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Advances in Disturbance Recording and Play Back

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Abstract

The COMTRADE standard has become an indispensible tool for fault data recording and post mortem analysis. Following a disturbance, recorded fault data by the various relays and FDRs are collected and analyzed to determine the root cause of the fault/disturbance. Individual relays and FDRs collect a subset of disturbance data (only the voltages, currents and breaker status that they monitor) and for a relatively short period of time. In addition, relays may be on different clocks and therefore their time stamp may be different among different relays. Thus, it is necessary to combine fault data from various devices and align their time stamps for the purpose of reconstructing the disturbance. This task is time consuming and because the information is limited to whatever information is collected by the relays, it requires in general some interpretation. In the aftermath of the blackout of August 2003 the task of combining and aligning data from various recorders was an enormous undertaking and has brought this issue into focus. There is an alternative that provides the means of reconstructing system disturbances automatically. Recent work on the SuperCalibrator resulted in technology that provides an automatic reconstruction and "play back" of a system wide disturbance. The paper describes this technology. By the time the paper will be presented we will have experience from numerical experiments of this technology with two actual system: (a) on a five substation system (USVI-WAPA) and (b) on the Blenheim-Gilboa pumped hydro plant. The approach is briefly described as follows: At each substation, the SuperCalibrator system collects data from all relays, FDRs, PMUs, etc. and a state estimator is executed at user selected intervals (the C37.118 rates are supported). The computed substation state (data, substation model and connectivity) is stored in a COMTRADE like circular storage scheme (last in – first out) in the substation computer. A high end personal computer can store typically data for several months. At a central location (the control center) the data from each substation can be collected over a user specified interval (for example 10:00 am to 10:15 am), and "played back" to provide the system trajectory over this period of time at any time rate. Specifically, the retrieved data are used to reconstruct the overall system state at the specified rate (minimum of 10 times per second) and the system state is displayed with a variety of visualization options (for example voltage profile over the entire system, real power flows, reactive power flows, phase angles, etc.). The visualization options are interactive. The paper will describe the technology and the field experience so far. In addition, the paper will discuss planned improvements in the system under a three year DoE funded project.

Introduction

Phasor Measurement Units (PMUs) are beginning to be deployed at key locations on utility networks to implement or assist specific functions. In general these devices may be integrated with a number of other functions, such as protective relaying, metering, etc. This integration makes these devices multifunctional and justify the investment. As a result, many manufacturers have announced to integrate this technology in protective relays, fault recorders, etc. It is expected that in a very short time, the GPS synchronization technology will be an integral part of any intelligent device in the electric power system. There is much work devoted to developing applications that utilize data from these devices, most notably utilization of PMU data for state estimation, stability monitoring, voltage stability monitoring, interarea oscillations, etc.

The PMU technology naturally provides the capability of fault recording as any other intelligent electronic device. However the PMU technology can go one step further. Specifically, the PMU technology enables distributed state estimation that can verify collected data and reject any bad data without the need for a centralized state estimator. By the nature of this operation, the model of the system is part of the process. In addition any errors in the model of the system (both analog - unit parameters, transformer model, etc. - and digital - breaker status, etc.) are identified and corrected. The end result is that the technology provides in real time validated data as well as validated model of the system. In this setting one can develop a system that will be storing the model and any changes of the model as they occur (breaker operations, switching operations, etc.) as well as operating data (voltages, currents, frequency, rate of frequency change, etc.). Subsequently, the data can be "played back" to review the operation of the system over any user selected time interval. This process revolutionaries the fault recording - in this case we should be talking about disturbance recording and analysis. The steps towards achieving this goal are described in this paper. Specifically, the next section describes the distributed state estimation that enables the creation of the needed data and models. The next section describes the storage scheme of the data generated with the distributed state estimator. Following that the next section describes the procedure of re-creating the operating conditions of the system over a user selected time interval and the visualization and animation methods used in this part. Finally, the disturbance play back method is illustrated on two actual systems: (a) the NYPA Blenheim-Gilboa plant and (b) the Longbay substation of the USVI-WAPA system.

