Update On Distributed Dynamic State Estimators: Hybrid Inputs (PMUs, MUs, Numerical Relays) and Correction of Instrumentation Errors

Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Outline

Legacy State Estimators

New Technologies: The Changing SCADA System
  Relays provide SCADA
  Merging Units
  GPS Synchronization

Distributed Dynamic State Estimators
  Integrated with Protection System

Error Correction

Directions / Future Work
Legacy State Estimator
Introduced After the 1965 Blackout

Centralized State Estimator – Long Response (min)
Model Biased State Estimator

Power System SE: Basic Assumptions
• Positive Sequence Model
• P, Q, V measurement set
• Near-Simultaneous Measurements
• Single Frequency

Implications:
• Balanced Operation
• Symmetric Power System
• Biased SE
• Iterative Algorithm

Present Technologies Enable Removal of these Assumptions and Transition from Static to Dynamic State Estimators
Present Technologies

Relays/Merging Units provide 3-Phase GPS Synchronized SCADA

Typical Specs

GPS Synchronization

MU: Sampled Values at 80 s/c

Relays: Phasors at one s/c

Reality: Hybrid
Present Technology Enables Transition from Static State Estimators to Dynamic State Estimators.

- Dynamic State Estimators: Objective, Model (dynamic), Measurements

- Quasi-Dynamic State Estimators: Model Captures Slow Dynamics. Fast Electrical Dynamics are Ignored (Suitable for Operations).

- Dynamic State Estimators: Model Captures Slow and Fast Dynamics (Suitable for Protection).
Distributed Quasi-Dynamic 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
Distributed Quasi-Dynamic State Estimation Implementation

The Estimator is Defined in Terms of:
- Model (Q-D)
- State
- Measurement Set
- Estimation Method

Observability Redundancy

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

- Any Measurement at the Substation from Any IED
  (Relays, MU, Meters, FDR, PMUs, etc.)
- Data From at Least one GPS-Synchronized Device
- Augmentation of Data Set
  - 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 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

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

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
Distributed State Estimation

Virtual Measurements - Examples

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

Virtual Measurement

\[ z_m = 0 \] value

\[ \sigma_m = 0 \] standard deviation
Distributed SE Measurement Set

Non-Synchronized Measurements

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.

\[
\tilde{A}_\text{sync} = \tilde{A}_\text{meas} e^{j\alpha}
\]

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

\(\alpha\) 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 Quasi-Dynamic SE Algorithms

- Unconstrained WLS,
- Constraint WLS,
- Extended Kalman Filter (Provides Model Uncertainty)

**Important Observation:** Data and Model Fidelity is most important requirement for best performance
CPU Time Usage Indicates in Real Time the Portion of the Time Used by the SE Calculations.

100% corresponds to the time between two successive SE computations.

Example: if SE is set to execute 60 times per second, then:

100% → 16.6 ms
Implementation and Field Demonstrations

Snapshot of system: (a) visualization of system operation updated once per cycle (b) metric of data validity (c) displays of phasors and errors.
Data Integrity
Instrumentation Channel Error Correction
Effects of Input Data Accuracy

Quality of Data is Affected from:

(a) *Instrumentation Channel Errors*,
(b) *Hidden Failures* and
(c) *Cyber data attacks*.

All Affect Performance of Protection and State Estimation.

Relays and merging units are becoming more accurate by using higher resolution in data acquisition and higher sampling rates.

Errors from instrumentation channels remain practically the same. Instrumentation channel errors have been much higher than the errors introduced by the data acquisition even in earlier generations of sensor less systems.

Merging Units offer a unique opportunity to perform error correction within a merging unit → MU provides corrected data in primary quantities.
Given a measurement at the secondary of an instrumentation channel, can we extract the correct value of the primary quantity?

- Can it be done on a sample by sample basis?
Basic Approach to Error Correction

Construct the mathematical model of the instrumentation channel:
Example CT Channel

Use actual measurements and augment with:

(a) virtual measurements,
(b) derived measurements, and
(c) pseudo measurements

Perform dynamic state estimation → Best Estimate Of Primary Current
Dynamic State Estimation

**Measurements**

- Actual: Voltage or Current at Burden
- Add: Virtual, Derived, and Pseudo-Measurements

**Example Virtual Measurement:**

\[
0 = -g_m e(t) - i_m(t) + \frac{1}{n} i_p(t) + i_{L_1}(t) + g_{s_1}L_1 \frac{di_{L_1}(t)}{dt}
\]

**Example Derived Measurement:**

\[
i_b^m(t) = i_{L_1}(t) + g_{s_1}L_1 \frac{di_{L_1}(t)}{dt}
\]

**Example Pseudo Measurement:**

\[
0^m = v_4(t)
\]

21 Equations in 15 unknowns.

One of the unknowns is the Primary Current

**States:** 15

- Actual Measurements: 1
- Virtual Measurements: 14
- Derived Measurements: 5
- Pseudo measurements: 1
Example System

Example System Parameters
115-kV transmission system.
Current transformer on phase A CT ratio is 800:5A
Error class: 10C100.
CT instrumentation cable: #10 copper
Instr. cable length: 96 meters
Burden resistance: 0.1 Ω

Current Transformer Parameters

CT
Device Supplying Primary Current
3-Phase Overhead Transmission Line
CT on Terminal SOURCE1_A

Error Class
50.00
% at 20 x Rated Current

Voltage Class
50.00
Volts

Tap Selection
X1-X5

Selected Tap Parameters
Primary Rating
2000.00
Amperes
Secondary Rating
5.0
Amperes
Coil Resistance
0.00500
Ohms
Leakage Reactance
0.01000
Ohms
Core Conductance
0.00100
Siemens
Magnetizing Current
6.09109
Amperes
Exponent (n)
11

Log-Axis

Exponential Voltage (Vms)

Exponential Term (Vms)

CT Secondary Terminals
CTBUS_A
CTBUS_N

Fault 1
Fault 2

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Current Transformer Parameters
Example System Results
Example System Results – Mild CT Saturation
Simulated CT Secondary Current Waveform

Phase A to ground fault at “MIDBUS”
Example System Results – Mild CT Saturation
Error Correction Performance

Estimated results match actual primary current with less than 1% error
Intelligent Merging Units Provide Corrected Primary Values

Error Correction Integrated into Merging Units
(alternative: in substation computers)
Residual Analysis with/without Instrumentation Error Correction

Histogram of Residuals without Correction (300 SE Executions)

Histogram of Residuals with Correction (300 SE Executions)
The Future

The Digital Substation
Integration of Protection and State Estimation
Dynamic State Estimation Based Centralized Protection Scheme

Resilient Centralized Substation Protection (rCSP)
Concluding Remarks

IEEE and CIGRE Efforts Move Towards the DIGITAL SUBSTATION.

**Resiliency**: The entire process should be automated with self-healing capabilities against data errors, hidden failures and cyber attacks.

**Awareness**: Automatic provision of substation dynamic state.

**Asset Management**: Automated testing and in-line testing of active substation protection and control systems.