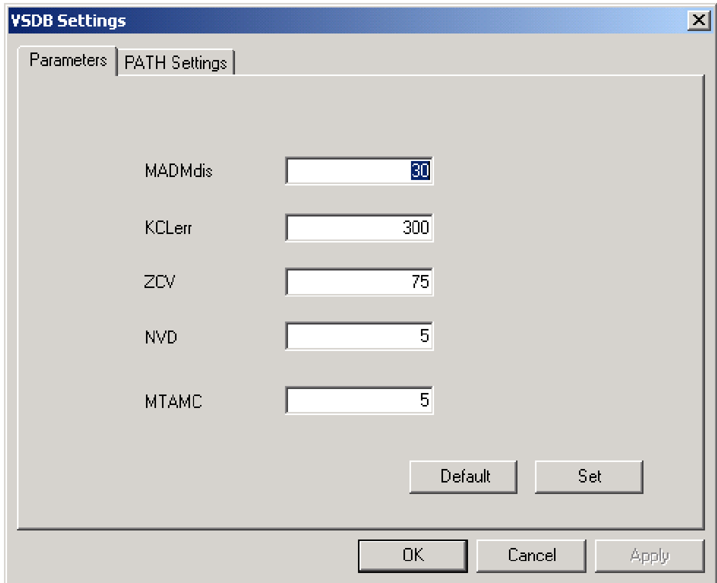


Figure 3.15 Settings: VSDB parameters

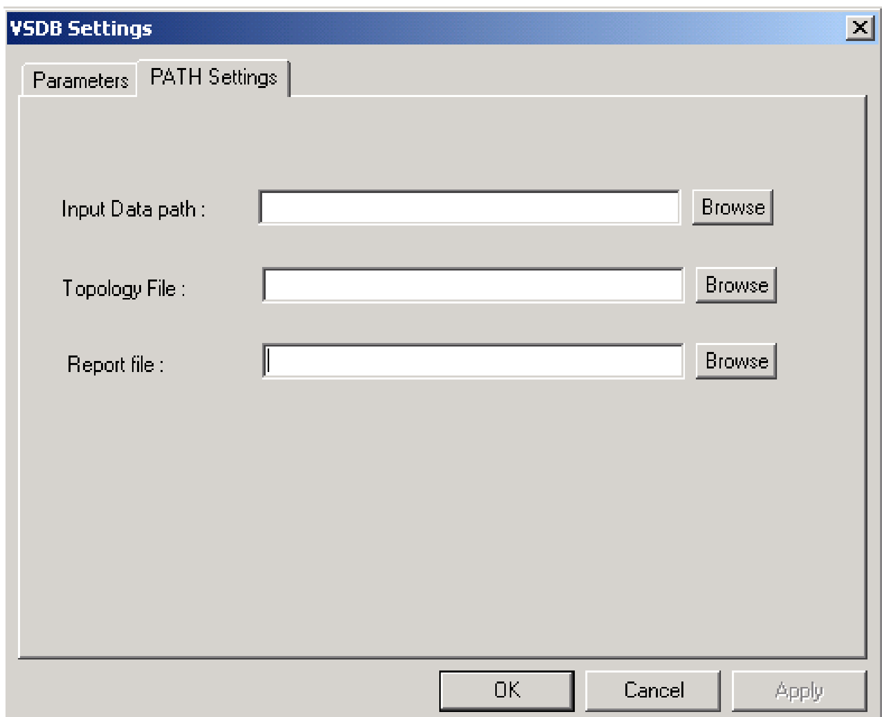


Figure 3.16 Settings: VSDB file paths

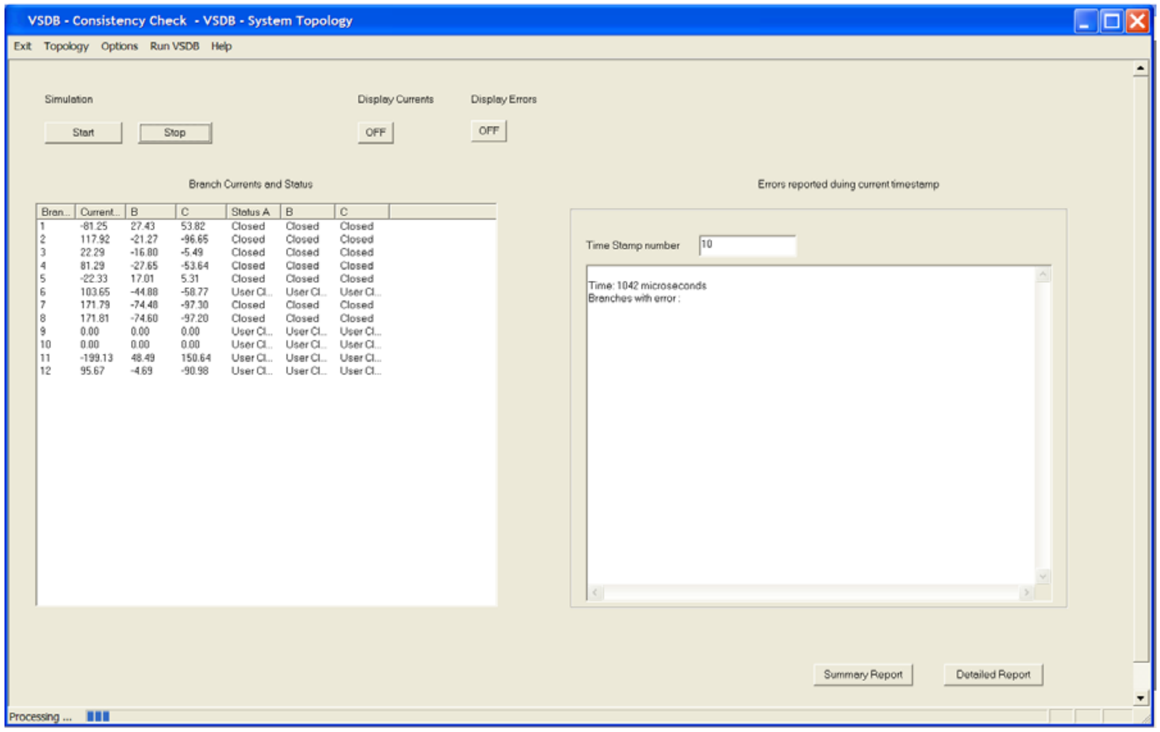


Figure 3.17 Run VSDB view

3.4 Substation Switching Sequences Verification

Substation Switching Sequence Verification (SSSV) is an independent software application. Its main task is to compare the user-defined switching sequences with the actually measured switching sequences, to find if there exists any discrepancy and determine which devices might have problems within a substation. Figure 3.18 shows the architecture of the SSSV application.

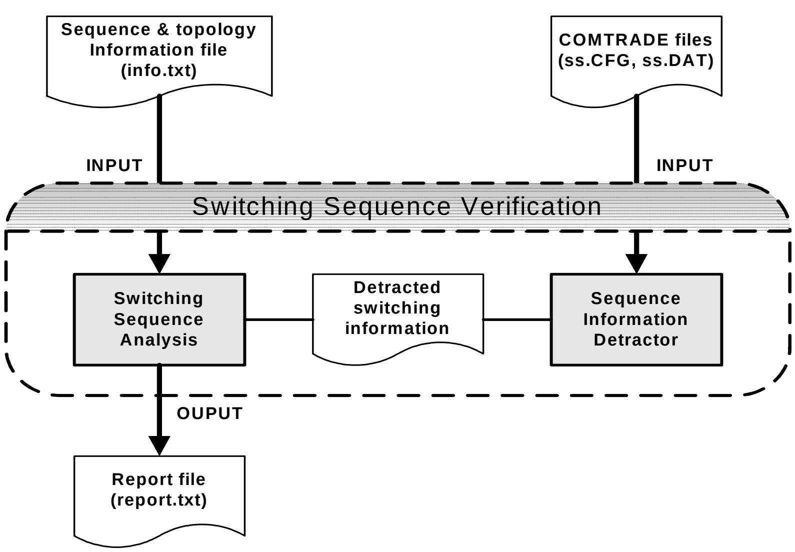


Figure 3.18 SSSV Software architecture

3.4.1 Input Data Specification

The Switching Sequence Verification software module takes two types of files as input: the topology/events information file, and the data files.

The topology/events information file (INFO.TXT) basically describes what the desired switching sequence should be. It could be a desired operator switching sequence, or a description of faults.

The data files, on the other hand, are coming from the ATP data simulation or DFR records, which contain the analog and digital measurements in the substation during a switching scenario. The data files can be either a PL4 file or a group of COMTRADE files (.CFG, .DAT). If PL4 file is provided, it will be converted to COMTRADE format internally before any verification functions are executed.

3.4.2 Output Data Specification

The output report consists of two sections: verification of faults & relay operations; verification of operator switching sequences.

Verification of Faults & Relay Operations
If the topology/events information file (INFO.TXT) contains the description of faults, the SSSV application will verify whether the described faults have occurred and whether they have been correctly cleared by the relay operations. The provided verification results include: the location and type of fault; the fault duration times; the fault clearing time; whether the correct CBs are operated; whether auto-reclosing is executed, etc.

Verification of Operator Switching Sequences
This section consists of the following seven parts:
Original Switching Sequence. The user-defined switching sequence (as shown in the topology/switching information file) is listed in this part. The switching operations are sorted by their occurring times.

Real Switching Sequence. The actual measured switching sequence is listed in this part. If any circuit breakers failed during the simulation time, backup circuit breakers would have operated instead. The real switching sequence reflects the actual operations and thus might differ from the user-defined switching sequence.

For an opening switching operation, since a switch is not allowed to operate until the next instant when the current crosses zero, the device's real opening time may be delayed after the trip signal is set. Both the times that operation signals are set and the real operation times are listed in this section.

CB Switching Sequence Analysis. This part shows the analysis of the actual switching sequence of circuit breakers. A step-by-step analysis procedure is done for each event in the real switching sequence. Status of each operation and the description of analysis result are listed for each event. Possible combinations of operation statuses and descriptions are list in Table 3-6.

Table 3-6 Switching operation statuses and descriptions

Operation Status	Description
OK	Normal operation was executed correctly.
	Backup operation was executed correctly.
SKIPPED	The backup CB was already OPEN.
	Operation was blocked due to breaker failure requirements.
	The operation time was out of the simulation period.
FAILED	Device failed to open. Breaker failure scheme was initiated.
	CB failed to close.
	Device did not respond because of a previous failure.

CB Statuses. This part shows the change of circuit breaker statuses in the substation at different times. Each time when there is a change in any of the circuit breaker statuses, a column will be added to the status table, showing the statuses of all circuit breakers at that particular time.

Table 3-7 Circuit breaker statuses

Bit	0	1	2
Value	C = CLOSED, O = OPEN	E = ENABLED, D = DISABLED	H = HEALTHY, U = UNHEALTHY

Circuit breaker statuses are expressed by a 3-bit binary code, as shown in Table 3-7.

Bit 0 is either CLOSED or OPEN, indicating the close/open status of a circuit breaker.

Bit 1 is either ENABLED or DISABLED. When a circuit breaker is ENABLED, it accepts operation signals; otherwise all operation signals issued to this circuit breaker are blocked and the circuit breaker cannot be operated until its status is ENABLED again.

