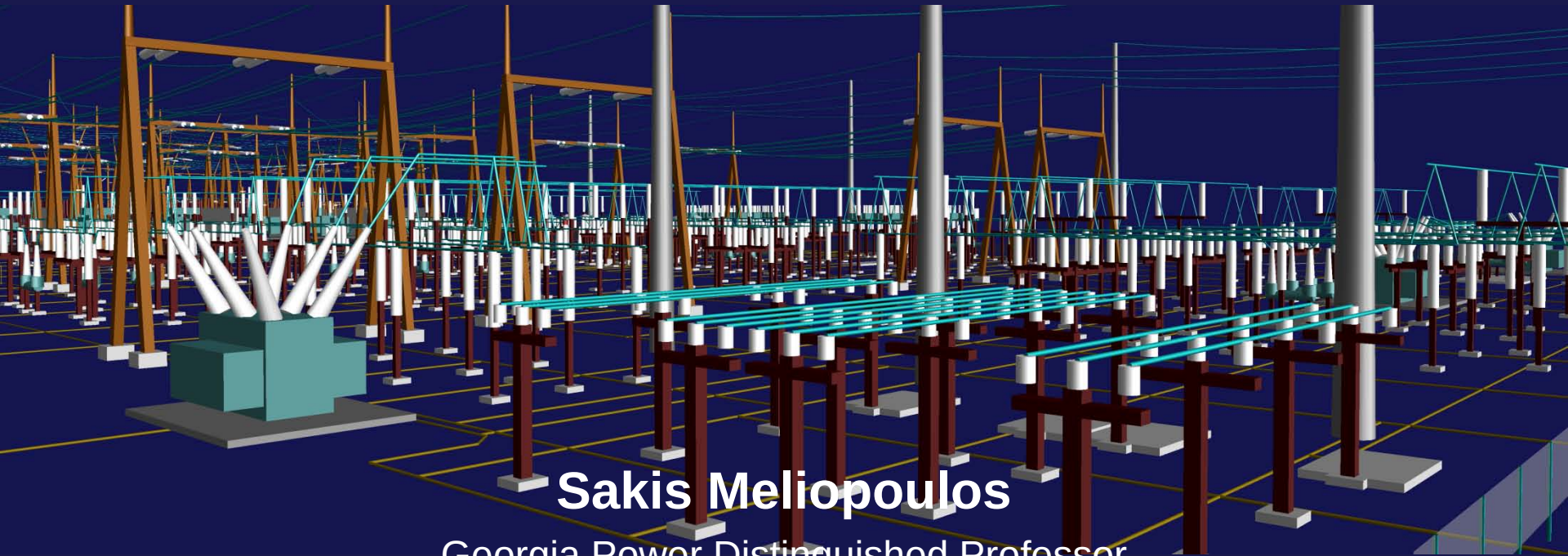


Substation of the Future: A Feasibility Study



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Acknowledgements

Research Team

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Project Summary

Digital technologies for data acquisition, automation and control have been continuously evolving for the last three decades. We formulated a revolutionary utilization and integration of existing and proposed technologies for the design of the substation of the future.

The formulated substation of the future is based on a synchronized, in-site (voltage transformer (VT), current transformer (CT), breaker, etc), digital data acquisition system that meets the requirements of all substation applications. Data transportation is all digital and granular. The system feeds data to the various applications in the form that is needed by the particular application. Data are validated via state estimation methods running at very fast rates. Applications that have been considered are: (a) SCADA and visibility functions, (b) protection and control functions, (c) power quality monitoring, (d) equipment health monitoring, and (e) enterprise data needs.

A feasibility study has been performed that provided data for the expected performance of the new approach.

The proposed project is a feasibility study to determine the feasibility of the approach and the implications, i.e. advantages and disadvantages.



Presentation Overview

History of Substation Automation/Control Centers
Project Background

Experimental SetUp

Substation Level Data Acquisition and Processing

Substation Level Data Filtering and Calibration

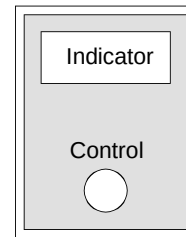
Substation-Control Center Functions

Project Achievements

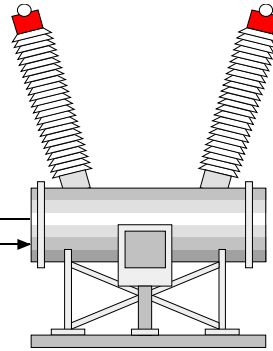
Future Work



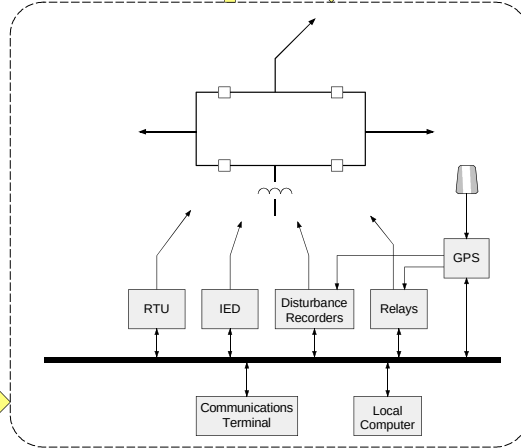
History: Evolution of Utility Automation