Review of Distributed Dynamic State Estimation

The distributed dynamic state estimator operates at the substation using only local data (any data collected with IEDs within the substation). In particular, the distributed dynamic state estimation algorithm utilizes a three-phase breaker-oriented and instrumentation channel inclusive model of the substation along with the set of measurements from PMUs, relays, DFRs, meters, etc. Using the above described substation model and the measurements a state estimation is performed to extract the real time dynamic model of the substation. In this paper a quasi-dynamic state estimation model is considered, that is the electromechanical dynamics of the system are modeled but the fast electrical transients are neglected. The dynamic state of the substation is defined as the voltage magnitude and phase angle at each bus of the substation as well as the buses at the other ends of the lines/circuits connected to the substation. The state is extended to include internal states of the devices (e.g. torque angle, generator rotor speed, etc.) as shown in Figure 1.

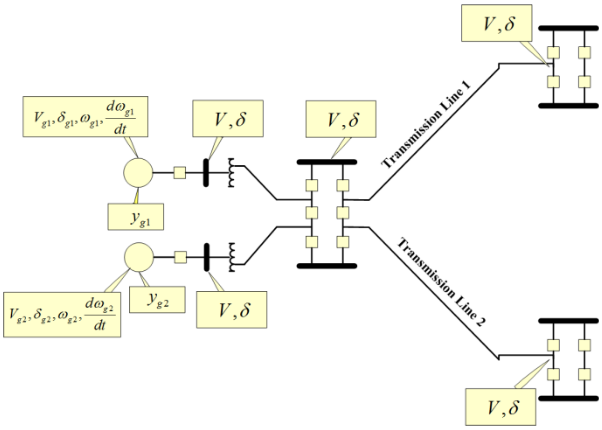


Figure 1: Distributed Dynamic State Estimation-State Definition

The dynamic state estimator operates on the streaming data sets as follows. The measurements from all available devices are collected in a station bus and converted into a C37.118 data stream. For each specific instant of time the data are time aligned and the dynamic state estimator operates on this data to generate the dynamic state of the system. Subsequently the estimated dynamic state of the system is converted into streaming C37.118 data. The flow of data is illustrated in the Figure 2.

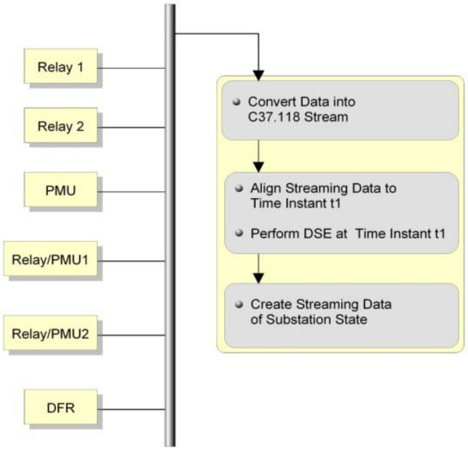


Figure 2: Distributed Dynamic State Estimation-Data Flow

Historical Estimated Data Storage Scheme

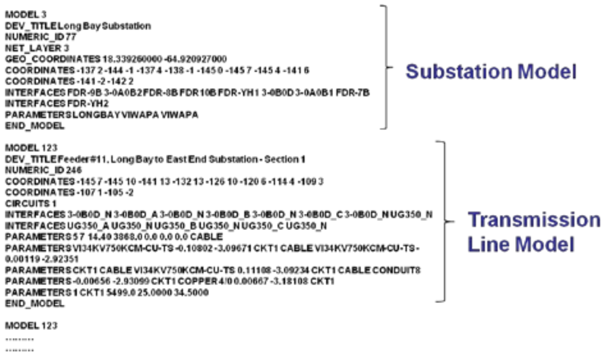
For the purpose of disturbance analysis, the information describing the system (both model and operating state) is stored each time the dynamic state estimation is performed. This storage allows the reconstruction of the operating state of the system at the discretion of the operator for any operator selected past time interval. The reconstruction is presented via graphical visualization techniques with multiple user options over a user specified time interval. This system enables to recall disturbance data for any past time interval and then played back. Of course the "play-back" capability is not limited to disturbance data only. It equally applies to normal operating conditions. This capability is superior to the present practice of capturing disturbance data with relays and then requiring user manual work to align multiple records from relays and interpret the data.