Bit 2 is either HEALTHY or UNHEALTHY. When a circuit breaker is HEALTHY, it is in a normal state and can execute operations correctly; otherwise the circuit breaker has failed and needs repairing.

It should be noted that a DISABLED circuit breaker is not necessarily an UNHEALTHY circuit breaker. For example, in a breaker failure scheme, the backup breaker is HEALTHY but it becomes DISABLED after it has operated, because it has to isolate the failed circuit breaker and thus is not allowed to operate again. Likewise, an ENABLED circuit breaker is not necessarily HEALTHY, because although a circuit breaker can accept operation commands, it might physically fail at the time of execution.

CB Operation Times. This part shows the actual device operation times of circuit breakers that are reflected in the COMTRADE data files. A list of operation times, when applicable, is formed for each of the circuit breakers and listed in the timetable.

Disconnect Isolator Report. Disconnect isolators usually have no current breaking ability and thus are not allowed to open when there is residual current in the circuit. If there is any operation aimed at opening disconnect isolator during the simulation, the switching sequence verification software will check to see if at the time of opening, there is no residual current in the circuit and the operation is safe. The summary of such verification is listed in this part.

Conclusions. The "Conclusions" part lists the names of all circuit breakers that have failed or operated as a breaker failure scheme. It also lists all disconnect isolators that opened when there was residual current.

3.4.3 Functional Specification

A Win32 SSSV application was compiled using Visual C++. Figure 3.19 shows the file selection dialog box that is shown when the user starts the application. The user can then select the input files and the output report file name. The application is also capable of updating the main GUI with the circuit breaker status display. Those circuit breakers that failed will be marked in red color for easier observation purposes.

When the user clicks the "OK" button, the verification process will start. After the verification report is created, it will be displayed in a dialog box shown in Figure 3.20. A copy of such a report will be automatically saved using the IEEE file naming convention. The user can also select to save the report to another location.

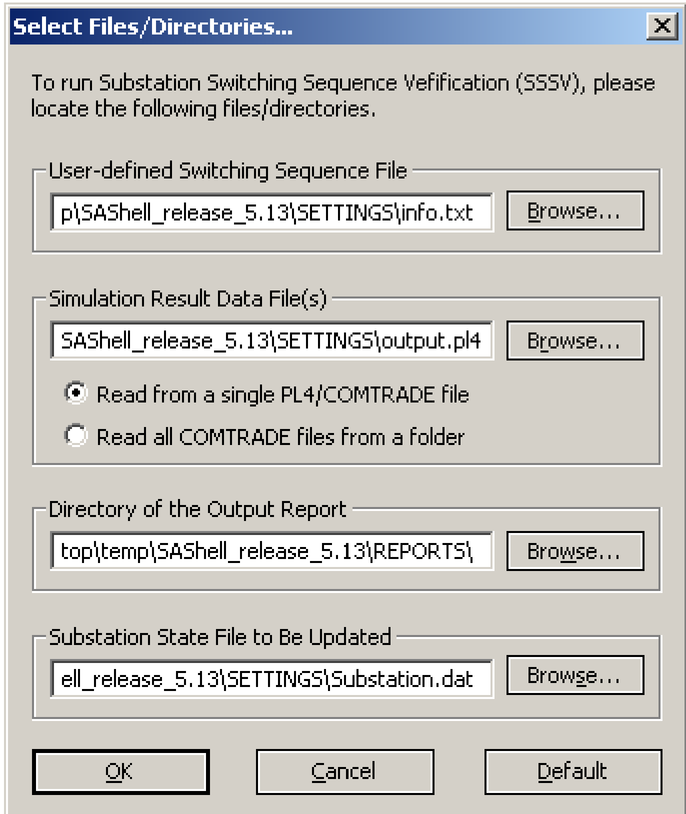


Figure 3.19 File Selection Dialog Box

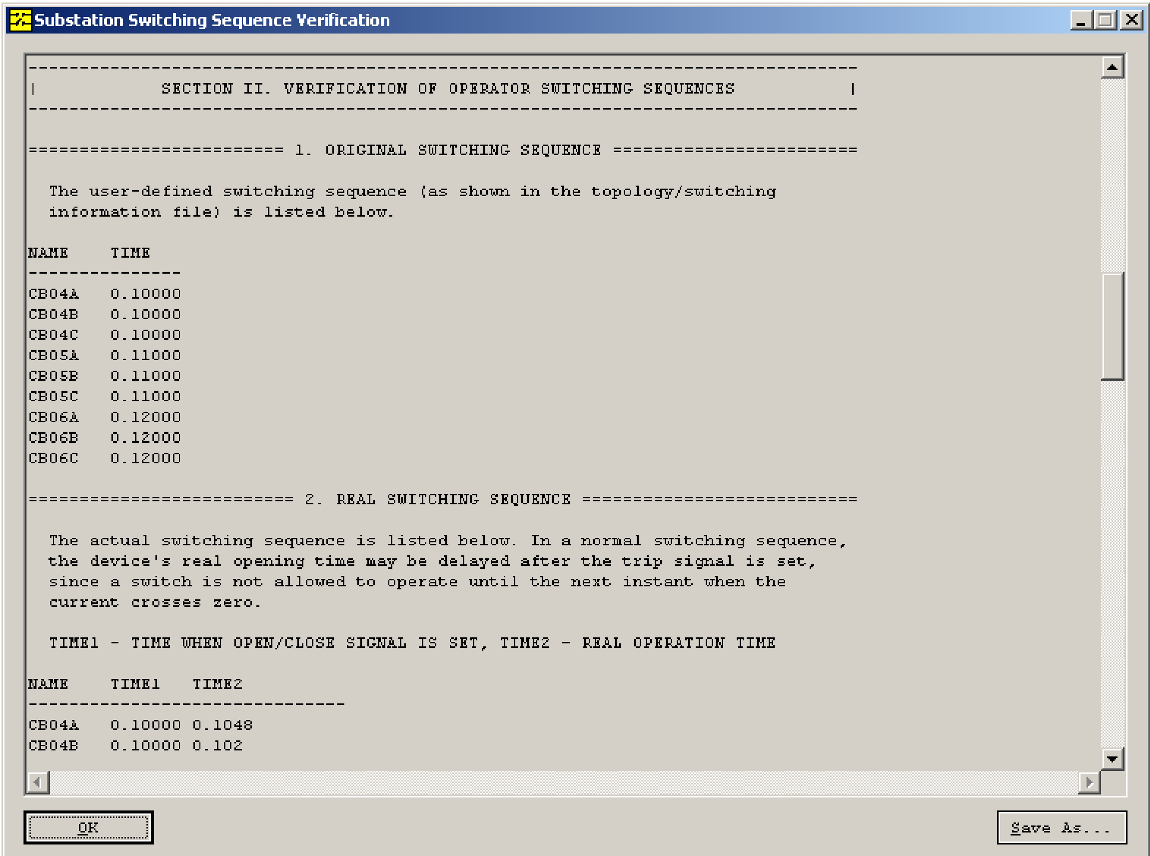


Figure 3.20 Verification Report Dialog Box

3.5 Digital Protective Relay Analysis

By virtue of the power of microprocessors, a modern digital protective relay can provide users with abundant data related to protection, control and monitoring during certain power system disturbances. They are usually saved in the form of several relay reports and files such as event record reports, fault reports, oscillography files and setting files for further use. Since these data actually record what the relay saw and how it responded, it is possible for users to utilize these data to validate the correctness of relay operation and diagnose the reasons for failures and misoperations.

The Digital Protective Relay Data Analysis (DPRA) application is an expert system based analysis application which automates validation and diagnosis of relay operation. It takes various relay reports and files as inputs, displays their contents in graphic user interface, uses embedded expert system to automate the analysis and generates a report on the results of analysis.

This section specifies the inputs and outputs of the application and details the design of analysis algorithms. Section 3.5.1 specifies the inputs of the application. Section 3.5.2

specifies the output of the application. Section 3.5.3 details the design of knowledge base of expert system.

3.5.1 Input Data Specification

Input data of DPRA application comes from external disturbance information, relay performance specification, and relay reports and files which include an event record report, an oscillography file and a setting file. They are explained as follows:

A) External disturbance information

External disturbance information includes fault type, fault location, fault inception time, fault disappearance time, current interruption time and current resume time of associated circuit breakers. It is the fundamental information used to predict expected relay behavior. The information is supposed to be manually entered by users or be automatically obtained from the reports of external fault analysis applications based on advanced algorithms and techniques such as expert system, neural network and synchronized sampling. In the demo environment, if automatic input option is chosen, the information about fault type, fault location, fault inception time, and fault disappearance time is extracted from the info.txt file which is for disturbance simulation specification purpose while the information about current interruption time and current resume time of associated circuit breakers is obtained by the signal processing function of DPRA based on the data contained in the oscillography file. Figure 3.21 is the dialog for disturbance information input.

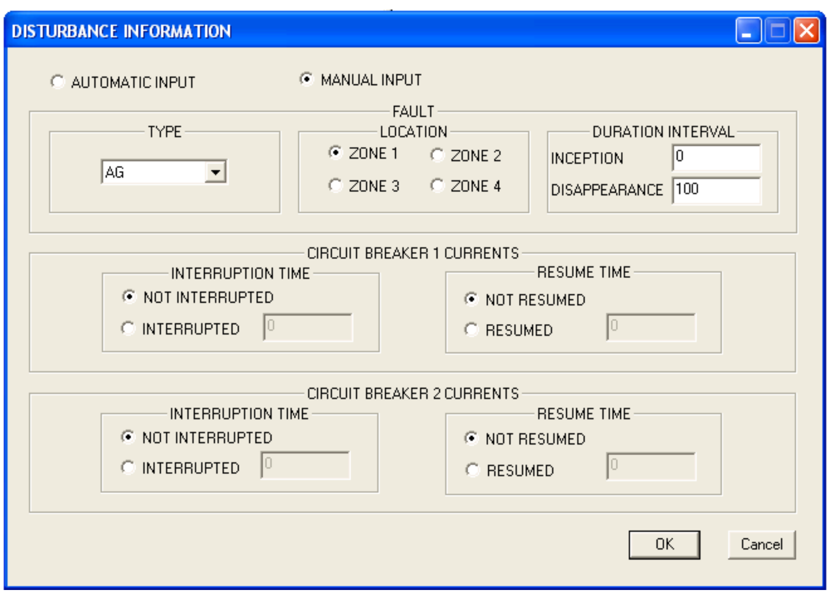


Figure 3.21 Dialog for disturbance information input

B) Relay performance specification

Relay performance specification includes time delay parameters and operating speed timing tolerance for each protection element and associated circuit breaker. It is the complementary information of relay setting used to predict expected protection behavior. The information is entered by users manually according to user's manuals of relays and circuit breakers and the users' empirical knowledge. Figure 3.22 is the dialog for performance specification input.

C) Event record report

An event record report is a list of time-stamped relay logic operands in chronological order corresponding to certain disturbance event. It contains most of the information of actual protection behavior. Each record item in the list consists of the event number, the event time, and the event cause in the form of relay logic operands. An example of event record reports is displayed in the left view of the GUI shown in Figure 3.23.

D) Oscillography file

An oscillography file is in COMTRADE format. It consists of a configuration file and a data file. The configuration file specifies what are the data and how the data are stored in the data file. The data file stores actual data in binary or ASC II format. It usually contains analog values of three-phase voltages and currents and digital status (0 or 1) of logic operands which are selected to be recorded by users. The status and timing of logic operands which are also contained in the event record report are checked about their consistency. The status and timing of logic operands which are not contained in the event record report are used as complementary information of actual protection behavior. An example of oscillography files is displayed in the right view of the GUI shown in Figure 3.23.