SCADA circa 1923

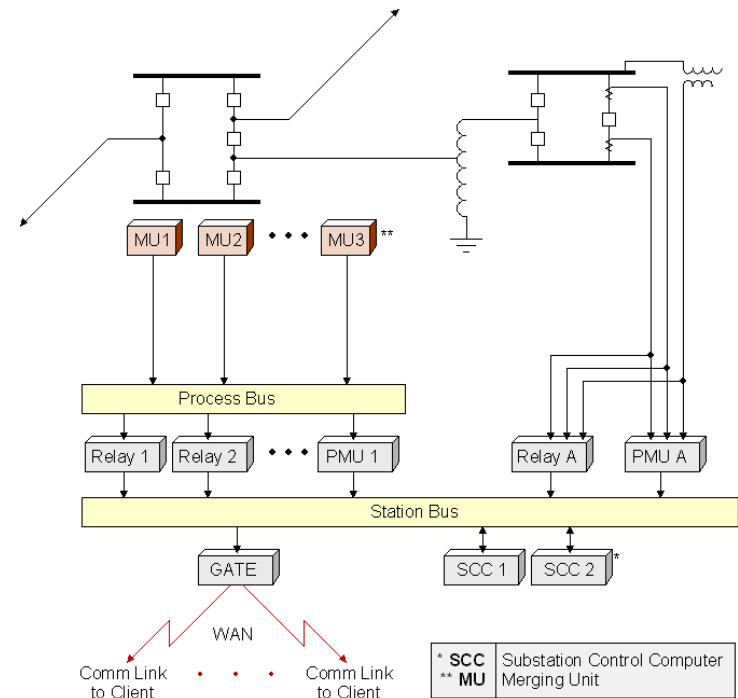


To Data Base Remote Access



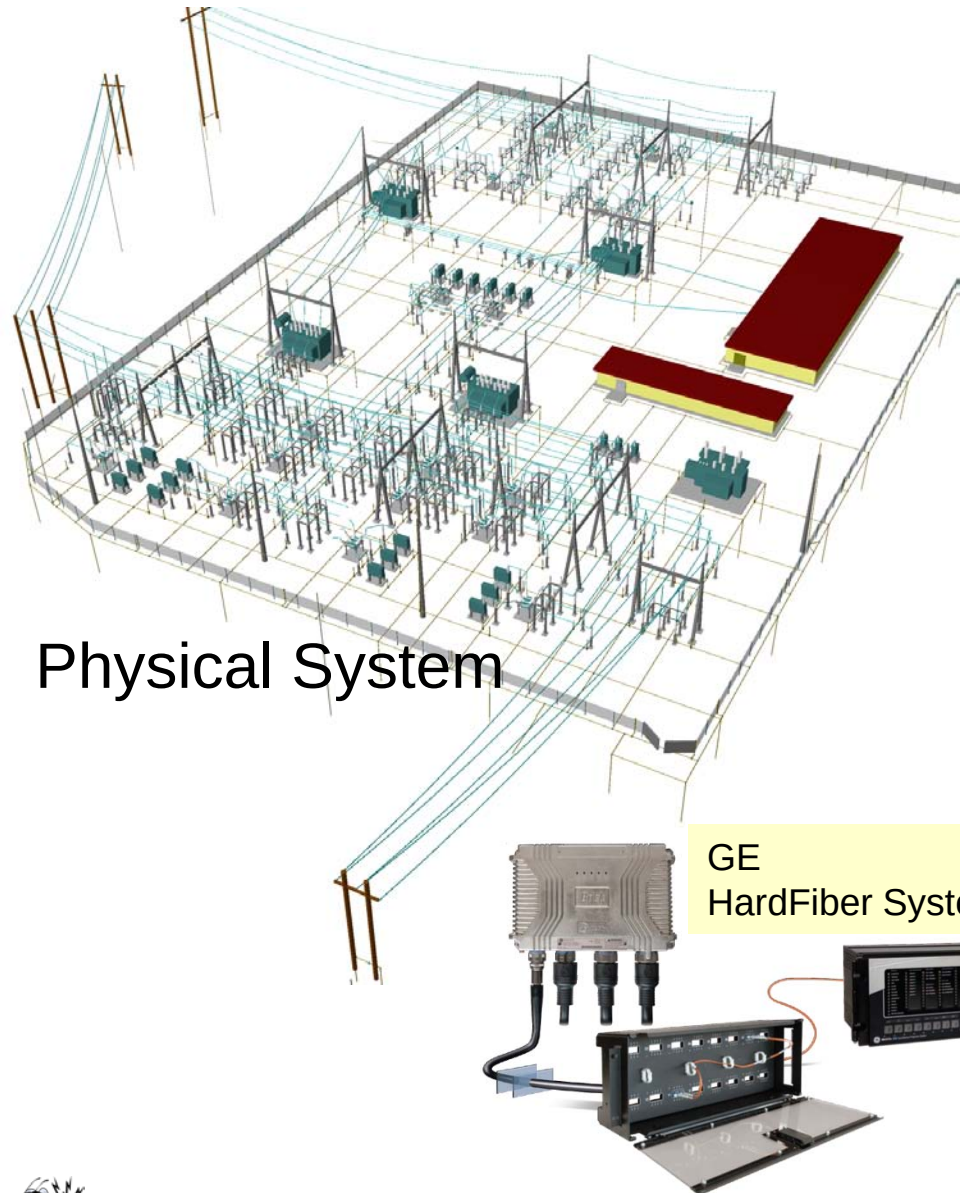
SCADA circa 2003

Communication Standards



Substation Automation - Present

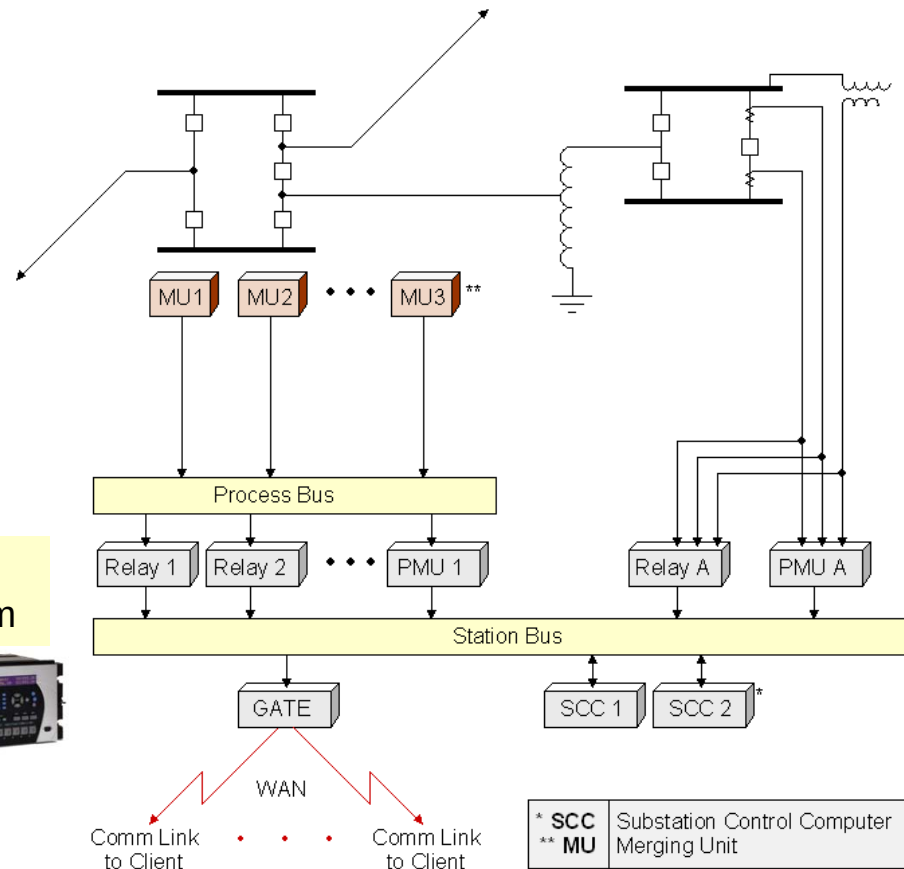
Project Background: Substation Architectures: SmartGrid



Physical System

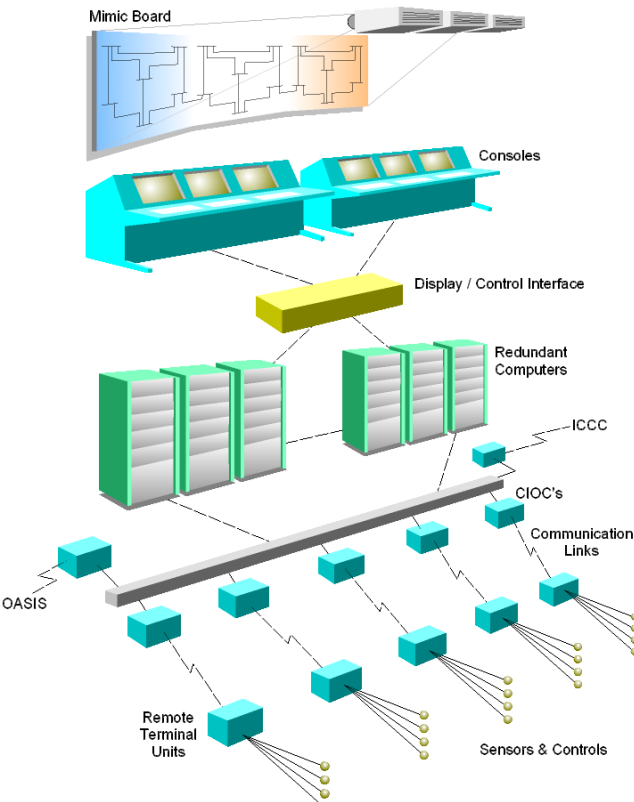
GE
HardFiber System

Protection, Control, Communications



Note: GE announced the HardFiber product months after we submitted the proposal

Control & Operation



Real Time Model

State Estimation

Applications

Load Forecasting
Optimization (ED, OPF)
VAR Control
Available Transfer capability
Security Assessment
Congestion management
Dynamic Line Rating
Transient Stability
EM Transients, etc.
Visualizations

Markets:

Day Ahead, Power Balance,
Spot Pricing, Transmission
Pricing (FTR, FGR), Ancillary
Services

A Large Number of Standards – Examples:

OASIS: Open Access Same-Time Information System

UCA: Utility Communication Architecture

ICCP: Inter-Control Center Communications Protocol

C37.118, IEC 61850, DNP3.0, ..

CCAPI: Control Center Application Program Interface

CIM: Common Information Model

Smart Grid Focus: Real
Time Model, Component
and System Protection,
Communications

Protection & Control

Component Protection

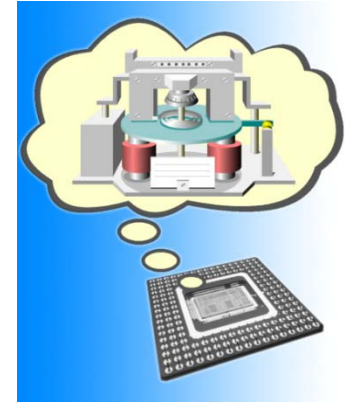
generators, transformers,
lines, motors, capacitors,
reactors

System Protection

Special Protection
Schemes, Load Shedding,
Out of Step Protection, etc.