Model and Data Storage Scheme

The basic requirement of the proposed "play back" capability is that historical data/measurements should be stored together with coincidental model data. Therefore three types of coincidental information should be stored: full model, model changes, and data. Brief description follows.

A. Full model

System full model means the description of all component models that make up the system used in the dynamic state estimation. The model is stored in WinIGS format that allows the physically based modeling of the components. It is important to note other standard formats can be used, for example the CIM if it is augmented to support the requirements of reconstruction as defined in this paper. Figure 3 illustrates a substation and a transmission line model based on this format (in terms of the physical parameters of the component). The substation model includes geographic coordinates, interfaces, parameters, and so on. The transmission line model includes geographic coordinates, interface, line parameters, and so forth. The time of day for which the full model is stored can be arbitrarily selected for example 2 am.

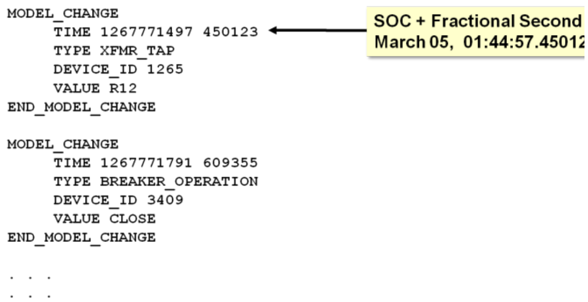


```
MODEL 3
DEV_TITLE Long Bay Substation
NUMERIC_ID 77
NET_LAYER 3
GEO_COORDINATES 18.339260000 -64.920927000
COORDINATES -137 2 -144 -1 -137 4 -138 -1 -145 0 -145 7 -145 4 -141 6
COORDINATES -141 -2 -142 2
INTERFACES FDR-9B 3-0A0B2 FDR-8B FDR10B FDR-YH1 3-0B0D 3-0A0B1 FDR-7B
INTERFACES FDR-YH2
PARAMETERS LONGBAY VIWAPA VIWAPA
END_MODEL

MODEL 123
DEV_TITLE Feeder#11, Long Bay to East End Substation - Section 1
NUMERIC_ID 246
COORDINATES -145 7 -145 10 -141 13 -132 13 -126 10 -120 6 -114 4 -109 3
COORDINATES -107 1 -105 -2
CIRCUITS 1
INTERFACES 3-0B0D_N 3-0B0D_A 3-0B0D_N 3-0B0D_B 3-0B0D_N 3-0B0D_C 3-0B0D_N UG350_N
INTERFACES UG350_A UG350_N UG350_B UG350_N UG350_C UG350_N
PARAMETERS 5 7 14.40 3868.0 0.0 0.0 0.0 CABLE
PARAMETERS VI34KV750KCM-CU-TS -0.10802 -3.09671 CKT1 CABLE VI34KV750KCM-CU-TS -
0.00119 -2.92351
PARAMETERS CKT1 CABLE VI34KV750KCM-CU-TS 0.11108 -3.09234 CKT1 CABLE CONDUIT8
PARAMETERS -0.00656 -2.93099 CKT1 COPPER 4/0 0.00667 -3.18108 CKT1
PARAMETERS 1 CKT1 5499.0 25.0000 34.5000
END_MODEL

MODEL 123
.........
.........
```

Figure 3: Examples of WinIGS format for Component Model Parameters

B. Model changes

Model changes should be recorded and stored as well as the time stamp at which the model change occurs. The requirement is that the stored full model and model changes should provide the information needed to reconstruct the system model at any time. To limit storage space, model changes are stored by exception. That is, whenever the system model is changed, the event should be reported and recorded in the storage scheme. As shown in Figure 4, the report consists of the time when the event occurs, the type of the corresponding model change and its identification number, the value changed, and so on. The event time is based on UTC time comprising the second of Century (SOC) and fractional second. Also, each line in the file format begins with a keyword optionally followed by one or more arguments.



