Optimized Fault Location

Final Project Report

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Optimized Fault Location

**Concurrent Technologies Corporation
Final Project Report**

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Executive Summary

Currently large amounts of data are collected by Intelligent Electronic Devices (IEDs) at the substation level. Beyond the traditional Supervisory Control and Data Acquisition (SCADA) data collected by Remote Terminal Units (RTUs), very little of other IED data is integrated into current Energy Management System (EMS) solutions. The goal of the project is to investigate the potential benefits of integrating information obtained from the substation IED data, beyond what is obtained from RTU data, into the EMS.

This report describes development of the software aimed at automated fault location analysis and visualization. This application is an example of how IED and EMS data may be integrated to provide the best results. The report first presents the existing procedure for fault location and defines problem that should be solved. Then it outlines the new approach and points out how new development improves existing approach. The report then gives a detailed description of the architecture used in the new approach, and, finally, it demonstrates realized features and explains future steps.

A complete system for automated fault location (FL) analysis including visualization of results and behavior of equipment is developed. This system automatically retrieves recordings from multiple types of IEDs and using intelligent software executes appropriate automated analysis. In addition, PI Historian SCADA data is utilized as needed to identify the power system switching state prior and after the fault. This document gives the summary of developments and achievements in the 1st year of the project activity. The solution using IED data and related automated processing, combined with selected SCADA data, offers two major benefits: the fault location accuracy is significantly improved, and the response time of system restoration is significantly reduced.

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Part 1: Background Information

1.1. Introduction

Basic goal of the power system is to continuously provide electrical energy to users. Like with any other system, failures in power system can occur. In those situations it is critical that remedial actions are applied as soon as possible. To apply correct remedial actions it is important that accurate fault condition and location are detected. The protection system is a part of the control system responsible for fault detection and execution of automated remedial actions. When fault appears in power system different events are triggered. Protection equipment consisting of protection relays and circuit breakers (CBs) will operate in order to de-energize the faulted line. Different Intelligent Electronic Devices (IEDs) located in substations will be automatically triggered by the fault and will record corresponding current, voltage and status signals. Those records are later used by different user groups for fault investigation. Changes in the switching equipment status will automatically be seen in the control center by operator who will make a note of the fault event and inform other users like protection group or maintenance. Depending on the means for uploading the data, retrieving row data from monitoring devices can last from few minutes to few days. Frequently a lot of time is spent while one group is waiting for the input from the other group.

In general, faults can appear due to bad whether conditions, equipment damage, equipment failure, environment changes and many other reasons. Depending on the Fault Location (FL) and nature of the fault, completely different techniques and tools may be used for repairing faulted condition.

1.2. Existing Procedure for Fault Location

When fault appears, protection equipment reacts and initiates CBs that in turn operate and de-energize faulted part. This must be done before excessive currents and voltages last long enough to cause equipment damage. CBs have the purpose to connect or disconnect different parts of the power system in order to isolate the faults and/or re-route the power flow. When there is a fault on an element in the power system, it is necessary to open all circuits supplying the fault current very fast. In order to open all circuits that supply the fault current, more than one circuit breaker typically needs to be operated. Various bus-bar arrangements are used to minimize the number of circuits that must be opened in a case of a fault [1]. Depending on a bus arrangement and status of breakers, different breakers are opened in case of different faults. After some time control of each CB involved in fault clearing event assumes that fault is cleared and it will try to reclose the CB automatically. Typical sequences occurring because of a fault present somewhere on a transmission line is shown on Fig 1.1.

Process of reclosing can be repeated a couple of times and it is initiated in order to determine whether fault, which caused opening of breaker, is still present. In the case that fault is present after a reclosing, breaker will wait for the time out to pass and initiate reclosing again. If after selected number of attempts of reclosing fault is still present, breaker lockout is taking place. There will be no more attempts to reclose automatically the breaker again. The length of sequences and time outs depend not only on the type of the breaker, but also on the location of the CB and the reclosing scheme used.

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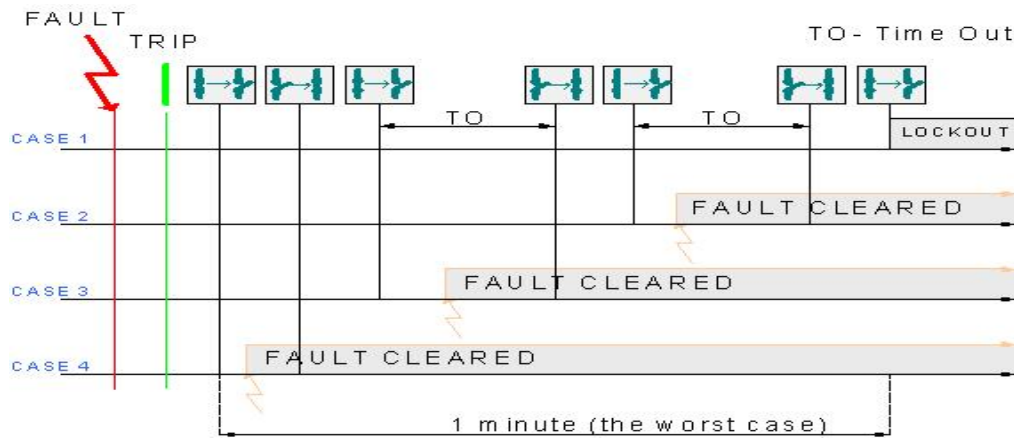
Figure 1.1: Trip and reclose sequences on a single breaker

In case of breaker lockout the assumption taken by the operators is that fault is permanent. From above, two types of faults are recognized: a) temporary and b) permanent. Each of these faults will initiate different actions among utility personnel.

a) In the case of a **temporary fault**, operator will notice CB status change on the corresponding one line diagram. This information is tracked through the SCADA system. Sequence of openings and reclosings of group of CBs will end with CBs that were involved in the switching case being restored. All the equipment actions are executed automatically and fault is cleared. In this case there is no need for operator action, but occurrence of the event is recorded and archived.

b) In the case of a **permanent fault**, operator will notice CB status change on the corresponding one line diagram. Sequence of openings and reclosings of a group of CBs will end with CBs that were involved in clearing the fault staying open. Automatic fault clearing has disconnected faulted part from the rest of the system, and further attempts to automatically restore the system to the original healthy state are not taken. This is called LOCKOUT. Disconnected part must be restored manually. Corresponding actions initiated with this event are shown on Fig.1.2.

There are few features of the existing approach that should be evaluated a) data availability, b) response time and decision quality and c) personnel productivity.
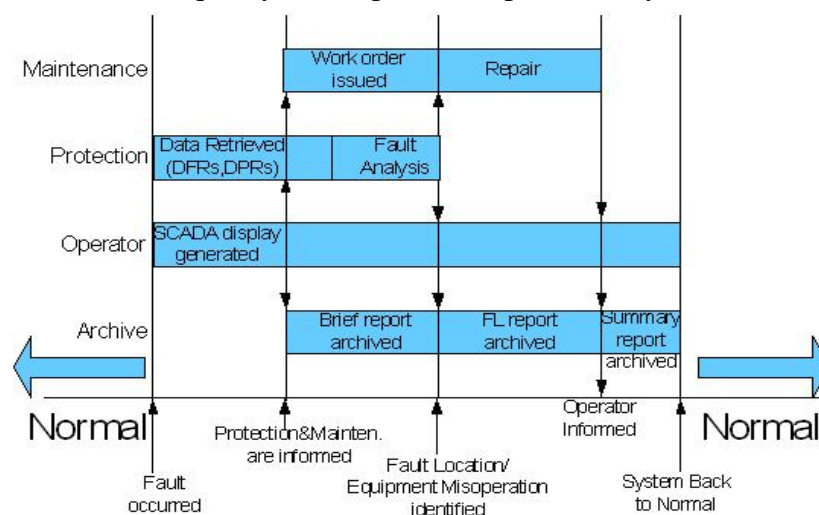
Figure 1.2: Timeline of utility personnel actions in case of permanent fault

1.2.1. Data availability

It should be noticed that different data and information are available to different utility groups. Operators have access to SCADA data all the time. Protection group has to retrieve fault recordings from IEDs located in substations in order to do fault analysis. Protection group does not have SCADA information readily available. Maintenance is informed by the operator that a permanent fault is present, but they cannot take actions before they get FL estimation from the protection group. Maintenance typically does not have access to other data sources beside the archived data.

1.2.2. Response time and decision quality

Depending on correctness of available data and information entered by different user groups, fault can be cleared in varying time intervals. For operator it is very important to have as fast response from other groups about fault event as possible in order to know when faulted line can be restored. In case of protection group, if they need measurements from different substations to figure out fault location, actions of other groups have to be delayed until protection staff gets the required data and makes conclusions. If estimated FL is not correct maintenance crew will have to patrol the line longer until they find the fault through visual inspection.

1.2.3. Personnel productivity

Separation of available data by different utility groups leads to a lot of waiting because the groups depend on each other when making final decisions. In case that there are more fault events occurring as a result of a bad storm, protection group may be burdened by analysis of multiple events. They have to retrieve measurements, sort them according to corresponding fault event, process them and bring correct conclusions about actions that should be taken. Maintenance crew is alarmed when fault event is present but is not capable of knowing where exactly to go before protection group identifies fault location.

1.3. Problem Definition

Once fault is present in the system there are few requirements that should be satisfied:
1. Protection equipment should take actions as soon as possible.
2. In case of temporary fault operator should be able to doubtlessly conclude from available data that the automated system restoration is done correctly.
3. In case of permanent fault maintenance crew should obtain estimation of fault location and repair the fault as soon as possible. Operator should get trusty information about status of faulted line after the repair and then restore the line.

From previous section several flaws of the existing approach may be noticed:
- Complete data is not made available to all the utility groups, which reduces the quality of their decisions and prolongs the time for the decisions to be made.
- Data retrieval is not automated, which influences the time response.
- Fault location is calculated by the protection group, which influence time response of fault restoration since the working hours of protection group are typically 8am-5pm while the faults may occur randomly at any time.

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- Fault analysis executed by protection group may be based on fault location algorithm that is not suitable for all fault cases.

- In case of temporary faults operators do not have a way of confirming fault location and evaluating whether equipment reacted as expected.

- Final extracted fault information may be in a textual form, which may be difficult to interpret and not easy for perception.

With technological advancements, filed measurements taken from different locations can be synchronized. IEDs are capable of communicating data to a central location. Data storage is easily interfaced from different access points and intelligent techniques can be used for fast fault analysis. These benefits could be used to enhance existing fault investigation process. This development aimed to improve the existing drawbacks by a) speeding up fault location procedure through automation, b) applying the most suitable algorithm on available recordings, and c) visualizing the fault location and involved equipment through different graphical means.

PART 2: New Approach

2.1. Introduction

New approach is aimed at improving the existing fault location procedure by introducing four blocs that will be explained in the rest of this chapter:

- Automated Data Retrieval
- Optimal fault location algorithm
- Visualization of equipment
- Visualization of fault location

2.2. Automated Data Retrieval

Automation of data retrieval process will enable the users to access the collected data from different locations. At the same time each user can get results fast, as soon as automatic fault analysis is done. As the result fault location (FL) repair is accelerated as Fig. 2.1 shows.
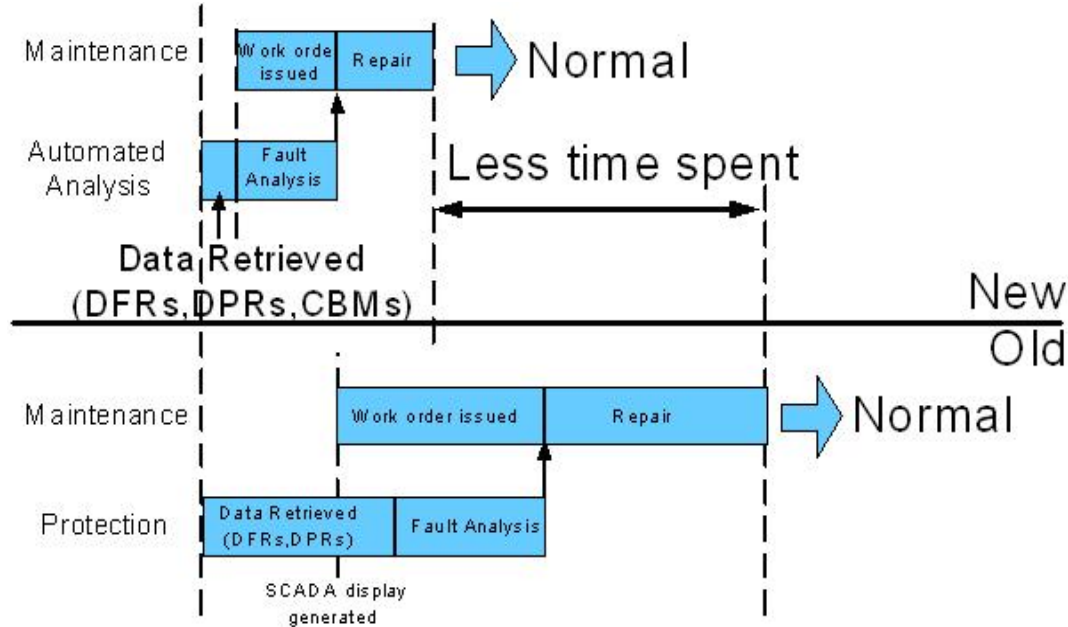
Figure 2.1: Comparison between New and Old approach in case of permanent fault

In order to calculate FL two types of data are needed: event data and power grid topology and status data. Different sources can be used to obtain these data. They will be evaluated in the rest of this section.