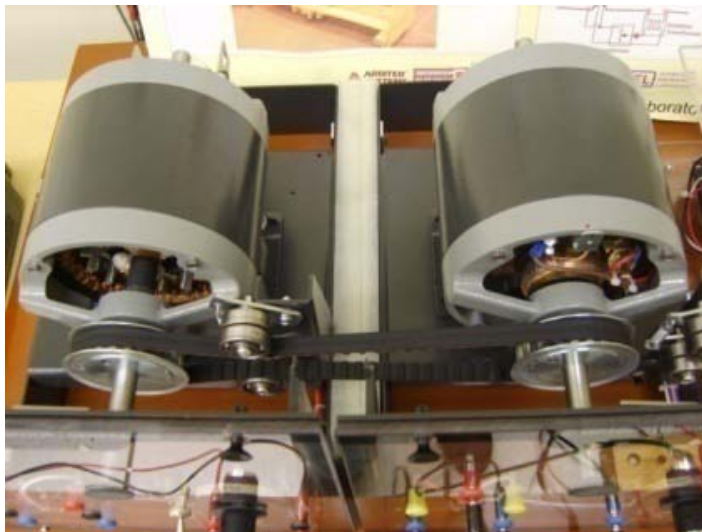
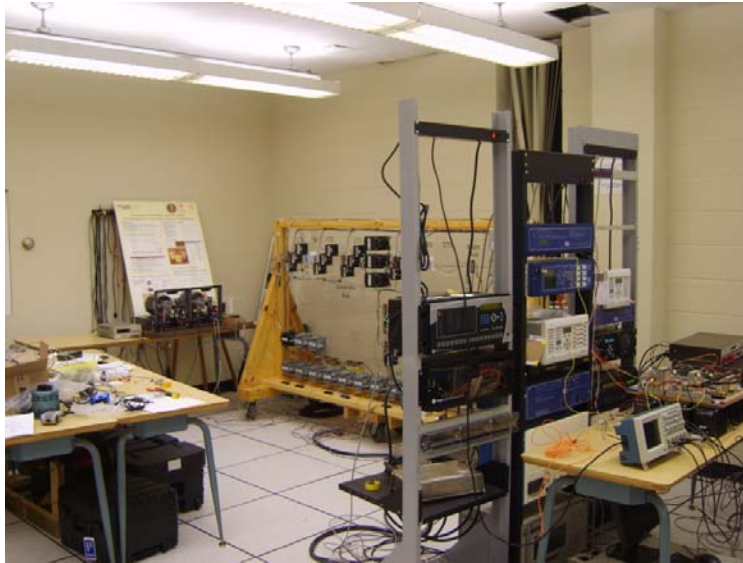
Communications

Substation Automation,
Enterprise, InterControl
Center

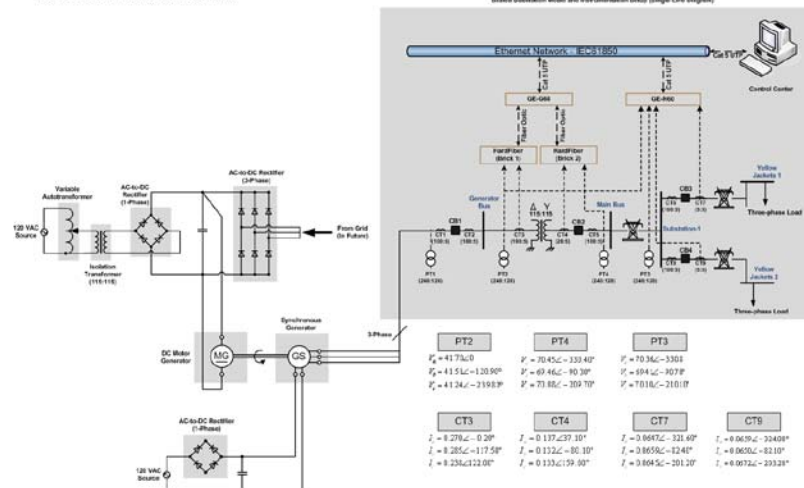


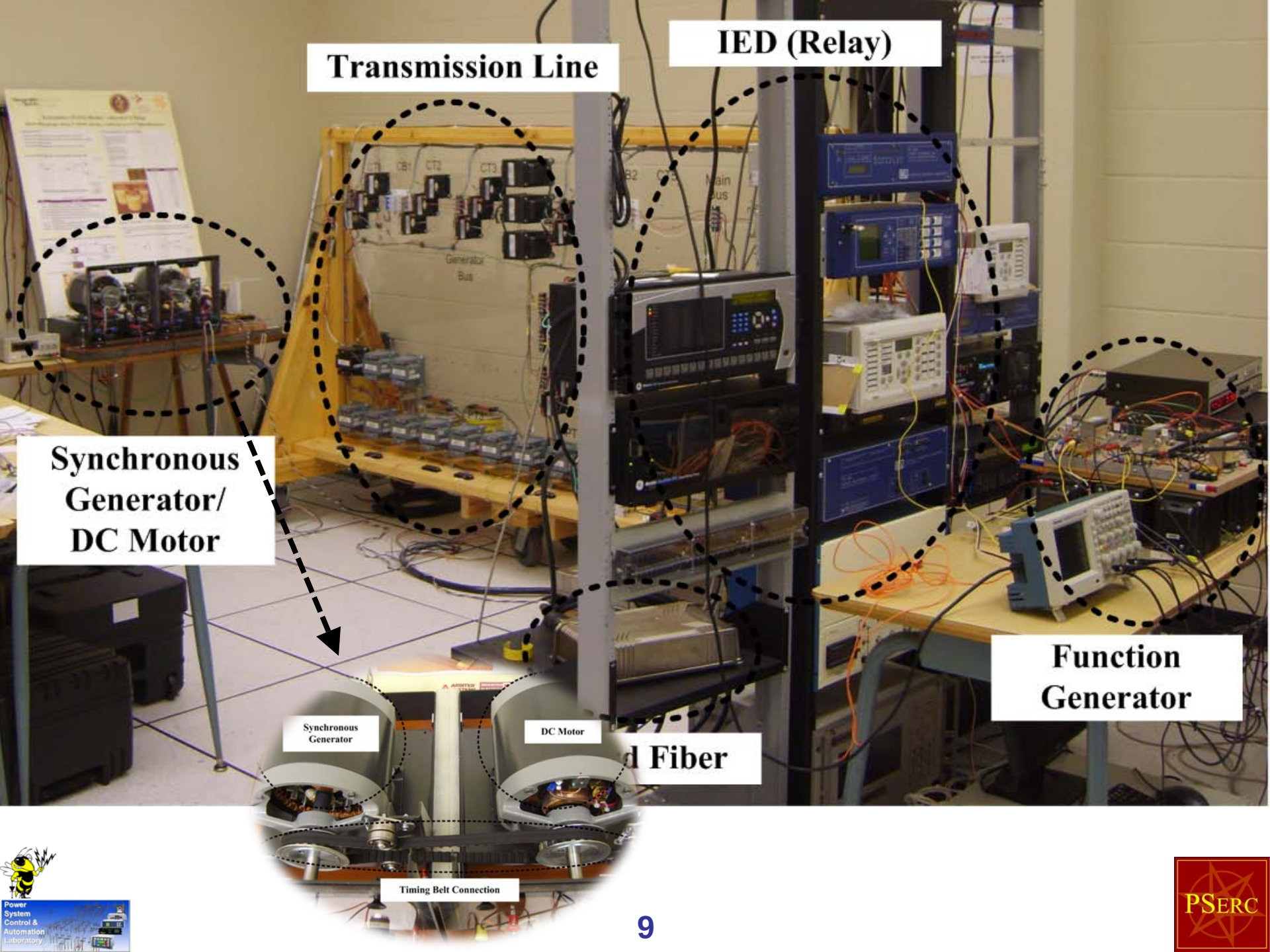
Laboratory SetUp For Evaluating Proposed Approaches

Scale Model with Instrumentation, Relays and Local Area Network



MICROGRID SCHEMATIC DIAGRAM





Transmission Line

IED (Relay)

