Distributed Dynamic State Estimator, Generator Parameter Estimation and Stability Monitoring

DoE-NETL Demonstration
USVI-WAPA
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Demonstration: USVI-WAPA

Project Team

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Demonstration: USVI-WAPA

Project Overview
Project Objectives and Scope

This project addresses four fundamental problems in the operation of any electric power network, let it be the national grid, a distribution circuit with distributed resources or a μGrid:

(a) Real time modeling of the system via the proposed distributed dynamic state estimation using synchrophasor technology

(b) Parameter identification of important components of the system such as generating units

(c) Stability monitoring and prediction of eminent instabilities

(d) Disturbance “Play Back”

This work is fundamental for power system operations and optimization – we believe that the successful completion of the proposed work will provide a better infrastructure for power system operations and control.
Demonstration: USVI-WAPA Distributed State Estimator
Distributed State Estimation

Substation Level SE → Synthesis of System Wide State at the Control Center

Enabling Technology: GPS-Synchronized Measurements

State Estimator: Extracts Information from Data
- Minimum Data Traffic
- No Information Loss
The SuperC Concept (Distributed SE)

The SuperC is conceptually very simple:

1. Utilize all available data (Relays, DFRs, PMUs, Meters, etc.)

2. Utilize a detailed substation model (three-phase, breaker-oriented model, instrumentation channel inclusive and data acquisition model inclusive).

3. Use “Derived” and “Virtual” Measurements by Application of Physical Laws

4. At least one GPS synchronized device (PMU, Relay with PMU, etc.) → Results on UTC time enabling a truly decentralized State Estimator
Distributed Dynamic State Estimation Implementation

The Estimator is Defined in Terms of:
- Model
- State
- Measurement Set
- Estimation Method

Observability

Redundancy

System is Represented with a Set of Differential Equations (DE)
The Dynamic State Estimator Fits the Streaming Data to the Dynamic Model (DE) of the System
Distributed SE Measurement Set

- Any Measurement at the Substation from Any IED (Relays, Meters, FDR, PMUs, etc.)
- Data From at Least one GPS-Synchronized Device
- Derived Measurements
  - Based on Topology
- Virtual Measurements
  - Kirchoff’s Current Law
  - Model Equations
- Pseudo-Measurements
  - Missing Phase Measurements
  - Neutral/Shield Current Measurement
  - Neutral Voltage
Object Oriented Measurement Model

Measurement Types:
• Actual Across Measurement: eg. voltage measurement
• Pseudo Across Measurement: eg. neutral voltage measurement
• Actual Through Measurement (related to a device): eg. current measurement
• Pseudo Through Measurement (related to a device)

Power System Component Model (Dynamic Model → Integration → Algebraic Model):

\[
\begin{bmatrix}
  i(t) \\
  y(t) \\
  y(t_m) \\
  y(t_m)
\end{bmatrix} = Y_{eq} \begin{bmatrix}
  v(t) \\
  y(t) \\
  y(T_{m}) \\
  y(T_{m})
\end{bmatrix} + \begin{bmatrix}
  v^T(t) \\
  v^T(T_{m}) \\
  v^T(T_{m}) \\
  v^T(T_{m})
\end{bmatrix} F_{eq} \cdot \begin{bmatrix}
  v(t) \\
  y(t) \\
  y(T_{m}) \\
  y(T_{m})
\end{bmatrix} - b_{eq}
\]

where

\[
b_{eq} = \sum_i A_i \cdot \begin{bmatrix}
  v(t - i \cdot h) \\
  y(t - i \cdot h)
\end{bmatrix} + \sum_i B_i \cdot \begin{bmatrix}
  i(t - i \cdot h) \\
  0
\end{bmatrix} + C
\]

Each Measurement is expressed as a function of the states (at most quadratic):

\[
z_k(t) = \sum_i a_{i,t}^k \cdot x_i(t) + \sum_i a_{i,m}^k \cdot x_i(t_m) + \sum_{i,j} b_{i,j,t}^k \cdot x_i(t) \cdot x_j(t) + \sum_{i,j} b_{i,j,m}^k \cdot x_i(t_m) \cdot x_j(t_m) + c_k(t) + \eta_k
\]
Object Oriented QSE