2.2.1. Available Devices for Obtaining Fault Recordings

Typical devices capable of recording signals, which are used for fault investigation, are Dedicated Fault Location devices (DFLs), Digital Protective Relays (DPRs) and Digital Fault Recorders (DFRs). DFLs are not so common because it is expensive solution as it accommodates only one function [2]. Protective relays are commonly used on all transmission lines. Lately, DPR based on microprocessors are becoming very popular. Those types of relays are capable of

saving measured recordings and all of them have communication interfaces so that recordings can be transferred to different locations. Finally, there are DFRs, which are commonly used in high-voltage transmission substations to record voltages and currents on several transmission lines. They are usually triggered by abnormalities in measured signals caused by the fault in the area of observations.

To monitor circuit breaker (CB) status, a Circuit Breaker Monitor (CBM) capable of recording signals from CB control circuit is introduced [3]. This makes possible evaluation of CB operation and determination of CB status (opened or closed).

2.2.2. Retrieval of the Power Grid Status

The power grid topology describes connectivity of the various components in the power system. In order to process retrieved fault event recordings, they must be related to a specific position from which they are measured and the information how the measurement positions were interconnected at the time of the fault occurrence. Therefore, the system topology must be known. Beside the connectivity it is necessary to obtain information about component characteristics at a specific moment. Most utilities have system model in a format that is defined by the PSS/E Short Circuit program [4].

In order to retrieve pre fault power grid status during fault investigation SCADA PI Historian is used. It is capable of saving the load, branch and generator data scan in the period before the fault event. Using PSS/E program, the status of the equipment is changed in system model according to the obtained values.

2.2.3. Data Transfer and Storage requirements

In the existing approach fault recordings are retrieved manually and obtained data are not dispersed among different utility groups. In order to solve this problem architecture that uses centralized repository for data storage is needed. In [5] author proposes solution in which recordings from different Intelligent Electronic Devices (IEDs) are automatically transferred to the centralized repository. In the rest of the research we will assume that such repository of DFR and CBM recordings is available. All the IEDs should provide their recordings in the COMTRADE format [6].

2.3. Optimal fault location algorithm

Typical power system contains several thousands of transmission lines. Installation of recording devices at each transmission line is very expensive and it cannot be found in practice. It is common that DFRs are placed in critical substations. Protective relays are spread all over the system, but most of them are still electromechanical and they do not have capability to record measurements. As a result, in some cases it may happen that there are no recordings at all available close to a fault. For a case shown on Fig. 2.2 for a fault on line 1 different DFRs are triggered and all of them are distant to the FL. It is clear that depending on data availability different FL algorithms may be used.
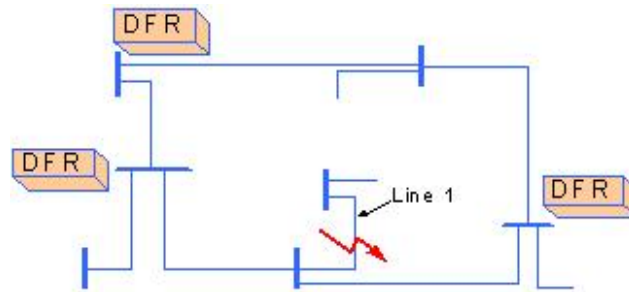
Figure 2.2: Layout of closest DFRs to a fault in case of fault present on Line1

2.3.1. Review of Fault Location Algorithms

The classification of the existing fault location (FL) algorithms depends on the line model and the signal component used [2]. There are two main groups of FL algorithms:

- Phasor- based algorithms that use the fundamental component of the signals only.

- Partial differential equation-based algorithms that use transient components of the signal and distributed-parameter line model.

Phasor-based algorithms are standard approaches for FL. Depending on a number of available measurements we recognize the following: a) two-end b) one-end and c) system wide sparse measurements FL algorithms. Different representatives of these types of algorithms are investigated in order to understand which algorithm is the most suitable for fault analysis depending on given set of input data and power system parameters. Some of them are listed bellow:

a) Two-ended FL algorithm

FL using synchronized sampling at two ends of a transmission line belongs to time based methods and it uses both lumped and distributed transmission line model depending on the line length [7]. This algorithm is based on fact that the voltages and currents from one end of line can be expressed in term of the voltages and currents from the other end. Although this algorithm is very precise it is applicable only when samples from two ends are synchronized. In [10], an unsynchronized sampling two-end FL algorithm is proposed.

b) Phasor-based single ended algorithm

One of the well-known single end algorithms is presented in [8]. Since this algorithm had several claims like necessity of pre-fault current recordings or assumption of constant fault impedance, it is necessary to use different algorithm when those assumptions are not satisfied. In [2], FL method, which uses a positive sequence model of transmission line and source impedances at the two ends of the line, is proposed. In general, these algorithms require relatively simple calculation and their implementation is not tedious. Their accuracy depends on the simplified assumptions.

c) System-wide sparse measurement algorithm

It is very common that all of the available recordings are distant to FL. System-wide sparse measurement algorithm based on genetic algorithm [9] is one of rare algorithms applicable in this case. This algorithm is based of fact that if power grid status, FL and fault resistance are known to a short circuit program, simulated waveform will completely match with recorded waveform for corresponding fault case and selected measurement points. Waveform matching approach is based on the idea of comparing the recordings from the fault event against the simulated values across the same power grid. By posing fault at different locations in the short

circuit program, different simulations are obtained. The case that provides the best match between simulated and recorded waveforms reveals FL in the actual system.

2.3.2. Description of an Optimal Fault Location Algorithm (OFLA)

There are three kinds of input data available from external data analysis tools that could influence FL calculation:

- New event recordings consisting of either synchronized or unsynchronized samples from one or more locations.

- Power grid information (transmission line parameters, topology information etc.)

- Preprocessed information (fault type, fault resistance, initial estimation of FL)

By processing the input data an optimal FL algorithm is chosen. In the case when data from two ends of faulted transmission line are available the two-end FL algorithm is the most accurate approach and should have priority. Otherwise it is checked whether data from only one end of the faulted line is available. In the case of the two-end algorithm, if input samples are synchronized, synchronized sampling two-ended algorithm is the most appropriate. Otherwise unsynchronized sampling two-ended algorithm is the most suitable. Similar logic is applied further and as conclusion Optimal Fault Location Algorithm (OFLA) shown on Fig. 2.3 is developed.
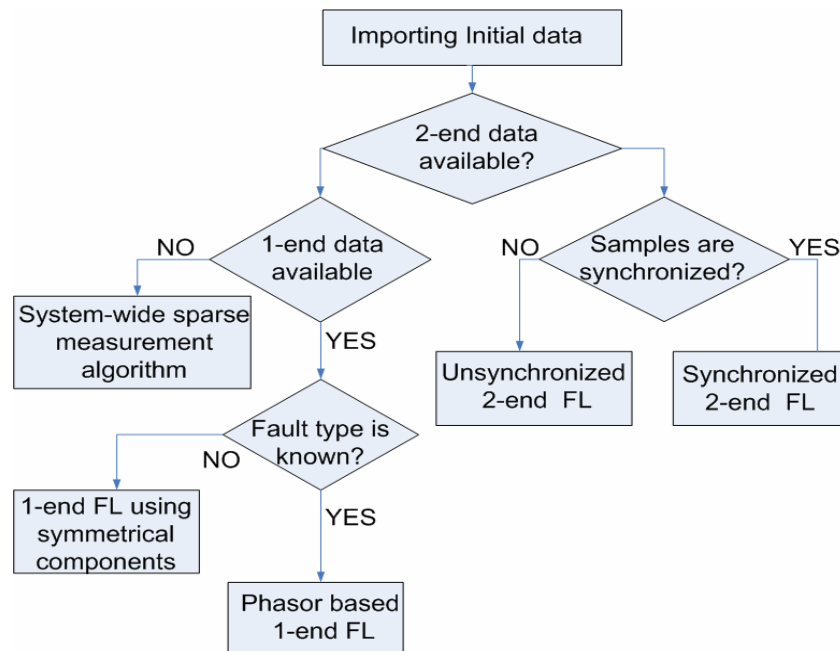
Figure 2.3: Optimal fault location algorithm block diagram

It should be noticed that in some cases multiple algorithms are applicable and it would be interesting to check how averaging results from different FL estimations using different weight functions for different algorithms could influence the results. In order to enable an easy way for further testing and enhancing OFLA, decision tree is used for implementation of this algorithm.

2.4. Visualization of equipment

Two types of equipment will be modeled in the new approach:

- Transmission Tower
- Circuit Breaker

2.4.1. Transmission Tower

The tower is a complex structure that holds the transmission lines through insulators. If any fault occurs on a particular segment of a transmission line, it is most likely that the fault occurs on the tower structure or the insulators. The tower structure varies with voltage level and also depends on the type of the transmission line it carries (either single circuit or double circuit). Based on the conductor arrangements, towers can be classified into single-level, two-level, three-level etc. Fig 2.4 shows various types of tower structures [11].

Figure 2.4: Various types of tower structures

A construction view of the tower in 3D is developed, helping the maintenance crew to visualize the type of the tower, insulators etc before proceeding t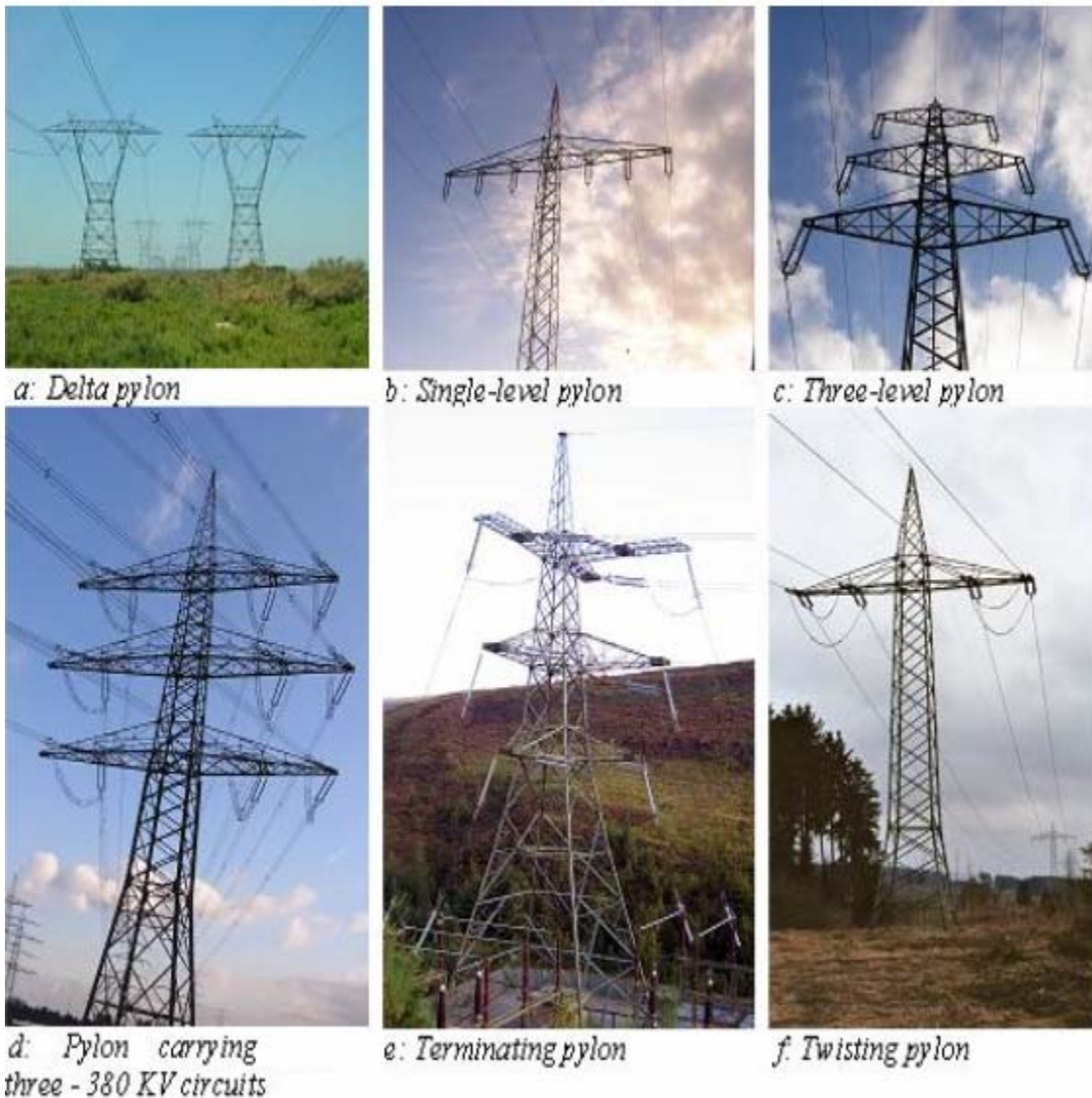o the actual filed site. Following are few of the parameters that are needed for developing the 3D models of the towers. These parameters are taken from the Alternate Transients Program (ATP) rulebook [12].