**Synchronous
Generator/
DC Motor**

**Function
Generator**

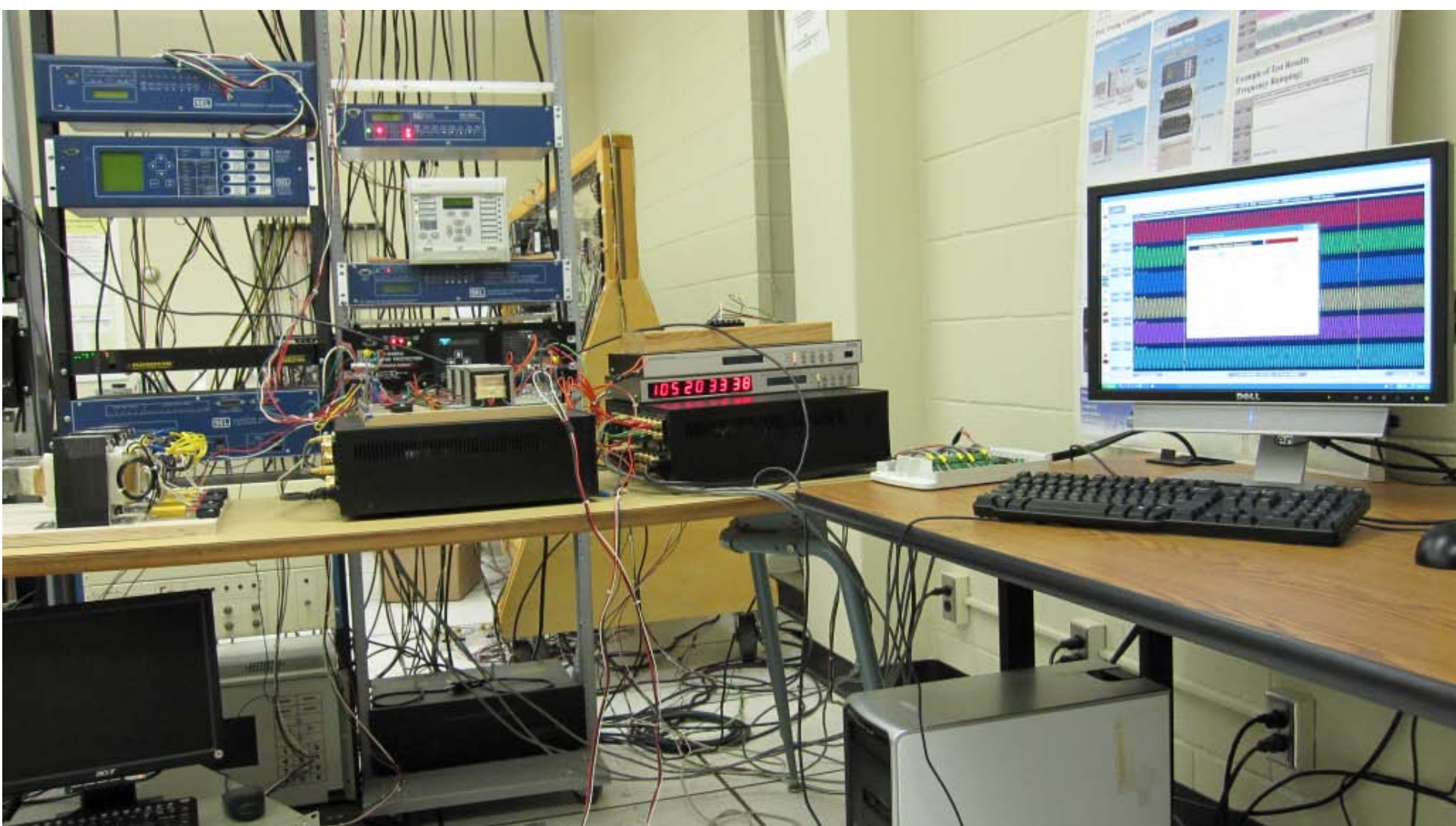
**Synchronous
Generator**

DC Motor

and Fiber

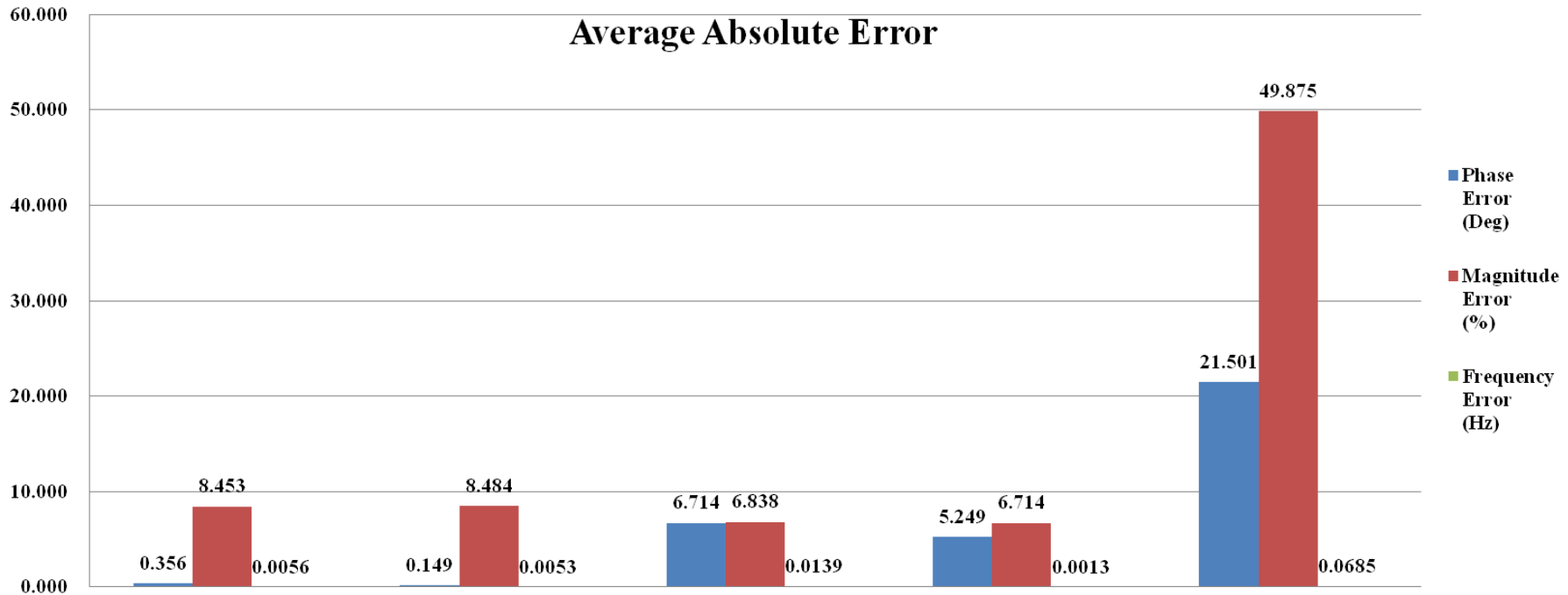
Timing Belt Connection

Test Set-up For Assessing the Quality of Data



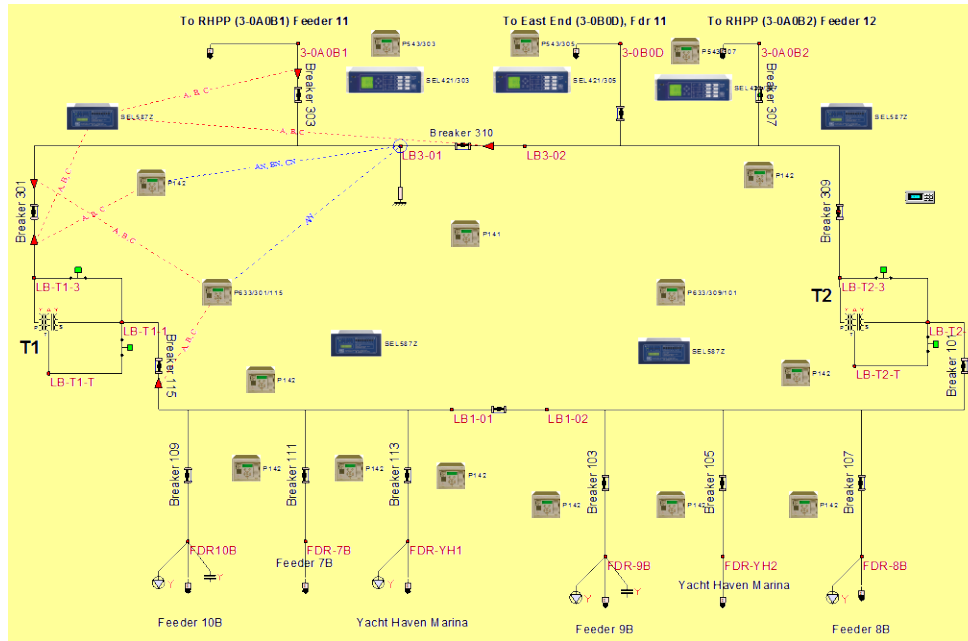
Test-B: Voltage Step & Frequency Ramp

Test Results for 5 Devices with PMU Capability



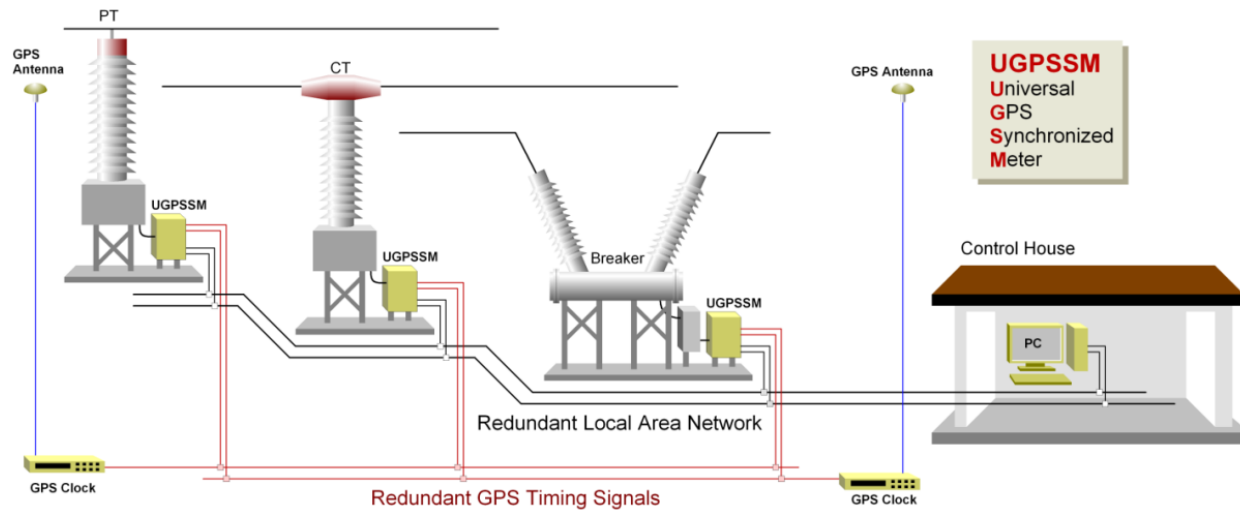
Errors under transient conditions can be high. State estimation methods are necessary to filter out the errors