Across (Voltage) Measurement:

\[ \tilde{z}_j(t) = \tilde{x}_j(t) + \eta_j \]

Through (Current, Torque, etc.) Measurement:
Measurement \( z_j(t) \) represents a quality associated with one row of the Object oriented model.

\[ \tilde{z}_j(t) = \text{row } k \text{ of Object Oriented Model} + \eta_j \]

Object Oriented Model

\[
\begin{bmatrix}
\tilde{I}(t) \\
0 \\
\tilde{I}(t_m) \\
0
\end{bmatrix} = Y_{eq} \begin{bmatrix}
\tilde{V}(t) \\
\tilde{Y}(t) \\
\tilde{V}(t_m) \\
\tilde{Y}(t_m)
\end{bmatrix} + \begin{bmatrix}
\tilde{V}^T(t) \\
\tilde{Y}^T(t) \\
\tilde{V}^T(t_m) \\
\tilde{Y}^T(t_m)
\end{bmatrix} \cdot F_{eq} \cdot \begin{bmatrix}
\tilde{V}(t) \\
\tilde{Y}(t) \\
\tilde{V}(t_m) \\
\tilde{Y}(t_m)
\end{bmatrix} - B_{eq}
\]

where \( B_{eq} = \sum_i A_i \begin{bmatrix}
\tilde{V}(t - i \cdot h) \\
\tilde{Y}(t - i \cdot h)
\end{bmatrix} + \sum_i B_i \begin{bmatrix}
\tilde{I}(t - i \cdot h) \\
0
\end{bmatrix} + C \)

QSE states are

**Phasors, Speed, etc**
Distributed State Estimation

Derived Measurements - Examples

Derived Measurement

Actual Measurement

Derived Measurement
Distributed State Estimation

Virtual Measurements - Examples

\[ 0 = \tilde{I}_1 + \tilde{I}_2 + \tilde{I}_3 \]

Virtual Measurement

\[ z_m = 0 \quad \text{value} \]
\[ \sigma_m = 0 \quad \text{standard deviation} \]
Non-GPS Synchronized Relays provide phasors referenced on “phase A Voltage”. The phase A Voltage phase is ZERO.

The SuperC provides a reliable and accurate estimate of the phase A voltage phasor.

\[
\tilde{A}_{sync} = \tilde{A}_{meas} e^{j\alpha} = A_{real} \cos \alpha - A_{imag} \sin \alpha + j(A_{real} \sin \alpha + A_{imag} \cos \alpha)
\]

\(\alpha\) is a synchronizing unknown variable.

\(\cos(\alpha)\) and \(\sin(\alpha)\) are unknown variables in the state estimation algorithm.

There is one \(\alpha\) variable for each non-synchronized relay.
Distributed SE: Algorithm

\[ Min \ J = \sum_{v \in \text{phasor}} \frac{\tilde{\eta}_v^* \tilde{\eta}_v}{\sigma_v^2} + \sum_{v \in \text{non-syn}} \frac{\eta_v \eta_v}{\sigma_v^2} \]

Solution: \[ x^{v+1} = x^v + A[z - h(x)] \]

where: \[ A = \left[ H^T WH \right]^{-1} \left[ H^T W \right] \]

**Efficiency**

Demonstrated the ability to execute the state estimator 60 times per second for substantial size substations.

There is still space for improved computational efficiency.
Distributed State Estimation
Synthesis of System Wide State at the Control Center

State Estimator: Extracts Information from Data
→ Minimum Data Traffic
→ No Information Loss

Control Center
Full System Visualization
Demonstration: USVI-WAPA

Master DSE
SuperCalibrator Master - Client
SuperCalibrator Master Reports

- General Performance
- Cross-Check Performance
- Animated SLD’s
- Etc…
SuperCalibrator Master & Client
Demonstration: USVI-WAPA

The USVI-WAPA System
The USVI-WAPA System
Installation of PMUs at Longbay:

SEL 421 (3)