- Phase number
- Resistance and Reactance
- Circuit type (for example: single circuit or double circuit)
- Horizontal separation from center of the conductor to a reference line
- Vertical height of the conductor above the ground, at tower
- Vertical height of the conductor above the ground, at mid span
- Presence of ground wire
- Length of the transmission line
- Transposed or un-transposed
- In case of bundled conductors: Angular position of first conductor of the bundle, separation between adjacent conductors in the bundle, number of conductors in the bundle
- Presence of communication circuit
- Type and number of insulators per phase

The construction view of insulators is also considered in this project. Overstress in insulators result in small cracks, reducing their insulation strength, hence possibly causing faults. Pin, disc and suspension type insulators are commonly used for overhead transmission lines. Fig 2.5 shows few pictures of the insulators taken from real situations.
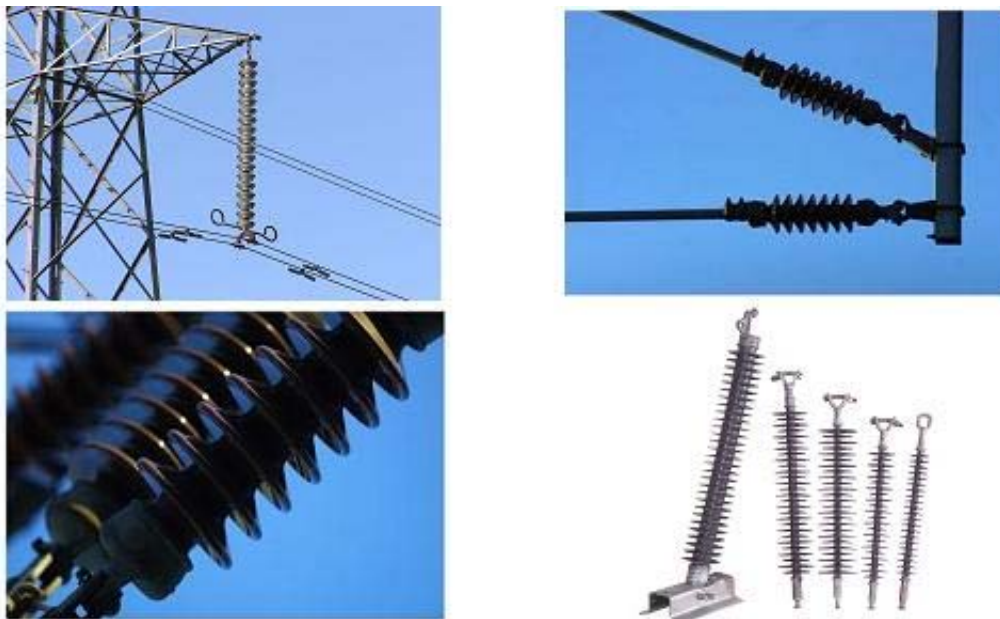
Figure 2.5: Various types of insulators

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2.4.2. Circuit Breaker

Circuit breaker is an electro mechanical device, which has several mechanical components such as trip and close coils, trip and close latch mechanisms, connecting rod, rollers, cams etc. Visualization of these parts will help maintenance crew take better decisions for both diagnose and maintenance purposes. Visualization of circuit breaker is divided into two separate options:
- Construction view
- Operational view

a) Construction View

This view is basically a 3D representation of the CB operating mechanism. A Westinghouse made vacuum circuit breaker of type 3 is used in developing the 3D representation. This particular breaker is equipped with spring operating mechanism and the principle parts are shown Fig. 2.6. Even though the spring operating mechanism was selected in this project, similar treatment can be applied to other types of operating mechanisms such as pneumatic or hydraulic.

1. Shunt Trip Coil *(IEEE Device 52 / TC)*
2. Trip Shaft
3. Trip Latch Constraining Link
4. Trip Latch
5. Close Cam
6. Stop Roller
7. Spring Release Latch
8. Spring Release Device *(IEEE Device 52 / CC)*
9. Oscillator Pawl
10. Ratchet Wheel
11. Hold Pawl
12. Drive Plate
13. Manual Charge Pawl
14. Oscillator
15. Crankshaft
16. Manual Charge Device
17. Crankarm (2)
18. Closing Spring (2)
20. Closing Spring Anchor
21. Manual Trip Lever
22. Motor (52/M)
23. Manual Charge Handle
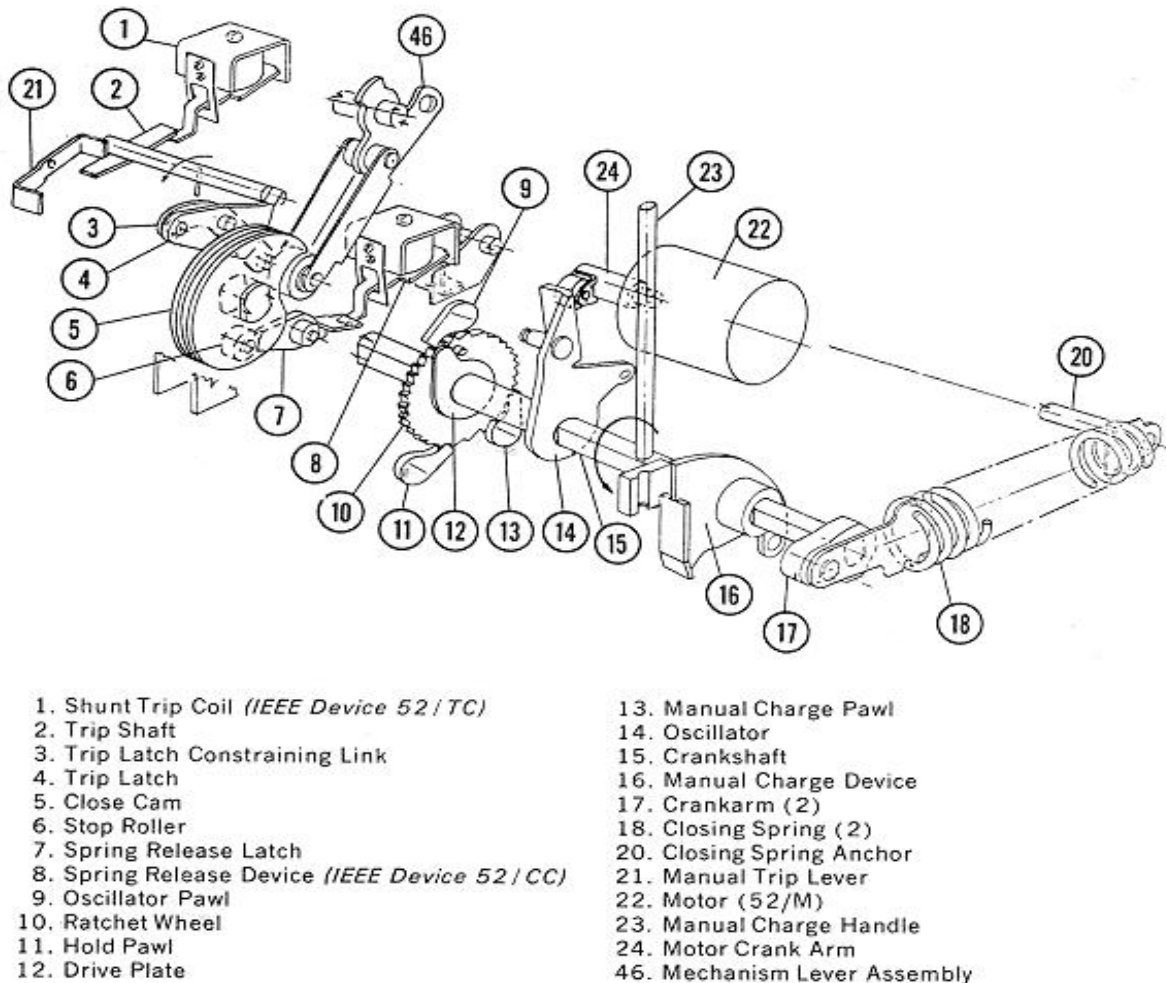24. Motor Crank Arm
46. Mechanism Lever Assembly

Figure 2.6: General arrangement of principle parts of the CB mechanism (Source: Westinghouse reference manual)

b) Operational View

With availability of recordings from a CBM device [13] which records CB control circuit signals, each operation of CB could be evaluated through an analysis. The idea of the operational view is to show how the operating mechanism behaves during the operation of the circuit breaker. As the operating mechanism is often covered in a box, it is not easy to observe the movement of the various parts. This section presents the background that is needed to show the animation of the CB operation in 3D. Fig. 2.7 shows the electrical representation of the CB control circuit. Table 1 gives a general description of an operation process and makes a correlation among the control circuit changes, CB mechanism actions and related waveform indications.
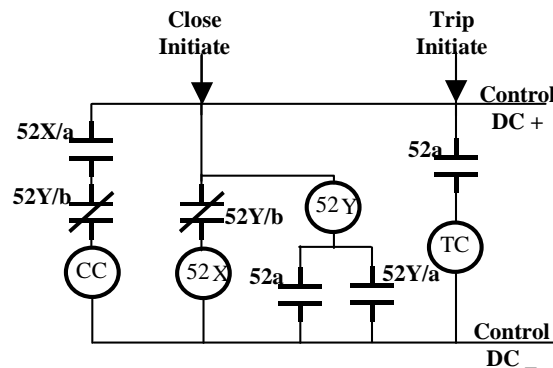

Figure 2.7 Electrical representation of circuit breaker control circuit [13]

TABLE 1: SEQUENCE OF CIRCUIT BREAKER OPERATION [13]

Control Circuit	Mechanism	Waveforms
1) Initiate signal flows down to coil (TC, CC) 2) Coil is energized to move the armature		1) Initiate signal switches to a high level 2) Coil current ramps up
	3) Armature moves up to release the latch 4) Stored energy is released in turn to move CB's main contacts	3) Coil current saturates and dips 4) Coil current reaches its sustained value 5) A & B contacts changes from High to Low or vise versa
5) Auxiliary switches A & B change its status with the main contacts 6) Coil is de-energized		
	7) CB fully opens or closes	6) Coil current ramps down 7) Phase current breaks or makes

A representative set of signals during close operation of the breaker is shown Fig. 2.8. Separate events that represent the operation of the breaker and the associated signal parameters are defined and described in Table 2.
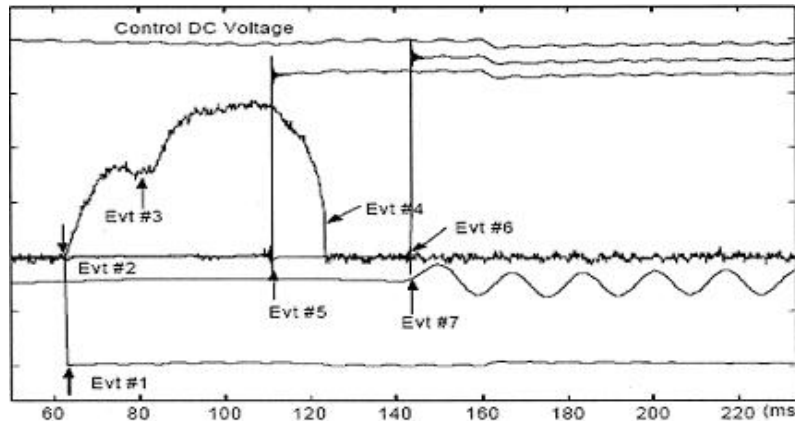
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Figure 2.8: Control circuit signal during close operation of circuit breaker [13]

TABLE 2: WAVEFORM ABNORMALITIES AND SIGNAL PARAMETERS [13]

Event	EVENT DESCRIPTION	Signal Parameter
1	Trip or close operation is initiated (Trip or close initiate signal changes from LOW to HIGH)	T1
2	Coil current picks up	T2
3	Coil current dips after saturation	T3
4	Coil current drops off	T4
5	"b" contact breaks or makes (a change of status from LOW to HIGH or vice versa)	T5
6	"a" contact breaks or makes	T6
7	Phase currents breaks or makes	T7
8	X coil current picks up	T8
9	X coil current drops off	T9
10	Y coil current picks up	T10

The operational view shows the animation of the operating mechanism while CB operates. The signal parameters mentioned in Table II are utilized to control the animation process. Consider the opening of the breaker. Upon the trip command is given at time T1, the trip coil current ramps up at time T2 and the trip coil gets energized. The trip latch is released at time T3, which enables the movement of the operating mechanism, and the breaker starts opening. The auxiliary contact 'a' changes it status in accordance with main contacts at time T6. The animation process is governed by these timings T2, T3 and T6. Though other parameters have their own significance in the CB operation they do not affect the animation process and hence are not considered. The animation process can be divided into three parts as given below.

1. The time between the instant at which the trip/close command is given and the instant at which the coil currents ramp up. This time period is equal to T2-T1 and no movement in the mechanism process can be observed.

2. The time between the instant at which the coil current ramps up and the observed dip. This time is equal to T3-T2 and is called the 'armature free travel time'. The movement of the trip/close latch is shown.

3. The time between the instant at which the dip in the coil current and the auxiliary contact changes their status. This time is equal to T6-T3 for open operation and T5-T3 for close operation. This time is also called the 'mechanism travel time'. The movement of the connecting rod, springs and other related parts is shown.

It is also possible to see the abnormal operation of the individual parts of the operating mechanism. For example, problem associated with the trip coil can be shown by a flashing red color around the trip coil in the 3D view.

2.5. Visualization of fault location

Once FL is calculated it is very important that it is effectively presented to maintenance crew. Knowing environment around FL and construction of involved equipment enables them to bring necessary tools needed for fault repair. A pilot area near the substation X was picked for the transmission line visualization part in the first phase of the project. Two views are exported:

2D View: the faulted line and fault location are marked on the 2D satellite image, while natural environment around fault location is kept.

3D View: the 3D model is exported for an interactive demonstration of the constructional view of the transmission lines.