Overall Approach

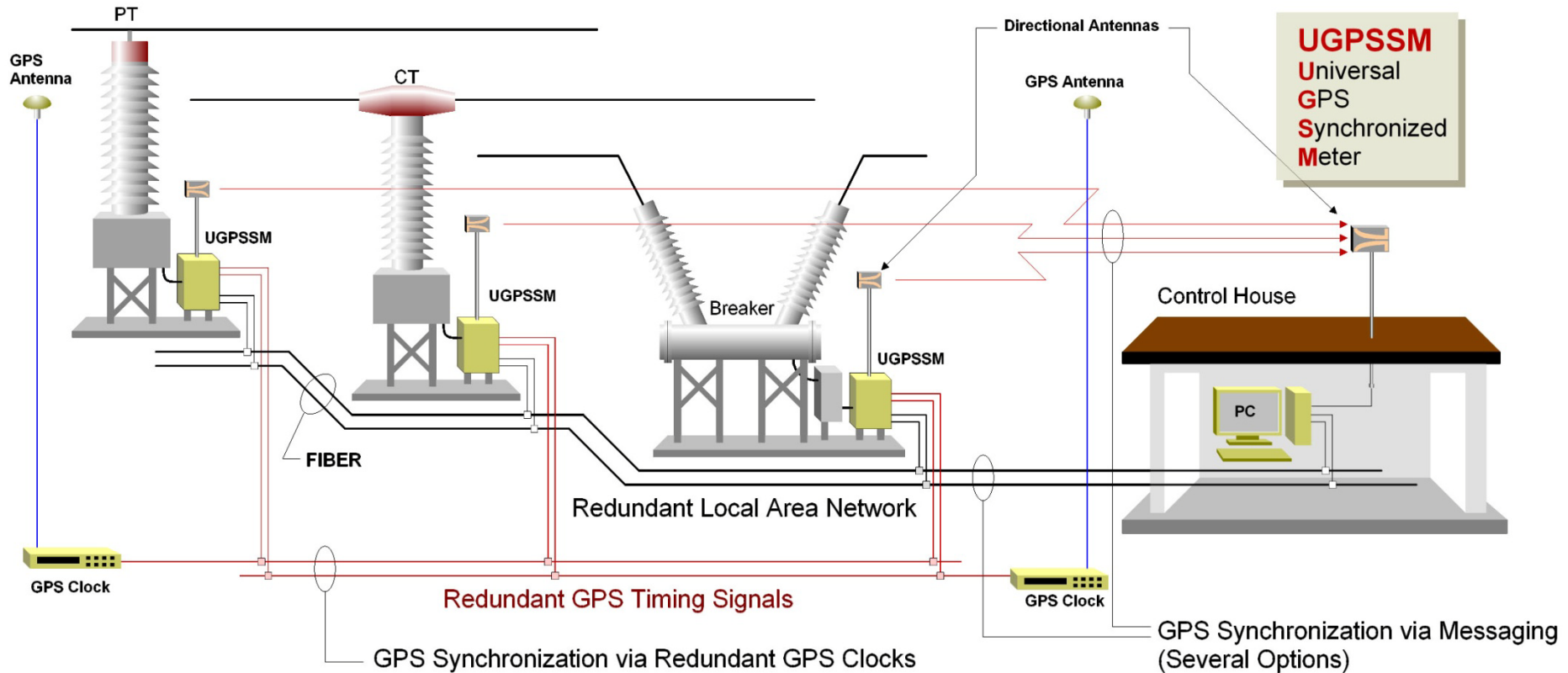


From
This

To
This



Overall Approach



Communication Options: Merging Units to Control House

1. Fiber
2. Wires
3. Highly Directional, GigaHertz Antennas



Conceptual Design of UGPSSM

Basic Design Requirements

- Fidelity

- Reliability

- Minimal time latencies (goal: better than 1 msec) – achieved using GE's Hard Fiber

GPS Synchronization

- Redundant GPS input signals

- Independent data acquisition channels (no multiplexing)