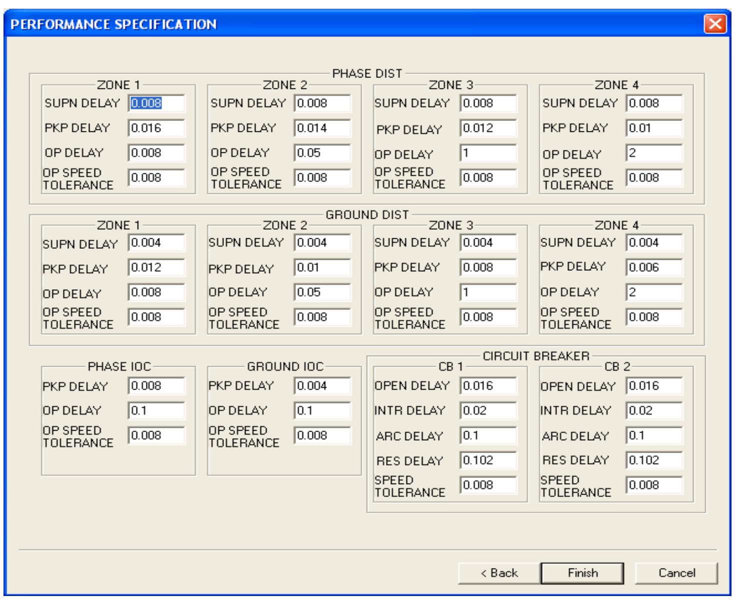


Figure 3.22 Dialog for performance specification input

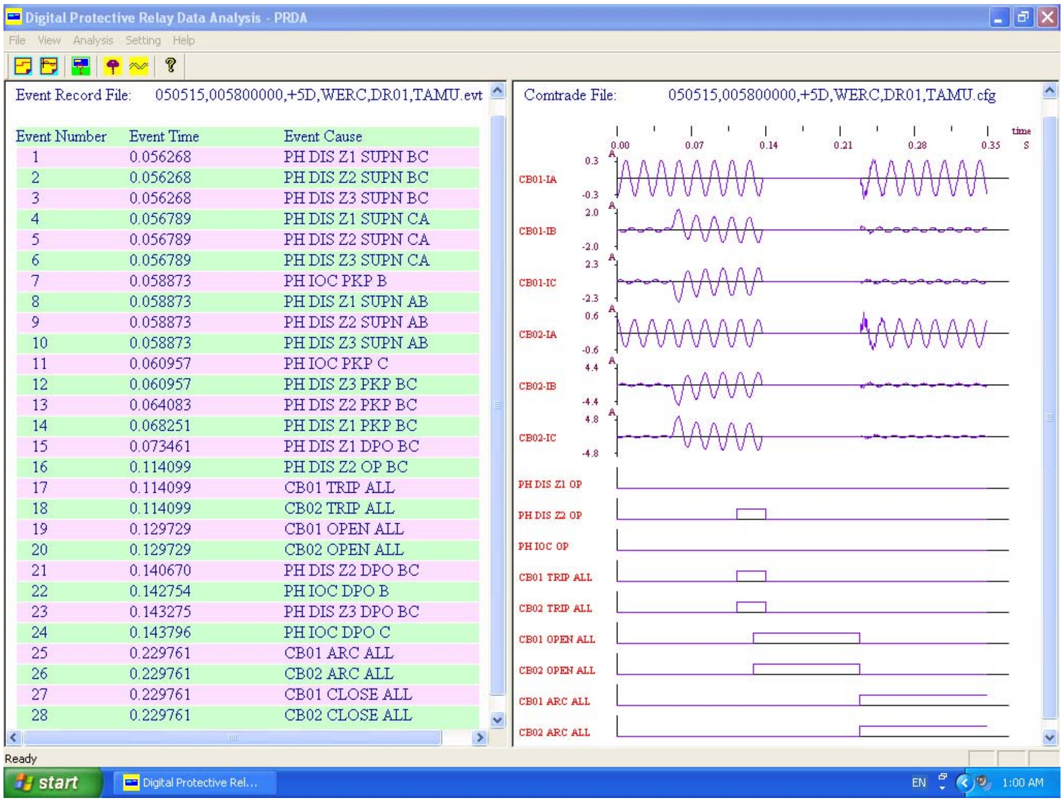


Figure 3.23 GUI for an event record report and an oscillography file

E) Setting file

A setting file contains relay information, power system information, relay setting, and logic operand selection. Relay information includes relay ID, protected line ID, and associated circuit breaker ID. Power system information includes protected line parameters, load parameters, and ratios of current transformers and voltage transformers. Relay setting specifies the operating parameters of protection elements, including Phase Distance (PAHSE DIST) element, Ground Distance (GROUND DIST) element, Phase Instantaneous Over Current (PHASE IOC) element, Ground Instantaneous Over Current (GROUND IOC) element, and Autorelosing Logic. Table 3-8 lists the operating parameters of each protection element. Logic operand selection specifies the logic operands to be recorded in the oscillography file.

Table 3-8 Operating parameters of protection elements

Protection Element	Operating parameters
PHASE DIST	Enable/Disable Option
	Supervision current level
	Operation time delay
	Zone boundary
GROUND DIST	Enable/Disable Option
	Supervision current level
	Operation time delay
	Zone boundary
PHASE IOC	Enable/Disable Option
	Pickup current level
	Operation time delay
GROUND IOC	Enable/Disable Option
	Pickup current level
	Operation time delay
Autoreclosing Logic	Enable/Disable Option
	Operation time delay

3.5.2 Output Data Specification

Output data of DPRA application are contained in the analysis report. The report includes four information sections, which are relay information, fault information, summary of protection operation, and diagnosis information respectively. Relay information includes relay ID, protected line ID, associated circuit breaker ID, oscillography starting time, and oscillography ending time. Figure 3.24 shows an example of the relay information section of an analysis report. Fault information includes fault type, fault location, fault inception time, and fault disappearance time. Figure 3.25 shows an example of the fault information section of an analysis report. Summary of protection operation lists the expected operation and the actual operation. Figure 3.26 shows an example of the summary of protection operation section of an analysis report. Diagnosis information gives detailed diagnosis results in the way of cause-effect chaining. Figure 3.27 shows an example of the diagnosis information section of an analysis report. In this section, several symbols are used to denote the cause-effect relation. The sentence immediately behind "←" is the cause for the effect sentence immediately before this "←". "**" and "****" mean that there are one or more cause sentences for one effect sentence.

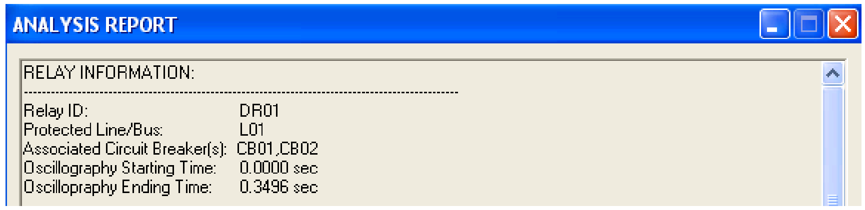


Figure 3.24 An example of the relay information section of an analysis report

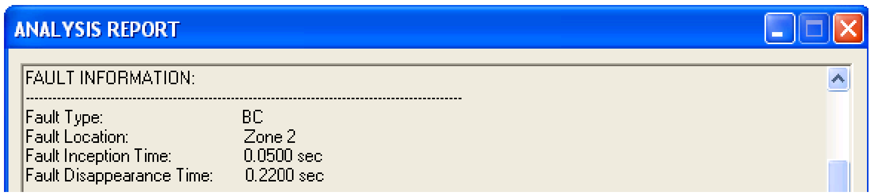


Figure 3.25 An example of the fault information section of an analysis report

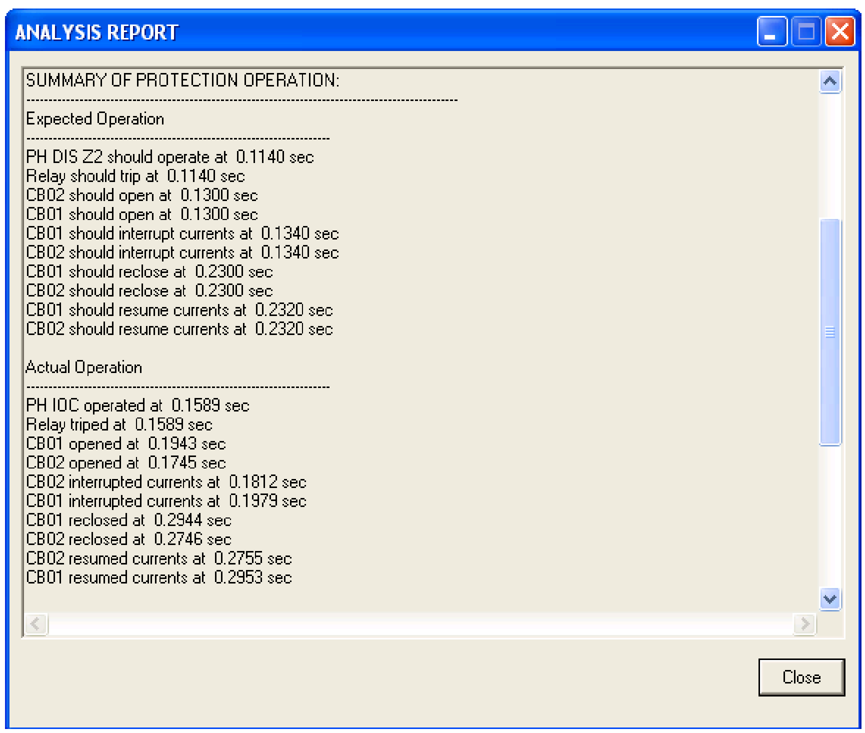


Figure 3.26 An example of the summary of protection operation section of an analysis report

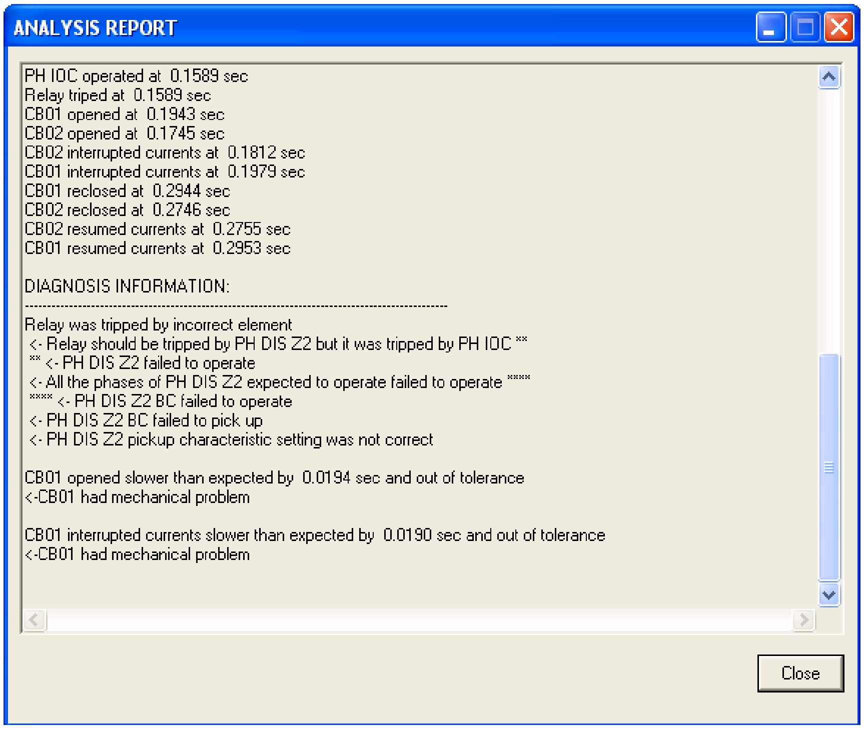


Figure 3.27 An example of the diagnosis information section of an analysis report

3.5.3 Design of Knowledge Base

Conceptual strategy of analysis

Validation and diagnosis of relay operation is fundamentally based on comparison of expected and actual relay behaviors in terms of the status and timing of logic operands. If the expected and actual status and timing of an operand is consistent, the correctness of the status and timing of that operand is validated. If not, certain failure or misoperation is identified and diagnosis will be initiated to trace the reasons by logic and cause-effect chain.