Developed views in the case of the pilot area are presented in chapter 4. Modeling a bigger landscape manually is time consuming process. Instead, a program should be developed to extract landscape data which enables user to mark entities on a satellite image like houses, trees, roads, and more importantly substations and transmission towers. If the coordinates of corresponding elements are already available in .txt format program should be able to connect them with corresponding points on the satellite image. By using this software, large amount of data can be extracted from a satellite image and can be saved to a topological scene file. For the constructional view, the model of the area can be built by combining pre-modeled entities (i.e. towers, substations) based on the topological scene file as Fig 2.9 shows.
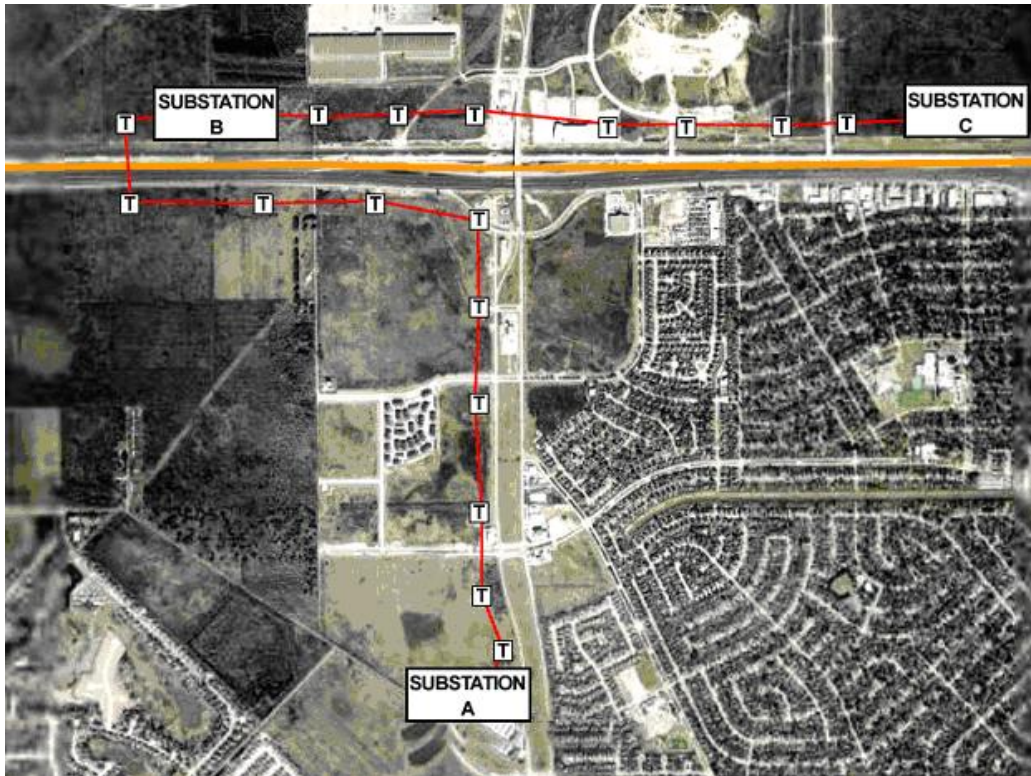
Figure 2.9: Overlaying pre-modeled entities and satellite image

In the next phase of the project above described process should be automated. This requires storing all the topology in a graph where each substation is a node in the graph. Each node should store the substation name, id, location (x and y coordinates), and list of links to other nodes in the graph. Each link can be a represented as a data structure, which contains the links to the two of the graph nodes that the link connects. It should also include the list of all transmission towers between the two nodes with their locations as shown on Fig. 2.10.The topology can be easily mapped to the satellite image, when two points on the image (i.e. two substation nodes) are referenced to the corresponding nodes in the graph.
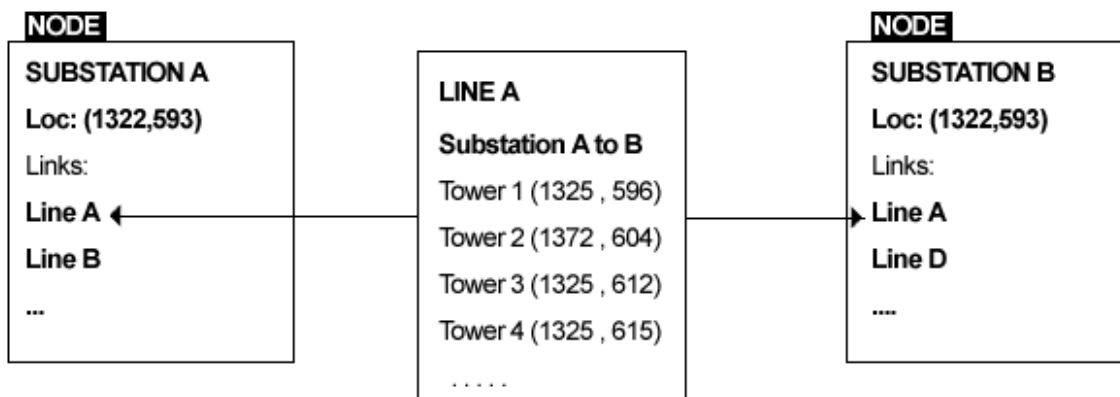

Figure 2.10: Data structure

In the proposed system, a FL can be reported by giving the two end substations and the fault's distance from one of the substation. By looking at all the links that a substation has, one can easily find the link that connects it to the other given node. Once the link is found, starting from the first tower in the list, the list should be iterated tower by tower and the distance between each tower should be added up until the given fault distance is smaller than the cumulative distance. The last two towers in this iteration will be the ones that the fault has occurred in between. Then the fault can be easily located on to the image by linearly interpolating the locations of these two towers. The system requires the locations of the transmission towers for accurate result, which can be extracted easily by using the data structures described above.

Part 3: Proposed Solution Architecture

3.1. Introduction

Utilities should be able to reduce outage time and improve the quality of power delivery by using the proposed development aimed at reaching this goal by:

a) Speeding up fault location procedure through automation, where both data retrieval and fault analysis are automated. Obtained data and calculated results are available to all users at the same time.

b) Applying the most suitable algorithm on available recordings that correspond to same fault event. Additionally, implementing appropriate architecture and using different sources for getting redundant raw and preprocessed data will improve accuracy of fault location (FL) algorithms.

c) Providing final results through Visual-Interactive-Distributed (VID) Spreadsheet, which provides view into physical environment that surrounds fault location and views into involved equipment.

3.2. Software Architecture

In order to achieve above goals solution must merge different data sources and automated analysis steps. The architecture of the solution is shown on Fig. 3.1.
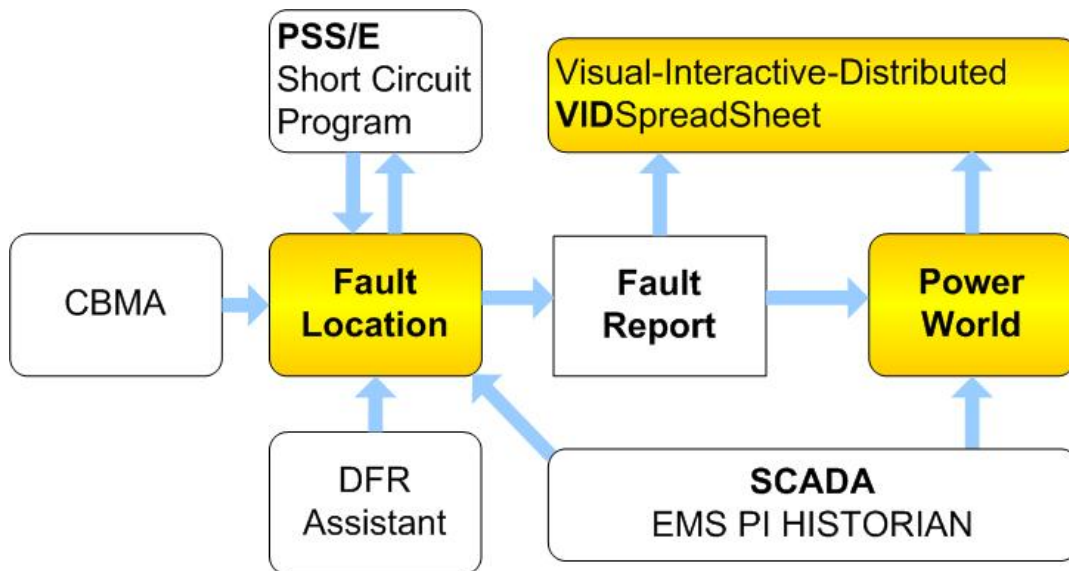

Figure 3.1: Architecture of proposed approach

Two main segments should be recognized:

1) Fault Location Module

2) Visualization Module

Each of these segments is fed by external software tools. They consist of applications that automatically retrieve measured data and analyze them, execute power flow analysis, provide user interface used for running developed applications etc. Some external tools are used only by one segment while the others are used by both segments. The communication between two main segments is achieved using Fault Report. This report is generated by the fault location module

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and it gives all necessary input information to the VID Spreadsheet. Both segments will be presented in more details in following sections.

3.3. Fault Location Module

FL module should update power system status with retrieved data, process new event files, decide the most suitable fault location algorithm and execute it. Architecture of this module is shown on Fig. 3.2.
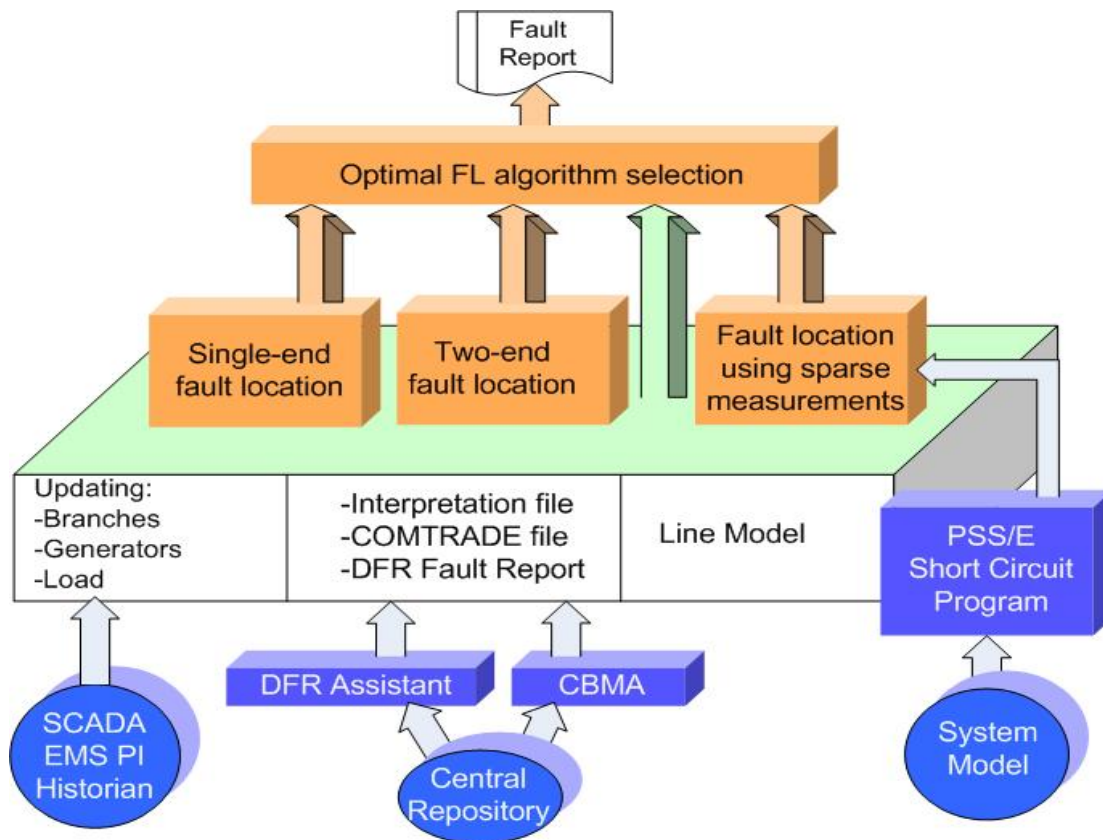

Figure 3.2: Architecture of fault location module

FL algorithms that are used as possible selection are:

      a) Synchronized sampling two-ended algorithm [7]

      b) Unsynchronized sampling two-end algorithm [10]

      c) System-wide sparse measurement algorithm [9]

      d) Phasor-based single ended algorithm [8]

      e) Single ended FL using symmetrical components [2]

Optimal FL algorithm selection is done by Optimal Fault Location Algorithm (OFLA). External tools used by this module are:

a) SCADA PI Historian, which is used for obtaining the latest load, branch and generator data in order to update system model before FL calculation starts.

b) DFR Assistant [14], which provides new event recordings from central repository in the COMTRADE format [6], as well as the preliminary fault report. The report describes

behavior of protection equipment, recognizes type of fault and it is used by other algorithms as input file.

c) PSS/E Short Circuit program [4], which is accessed during fault calculation by some algorithms in order to run power flow and short circuit analysis automatically.

d) System model in PSS/E format, which is updated before any calculation starts in order to reflect the system state prior to a fault. This is very important feature especially if topological changes take place in the mean time.

e) CBM Application [3], which provides new CB operation event recordings from a centralized repository in the COMTRADE format [6] and analysis results about the CB operation from an expert system report. The report describes behavior of executed operation, final status of the equipment and provides precise timings of event, which can be used to align in time the group of operations that belong to the same event.

Output of this module is the Fault Report. Analyzed information about fault event, fault location and circuit breaker behavior is merged into this report and it is used to feed the VID Spread Sheet.