- Direct GPS synchronization

- Transfer function better than best expected instrument transformer

- Redundant communication channels

- Steaming data - throughput

Mapping Information

- Device identity to define network point

- Instrumentation channel model

- Data error correction

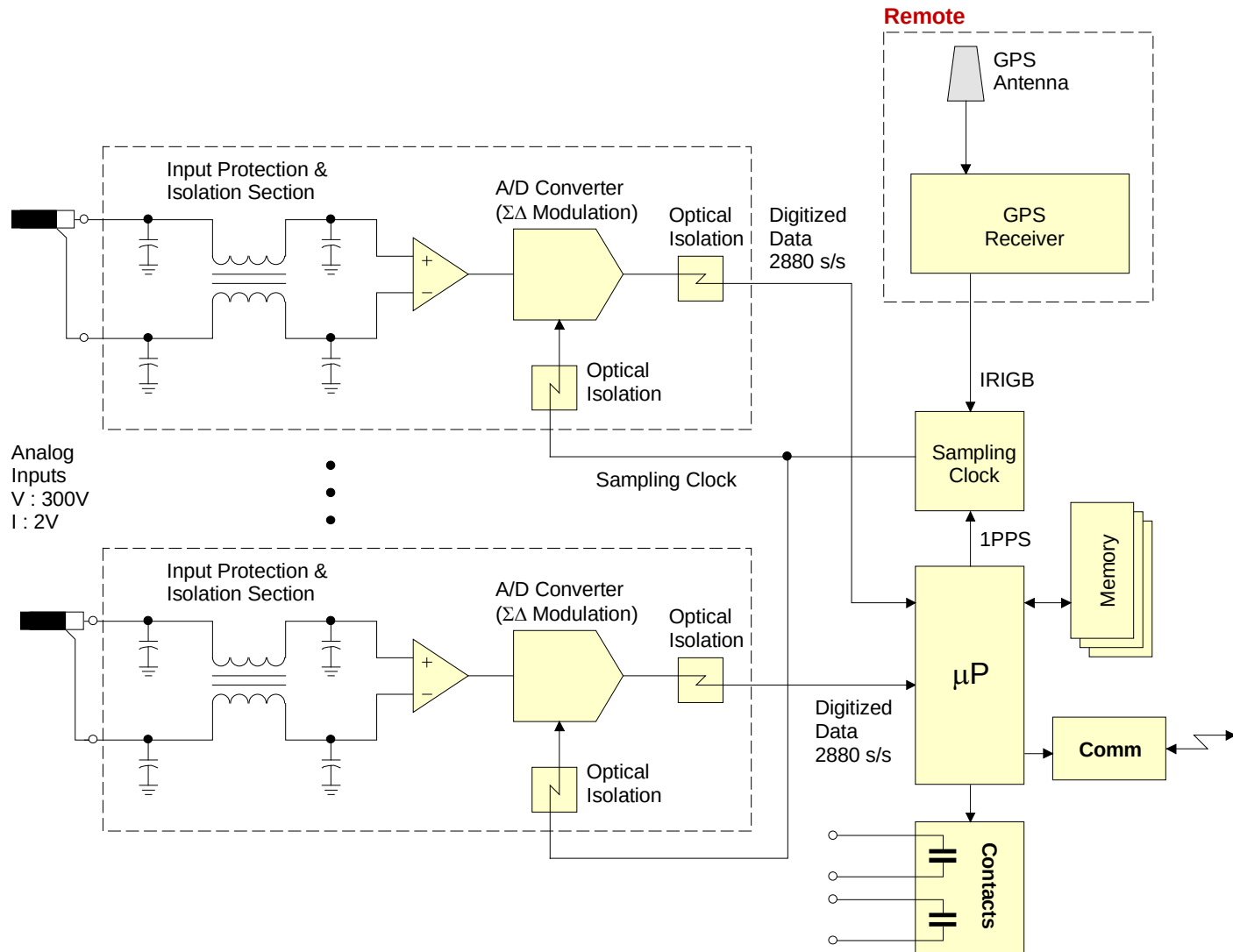
Overall Performance

- Timing error metrics have been measured using the laboratory setup

- Additional metrics to be examined are: throughput and total latency



Conceptual Design of UGPSSM



Design is Based on Macrodyne's First PMU 1620
Jay Murphy, January 1992

Conceptual Design of UGPSSM

The UGPSSM handles the following data:

CONNECTIVITY:

The name of node connected with other components

- e.g. GEN_A, GEN_B, GEN_C, GEN_N

MODELS:

Object Oriented Device Model: $i(t)$: current, $v(t)$: voltage, $y(t)$: internal variable

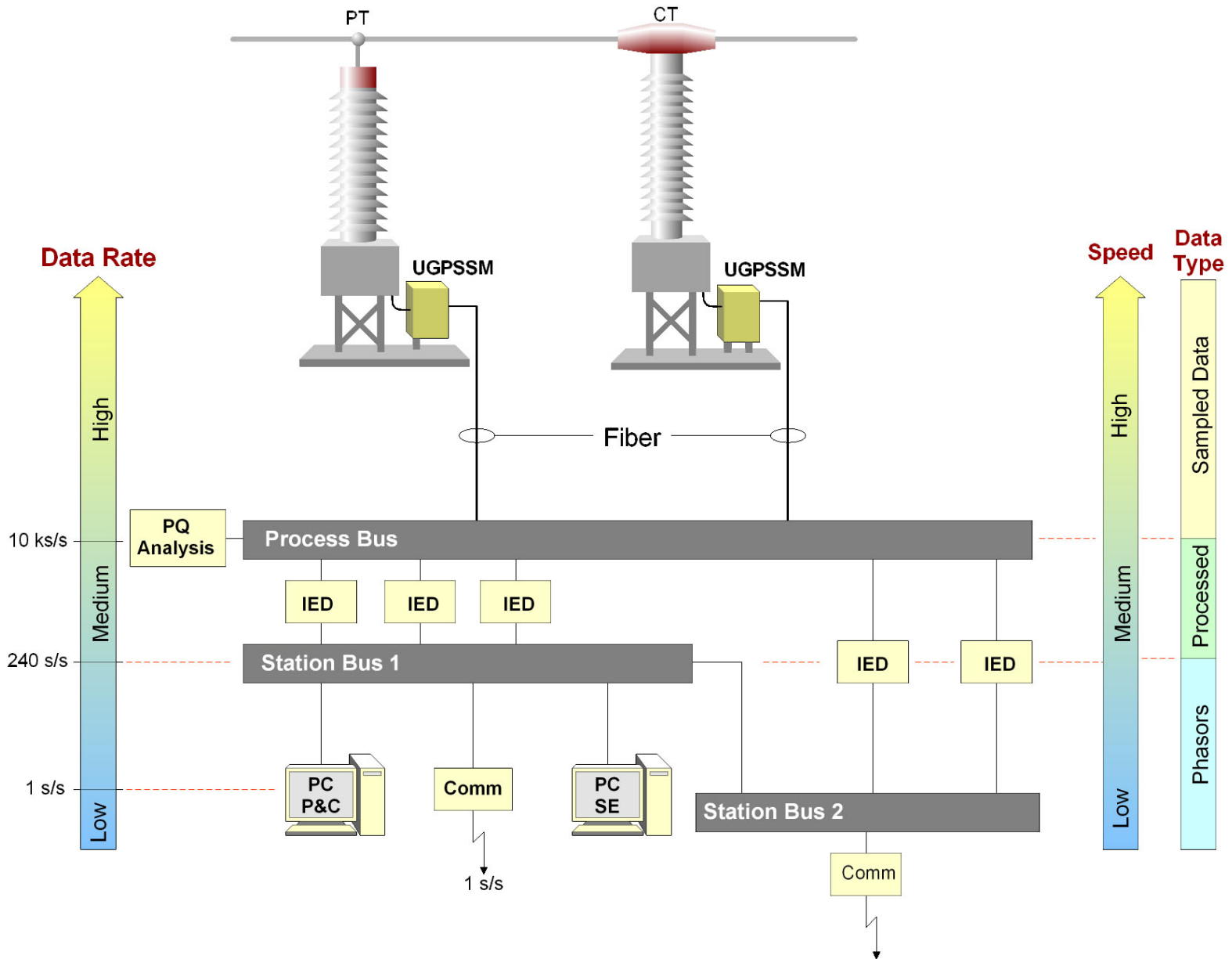
$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} - \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix} + \begin{bmatrix} f_1(t) \\ f_2(t) \end{bmatrix}$$

MEASUREMENTS:

Numerical value and measurement model:

$$z_m = c + \sum_i \alpha_i x_i + \sum_{i,j} \beta_{i,j} x_i x_j + \eta_m$$

Data Flow / Applications



Substation Data Filtering and Calibration Using The SuperCalibrator Concept

Substation State Estimator and Device Calibration

Filter all substation data with two estimators (only substation local data are used):

- (a) static state estimator (fully demonstrated)
- (b) dynamic state estimator (also supported by a DoE project)

Performance Evaluation Criterion 1: For a medium size substation (96 states, 880 data) it requires 100k multiply adds – speeds of 20 state estimations per second are achievable on a PC! A PC with quad processors can achieve more than 60 state estimations per second.

Performance Evaluation Criterion 2: Only the state estimate needs to be communicated upwards to the Control Center or to the Enterprise. This reduces communication requirements. In the case of a medium substation with 96 states and 880 data points, only 48 numbers need to be communicated.

Automated Calibration

The state estimator provides error analysis of all measurements. Any detected bad measurement can be tracked to determine if errors are systematic. In this case a calibration signal is sent to the proper UPGSSP that will make this measurement consistent. If errors are not systematic but random, then technician can be deployed to debug the instrumentation channel.