Figure 3.28 illustrates the conceptual strategy of validation and diagnosis of relay operation. The expected behaviors of the relay are predicted by an expect system module call Relay Operation Logic which simulates the relay operation logic. Inputs to this module are disturbance information, relay settings and performance specification. The expected status and timing of each active operand of the relay are inferred by forward chaining rules. The results are regarded as hypothesis of relay behaviors. The actual status and timing of relay operands which are obtained from the event record report and the COMTRADE file are regarded as facts of relay behaviors. With both the hypothesis and facts of relay behaviors as inputs, an expert system module called Validation and Diagnosis performs validation based on hypothesis-fact matching and diagnosis based on logic and cause-effect chain.

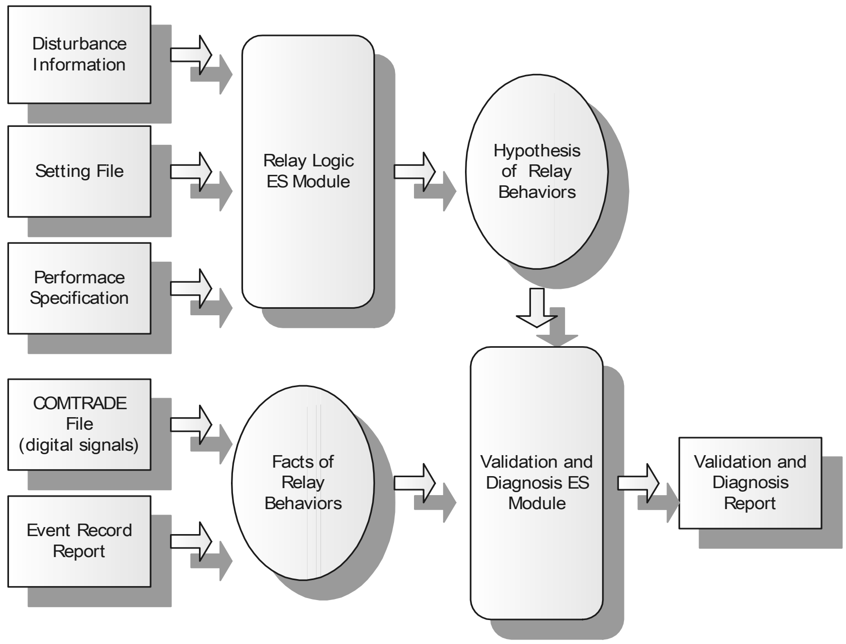


Figure 3.28 Conceptual strategy of validation and diagnosis of relay operation

Rules of knowledge base

The knowledge base for validation and diagnosis of relay operation includes two parts: rules for Relay Operation Logic Module and rules for Validation and Diagnosis Module.

A) Rules for relay operation logic

The rules for relay operation logic are developed at five levels: operation of individual phases of an element, operation of an element, relay trip and circuit breaker opening and current interruption by circuit breaker. The reasoning is in a bottom-up manner, i.e., from operation of individual phases of an element to current interruption by circuit breaker, which is actually a forward chaining process. Figure 3.29 illustrates the rules for relay operation logic, which only details the logic for GROUND DIS Element. Operation logic for other elements is quite similar. The time delay parameters such as dT_{SUPN}, $dT_{PKP\_P\_Z}$, $dT_{OP\_P\_Z}$, which are used to infer the timing relations, are obtained from relay performance specification and relay settings.

B) Rules for validation and diagnosis of relay operation

The rules for validation and diagnosis of relay operation can be divided into three parts according to their functions including validation and diagnosis of status of operands, evaluation of operating speed of protection elements and associated circuit breaker and examining whether the relay is tripped by the expected element.

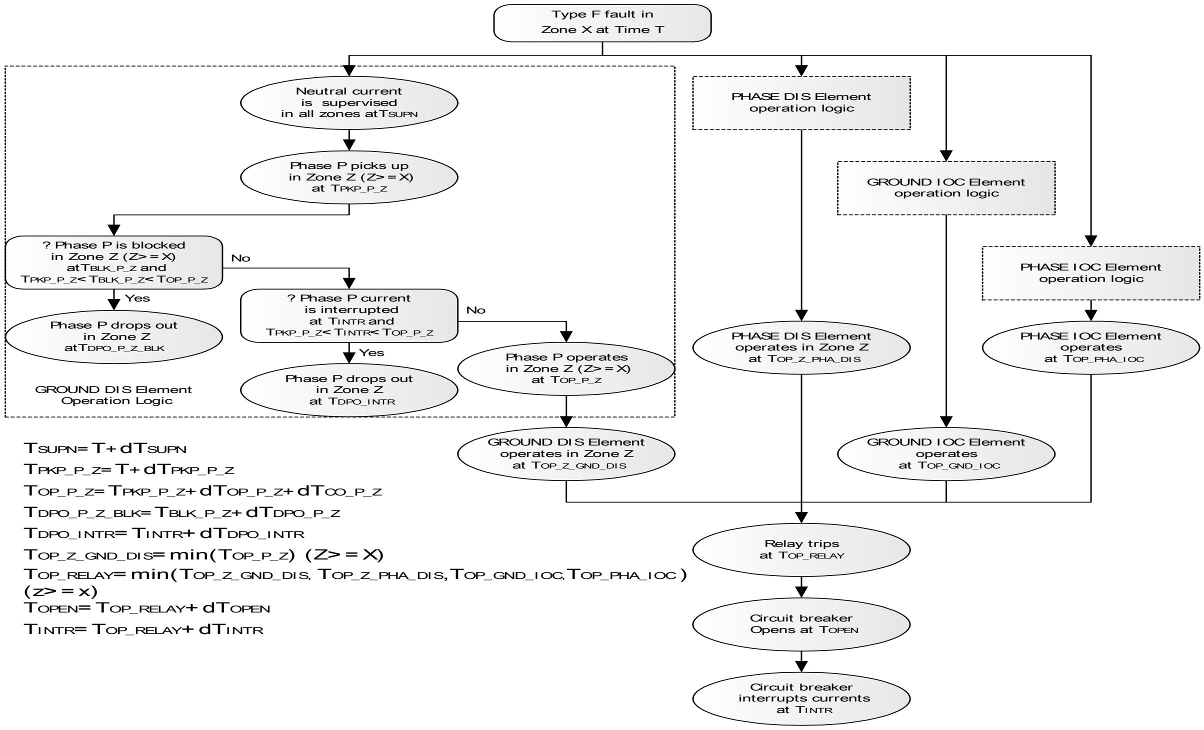


Figure 3.29 Rules for relay operation logic

Validation and diagnosis of status of operands is performed in two stages. Figure 3.30 illustrates the rules. In the first stage, the validation of correctness of status of operands and diagnosis of the direct reason for incorrectness of status of operands is performed at all of the five levels. In the second stage, the final reasons for symptoms identified in the first stage will be traced in top-down manner by relating together the direct reasons for symptoms found in the first stage, which is a backward reasoning process.

The operating speed of protection elements and associated circuit breaker is evaluated by examining the timing of status of logic operands. Figure 3.31 illustrates the rules for evaluating the operating speed of protection elements. The rules for evaluating the operating speed of the circuit breaker are similar.

With the validation and diagnosis information of status of operands and operating speed of protection elements available, whether the relay is tripped by the expected element is examined and the diagnosis is performed. Figure 3.32 illustrates the rules.