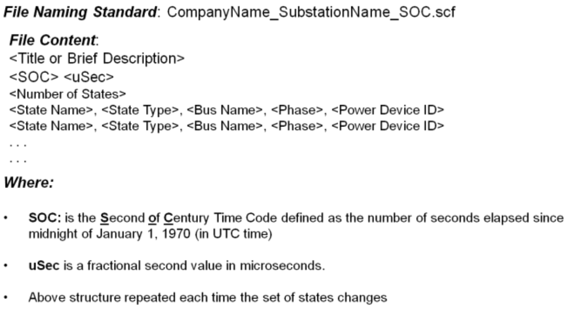
```
MODEL_CHANGE
     TIME 1267771497 450123
     TYPE XFMR_TAP
     DEVICE_ID 1265
     VALUE R12
END_MODEL_CHANGE

MODEL_CHANGE
     TIME 1267771791 609355
     TYPE BREAKER_OPERATION
     DEVICE_ID 3409
     VALUE CLOSE
END_MODEL_CHANGE

 . . .
 . . .
```

SOC + Fractional Second
March 05, 01:44:57.45012

Figure 4: Examples of Stored Model Changes

C. Data

At each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format. Three types of files are used: (1) configuration files, (2) state data files, and (3) triggered event files. The configuration files have the description of state names, types, and locations, and the state data files have state values as well as model change information. Finally, the triggered event files have waveform data recorded for each triggering event in COMTRADE format. The configuration files and state data files stored one for each day, and the triggered event files stored one for each event. Figures 5-7 exemplify the corresponding files.



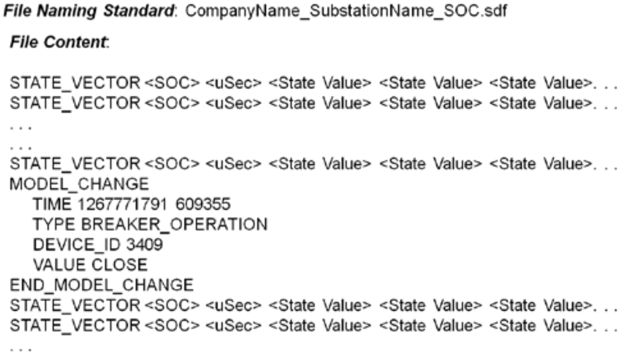
File Naming Standard: CompanyName_SubstationName_SOC.scf

File Content:
<Title or Brief Description>
<SOC> <uSec>
<Number of States>
<State Name>, <State Type>, <Bus Name>, <Phase>, <Power Device ID>
<State Name>, <State Type>, <Bus Name>, <Phase>, <Power Device ID>
. . .
. . .

Where:

- **SOC:** is the Second of Century Time Code defined as the number of seconds elapsed since midnight of January 1, 1970 (in UTC time)
- **uSec** is a fractional second value in microseconds.
- Above structure repeated each time the set of states changes

Figure 5 Configuration files

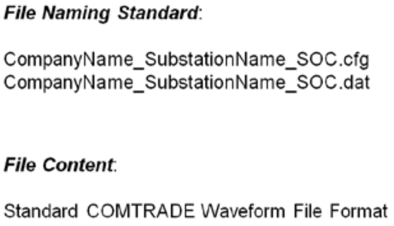


File Naming Standard: CompanyName_SubstationName_SOC.sdf

File Content:

```
STATE_VECTOR <SOC> <uSec> <State Value> <State Value> <State Value>. . .
STATE_VECTOR <SOC> <uSec> <State Value> <State Value> <State Value>. . .
. . .
. . .
STATE_VECTOR <SOC> <uSec> <State Value> <State Value> <State Value>. . .
MODEL_CHANGE
   TIME 1267771791 609355
   TYPE BREAKER_OPERATION
   DEVICE_ID 3409
   VALUE CLOSE
END_MODEL_CHANGE
STATE_VECTOR <SOC> <uSec> <State Value> <State Value> <State Value>. . .
STATE_VECTOR <SOC> <uSec> <State Value> <State Value> <State Value>. . .
. . .
```