Numerical Relays at Longbay:

SEL 587 (4)
AREVA MiCOM P543 (3)
AREVA MiCOM 633 (2)
AREMA MiCOM P142 (10)

PMU Measurements: 18

Numerical Relay Measurements: 132
VIWAPA – RHPP 35 kV Substation Instrumentation
VIWAPA – RHPP 35 kV Substation Instrumentation

Installation of PMUs and Relays at RPHH
SEL 421 (3)
SEL 451 (4)
GE 60 (1)

Numerical Relays at RPHH
SEL 487 (6)
AREVA MiCOM P142 (6)
AREVA MiCOM P543 (5)
AREVA MiCOM P632 (1)
AREVA MiCOM P642 (3)
AREVA MiCOM P645 (3)

PMU Measurements: 40 (max possible 71)
Numerical Relay Measurements: 150
VIWAPA – TUTU 35 kV Substation Instrumentation

Installation of PMUs at TUTU

SEL 734 (1)

Numerical Relays at TUTU

SEL 587 (1)
AREVA MiCOM P543 (2)
AREVA MiCOM P544 (2)
AREVA MiCOM 634 (1)
AREMA MiCOM P142 (6)

PMU Measurements: 3
Numerical Relay Measurements: 39
Installation of PMUs at EAST END

SEL 734 (1)

Numerical Relays at EAST END

AREVA MiCOM P542 (4)
AREVA MiCOM P543 (4)
AREVA MiCOM P633 (1)
AREMA MiCOM P141 (2)
AREMA MiCOM P142 (4)
AREMA MiCOM P143 (2)

PMU Measurements: 3
Numerical Relay Measurements: 51
VIWAPA – St JOHN 35 kV Substation Instrumentation

Installation of PMUs at St JOHN

SEL 734 (1)

Numerical Relays at St JOHN

AREVA MiCOM P633 (2)
AREVA MiCOM P542 (2)
AREVA MiCOM P543 (2)
AREMA MiCOM P141 (1)
AREMA MiCOM P142 (2)
AREMA MiCOM P143 (3)

PMU Measurements: 3

Numerical Relay Measurements: 36

3-Ph-Fault= 3.11, 3.12, 3.01 kAs
1-Ph-Fault= 3.13 kAs
2-Ph-Fault= 2.61 kAs
The USVI-WAPA System
The Communications Infrastructure
The USVI-WAPA System
The Communications Infrastructure

WAN Link

Main Ethernet Hub
Ruggedcom

Ethernet
Ruggedcom

GPS Antenna
GPS Clock

SEL 421
SEL 421
SEL 421

EIA485 / DNP3

SEL 587
SEL 587

EIA485 / MODBUS / TCP

Areva P142
Areva P633

Areva P543

IRIG-B

Data Concentrator PC
The USVI-WAPA System

The Communications Infrastructure

Substation Data Concentrator PC

- Data Concentrator
  - Synchrophasor Client (IEEE Std C37.118)
  - Synchrophasor Client (IEEE Std C37.118)
  - Synchrophasor Client (IEEE Std C37.118)
  - Local State Estimator
  - Synchrophasor Server (IEEE Std C37.118)
  - MODBUS Client
  - MODBUS Client

PMU / Relay

- LAN
  - ETHERNET

PMU / Relay

- LAN
  - MODBUS/TCP

Relay

- LAN
  - MODBUS/TCP

To Master Stations

WAN/VPN
Demonstration: USVI-WAPA Substation DSE and Master
Demonstration: USVI-WAPA
Substation DSE and Master

Master
UI and Visualization

Substation DSE
UI and Visualization
Demonstration: USVI-WAPA Performance Evolution
### Performance Evolution: QSE: Timing Results* - Year 1

<table>
<thead>
<tr>
<th></th>
<th>NYPA Gilboa-Blenheim Plant</th>
<th>USVI LongBay Substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>System States</td>
<td>96</td>
<td>164</td>
</tr>
<tr>
<td>Actual Measurements</td>
<td>168</td>
<td>171</td>
</tr>
<tr>
<td>Total Measurements (Actual + Virtual)</td>
<td>744</td>
<td>708</td>
</tr>
<tr>
<td>Average QSE Execution Time per Time Step</td>
<td>9.5 msec</td>
<td>13 msec</td>
</tr>
<tr>
<td>Variability</td>
<td>0.5 msec</td>
<td>1 msec</td>
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</tbody>
</table>