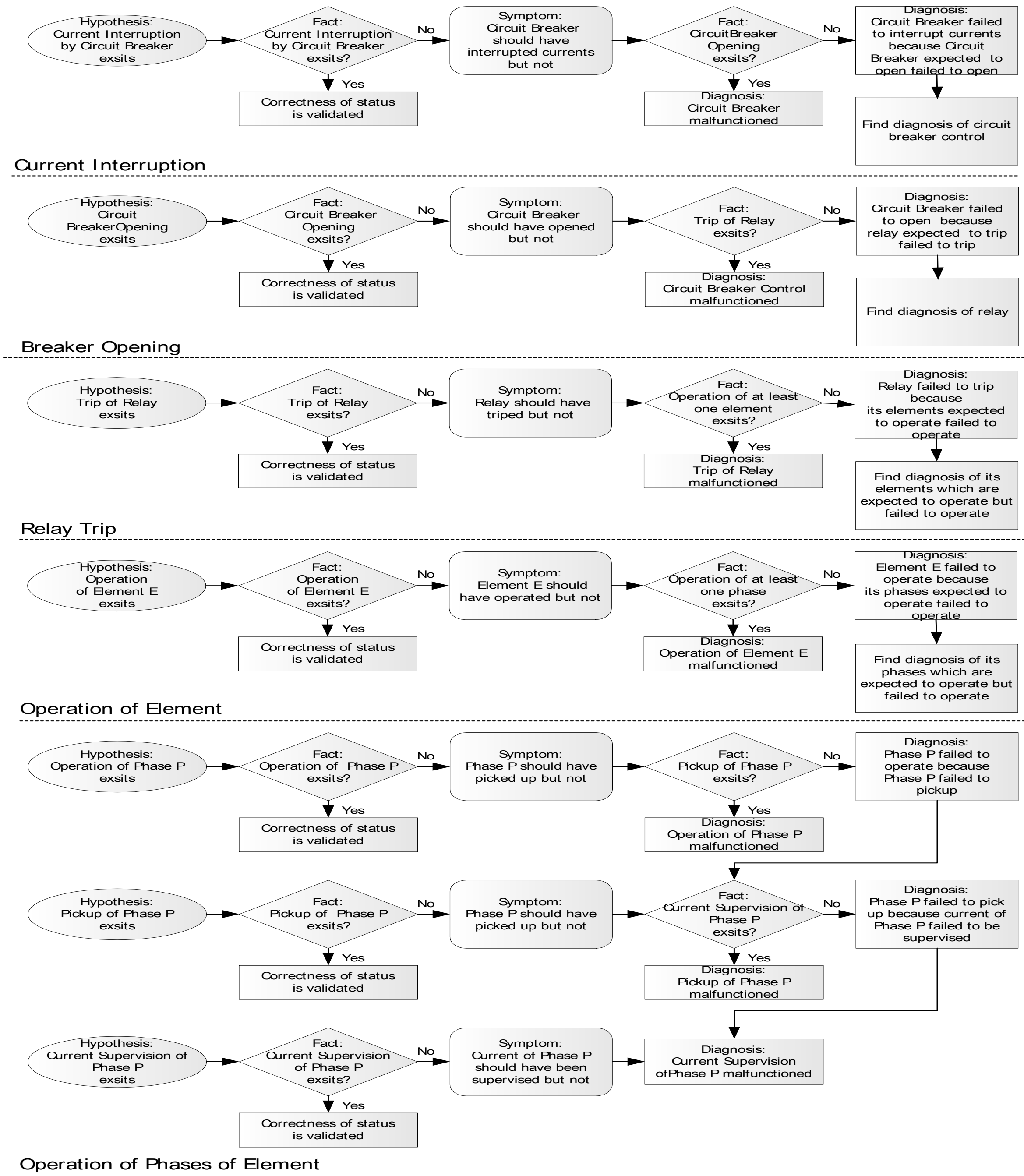


Figure 3.30 Rules for validation and diagnosis of status of logic operands

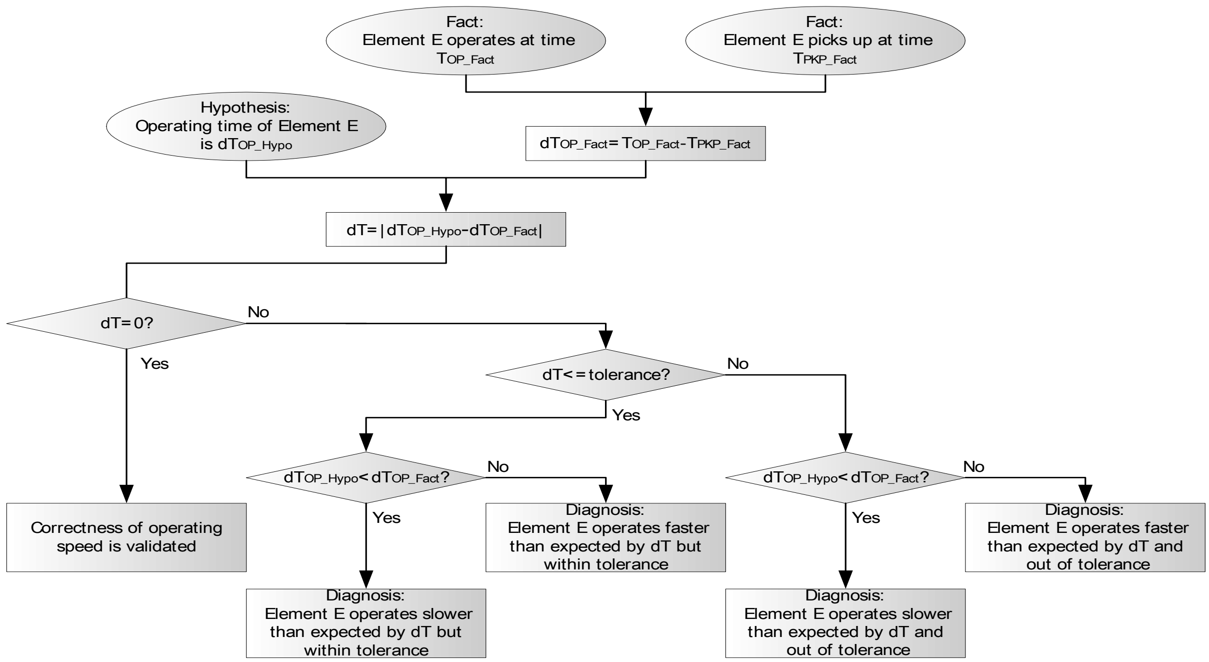


Figure 3.31 Rules for evaluation of operating speed of protection elements

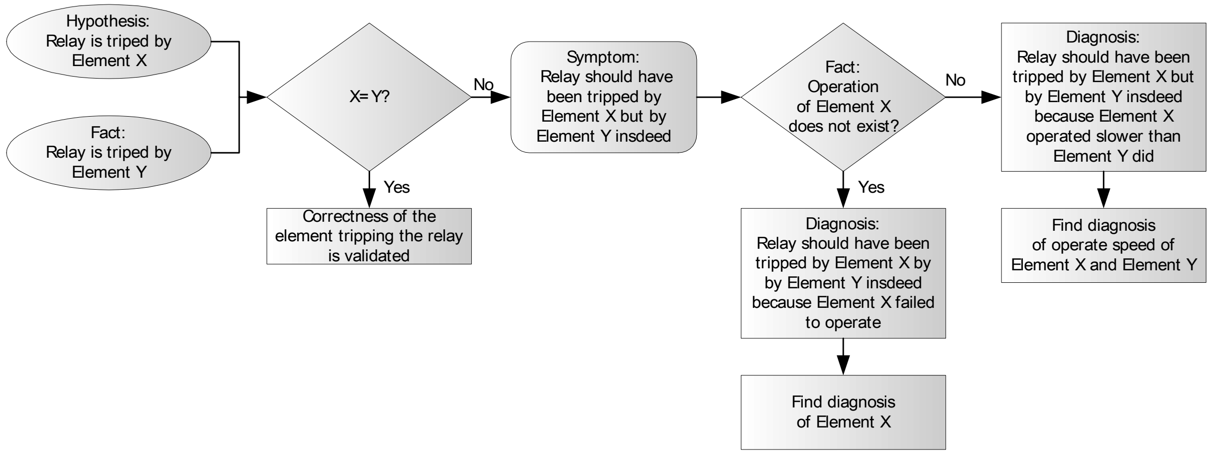


Figure 3.32 Rules for validation and diagnosis of the element tripping the relay

3.6 Conclusion

This section of the document described the functions of the integrated graphical user interface supporting the substation data analysis and verification applications, as well as functional requirements and implementation details of the three analysis and verification applications.

4. Testing

4.1 Summary of Demonstration Cases

In order to verify correctness of implemented algorithms and operation of the overall software solution, several test cases have been implemented and tested. In below, brief overview of the test cases is given. More details about each case can be found in the Appendices section.

4.2 Data Simulation

In this project, ATP is used as a simulation tool. Data Simulation software module utilizes ATP and provides all applications with transient analog and digital data. Its main task is to create correct ATP simulations according to user-defined switching sequence scenario, faults and circuit breaker failure possibilities.

4.2.1 Input Data Specification

Data simulation requires the following input data files:

- Substation data model – contained in an ATP format file (TEMPLATE.ATP)
- Topology and events – contained in an ASCII textual file, created by the GUI application (INFO.TXT).

Substation data mode

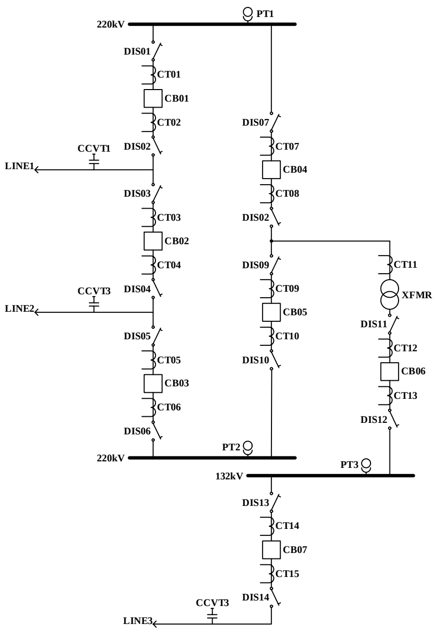
In order to start the data simulation, first a substation data model compatible with the ATP software requirements needs to be created using ATPs graphic tool ATPDraw.

The demonstration substation consists of three buses, three transmission lines, one transformer, seven circuit breakers, fourteen disconnecting isolators, fifteen current transformers, and six voltage transformers. Two voltage levels are involved: 220kV and 132kV. Figure below shows the one-line diagram of the demonstration substation, its corresponding template ATP model and layout of devices.

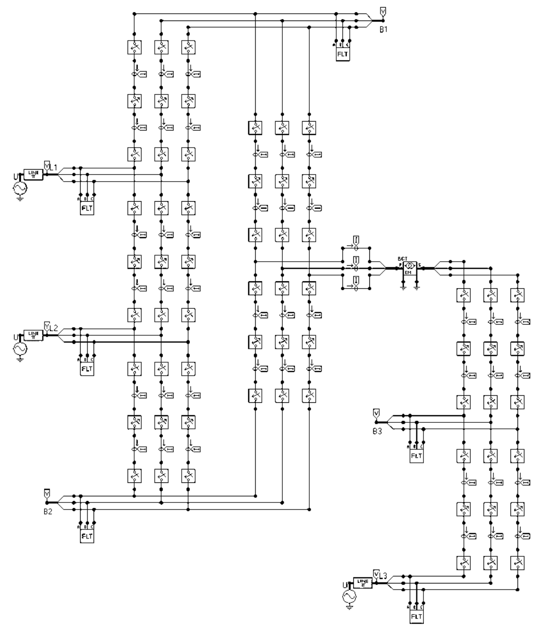
The template ATP model was created using ATPDraw 3.5 to reflect the steady state substation statuses (without faults or switching operations). Several custom group model symbols are used to make the model more compact in appearance. These symbols and their structures are shown in Table 4-2.

Table 4-1 Overview of test scenarios

Scenario 1 Incorrect current measurement by multiple CTs mixed with incorrect CB status reporting The VSDB successfully detected and corrected CB01A status random errors, detected absolute error in CT01A measured current and detected the absolute errors in CT05B, CT06B measured currents
Scenario 2 Disconnecting the transformer for maintenance CB04, CB05 and CB06 had to open to disconnect the transformer. Due to breaker operation error, all breakers except CB06, have opened correctly. CB06 had a failure and did not follow the operator command. The report identified CB06 as a failed CB.
Scenario 3 Permanent fault with reclosing logic error A permanent AB fault occurred on Line 1 and was successfully cleared by CB01 and CB02. The reclosing relay reclosed the breakers but failed to reopen, because of a fault in the reclosing logic. The verification report showed errors in the switching sequence.
Scenario 4 Incorrect setting of a phase distance element and slow opening of a circuit breaker A temporary fault occurred on Line 1. The fault was in Zone 2 of Relay DR01. The Phase Distance Zone 2 Element failed to pick up due to incorrect characteristic setting. Consequently, the Phase IOC Element instead of Phase Distance Zone 2 Element operated to make the relay trip. In addition, Circuit Breaker CB01 opened slower than expected because of mechanical problems. DPRA application reported two errors and identifies the reasons.
Scenario 5 Permanent fault with fault detection error of autoreclosing logic A permanent fault occurred on Line 1. Relay DR01 tripped Circuit Breakers CB01 and CB02. Then the relay reclosed the two breakers but failed to reopen them, due to incorrect fault detection function of the autoreclosing logic. DPRA application reported the error and identified the reason



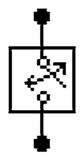
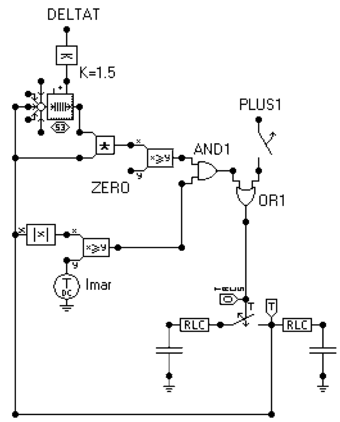
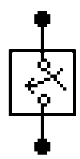
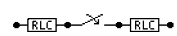
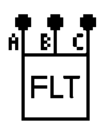
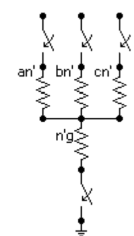
(a) One-line Diagram



(b) ATP Model

Figure 4.1 Demonstration Substation Model

Table 4-2 Custom ATP group models

Symbol	Meaning	Diagram
	Circuit breaker	
	Disconnecting Isolator	
	Phase-to-Ground or Phase-to-Phase Fault	

Topology and events

The topology and events descriptions are contained in file INFO.TXT created by user interface application.