Figure 6 State data files



File Naming Standard:

CompanyName_SubstationName_SOC.cfg
CompanyName_SubstationName_SOC.dat

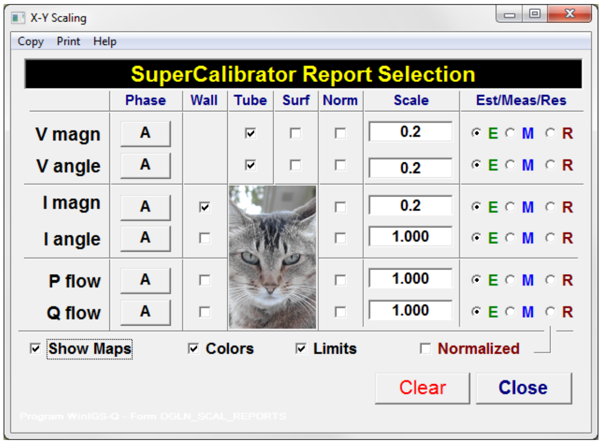
File Content:

Standard COMTRADE Waveform File Format

Figure 7 Triggered event files

Disturbance Playback

The distributed state estimator at each substation stores the streaming data with (a) time tag, (b) network status, and (c) substation real time model at the time. This data allows the reconstruction of the system model and operating conditions at each past time. The reconstructed operating conditions can be displayed in a variety of ways. To make the process easy and to avoid overwhelming the operator with a vast amount of data available from the storage scheme of the distributed state estimator (SuperCalibrator), an easy to use menu of visualizations and animations has been developed. The system includes a graphical interface that displays the data in 2-D or 3-D visualizations. This is a visualization tool that is incorporated in WinIGS software. Specifically, this user friendly graphic solution is called "Play Back". In more detail, this data can be “played back” for any user specified past time interval. Reconstructed state is presented via graphical visualization techniques (3-D rendering, animation etc) with multiple user options. Various visualizations as depicted in Figure 8 allow the user to observe specific performance parameters of the system. For example, (a) voltage profile evolution, (b) transient swings of the system, (c) electric current flow, etc. It will enable to move from fault recording with individual relays and fault recorders to system disturbance recording and playback capability.



	Phase	Wall	Tube	Surf	Norm	Scale	Est/Meas/Res
V magn	A		☑	☐	☐	0.2	● E ○ M ○ R
V angle	A		☑	☐	☐	0.2	● E ○ M ○ R
I magn	A	☑			☐	0.2	● E ○ M ○ R
I angle	A	☐			☐	1.000	● E ○ M ○ R
P flow	A	☐			☐	1.000	● E ○ M ○ R
Q flow	A	☐			☐	1.000	● E ○ M ○ R

☑ Show Maps ☑ Colors ☑ Limits ☐ Normalized

Figure 8 Disturbance PlayBack User Interface

As shown in Figure 8 there are several options for displaying the results. As an example, the voltage magnitude of each node can be visualized as a tube. The height of the tube is proportional to the voltage magnitude of this node. The numerical value can be the actual voltage (estimated), the measured voltage or the residual between measurement and estimated value - any one of this is selected by pressing the appropriate radio button on the form. The voltage phase of a node is visualized as an arc. The angle of the arc is proportional to the voltage phase angle of the corresponding node. Again for the phase angle, the user may select the estimated angle, the measured value or the residual as in the case of voltage magnitude. As another example, the current magnitude and the power flows of each circuit can be visualized as walls. The height of the wall is proportional to the magnitude of the corresponding quantity. Note also that the user can select the display of a specific phase of the system (A, B, or C), or the positive sequence values, negative sequence values, etc.