3.4. Visualization Module

Visualization module should provide user with an easy way to access relevant information when:
  a) Power system is in a normal state
  b) Fault is present and system changes its state. It is also necessary to efficiently alarm user when the power system changes its state.
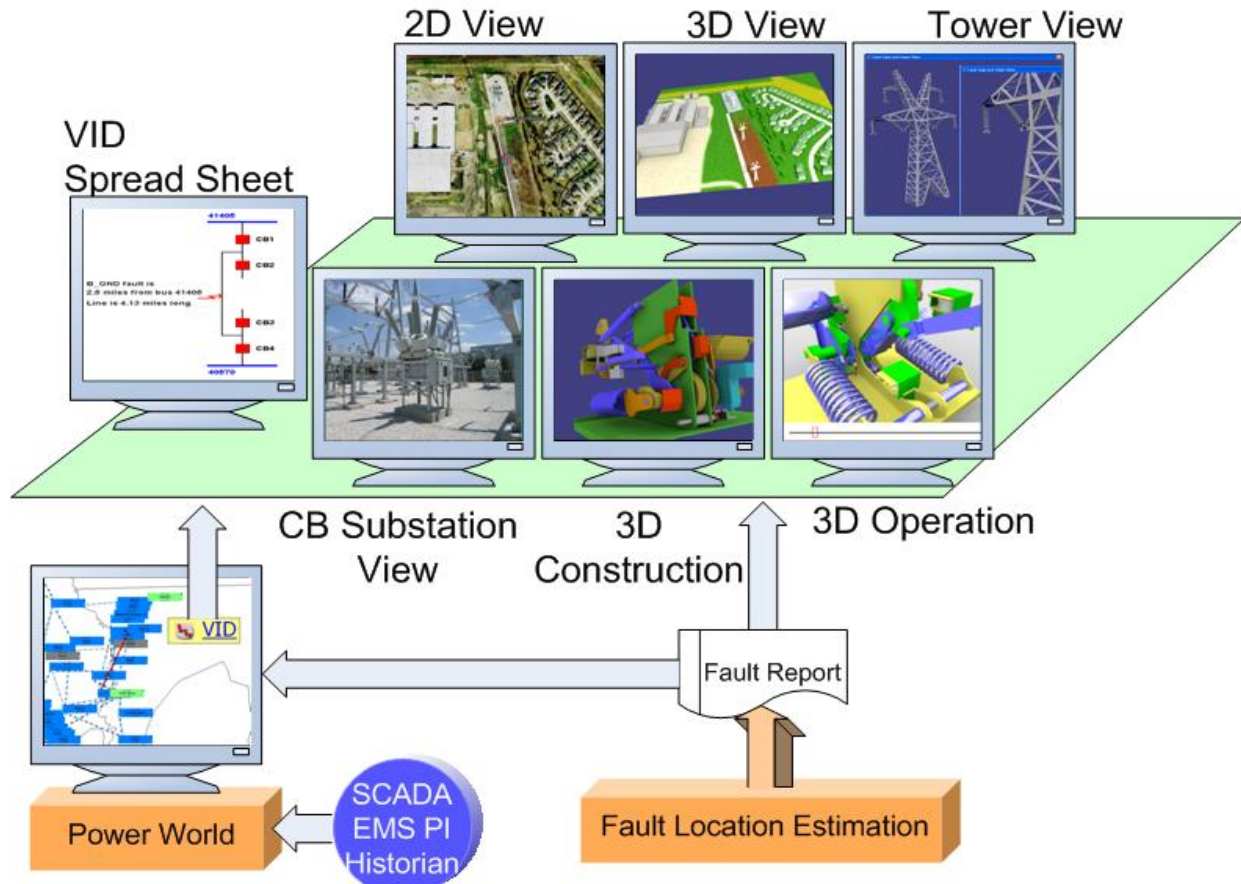
Architecture of this module is shown on Fig. 3.3.

Figure 3.3: Architecture of visualization module

Visualization module consists of two main blocks:

a) PowerWorld (PW) Retriever [16], which is tool for real-time visualization of power system operations. The retriever can import real-time data by connecting to data source services and it enables user to perform supervision and visual analysis of power system operations. In the proposed architecture this tool is used to track system behavior in the normal state. Real time data are obtained from SCADA PI Historian. Architecture of this tool is shown in Fig. 3.4.
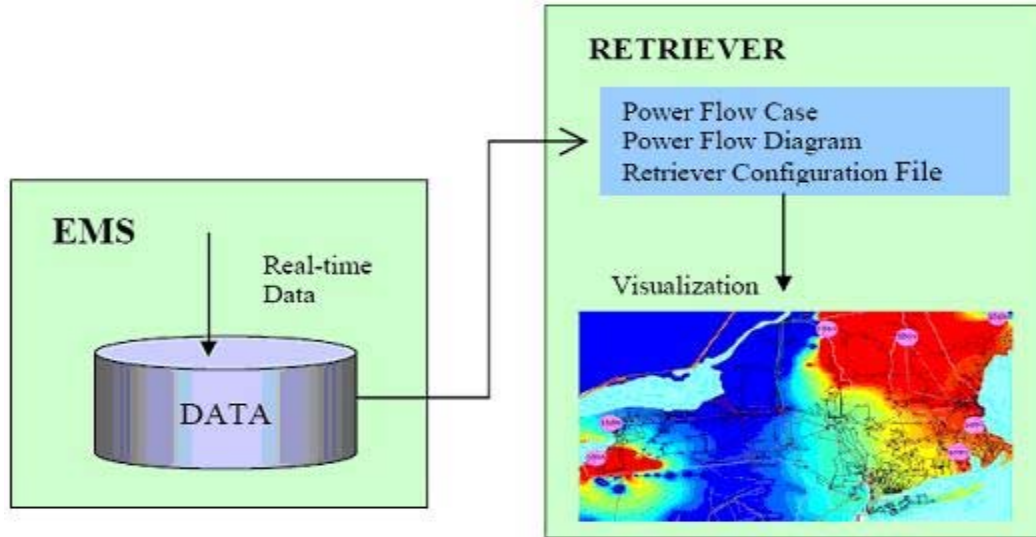
Figure 3.4: PowerWorld Retriever components

Currently this tool is not capable of providing alarm when a fault event occurs in the system. So it was extended with two features:

- Once new fault event is processed the corresponding faulted line starts blinking.
- Additional VID Spreadsheet button is added to the interface. Once user clicks this button VID Spreadsheet module is executed.

b) VID Spreadsheet provides user critical information about fault event through visualization. The following is critical information that needs to be extracted automatically as soon as possible after occurrence of the fault event: 1) fault type, 2) inception time, 3) clearance time 4) report on equipment behavior and 5) fault location. Figure 3.5 demonstrates views built in the VID Spreadsheet. Each of these views will be demonstrated and discussed in the next chapter.
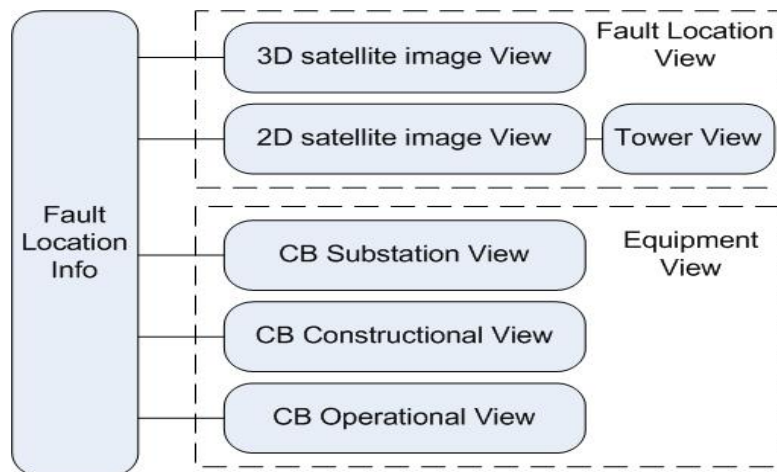

Figure 3.5: VID Spreadsheet components

Part 4: Implementation

4.1. Introduction

Developments of the proposed approach during the first year of the project are demonstrated in the following two sections. The first one describes available components in the proposed architecture, default assumptions that are made and test cases that are used during demonstration. The second one presents features and screenshots of current developments.

4.2. Mockup description

The demonstration is carried out using the CenterPoint Energy (CNP) transmission system cases from year 2000 as an example. There are 15 fault event cases available. These cases consist of DFR measurements, DFR Assistant report and precise information about fault locations obtained from CNP personal. Since in all cases only the measurements, which are distant to the FL are available, only the sparse measurement algorithm is applicable. Two of the fault event cases will be demonstrated. Demonstration is done without SCADA EMS PI Historian input, because this information was not furnished by CNP. Since CBMA data related to test cases was not available, only an example of the open and close CB operations will be presented in the operational view for the CB.

All events in the new approach are executed automatically. The FL module constantly observes fault event folder and once it notices that there is new fault event case it will start processing. When FL analysis is done corresponding result is written into the fault report and provided further to the PW Retriever, which will mark corresponding faulted line and it will start blinking on the single-line diagram. Once the transmission line starts blinking the user is alarmed and all data related to fault event is already calculated. Simply by clicking VID Spreadsheet button the user is able to visually find out more about the fault event.

Similarly the CBMA application constantly observes specific folder and waits for the event case from CBM device. Once there is new event related to some of the CBs, analysis is run and corresponding results written directly into the report that is later read by VID Spreadsheet. In future development, CBM information will be additionally processed by FL module in order to narrow down possible faulted area and update status of power system branches.

During demonstration two fault event cases will be analyzed. For each of them DFR recordings in COMTRADE format and corresponding reports from DFR Assistant software are available as can be seen from Fig. 4.1. Cases belong to different parts of the power system and topologies of faulted area are shown on Fig. 4.2 and 4.3 for each of the case respectively.

Figure 4.1: Fault event cases

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Case 1:

Event Data

- Event Date/Time: 08-23-2000 10:05:50
- Event Type: Phase B-GND fault
- Fault location: Ckt. 03, 1.63 miles from 40570 (Known Fault Location)
- Triggered DFRs: Sub1 (Event 316), Sub2 (Event 318), Sub3 (Event 322)
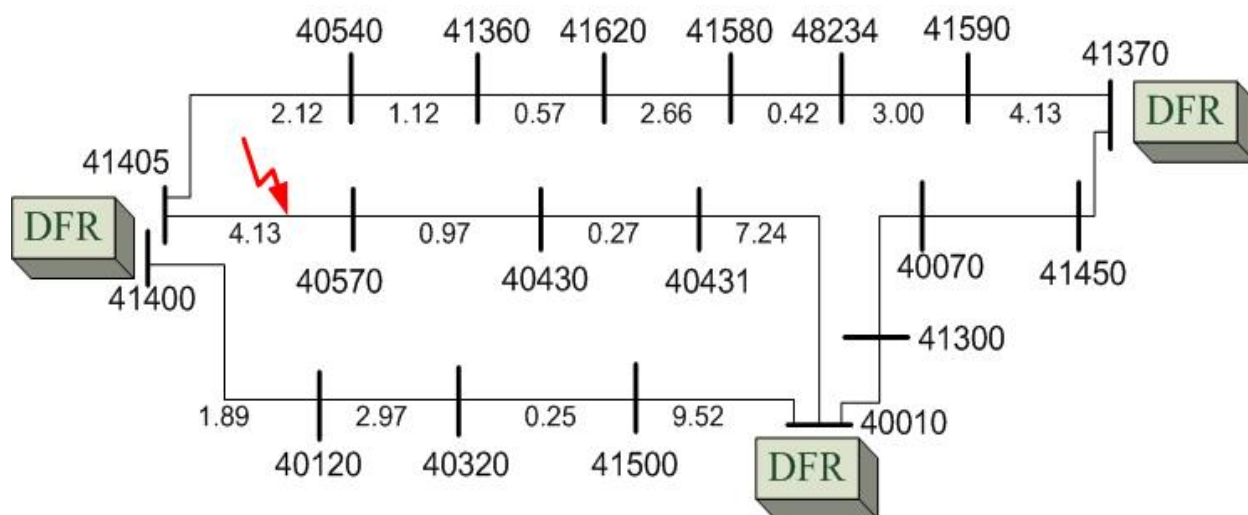

Figure 4.2: Case 1 topology

Case 2

Event Data

- Event Date/Time: 7-19-2000, 05:15:34
- Event Type: Phase B-C fault
- Fault location: Ckt. 84, in substation 41700 (Known Fault Location)
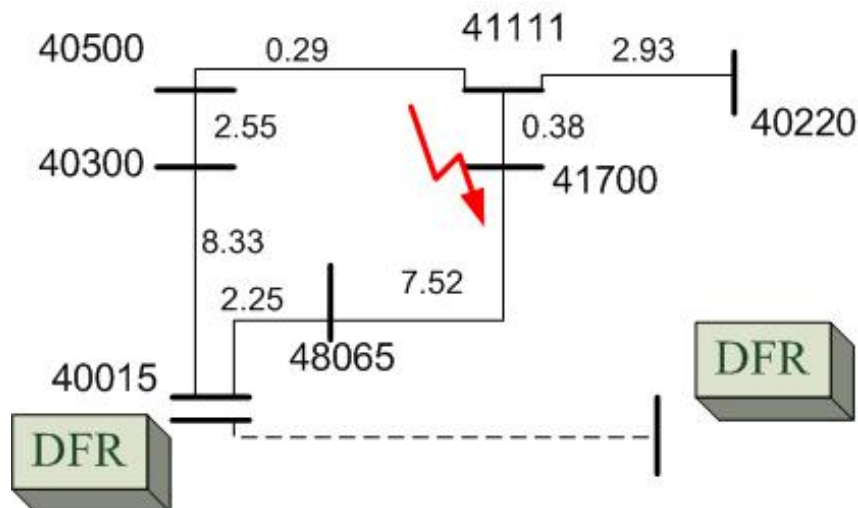- Triggered DFRs: Sub1 (Event 676), Sub2 (Event 680)

Figure 4.3: Case 2 topology

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4.3. Demonstration of the features

As said in previous section, before any analysis starts PW Retriever, FL Application and CBMA are set to work automatically.

PW Retriever is set to constantly check fault report, which should provide information about faulted line that should be marked. This is done using the Retriever Control Panel. First settings describing which file should be automatically checked in order to refresh power system status is marked and then by clicking "Begin auto-update" button automatic data refreshing loop is started. It will refresh data according to the marked time as Fig 4.4 shows.