*PC, i7-930 Processor, 2.8 Gz

**Additional Improvements Are Possible**
- Additional Code Optimization
- Use of Multi-core Computers
Performance Evolution: Distributed State Estimation

Timing Results – Year 3

Timing Experiment
Summary of the QSE for Long Bay Substation

<table>
<thead>
<tr>
<th>System States</th>
<th>82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Measurements</td>
<td>171</td>
</tr>
<tr>
<td>Total Measurements</td>
<td>784</td>
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<tr>
<td>Average QSE Execution Time per Time Step</td>
<td>0.42 msec</td>
</tr>
<tr>
<td>Variability</td>
<td>0.05 msec</td>
</tr>
</tbody>
</table>

- Two kV Level Substations
- Two Transformers
- Three Transmission Lines
- Six Distribution Circuits
Performance Evolution: Distributed State Estimation

Execution Time Monitor

CPU Time Usage Indicates in Real Time the Portion of the Time Used by the SE Calculations.

100% = Time Between Two Successive SE Computations. Example: if SE is set to execute 60 times per second, then 100% = 16.6 ms
Demonstration: USVI-WAPA
Disturbance Playback
Disturbance Playback
Via Distributed Dynamic State Estimation

**Objective**: to provide an automated playback capability of past operating conditions and disturbances.

Project objective has been accomplished.

**How**: the results of the distributed dynamic state estimation are stored in a circular buffer (months long) together with the model. Playback requires only start and end times.
Disturbance Play-Back: User Interface

New Approach to Historian: Substation Storage Scheme
Full Model + Model Changes + Data

System Operations Can Be “Played Back” Over a User Specified Time Interval (From time t1 to time t2)

Then as simple as pressing a button…
Important Application: Disturbance Play-Back

Objective:

• System Operation “Play Back” over a user specified time interval (from time t1 to time t2)

• Reconstructed state is presented via graphical visualization Techniques, (3-D rendering, animation etc) with multiple user options.

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)
Demonstration: USVI-WAPA Substation DSE
DSE Substation Module User Interface
DSE Substation Module User Interface – Long Bay
DSE Substation Module – IED Model

Longbay Sub SEL Access IP: 10.103.111.100

3-Ph-Fault=8.27, 8.25, 8.40 kAs
1-Ph-Fault=8.105 kAs
2-Ph-Fault=7.82 kAs
DSE Substation Module – The SuperCalibrator Element
DSE Substation Module – The SuperCalibrator Element
The SuperCalibrator SubModules

- Phasor Data Concentrator (PDC)
- PDC Client
- Test Data Server
- Historian
- Synchrophasor Server
- Reports
The SuperCalibrator Element – PDC Component
PDC Component Attributes

- IP Parameters
- Serviced IED List
- Desired Transmission Rate
- Max Latency
- Max Time Skew
- Test Data Server
- Historian
- Synchrophasor Server
- Reports
### PDC Automatic Configuration & Channel Mapping Validation

![SuperCalibrator - PDC Measurement Mapping](image)