Demonstration Example: USVI-WAPA System

A. Description of System

US Virgin Islands consist of the main islands of St. Croix, St. John, and St. Thomas, and many other surrounding minor islands. The electric power network is a stand-alone system i.e. not connected to the US national power grid, and the system is operated by the USVI Water and Power Authority (WAPA). As a matter of fact there are two stand alone systems, one for the islands of St. Thomas and St. John and another for the island of St. Croix. The SuperCalibrator has been implemented and installed on the St. Thomas and St. John islands as illustrated Figure 9. The system consists of five substations: Randolph Harley Power Plant (RHPP), Long Bay, Tutu, East End, and St. John. In the main island, i.e. St. Thomas, there is a single generating plant (RHPP) with eight units that has a total capacity of nearly 200 MW. The generating plant is connected to two networks: the 35 kV transmission network and the 13 kV distribution network. The distribution network that is directly connected to the generators consists of unbalanced loads. The transmission systems consist of overhead lines, underground cables and two submarine cables that interconnect the power systems of two islands, St. Thomas and St. John.

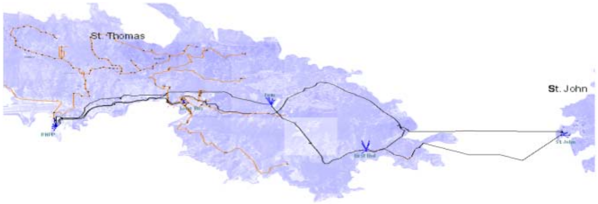


Figure 9 Single Line Diagram of the St. Thomas and St. John Electric Power System

Unlike the typical US mainland power systems that are highly interconnected to each other, the USVI-WAPA system is an isolated system with a very high R/X ratio and asymmetries. Small load changes can have a significant impact on stability. Therefore, events such as large frequency oscillations have been occurred frequently, which have sometimes led to blackouts. With an attempt to reduce the blackouts and enhance the system stability, many numerical relays, some of which have PMU capability, are installed at each substation providing measurement data to control center. For example the single diagram of Long Bay substation including all the IEDs is shown in Figure 10.

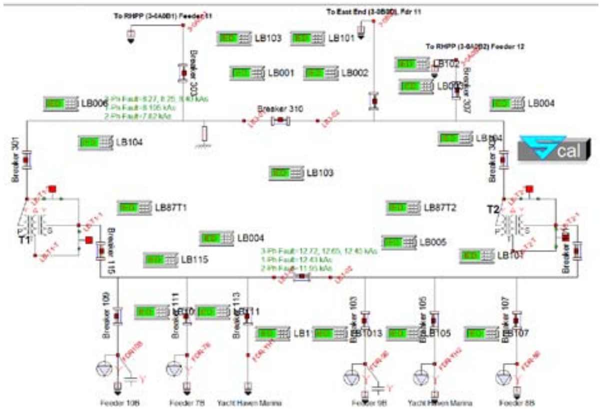


Figure 10 Single Line Diagram of Long Bay Substation including relays

B. Example Play Back

This section presents demonstrative results of the distributed state estimation performed at the Long Bay Substation with a time step of 1 estimation per cycle (60 times per second). The results include steady state and transient conditions after a three phase fault that was simulated close to RHPP substation.