Figure 4.4: Setting automatic mode in PowerWorld Retriever

Similarly, the automatic mode setting is set in FL and CBM application once they are started. This is shown on Fig. 4.5 and Fig. 4.6 respectively. After setting the automatic property, these programs are working in the background.
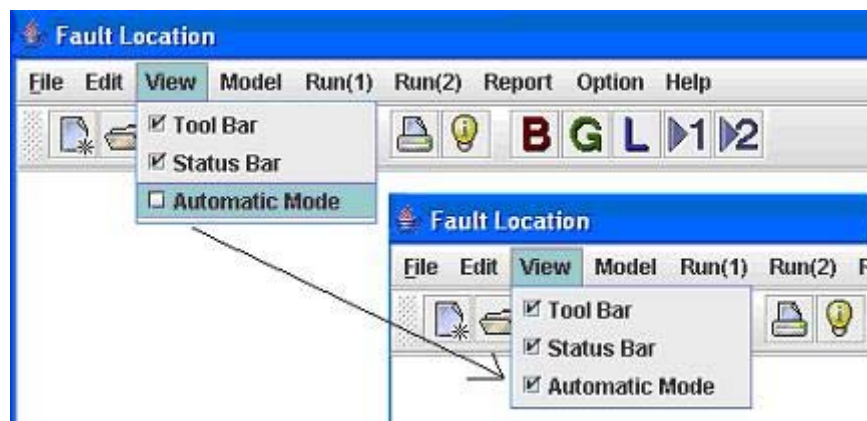

Figure 4.5: Setting automatic mode in FL application

```
c:\WINDOWS\system32\cmd.exe                                    _ □ ×

c:\UID\CB Monitoring\CB Analysis>cd c:\UID\CB Monitoring\CB Analysis\

c:\UID\CB Monitoring\CB Analysis>java -jar cbm.jar
Input files are taken from folder: C:\UID\CB Monitoring\RIS OUTGOING\.
Ouput files are put to folder: C:\UID\CB Monitoring\CB INCOMING\.
Error files are put to folder: C:\UID\CB Monitoring\ERROR\.

CB MONITORING PROGRAM IS RUNING.
Insert exit if you would like to quit the program
```

Figure 4.6: CBMA in the automatic mode

When system is in a normal state user can track system behavior through PW Retriever as Fig. 4.7 shows.
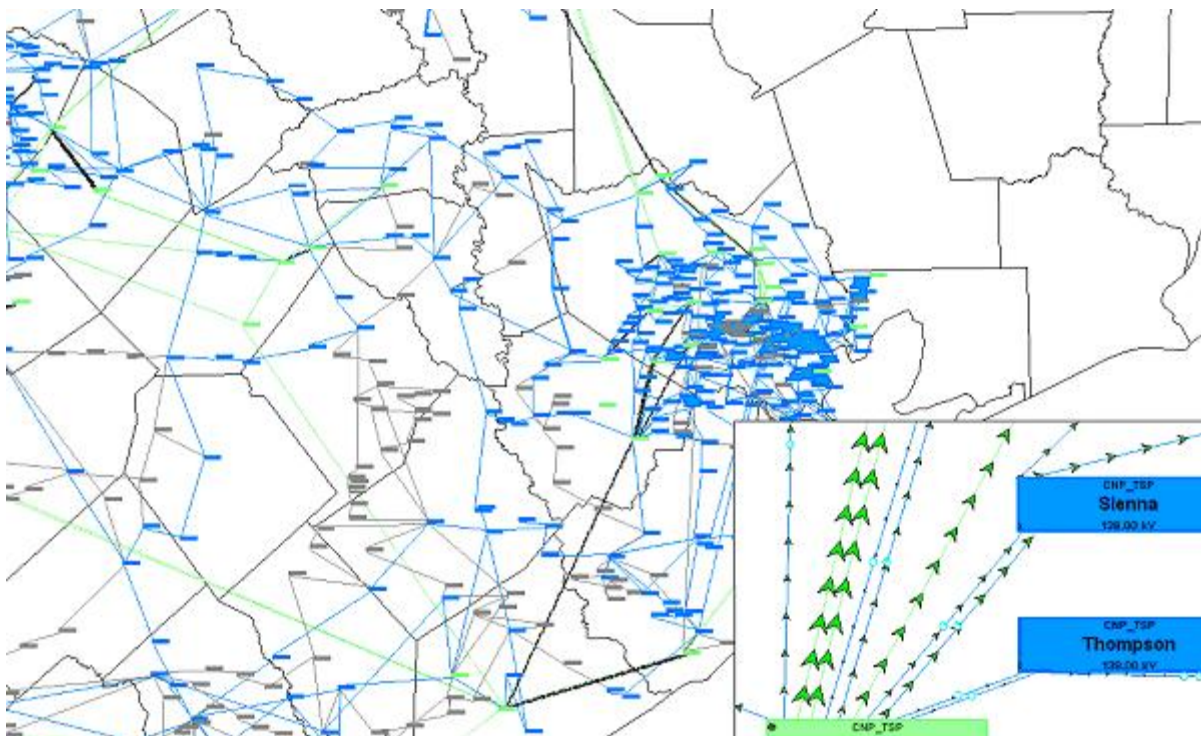

Figure 4.7: Tracking system behavior in normal state

First, fault case 1 is executed. Simply by coping fault event files shown on Fig. 4.1 into observed folder, automatic FL analysis is triggered. Depending on number of input DFR files FL analysis may last several minutes. Once fault is calculated PW diagram will mark faulted line and activate VID Spreadsheet button as Fig 4.8 shows. By clicking button user can view first layer of VID Spreadsheet. Fig 4.8 shows also results after processing the case 1.
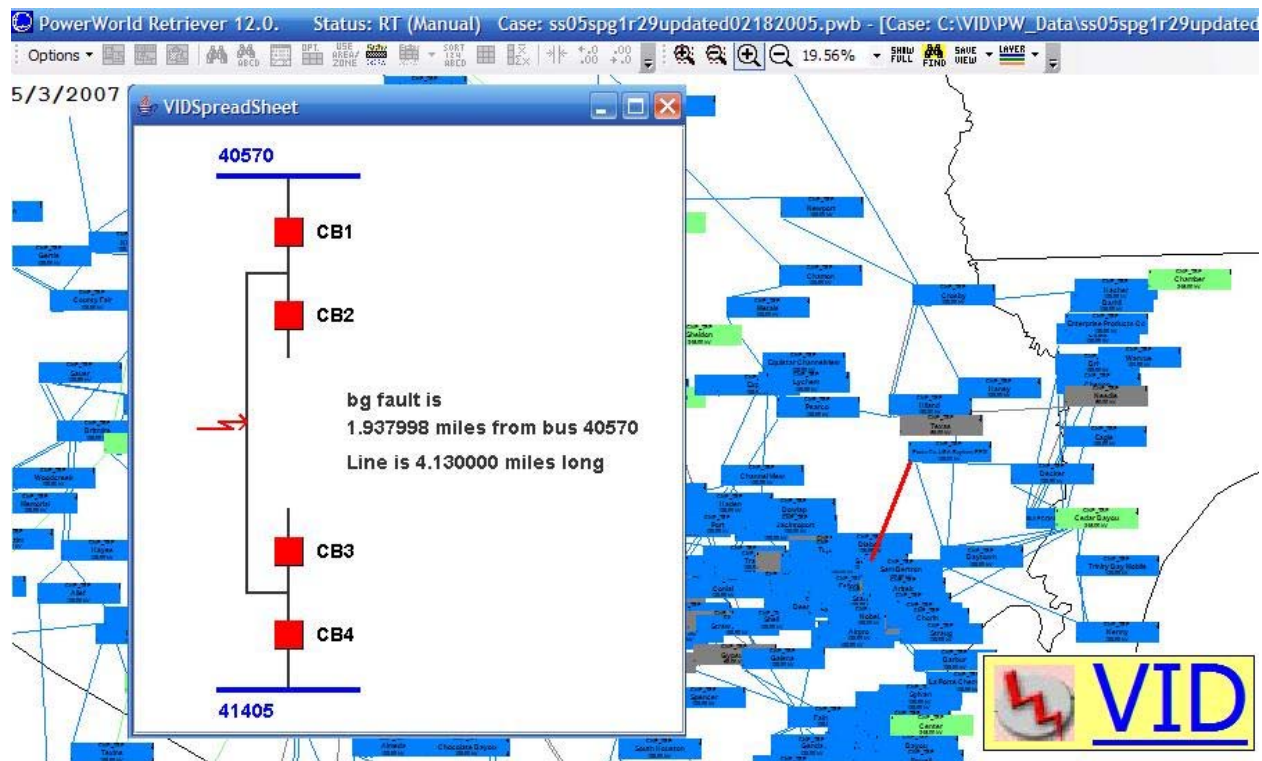
Figure 4.8: First layer of VID Spreadsheet after processing case 1

From the first layer of VID Spreadsheet different views can be accessed. Fault location views or different views of each CB involved in disconnecting the line can be chosen Fig. 4.9.
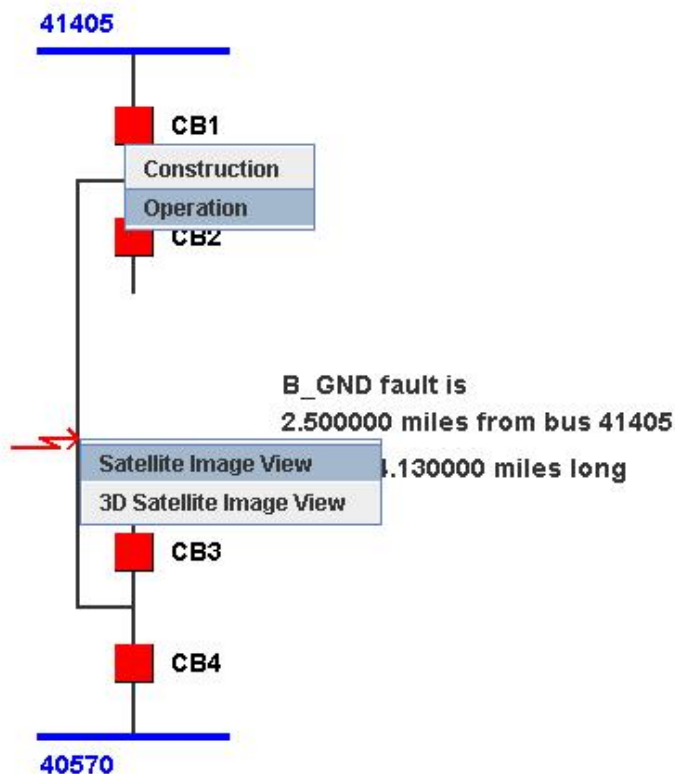

*Figure 4.9: Possible options in VID Spreadsheet*

By clicking the satellite image view user opens 2D view of the faulted area as shown in Fig. 4.10. For the transmission line visualization part of the project, a pilot area near the substation X was picked. In this phase of the project the area is roughly modeled based on a satellite image captured from Google Earth [16]. Additional lines were manually drawn over faulted line. A symbol indicating where the fault occurred was manually pasted on the top of the transmission lines. In the future, the process of overlaying transmission lines and the fault indicator to the satellite image will be automated.
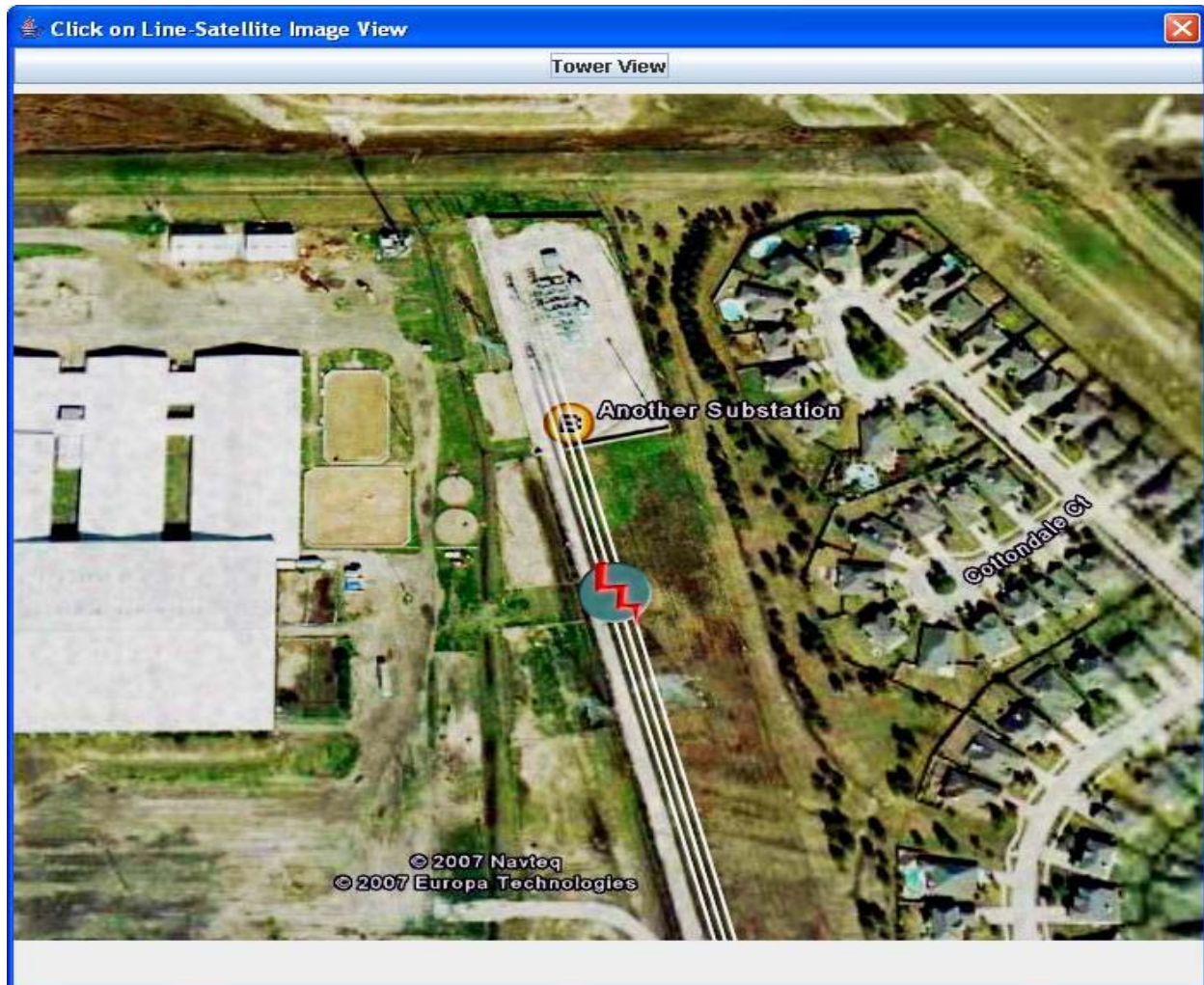
Figure 4.10: 2D View of fault location

The 2D satellite image doesn't provide clear information about the type of transmission towers that surround the fault location nor does it give information about the height of objects that surround the fault. The 3D model is exported for an interactive demonstration of the constructional view of the transmission line as Figure 4.11 shows. For the demonstration purpose, the area was modeled manually. As a next step, the satellite model should be generated in run time by combining pre-modeled elements (ex. houses, trees) according to a topology scene file. This would speed up the process of modeling the environment and decrease the required memory amount to store the data.