DQSE: Timing Results

Substation States	96
Actual Measurements	192
Total Measurements (Actual + Virtual)	880

**Average DQSE Execution Time per Time Step: 50 msec
(Variability: 1.5 msec)**

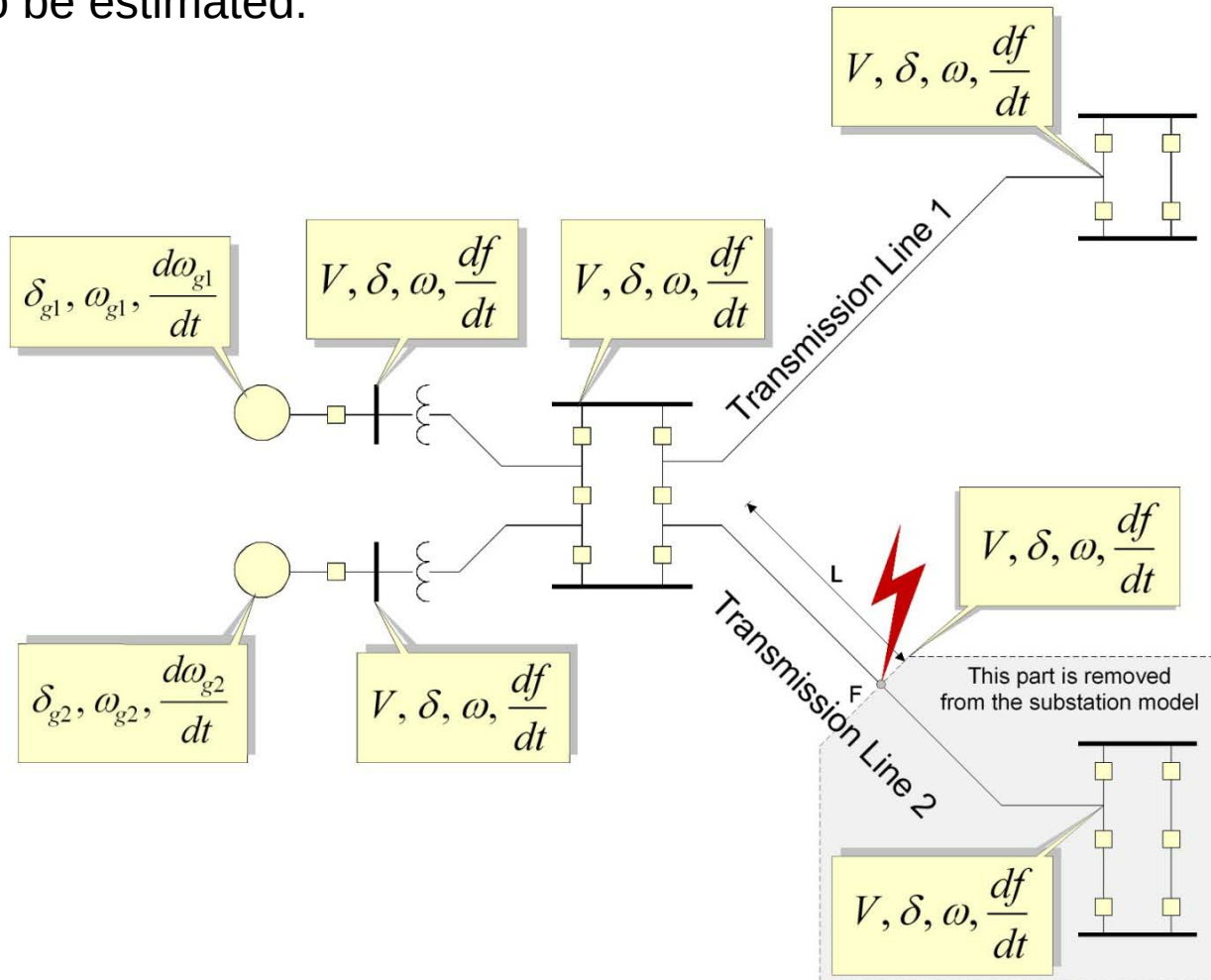
A PC with Quad Processors Can Perform 4 State Estimations per 50 msec or About 80 State Estimations per second. Further Improvements Can be Made by Optimizing Computer Codes

- PC, i7-930 Processor, 2.8 Gz
- Code is not optimized

We have identified a number of efficiency improvements

State Estimation Based Fault Locating

The Dynamic State Estimator Can Operate at speeds of 60 times per second. When a fault occurs it triggers the introduction of another state. Specifically the length to the fault (fault location) is introduced as another state variable to be estimated.



Conceptual Design of Alarms and Event Recording

Alarm Processing

- The approach provides the estimated state at very frequent intervals – 60 times per second is possible. The state estimate provides the exact state of the substation and therefore the root cause of any disturbance. Alarm initiation should be based on the root cause and not on individual alarms received from various devices.
- Issues of configuration for alarm processing have not addressed. It is believed that this is a straightforward procedure.

Archiving and Fault Recording

- The objectives of archiving and fault recording were defined as the capability to fully reconstruct the operation of the system for any interval of time for both the normal operation as well as disturbance conditions. Standards to achieve this goal are not presently available. For this reason, a new procedure and protocol was developed. It is described in the next few slides.
- The developed procedures provides the capability for full “play back” capability of the system operation for any interval of time.
- Storage capabilities are modest. It is estimated that up to six months of data can be stored in a standard PC for a medium size substation.



Objectives: Play-Back Normal Operation or Disturbance

Substation Storage Scheme

Full Model + Model Changes + Data

- System FULL MODEL stored once a day in WinIGS format – time of day can be arbitrarily selected, for example at 2 am. (example storage follows)
- Report system changes by exception – UTC time (example storage follows)
- Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format. (example storage follows)

Substation Storage Scheme

FULL MODEL + Model Changes + Data

System FULL MODEL stored once a day in WinIGS format.
Time of day can be arbitrarily selected, for example at 2 am.

Example storage:

```
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
```

Substation 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
```

Transmission
Line Model

```
MODEL 123
```

```
.....
.....
```



Substation Storage Scheme

Full Model + MODEL CHANGES + Data

Report system changes by exception – UTC time

MODEL_CHANGE

TIME 1267771497 450123

TYPE XFMR_TAP

DEVICE_ID 1265

VALUE R12

END_MODEL_CHANGE

SOC + Fractional Second

March 05, 01:44:57.450123

MODEL_CHANGE

TIME 1267771791 609355

TYPE BREAKER_OPERATION

DEVICE_ID 3409

VALUE CLOSE

END_MODEL_CHANGE

. . .
. . .
. . .

File Format – Each line begins with a keyword optionally followed by one or more arguments.



Substation Storage Scheme

Full Model + MODEL CHANGES + Data

Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format. The following File Types Are Used:

Configuration Files: Description of State Names Types and Locations

State Data Files: State Values plus Model Change Information

Triggered Event Files: Waveform data recorded for each triggering event in COMTRADE format.

Substation Storage Scheme

Full Model + MODEL CHANGES + Data

Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format.

Configuration File – One for Each Day

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



Substation Storage Scheme

Full Model + MODEL CHANGES + Data

Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format.

State Data File – One for Each Day

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> . . .
. . .
```



Substation Storage Scheme

Full Model + MODEL CHANGES + Data

Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format.

Triggered Event Files – One for Each Event

File Naming Standard:

CompanyName_SubstationName_SOC.cfg
CompanyName_SubstationName_SOC.dat

File Content:

Standard COMTRADE Waveform File Format

Conceptual Design of Substation Protection & Control

Protective Relaying Algorithms

The possibility of performing protection functions for the entire substation using **(a) filtered data (estimated data) and (b) entire substation state** has been investigated for a generic substation. Assuming that relaying decisions do not need to be faster than two cycles, the approach will yield reliable and secure relaying decisions.

The approach also provides the capability for integrated monitoring of the health and the settings of the relaying scheme. Failures of subsystems, for example blown fuse on a PT, single pole stuck, inaccurate CT data in relays, etc. can be immediately identified.

Validation Work 1: Application to generating substations: Consider all protection functions required at a generating substation and examine in a systematic way how each one of the functions can be performed in the proposed scheme. Develop metrics to assess performance. Compare traditional relay response and “substation relay” response using actual field data of various events.

Validation Work 2: Application to transmission substations: Consider all protection functions required at a transmission or distribution substation and examine in a systematic way how each one of the functions can be performed in the proposed scheme. Develop metrics to assess performance. Compare traditional relay response and “substation relay” response using actual field data of various events.



Control Center Operations

- **Monitoring (Data Acquisition)**

This is the main function of a control center. In this scheme, the data available from each substation is qualitatively and quantitatively different. The control center must subscribe to the particular set of data that the operator wants to monitor at each sub.

- **Supervisory Control**

There are only a few points – usually circuit breakers – that are manually controlled by the operator.