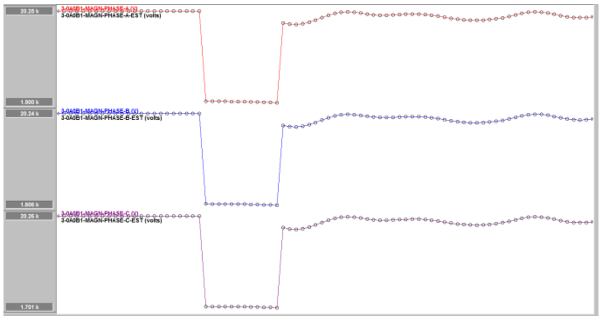


Figure 11 Estimated Voltage Magnitude of Bus 3-0A0B1

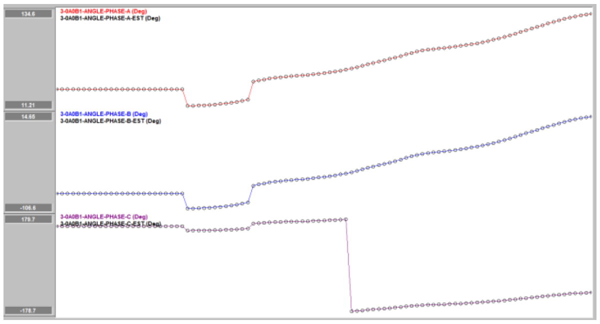


Figure 12 Estimated Voltage Phase Angle of Bus 3-0A0B1

The numerical experiments are performed as follows. First the system operation is simulated and measured data are stored. Subsequently the stored measured data are fed into the state estimation. The results of the state estimation are compared to the simulated data.

The voltage magnitude and the phase angles of each phase for bus 3-0A0B1 are shown as an example in Figures 11 and 12 using the 2-D visualization tool. The estimation results (dotted lines) are superimposed on the simulation results.

The estimation results can be also demonstrated using the 3-D visualization tool that was described before. As an example, the estimation results for phase A voltage magnitude and phase angle of the Long Bay substation are illustrated in Figure 13.

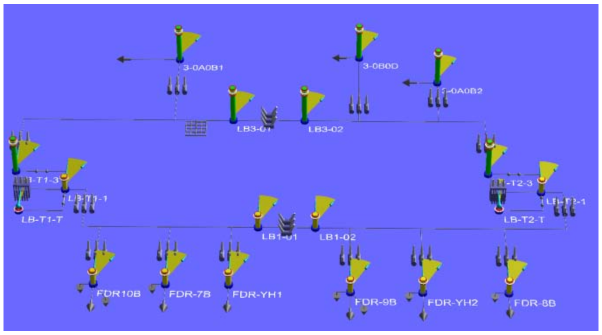


Figure 13 Long Bay substation - Bus Voltage Magnitude and Phase Angle Magnitude 3D Visualization

Demonstration Example: NYPA B-G System

A. Description of System

The NYPA Blenheim-Gilboa plant, which is located at the base of Brown Mountain in the southwest of Albany, has four generating units that produce hydroelectric power. The maximum generating capacity is 1,112 MVA, and these units supply electricity to New York customers via three 345 kV transmission lines as represented in Figure 14: Fraser-Gilboa, Gilboa-New Scotland, and Gilboa-Leeds.

Multi-vendor numerical relays are installed at NYPA Blenheim-Gilboa plant, some of which support GPS-synchronized measurement. These relays not only perform the basic protection functions, but also play a key role in data integration to control center where the distributed state estimator is installed. Figure 15 represents the system model of the Blenheim-Gilboa plant along with the numerical relays installed.