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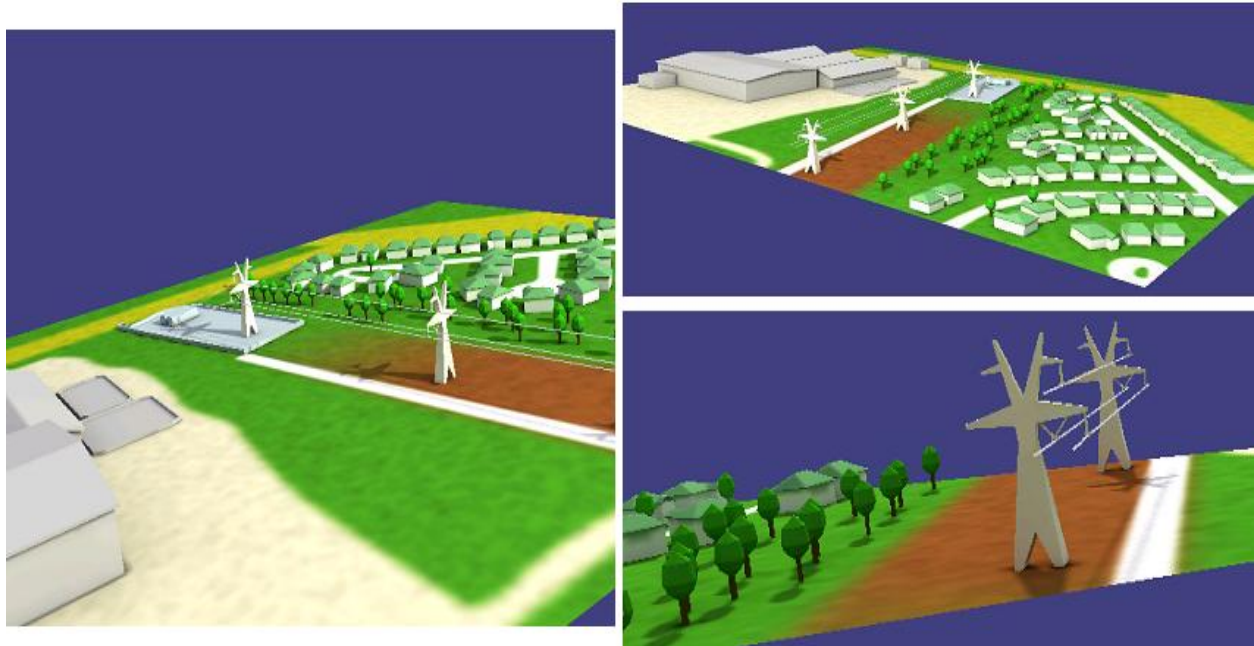
Figure 4.11: 3D View of fault location

The transmission towers and insulators were modeled with less detail in the 3D model of the faulted line due to hardware restrictions. A more detailed model of a transmission tower with details about insulators is provided in a separate window when the tower button from Fig 4.9 is clicked. The tower view is shown on Fig. 4.12. Similar to the 3D view of transmission line, tower view is interactive. It can be rotated, enlarged, and reduced as needed.
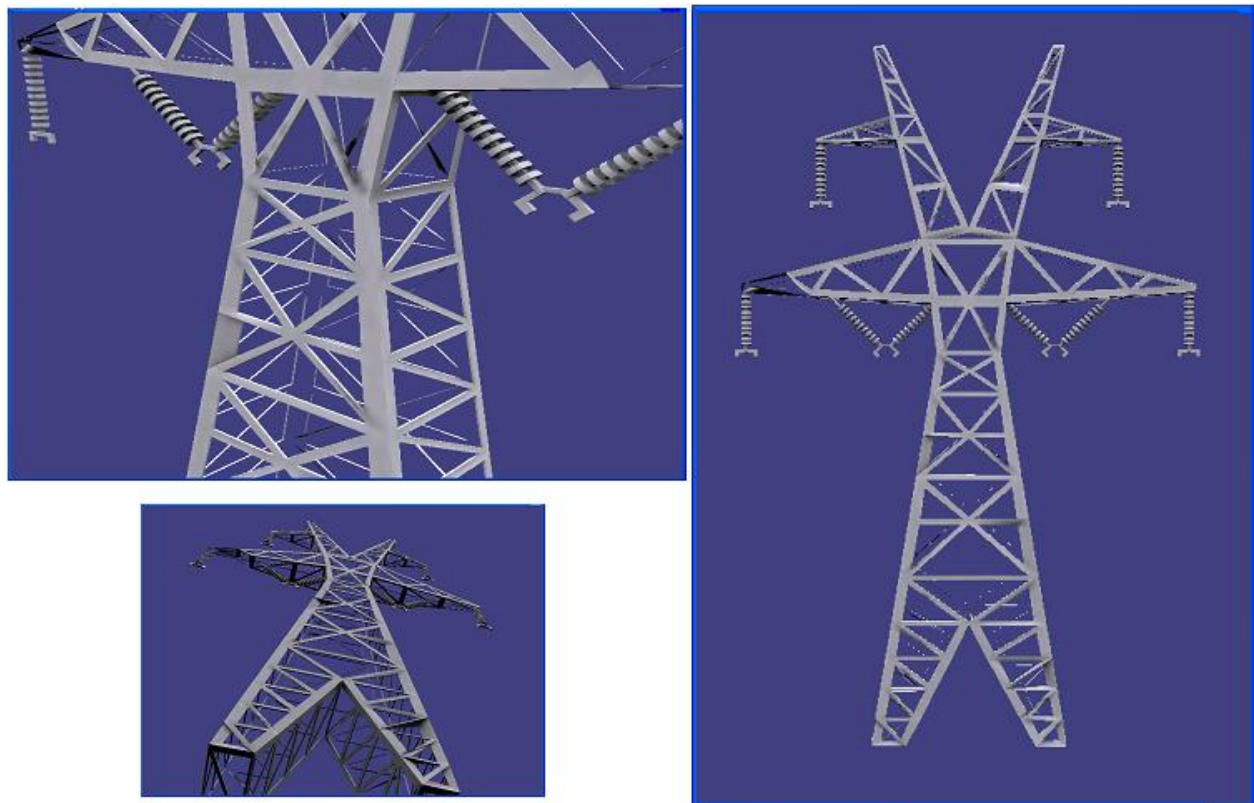
Figure 4.12: Constructional view of tower

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CB constructional view was modeled based on the figures and explanations from a user manual of a Westinghouse circuit breaker. An example of a CB operating mechanism of the same type of circuit breaker was also taken from a utility company and was physically observed in the lab for modeling purposes. A 3D construction view of the operating mechanism is developed allowing rotation of the object in all directions to give better understanding of the construction details as Fig. 4.13 shows.
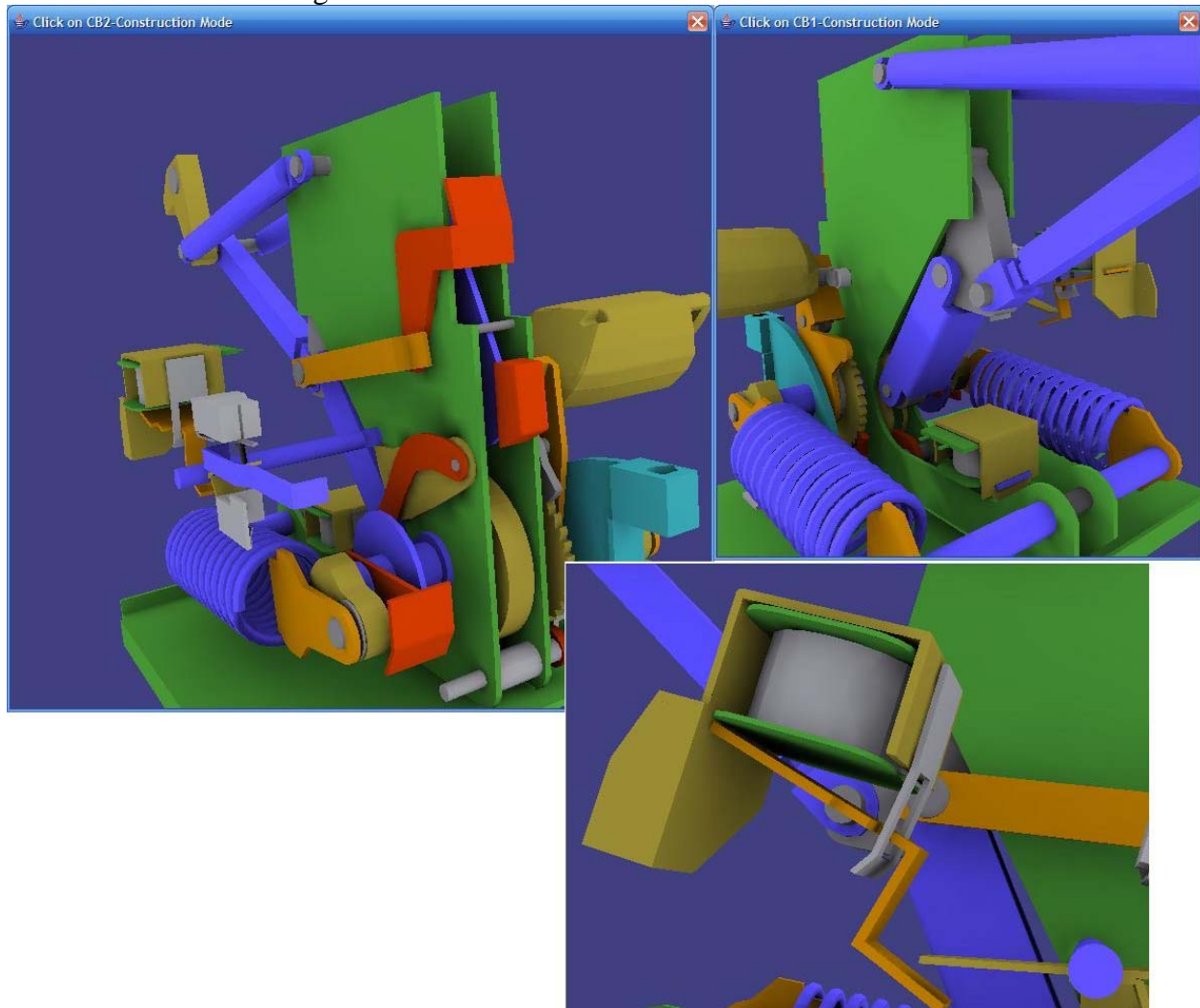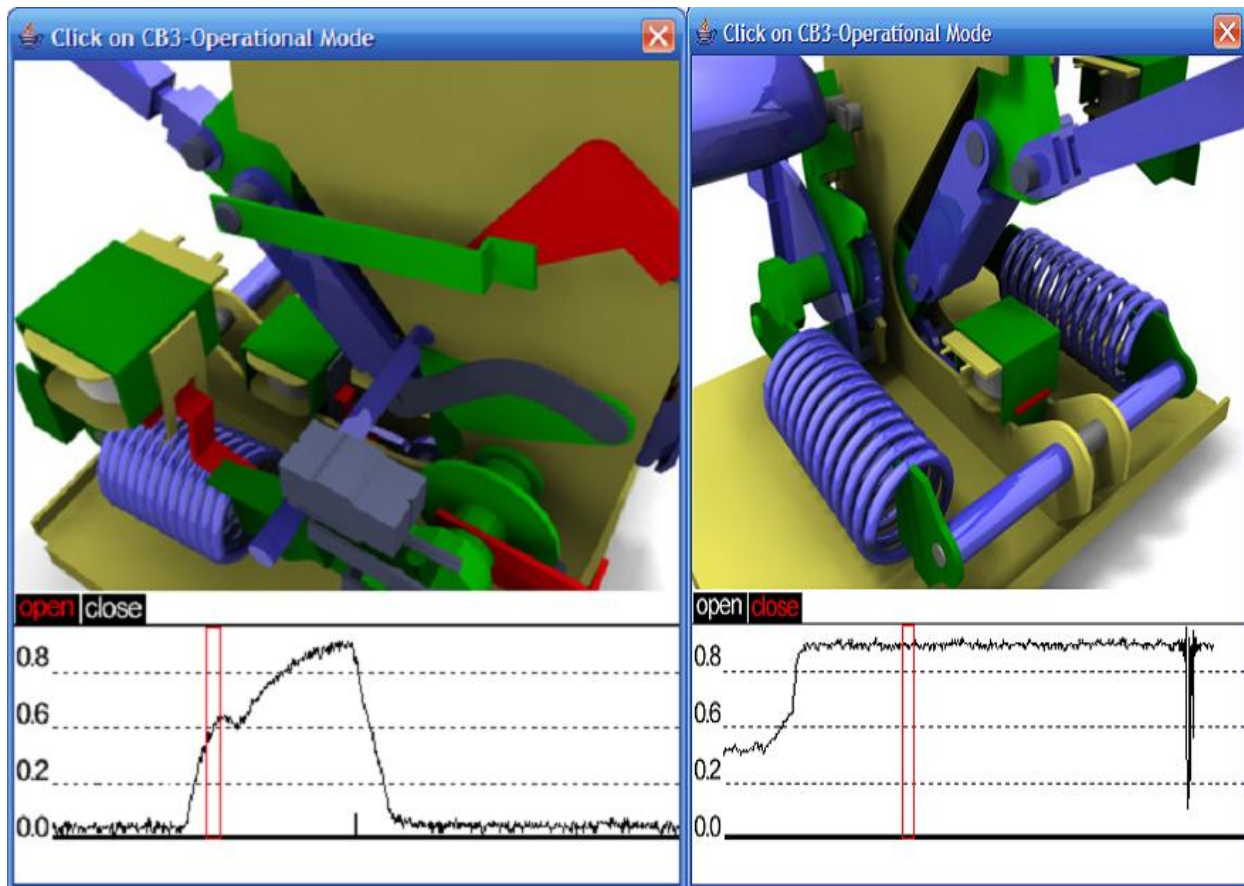