INFO.TXT consists of 5 sections:

- Topology and Switch Initial Statuses. This section defines name, type of each device, its from/to nodes in the ATP model, initial status, corresponding current transformers, backup circuit breakers, and failure possibilities.
- Fault Models. This section defines the times and types of fault occurrences and value of fault resistances.
- Switching Sequences. This section contains the switching sequence of switches, including their names and operation times.

- Simulation Parameters. This section consists of several simulation parameters needed for the ATP program and the PL4 to COMTRADE file conversion.
- DFR Configuration. This section points to another DFR configuration file which defines the channel allocations of the virtual DFR device. A DFR file will be simulated accordingly.

4.2.2 Output Data Specification

The output data of the Data Simulation software module are the analog and digital signals measured by the current/voltage transformers and contact signal probes in the ATP model. The output data file(s) can be in either PL4 format or COMTRADE format. These output files are named using the IEEE File Naming Convention. An example of the output file name is illustrated in Figure 4.2 below.

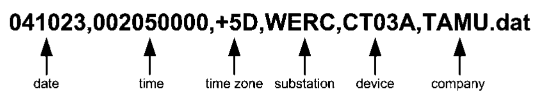


Figure 4.2 An example of a COMTRADE filename

The program is also capable of converting a single PL4 file into a group of COMTRADE files, with each COMTRADE file reflecting a single measurement device. These COMTRADE files are then assigned by the GUI to different devices for displaying purposes.

4.2.3 Data Flow

Figure 4.3 shows the software structure of the Data Simulation software module. Data simulation consists of following steps:

1. Before data simulation, two files need to be prepared – the Sequence/Topology Information File, and the Template ATP File.
2. These two files are then passed to the ATP File Generator as input parameters to create an ATP file that corresponds to a certain substation switching sequence.
3. The resulted ATP file can now be simulated using the ATP program.
4. The data simulation results are stored in a PL4 file, which is created by the ATP program.

The PL4 file can then be converted to a single pair of COMTRADE files (.CFG, .DAT) or a group of COMTRADE files with each device having one pair of files.

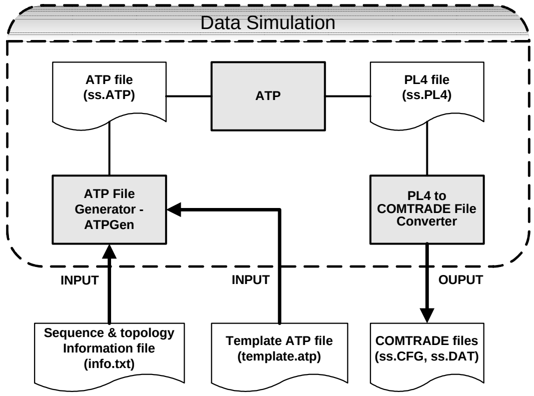


Figure 4.3 Data simulation software structure

4.3 Relay Model Description

A multifunctional digital relay model is developed to serve as the data source for the DPRA application and other individual applications. Table below lists the main features of the relay model.

Table 4-3 Main features of the relay model

Requirements	Features
Components	• analog filter • A/D converter • implementation of signal processing and protection algorithms
Interface	• up to 4 channels of node voltages inputs and 8 channels of branch currents inputs • up to 2 channels of breaker status contact inputs • up to 2 channels of pilot signal inputs • up to 6 channels of trip signal outputs • up to 2 channels of pilot signal outputs
Protection Functions	• phase distance • ground distance • phase instantaneous over-current • ground instantaneous over-current • autoreclosing
Others	• user-defined error insertion • setting file reading • generation of oscillography files, fault reports and event reports

The relay model is developed using MODELS language of ATP and C++ language, based on the “compiled foreign model” mechanism of MODELS language of ATP. The interface to power system network model, the analog signal filtering, and the A/D conversion is implemented in the MODELS section, while all other functions of the relay model are implemented in the C++ "foreign model".

Interface to the power system network model

The inputs from the power system network model are three phase voltages measured at bus nodes, three phase currents measured through circuit breaker switches, and statuses of circuit breaker switches. The outputs to the power system network model are control variables of the control nodes of the circuit breaker switches. The names of these nodes and switches are declared in the INPUT and OUTPUT directives of the MODELS section. In the USE statement of the MODELS section, the inputs from and outputs to the power system network model are referred by the generic relay model. In the USE statement of the generic relay model, the inputs and outputs associated with a specific relay location are further referred by a "foreign model". In such a way, the interaction between the power system network model and the relay model associated with a specific location is realized.

Analog filtering

In the relay model, an analog second order Butterworth low-pass filter is employed. Such a filter can be represented by the Z-plane digital transfer function. It is realized by the Z-transform transfer function of MODELS language.

A/D conversion

The sample and hold circuit of A/D converters is realized by the TIMESTEP MIN: "time step" directive in the USE statement of the relay model. This actually performs the interpolation on the original simulation time-stamp at the rate of the specified time step.

Protection algorithms

All the protection algorithms are implemented in the C++ "foreign model". Fourier Transform is used to extract the fundamental frequency phasors for phase voltages and currents, line voltages and currents, and zero sequence currents. The phasors of phase currents and the phasors of zero sequence currents are used for comparison with the pickup thresholds of the Phase IOC Element and the Ground IOC Element respectively. The phasors for line voltages and currents are used to calculate the line impedances for comparison with the MHO characteristic of the Phase Distance Elements. The phasors for phase voltages and currents are used to calculate the phase impedances for comparison with the quadrilateral characteristic of the Ground Distance Elements. Timers are simulated to ensure the required time coordination between the pickup and the operation of protection elements.

Relay file generation

In the relay model, the analog signals of input voltages and currents, and digital signals representing current supervision, pickup and operation of protection elements are stored in the arrays for oscillography use. The status changes of digital signals are detected and used for event report generation. At the end of the simulation, the file I/O functions of

C++ are employed to generate the event report and the oscillography files in COMTRADE format.

4.4 Conclusions

In this chapter the testing of the Substation Automation software developed for the project was discussed. The brief list of the demo cases was given in the beginning. The description of data simulation procedure followed. The section ended with the description of the implementation of the relay model in MODELS and C++ language, used in the data simulation procedure.

5. Conclusion

This report demonstrated how substation operation may be improved by the use of real-time data recorded by substation IEDs. Several improvements are demonstrated as follows:

- **Measurement Redundancy**. The substation Intelligent Electronic devices (IEDs) quite often measure the same signals from the substation switchyard. If the signal samples are collected in the substation database, one can then use the redundant measurements to improve accuracy of the measured signals.
- **Cause-Effect Relationship**. Since several IEDs may be involved in tracking substation operation, having data from different IEDs integrated, it is possible to capture various stages of the operation. This enables one to establish a cause-effect relationship in the changes of the measured signals. The ability to track cause-effect relationships in a control sequence, such as clearing of a fault, enhances ability to determine any problems or deviations from the expected.
- **Time Series Analysis**. Being able to track IED measurements for longer periods of time and stored for future time series analysis allows implementation of function that will be able to tell if performance of a given function or piece of equipment is deteriorating. The ability to identify deteriorating performance and have a subsequent maintenance or design action that will restore the required performance, provides an improvement in the reliability of substation operation.

The implementation of various substation automation functions documented in this report illustrates all the mentioned benefits and allows future implementations to take advantage of the concepts and approaches discovered in the course of this study.

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Appendices

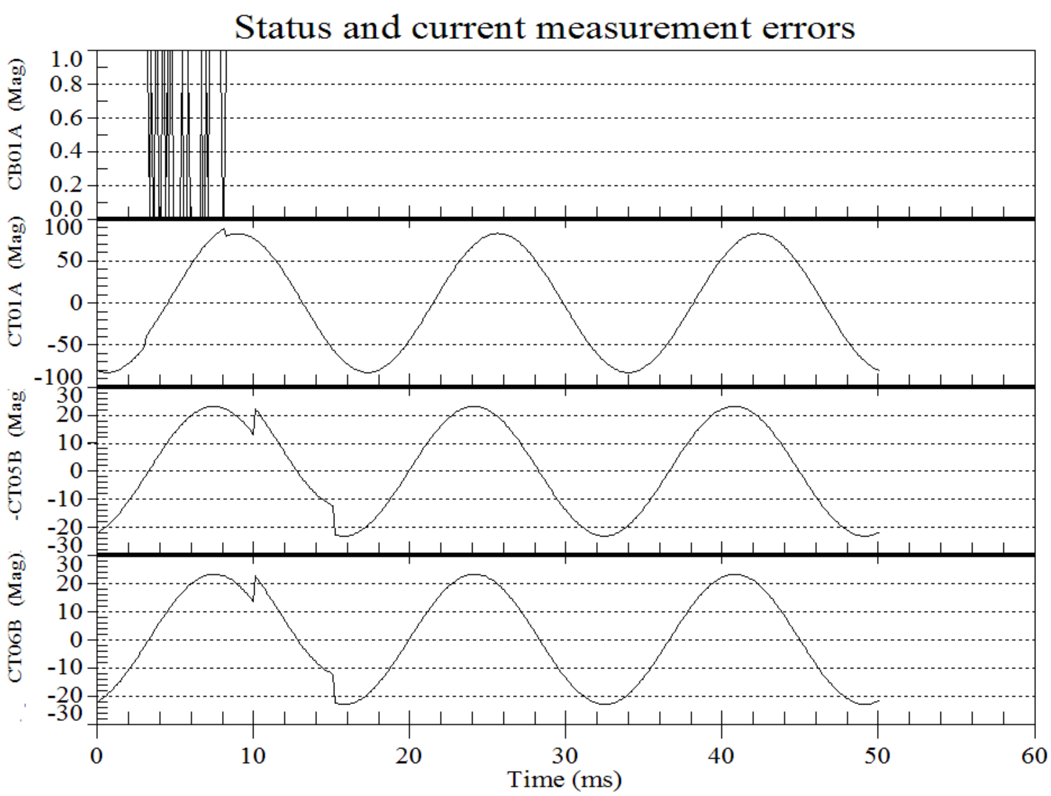
Appendix 1 Detailed Description of Demonstration Cases

Scenario 1 – Detection and correction of CB01A status random errors, detection of absolute error in CT01A measured current, detection of absolute errors in CT05B, CT06B measured currents

Errors

Device	Type
CB01A	Status measurement error
CT01A	Current measurement error
CT05B	Current measurement error
CT06B	Current measurement error