- **Automatic Control**

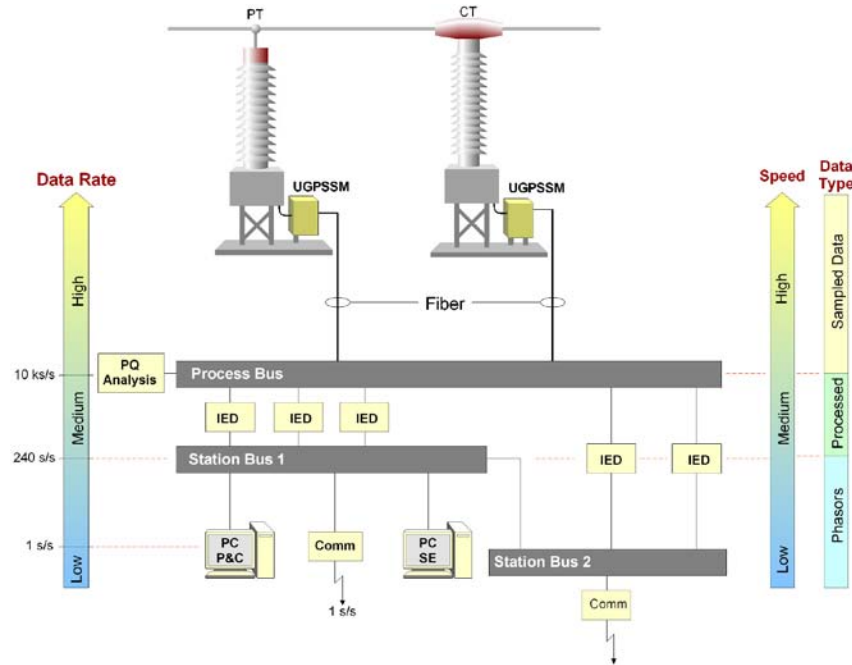
The only automatic control today is AGC but there may be many more in the future. Moreover, the control center need not be the only node where such control is done.

- **Applications**

Similarly, applications may not be computed at the control center although the results may need to be displayed to the operator.



Substation Level



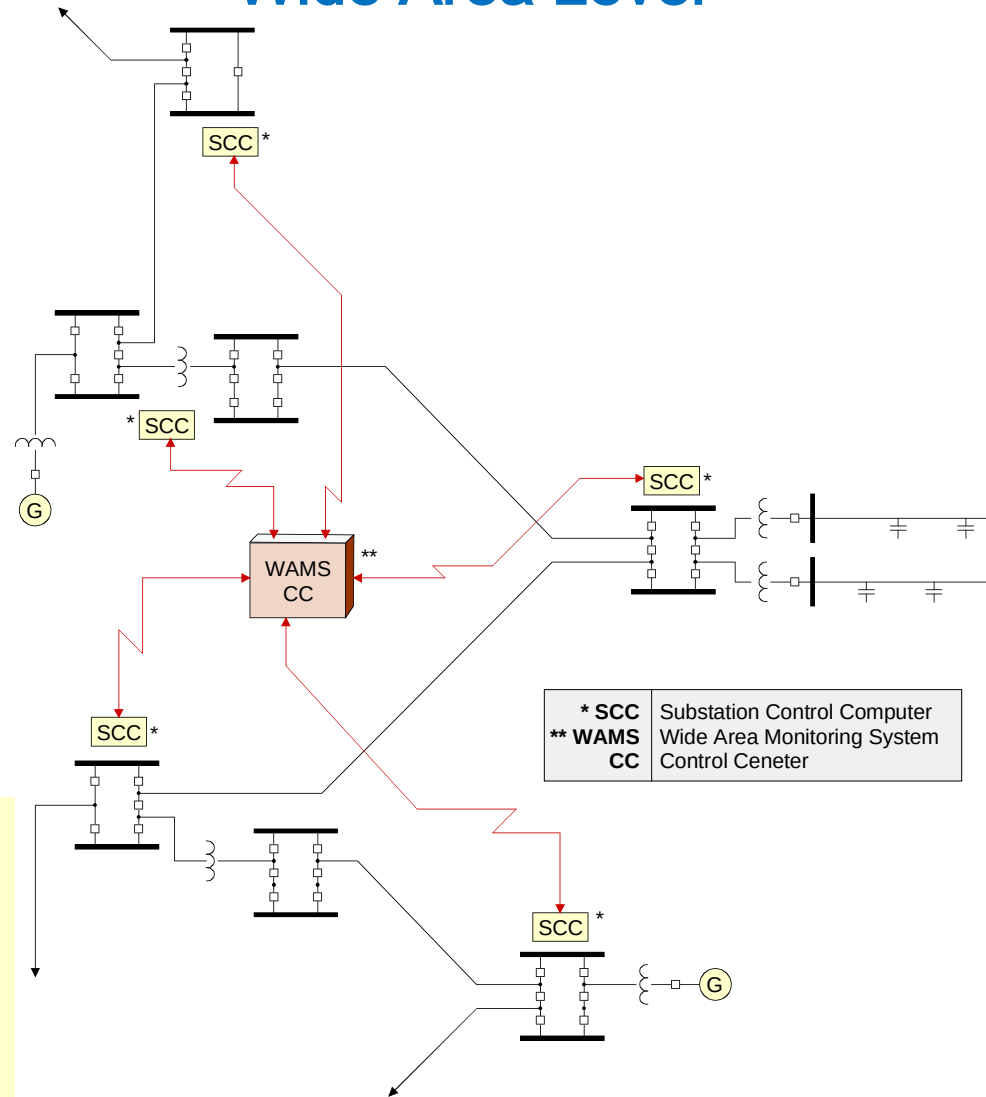
Control Center State Estimator: Collect substation real time model and synthesize system wide real time model (Distributed State Estimator). The approach enables system wide state estimation at rates of 60 times per second.

Wide Area Monitoring: Streaming data of validated substation state into the control center provides wide area monitoring at speeds of 60 phasors per second or better and unprecedented quality.

System Protection: Wide area monitoring at the above stated speeds provide the best infrastructure for system protection.

Control Center Applications: All control center applications can run on a validated real time model that updated 60 times per second.

Wide Area Level



Project Achievements

- Ability of the proposed approach to deliver data to substation computers with minimum latency (target value of 1 millisecond) without any loss of information. Status: Achieved with C37.118 (larger time latencies exist for IEC 61850)
- Performance Quantification of proposed approach on a variety of issues relative to vital applications in monitoring, control and protection of the system. Demonstrated for State Estimation, Power Quality Analysis, Fault Locating and Protection Functions
- Evaluation of the ability to perform all protective functions in a substation using the output of the substation dynamic estimator and the time latencies that will be involved in this process. Favorable impact on protection reliability, security and selectivity.
- Evaluation of the expected improvements in communicating with the control center and the company enterprise in general. Demonstrated that required throughput between substation and control center has been minimized.
- Substantial savings since there is no need for wiring within the substation versus the cost of equipping each instrument transformer with a UGPSSM and LAN interface.



Future Work

The present project was a feasibility study. Yet, a laboratory was established for evaluating some of the proposed architectures and procedures for the substation of the future.

The findings, expected performance and potential cost reductions justify further work on the subject. Therefore we propose the following future work:

1. Address the issue of migration of old substations with aging infrastructure to a fully automated substation closer to the vision of the substation of the future.
2. Additional developments in the laboratory to enable a complete setup of a substation of the future as designed in the present project. The objectives of the new work is to experimentally measure the performance of (a) dynamic state estimation using C37.118 and IEC 61850, (b) the performance of the state estimation based fault locating, (c) the performance of the storage and play back capability, and (d) the performance of the integrated protection functions based on filtered data and entire substation state (as opposed to present day relays that operate with limited information, for example three voltages and three currents).
3. Apply “lessons learned” and technologies to distribution systems. Develop advanced distribution management systems active distribution systems.



Active Future Distribution Systems (with distributed energy resources – solar, wind, PHEVs, fuel cells,...).

Smart Grid Technologies: Distributed Monitoring, Control, Protection and Operations system. Target Speeds 10 times per second. **One Important Driver:** Integration of Renewables and Other Resources into the Grid.

Functions: (a) Optimal operation of the distribution system under normal operating conditions, (b) Emergency management in cases of faults and assist the power grid when needed, (c) Assist Voltage recovery, (d) Assist cold load pickup, (e) Balance Feeder, (f) etc., etc.

Challenges

- Inertia-less Interface
- Protection/Control
- Disturbance ride-through requirements
- Safe Communications
- Safety
- Load/Generation Control
- Integrated Optimization