<table>
<thead>
<tr>
<th>PMU (PDC)</th>
<th>PMU (Scal)</th>
<th>PDC Channel</th>
<th>SCal Channel</th>
<th>PDC Match</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VW_LONGBAY_B305</td>
<td>LB002</td>
<td>VALPM</td>
<td>V_LB3-02_AN</td>
<td>Yes</td>
<td>Voltage Phasor</td>
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<tr>
<td></td>
<td></td>
<td>VBLPM</td>
<td>V_LB3-02_BN</td>
<td>Yes</td>
<td>Voltage Phasor</td>
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<tr>
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<td></td>
<td>VCLPM</td>
<td>V_LB3-02_CN</td>
<td>Yes</td>
<td>Voltage Phasor</td>
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<tr>
<td></td>
<td></td>
<td>IAWPM</td>
<td>C_3<del>OB0D_L3</del>OB0D_1<del>3</del>OB0D_A</td>
<td>Yes</td>
<td>Current Phasor</td>
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<tr>
<td></td>
<td></td>
<td>IBWPM</td>
<td>C_3<del>OB0D_L3</del>OB0D_1<del>3</del>OB0D_B</td>
<td>Yes</td>
<td>Current Phasor</td>
</tr>
<tr>
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<td></td>
<td>ICWPM</td>
<td>C_3<del>OB0D_L3</del>OB0D_1<del>3</del>OB0D_C</td>
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<td>Current Phasor</td>
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<tr>
<td>VW_LONGBAY_B303</td>
<td>LB001</td>
<td>VALPM</td>
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<td></td>
<td>VBLPM</td>
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<tr>
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<td></td>
<td>VCLPM</td>
<td>V_LB3-01_CN</td>
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<tr>
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<td></td>
<td>IAWPM</td>
<td>C_FDR11<del>GC_3</del>0A0B1_1<del>3</del>0A0B1_A</td>
<td>Yes</td>
<td>Current Phasor</td>
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<td></td>
<td>IBWPM</td>
<td>C_FDR11<del>GC_3</del>0A0B1_1<del>3</del>0A0B1_B</td>
<td>Yes</td>
<td>Current Phasor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ICWPM</td>
<td>C_FDR11<del>GC_3</del>0A0B1_1<del>3</del>0A0B1_C</td>
<td>Yes</td>
<td>Current Phasor</td>
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<tr>
<td>VW_LONGBAY_B307</td>
<td>LB003</td>
<td>VALPM</td>
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<td>Voltage Phasor</td>
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<td></td>
<td></td>
<td>VBLPM</td>
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<td>Voltage Phasor</td>
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<tr>
<td></td>
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<td>VCLPM</td>
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<td>IAWPM</td>
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<td></td>
<td>IBWPM</td>
<td>C_FDR12<del>GC_3</del>0A0B2_1<del>3</del>0A0B2_B</td>
<td>Yes</td>
<td>Current Phasor</td>
</tr>
</tbody>
</table>

**Update From File**  **Save to File**  **Clear**  **Auto-Set**  **Verify PDC Mapping**

All Measurements matched with PDC Channels

Program WinIGS-Q - Form IGS_M012_MEASMAP
SuperCalibrator PDC Client – Setup Window

Communication Parameters:
- **Local IP Address**: 172.20.2.231
- **Local Port Number**: 2000
- **Outstation IP Address**: 172.20.2.231
- **Outstation Port Number**: 2000
- **Outstation ID**: 10

Phasor Diagram:
- Frequency: 0.0000 Hz
- Time: 23:16:52.266666
- Rate: 60,000 fps

Log:
- Already Disconnected
- Connecting...
- Connected
- Requesting Configuration Frame
- Received Configuration Frame

SynchroFile_001

Program: WinCal-PDLC
- Connect
- Disconnect
- Frame Window
- Set Rate
- Buffer Usage
- Adjust Clock
- Save Stream to File

Edit Measurement Mapping
SuperCalibrator PDC Client – Input View Window
Test Data Server – Setup Window

Server Ready!
Connected to 172.20.2.231, Port 2000
Sending Configuration Frame

Server Off
Server Ready!
Connected to 172.20.2.231, Port 2000
Sending Configuration Frame
DSE - Estimator Setup Window
DSE - Synchrophasor Server – Setup Window
DSE - Estimator Setup Window
DSE - Reports

- State
- Measurements
- Performance Metrics
- Animated 3D - SLD
- Time Plots
Summary

- Distributed State Estimation Enables State Estimation at Each Cycle (Sixty Times per Second).

- The Approach Requires a Detailed Three Phase Substation Model and at Least One PMU Device.

- Four Demonstration Projects Have Provided and Will Provide Tremendous Experience.

- The Approach Has Enabled a New Disturbance Play Back Which Has Proven to be Very Useful.