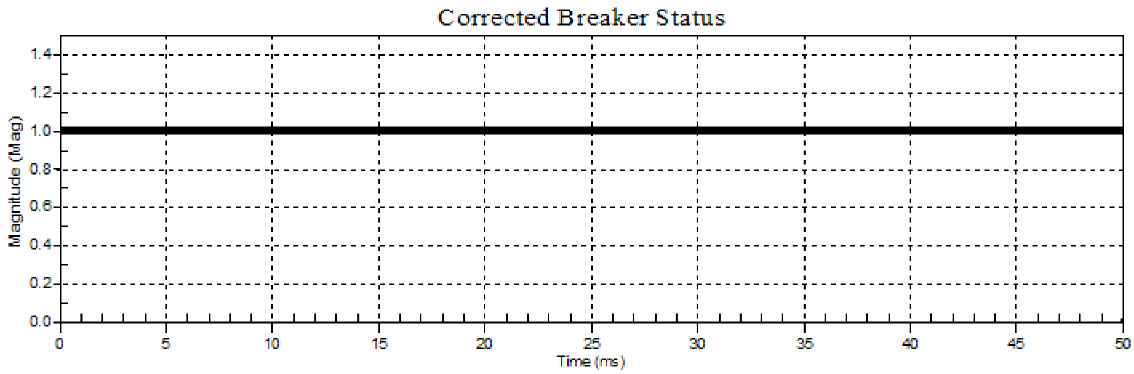
Waveforms



Reported output

Time[ms]	Device	Description
3-8	CB01A	Errors in status measurement detected and corrected by branch status check
3-8	CT01A	Errors in current measurement detected by double current measurement check
10-15ms	CT05B, CT06B	Errors in current measurement detected by KCL check

Waveforms



Scenario 2 Disconnecting the transformer for maintenance

In this scenario, CB04, CB05 and CB06 need to be open to disconnect the transformer. All breakers, except CB06, are opening correctly. CB06 has a failure and does not follow the operator command. The verification report identifies CB06 as a failed CB.

User defined switching events

Time[ms]	Location	Operation
100	CB04	open
110	CB05	open
120	CB06	open

Errors

Device	Type
CB06	Breaker fails to open when a tripping command is issued

Reported output

Time[ms]	Device	Description
120	CB06	Fails to open

Scenario 3 Permanent fault with reclosing logic error

In this scenario, a permanent AB fault occurs on Line 1 and is successfully cleared by CB01 and CB02. The reclosing relay recloses the breakers but fails to reopen them, because of a fault in the reclosing logic. The verification report shows errors in the switching sequence.

Fault events

Time[ms]	Type	Location
50	AB	LINE1

Errors

Device	Type
DR01	Reclosing logic error

Expected Protection Operation

Time[ms]	Device	Description
90	CB01, CB02	open
190	CB01, CB02	close
198	CB01, CB02	open

Reported output

Device	Description
CB01, CB02	Fail to reopen

Scenario 4 Incorrect setting of a phase distance element and slow opening of a circuit breaker

A temporary fault occurs on Line 1. The fault is in Zone 2 of Relay DR01. The Phase Distance Zone 2 Element fails to pick up due to incorrect characteristic setting. Consequently, it is Phase IOC Element instead of Phase Distance Zone 2 Element that operates to make the relay trip. In addition, Circuit Breaker CB01 opens slower than expected because of mechanical problems. DPRA application reports the two errors and identifies the reasons.

Fault events

Time[ms]	Type	Location
50.0	BC	L1 (Zone 2)
220.0	Cleared	L1

Major relay settings

Elements	Range (% of the line length)		Coordination Time Delay (Sec)
Phase Distance	Zone 1	75	0.008
	Zone 2	150	0.05
	Zone 3	230	1.0
Ground Distance	Zone 1	75	0.008
	Zone 2	150	0.05
	Zone 3	230	1.0
Phase IOC	N/A		0.1
Ground IOC	N/A		0.1
Autoreclosing	N/A		0.1

Errors

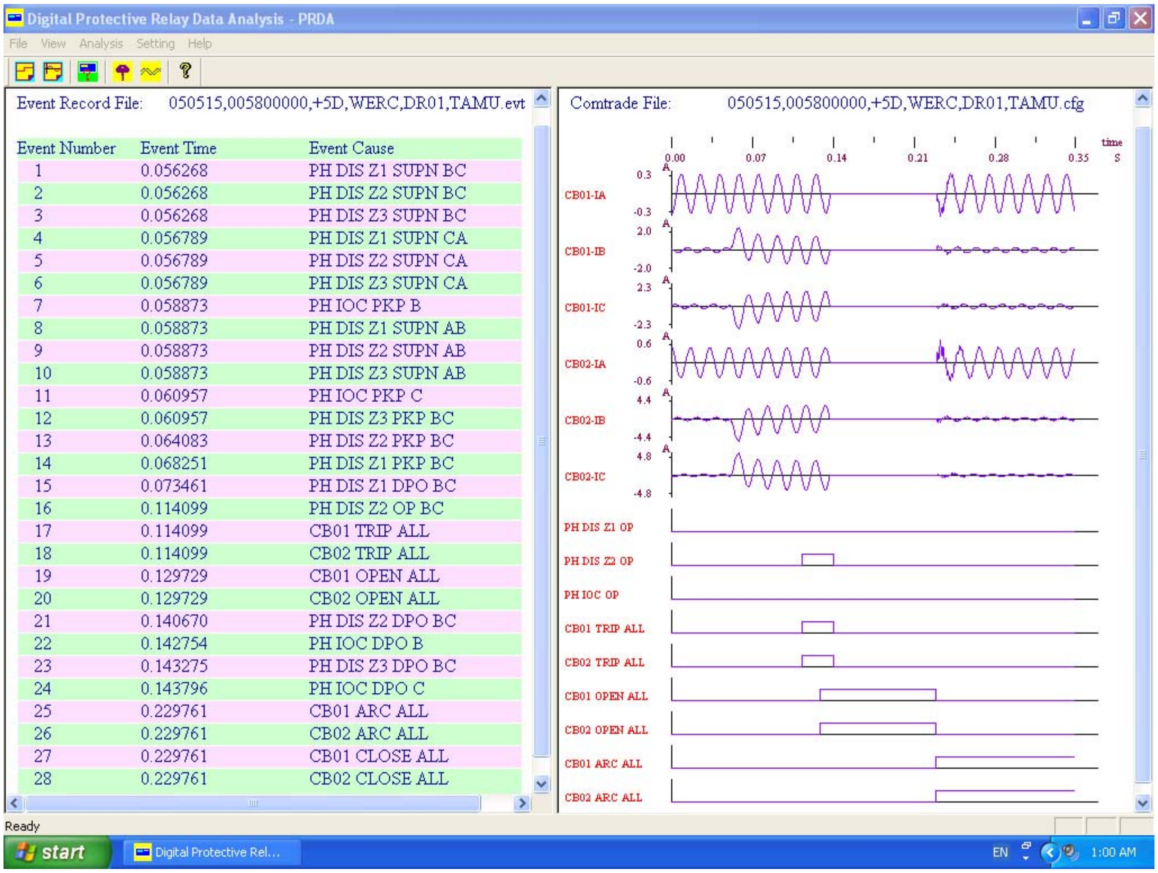
Device	Type
DR01	Incorrect setting of Phase Distance Zone 2 Element which causes failure of pickup of the element
CB01	Mechanical problem which causes slower opening of the circuit breaker

Expected Protection Operation

1) Events

Time[ms]	Device/Element	Description
114.0	Phase Distance Zone 2 Element of DR01	Operate
114.0	DR01	Trip
130.0	CB01, CB02	Open
230.0	CB01, CB02	Reclose

2) Event Report and Oscillography File

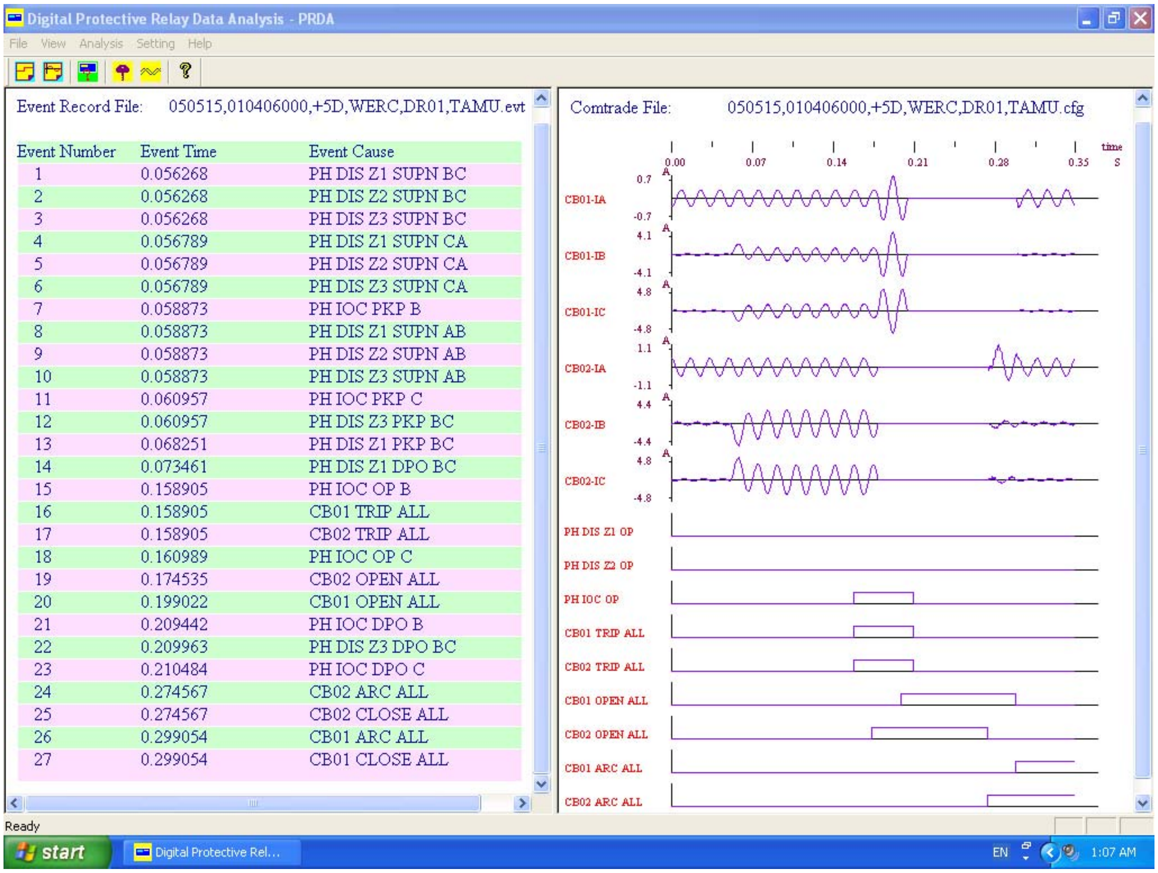


Reported output

1) Events

Time[ms]	Device/Element	Description
158.9	Phase IOC Element of DR01	Operate
158.9	DR01	Trip
174.5	CB02	Open
199.0	CB01	Open
274.6	CB02	Reclose
299.1	CB01	Reclose