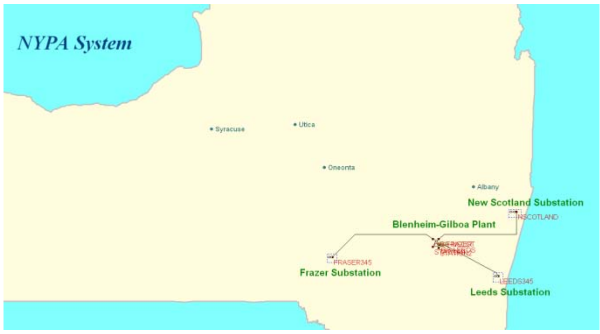


Figure 14 Single Line Diagram of NYPA Electric Power System

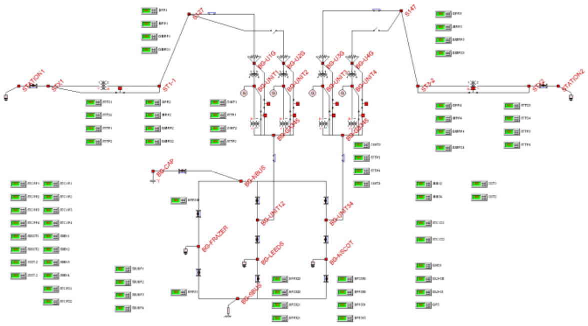


Figure 15 Single Line Diagram of Blenheim-Gilboa System including relays

B. Example Play Back

Demonstrative (numerical) results of the distributed state estimation performed at the Blenheim-Gilboa substation are presented in this section using the 2-D and 3-D visualization tools. The voltage magnitude and the phase angles of each phase for bus BG-UNIT1 are shown as an example in Figure 16 using the 2-D visualization tool. The estimation results (dotted lines) are superimposed on the simulation results.

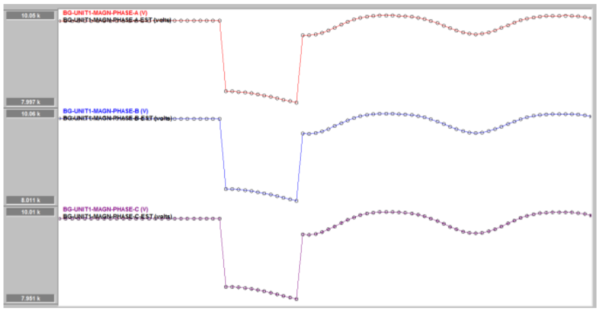


Figure 16 Estimated Voltage Magnitude of Bus BG_UNIT1 (Generator 1 Terminal)

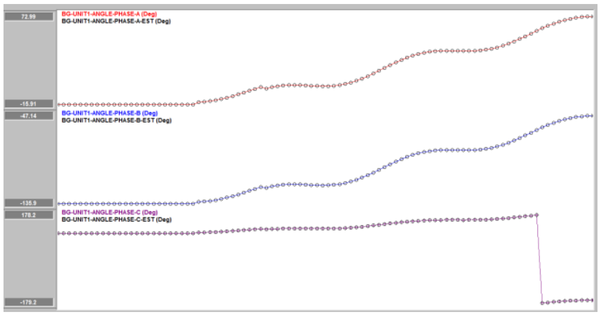


Figure 17 Estimated Voltage Phase Angle of Bus BG_UNIT1 (Generator 1 Terminal)

Phase A current magnitude is illustrated in Figure 18 in 3-D visualization. Note that the current for each device in the substation is computed based on the estimation results of the SuperCalibrator performed at the substation.

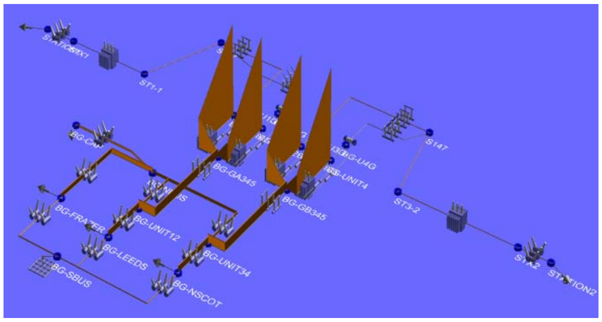


Figure 18 Blenheim-Gilboa substation - Circuit Current Magnitude 3D Visualization

Both of the above demonstrative (numerical) results of the pay back capability can be demonstrated in an animation fashion.

Summary

This paper has presented a new approach for disturbance recording and play back. Initially, a distributed dynamic estimator is presented that is performed at the substation level. Subsequently, a storage scheme that stores the information provided by the state estimator is proposed. The information that is stored and the storage format are explained in detail. The proposed scheme enables complete reproduction of the system model and operating conditions by simply selecting the start and end times. For the purpose of data playback for a specific and user defined time period, 2D and 3D visualization tools have been developed and presented in the paper. Finally, numerical examples from NYPA Gilboa-

Blenheim Substation and USVI-WAPA Long Bay Substation are presented. The state estimation results are played back and demonstrated using a 2D and a 3D visualization tool.

Acknowledgements

This work was supported by DoE project DE-0000117 and NEETRAC Project 2106BAV.

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Biographies

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