Figure 4.13: Constructional view of circuit Breaker

For operational view CB model is rigged and animated to visualize the opening and closing operations based on the user manual explanations and observation of the CB operating mechanism. The animations are precisely matched with the corresponding opening and closing signals. The animations are divided into two logical parts showing the animation of initiating trip/close coil and the rest of the operation. The two different parts are rendered as different shots from appropriate points of view to provide the best view to user. For the operational view, application that enables user to slide through the rendered animations, which are synchronized with waveform signals was developed. The application is also capable of stretching the playback of the animation to synchronize it with other signal waveforms. As future work, this application

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can be developed based on real time signals, which would not require pre-rendered animation for visualization. Operational view is shown on Fig. 4.14.

Figure 4.14: Operational view of opening and closing of circuit breaker

All the time during analysis of case 1 fault event, automated fault location application was observing a specific folder in the background. The fault case 2 is executed by coping fault event case 2 files shown on Fig 4.1 to the observed folder. Once fault is calculated, PW diagram will update faulted line and activate VID Spreadsheet button as Fig 4.14 shows. By clicking the button user can view first layer of VID Spreadsheet for fault case 2. Fig 4.15 shows results after processing the fault case 2.

It can be noticed that in both cases calculated fault location is close to actual fault location. In the case 1 real fault location happened on Ckt. 03, between busses 41405 and 40570, 1.63 miles from bus 40570. Calculated fault location was that fault was between busses 41405 and 40570, 1.93 miles from bus 40570. Calculated error was 0.3 miles in the case 1. In the case 2, real fault location was in substation 41700, which was exactly the same as calculated by the fault location application. Appendix 1 contains fault reports of fault cases demonstrated in this section.
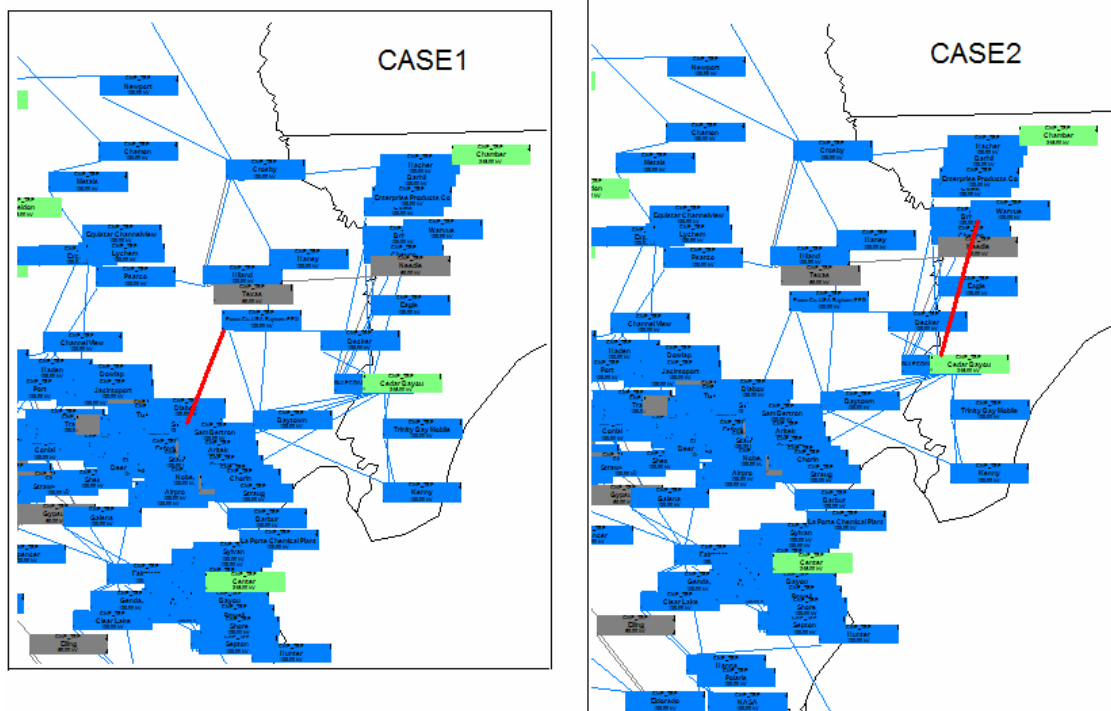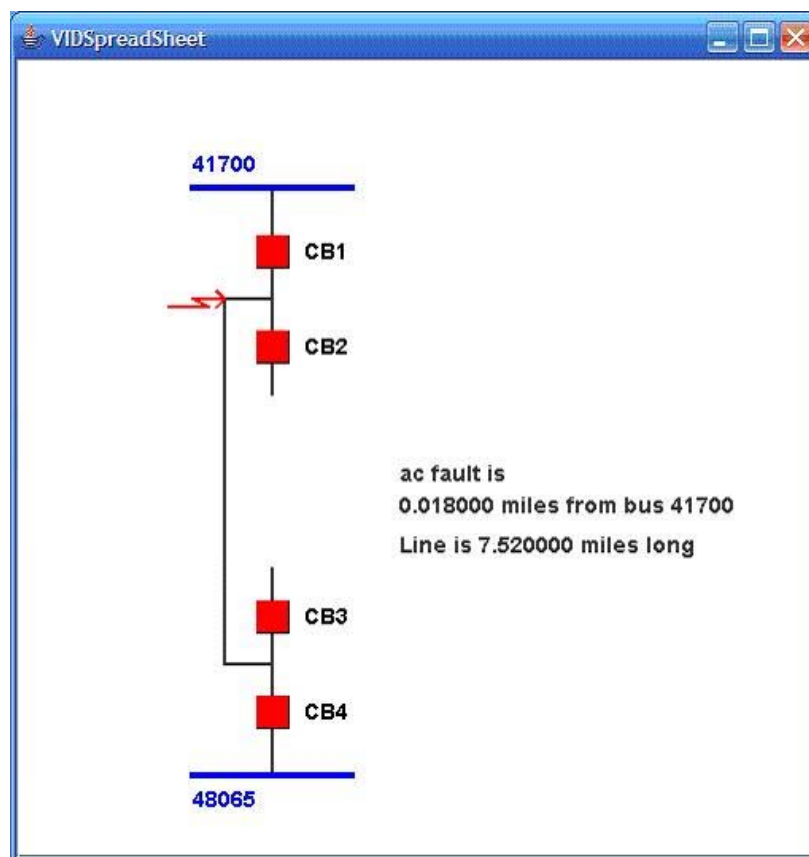
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Figure 4.15: Updated faulted line in PW Retriever view

Figure 4.16: First layer of VID Spreadsheet after processing case 2

Part 5: Conclusions

5.1. Introduction

This project proposes improvements in Fault Location (FL) calculation and presentation approach. It provides solution for obtaining more accurate and robust FL estimation and speeding up FL process. FL estimation is improved by applying the most suitable algorithm on the available recordings that correspond to a given fault event. Using automation, this approach speeds up centralized FL procedure. The complete process from retrieving and preprocessing row data to calculating fault location is done automatically which drastically decreases computation time. On the other hand the automation makes the program robust and immune to human errors. In additional enhancements in the proposed FL location approach is achieved by providing user critical information through powerful visualization.

5.2. Benefits

The following is a summary of the benefits achieved with this solution:

- System operators: Their main tool today is the SCADA system. The information used in proposed approach is automatically obtained using additional data from substation IEDs. This will speed up decision made by operator in restoring the system.

- Protection engineers: Instead of spending a lot of time on processing IED data manually, this group will be unburdened from the routine analysis tasks that will be performed automatically and will able to concentrate on complicated cases that require their involvement.

- Maintenance staff: Automatic analysis will immediately provide information about the fault location and this group will be able to take some actions right away instead of waiting for instructions from other groups. This will significantly reduce the time spent on fault repair and system restoration. At the same time CB maintenance process is improved, because each CB operation is automatically analyzed and results are accessible through different views.

5.3. Future Work

Modular structure of the proposed approach makes it possible to easily extend the architecture with new techniques. Many additional data are measured all over power system and by generalizing idea of automated collection of data into central repository redundancy and accuracy of input data can be drastically improved. Examples of additional data that could be incorporated are data from Digital Protective Relays and lightning detection data [17]. In the first phase of the project the concept of proposed solution is demonstrated for selected fault case. In future, the solution should be extended to a wider area. Process of modeling faulted area should be automated. One of possible solutions for solving this task is GIS [18].

When it comes to equipment views, several tasks may be pursued. It is possible to model the stress levels in insulators by showing the cracks automatically. One can extend the CB operational view by controlling the animation process according to the control signals 'automatically'. It is also possible to show possible problems associated with CB operation. The problems associated with individual parts can also be showed automatically. An algorithm that covers all possible fault cases can be developed to automatically do the whole animation process (both normal and abnormal operation, according the condition of the input signals).

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Appendix 1

Case 1 - *****Fault Location Report*****

The Genetic-Algorithm based Approach is selected by the program

The estimated fault type is: bg
The possible fault locations are listed below:
The columns represent Fitness value, beginning bus #, terminating bus #,
circuit #, fault location from bus 1 (miles), per unit fault location,
fault resistance (p.u.), and fault type
-51.42832,40570,41405,03,3.59,0.869249,0.012549,bg
-52.49327,40570,41405,03,3.29,0.79661,0.00941177,bg
-59.99707,40570,41405,03,1.13,0.273608,0.00627451,bg

The most possible fault location is obtained as:
On the line from 40570(EXXON_) to 41405(S_R_B_W8) (circuit# is 03)
The fault is 0.469249 p.u. (1.93miles) from the bus40570(EXXON_)
The fault resistance is 0.012549 p.u.

The voltages at the fault point are:
Phase A Magnitude(p.u.): 1.017991252632693, Angle(degrees): 27.02884976179119
Phase B Magnitude(p.u.): 0.6916974821665441, Angle(degrees): -140.31949209332805
Phase C Magnitude(p.u.): 1.1403026860803749, Angle(degrees): 139.2361145382235

The currents through the fault path are:
Phase A Magnitude(p.u.): 1.768541884190458E-5, Angle(degrees): 82.25292677817117
Phase B Magnitude(p.u.): 55.119709573130436, Angle(degrees): -140.31943495307587
Phase C Magnitude(p.u.): 4.953644028880852E-5, Angle(degrees): -147.3804852355428

Case 2 - *****Fault Location Report*****

The Genetic-Algorithm based Approach is selected by the program

The estimated fault type is: ac
The possible fault locations are listed below:
The columns represent Fitness value, beginning bus #, terminating bus #,
circuit #, fault location from bus 1 (miles), per unit fault location,
fault resistance (p.u.), and fault type
-61.81889,41700,48065,84,0.0179999,0.0023936,0.219608,ac
-61.92694,41700,48065,84,0.0581174,0.00772838,0.279216,ac
-61.93235,41700,48065,84,0.17847,0.0237328,0.175686,ac

The most possible fault location is obtained as:
On the line from 41700(WARVUE) to 48065(CD2TAP 8) (circuit# is 84)
The fault is 0.0023936 p.u. (0.0179999miles) from the bus 41700(WARVUE)
The fault resistance is 0.219608 p.u.

The voltages at the fault point are:
Phase A Magnitude(p.u.): 0.9729209555576548, Angle(degrees): 19.519512949800777
Phase B Magnitude(p.u.): 1.0181934396117573, Angle(degrees): -97.49682651530681
Phase C Magnitude(p.u.): 1.0408140213982724, Angle(degrees): 138.8860708434178

The currents through the fault path are:
Phase A Magnitude(p.u.): 3.9591916260524753, Angle(degrees): -11.934108308105667
Phase B Magnitude(p.u.): 7.546762923128567E-4, Angle(degrees): 172.0279546511029
Phase C Magnitude(p.u.): 3.9582049094944094, Angle(degrees): 168.06117180104854