2) Event Report and Oscillography File



Event Number	Event Time	Event Cause
1	0.056268	PH DIS Z1 SUPN BC
2	0.056268	PH DIS Z2 SUPN BC
3	0.056268	PH DIS Z3 SUPN BC
4	0.056789	PH DIS Z1 SUPN CA
5	0.056789	PH DIS Z2 SUPN CA
6	0.056789	PH DIS Z3 SUPN CA
7	0.058873	PH IOC PKP B
8	0.058873	PH DIS Z1 SUPN AB
9	0.058873	PH DIS Z2 SUPN AB
10	0.058873	PH DIS Z3 SUPN AB
11	0.060957	PH IOC PKP C
12	0.060957	PH DIS Z3 PKP BC
13	0.068251	PH DIS Z1 PKP BC
14	0.073461	PH DIS Z1 DPO BC
15	0.158905	PH IOC OP B
16	0.158905	CB01 TRIP ALL
17	0.158905	CB02 TRIP ALL
18	0.160989	PH IOC OP C
19	0.174535	CB02 OPEN ALL
20	0.199022	CB01 OPEN ALL
21	0.209442	PH IOC DPO B
22	0.209963	PH DIS Z3 DPO BC
23	0.210484	PH IOC DPO C
24	0.274567	CB02 ARC ALL
25	0.274567	CB02 CLOSE ALL
26	0.299054	CB01 ARC ALL
27	0.299054	CB01 CLOSE ALL

3) Diagnosis Information

- Relay trip was issued by incorrect element
  <- Relay trip should have been issued by PH DIS Z2 but it was issued by PH IOC
  <- PH DIS Z2 BC failed to pick up
  <- PH DIS Z2 pickup setting was not correct

- CB01 opened slower than expected and out of tolerance
  <-CB01 had mechanical problem

- CB01 interrupted currents slower than expected and out of tolerance
  <-CB01 had mechanical problem

Scenario 5 Permanent fault with fault detection error of autoreclosing logic

A permanent fault occurs on Line 1. Relay DR01 trips Circuit Breakers CB01 and CB02. Then the relay recloses the two breakers but fails to reopen them, due to incorrect fault detection function of the autoreclosing logic. DPRA application reports the error and identifies the reason.

Fault events

Time[ms]	Type	Location
50	AB	L1 (Zone 1)

Major Relay Settings

Elements	Range (% of the line length)		Coordination Time Delay (Sec)
Phase Distance	Zone 1	75	0.008
	Zone 2	150	0.05
	Zone 3	230	1.0
Ground Distance	Zone 1	75	0.008
	Zone 2	150	0.05
	Zone 3	230	1.0
Phase IOC	N/A		0.1
Ground IOC	N/A		0.1
Autoreclosing	N/A		0.1

Errors

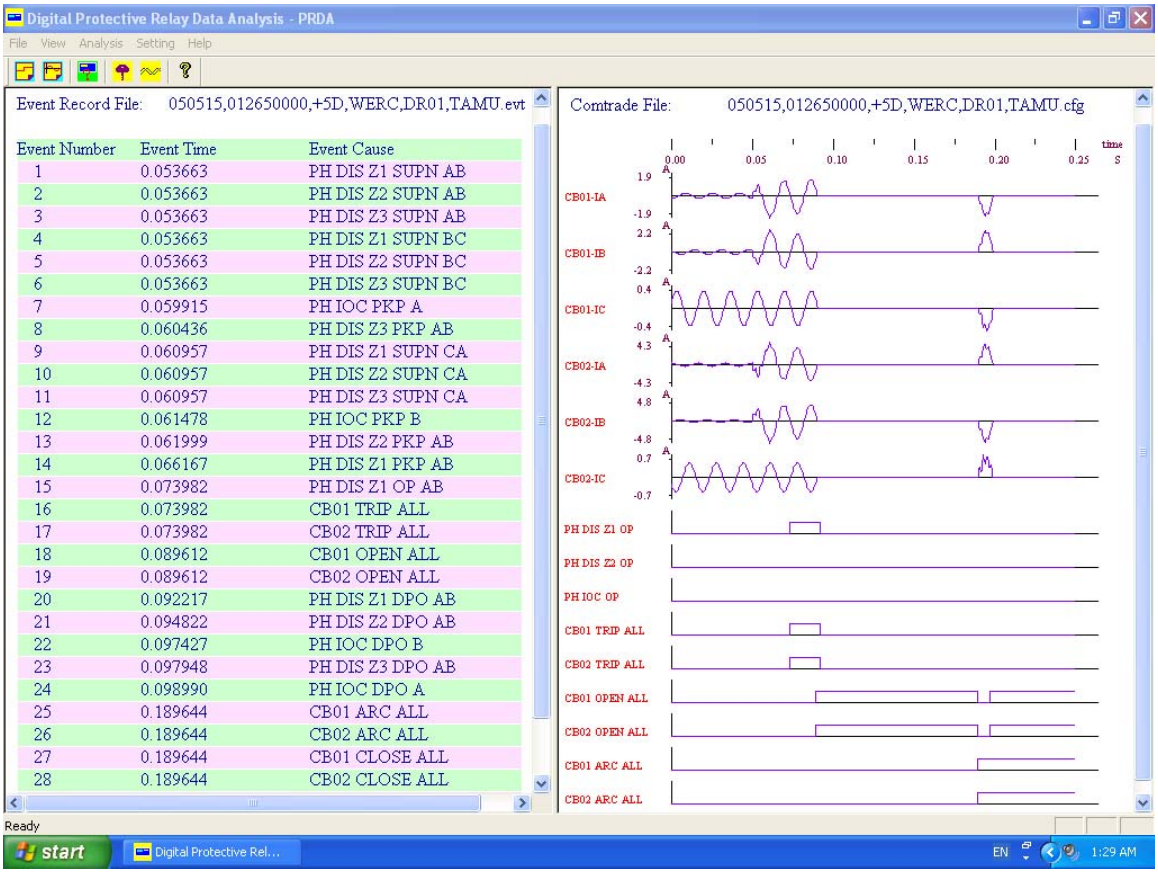
Device	Type
DR01	Incorrect fault detection function of autoreclosing logic

Expected Protection Operation

1) Events

Time[ms]	Device/Element	Description
74.0	Phase Distance Zone 2 Element of DR01	Operate
74.0	DR01	Trip
90.0	CB01, CB02	Open
190.0	CB01, CB02	Reclose
198.0	CB01, CB02	Reopen

2) Event Report and Oscillography File

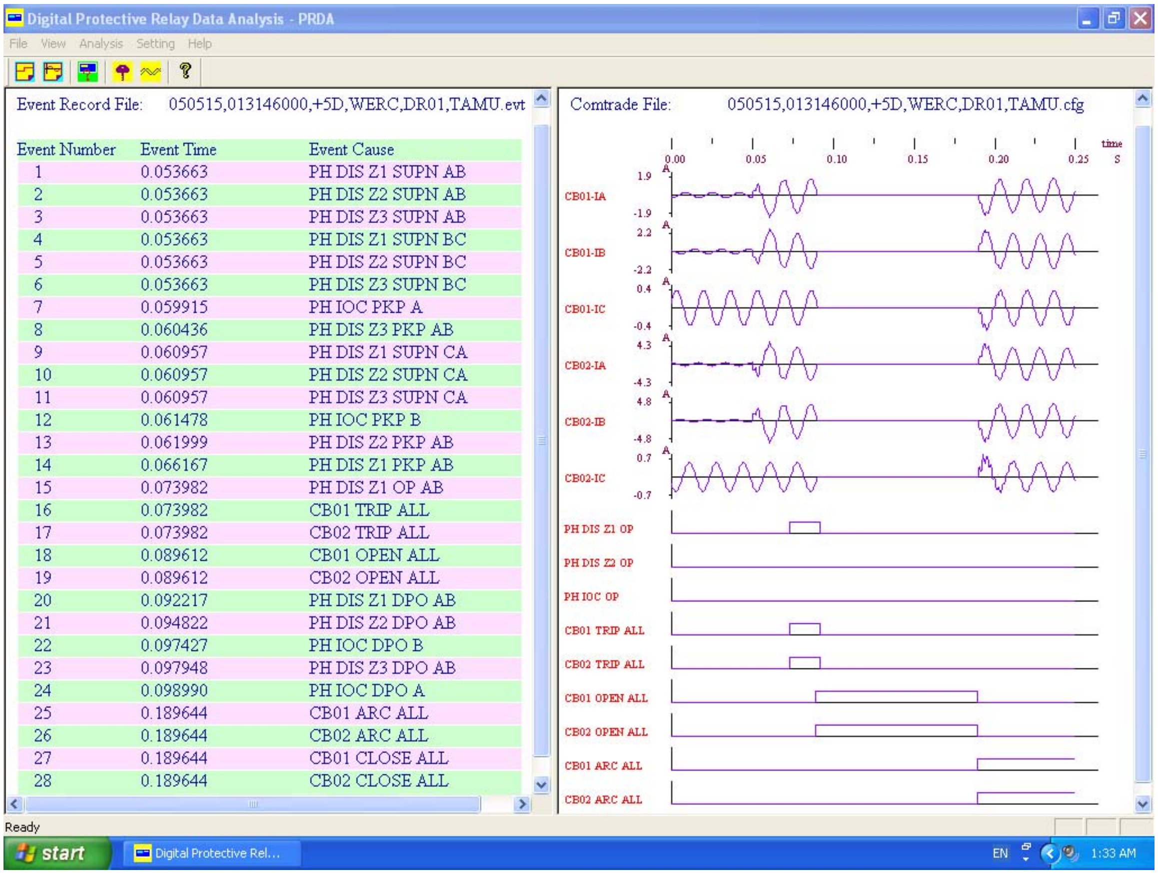


Reported output

1) Events

Time[ms]	Device/Element	Description
74.0	Phase Distance Zone 1 Element of DR01	Operate
74.0	DR01	Trip
89.6	CB01, CB02	Open
189.6	CB01, CB02	Reclose
190.6	CB01, CB02	Resume currents

2) Event Report and Oscillography File



Event Number	Event Time	Event Cause
1	0.053663	PH DIS Z1 SUPN AB
2	0.053663	PH DIS Z2 SUPN AB
3	0.053663	PH DIS Z3 SUPN AB
4	0.053663	PH DIS Z1 SUPN BC
5	0.053663	PH DIS Z2 SUPN BC
6	0.053663	PH DIS Z3 SUPN BC
7	0.059915	PH IOC PKP A
8	0.060436	PH DIS Z3 PKP AB
9	0.060957	PH DIS Z1 SUPN CA
10	0.060957	PH DIS Z2 SUPN CA
11	0.060957	PH DIS Z3 SUPN CA
12	0.061478	PH IOC PKP B
13	0.061999	PH DIS Z2 PKP AB
14	0.066167	PH DIS Z1 PKP AB
15	0.073982	PH DIS Z1 OP AB
16	0.073982	CB01 TRIP ALL
17	0.073982	CB02 TRIP ALL
18	0.089612	CB01 OPEN ALL
19	0.089612	CB02 OPEN ALL
20	0.092217	PH DIS Z1 DPO AB
21	0.094822	PH DIS Z2 DPO AB
22	0.097427	PH IOC DPO B
23	0.097948	PH DIS Z3 DPO AB
24	0.098990	PH IOC DPO A
25	0.189644	CB01 ARC ALL
26	0.189644	CB02 ARC ALL
27	0.189644	CB01 CLOSE ALL
28	0.189644	CB02 CLOSE ALL

3) Diagnosis Information

- CB01 failed to reopen after reclosing onto fault
  <- fault detection function of autoreclosing logic was not correct

- CB02 failed to reopen after reclosing onto fault
  <- fault detection function of autoreclosing logic was not correct