Distributed State Estimator - SuperCalibrator Approach
Delivering Accurate and Reliable Data to All

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Present State of the Art: C&O and P&C

Model Based Control and Operation

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

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,
Enterprize, InterControl
Center

The Infrastructure for Both Functions is Based on Similar Technologies: Thus the Opportunity to Merge, Cut Costs, Improve Reliability Integration of New Technologies
Traditional State Estimation
Introduced After the 1965 Blackout

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
The SuperCalibrator 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. At least one GPS synchronized device (PMU, Relay with PMU, etc.) → Results on UTC time enabling a truly decentralized State Estimator.
Key Projects That Led to the SuperCalibrator Concept

1989: HMS Project, NYPA

2004-6: PSERC S-22 Project: Advanced State Estimation
Jerry Heydt, Ali Abur, Sakis Meliopoulos

2006-2008: DoE/CTC Project
Distributed 3-Phase SE
SuperCalibrator Approach
Static State Estimator Model

The Estimator is Defined in Terms of:

• **Model** (Model Fidelity Impacts SE Performance)
• **State**
• **Measurement Set**
• **Estimation Method**
Substation State

SuperCalibrator
Static State Estimation

State Definition

Definition of State for a Substation

\[ \tilde{V}_{1s} \quad \text{Vector of dimension 4:} \quad \tilde{V}_{1s,a}, \tilde{V}_{1s,b}, \tilde{V}_{1s,c}, \tilde{V}_{1s,n} \]

\[ \tilde{V}_{2s} \quad \text{Vector of dimension 4:} \quad \tilde{V}_{2s,a}, \tilde{V}_{2s,b}, \tilde{V}_{2s,c}, \tilde{V}_{2s,n} \]

\[ \tilde{V}_{1e} \quad \text{Vector of dimension 4:} \quad \tilde{V}_{2e,a}, \tilde{V}_{2e,b}, \tilde{V}_{2e,c}, \tilde{V}_{2e,n} \]

\[ \ldots \quad \ldots \quad \ldots \]

\[ \tilde{V}_{4e} \quad \text{Vector of dimension 4:} \quad \tilde{V}_{4e,a}, \tilde{V}_{4e,b}, \tilde{V}_{4e,c}, \tilde{V}_{4e,n} \]
SuperCalibrator Measurement Set

- Any Measurement at the Substation from Any IED (Relays, Meters, FDR, PMUs, etc.)

- Data From at Least one GPS-Synchronized Device

- Pseudo-Measurements
  - Kirchoff’s Current Law
  - Remote End State Measurement
  - Missing Phase Measurements
  - Neutral/Shield Current Measurement
  - Neutral Voltage
SuperCalibrator Measurement Set
Non-Synchronized Measurements

Non-GPS Synchronized Relays provide phasors referenced on “phase A Voltage”. The phase A Voltage phase is ZERO.
The SuperCalibrator provides a reliable and accurate estimate of the phase A voltage phase.

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

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

alpha is a synchronizing unknown variable
Cos and sin of alpha are unknown variable in the state estimation algorithm
There is one alpha variable for each non-synchronized relay
SuperCalibrator Pseudo-Measurement Set

Kirchoff’s Current Law

\[ \tilde{I}_1 + \tilde{I}_2 + \tilde{I}_6 = 0 \]

Expected Error: 0.001%

\[ k_1 (\tilde{I}_3 + \tilde{I}_4) + k_2 (\tilde{I}_1 + \tilde{I}_2) + \tilde{I}_m = 0 \]

Expected Error: 0.001%

Remote End State Measurement

\[ \tilde{V}_{pseudo,m} = (I - Z_{22}Y_{22})^{-1}Z_{21}\tilde{I}_S + (I - Z_{22}Y_{22})^{-1}Z_{22}Y_{22}\tilde{V}_S \]

Expected Error: 0.01%
**SuperCalibrator: Estimation Method**

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

**GPS-Synchronized Measurements**

**Voltage Phasor**

\[ \tilde{z}_v = \tilde{V}_{k,A} - \tilde{V}_{k,N} + \tilde{\eta}_v \]

**Current Phasor**

\[ \tilde{z}_v = \tilde{I}_{d1,k,A} + \eta_v = C_{d1,k,A}^T \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \end{bmatrix} + \tilde{\eta}_v \]

**Non-Synchronized Measurements**

**Voltage Magnitude**

\[ z_v = |\tilde{V}_{k,A} - \tilde{V}_{k,N}|^2 + 2\eta_v = \left( (V_{k,A} - V_{k,N})^2 + (V_{k,A} - V_{k,N})^2 \right) + 2\eta_v \]

**Real Power**

\[ z_v = P_{d1,k,A} + \eta_v = \text{Re} \left\{ \tilde{V}_{k,A} \begin{bmatrix} C_{d1,k,A}^T \\ \tilde{V}_{k,B} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \end{bmatrix} \right\}^* + \eta_v \]
SuperCalibrator: Estimation Method

\[
\begin{align*}
\text{Min} & \quad J = \sum_{\nu \in \text{phasor}} \frac{\tilde{\eta}_\nu^* \tilde{\eta}_\nu}{\sigma_\nu^2} + \sum_{\nu \in \text{non-syn}} \frac{\eta_\nu \eta_\nu}{\sigma_\nu^2} \\
\end{align*}
\]

Solution

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

where:

\[
A = [H^TWH]^{-1}[H^TW]
\]

Efficiency

Example, Long Bay Substation, High End PC
One Iteration: 18,000 multiply-adds (0.002 seconds)
Compute Matrix A: Variable (sparsity) – Almost Invariant (0.010 secs)
SuperCalibrator

Implementation
Present State of the Art: Smart Grid Infrastructure
Providing Validated and High Accuracy Information

Model Based Data Validation and Information Extraction
(Redundancy, Bad Data Rejection, Statistical Estimation, etc.)
SuperCalibrator Implementation
Description: The VIWAPA System

- 35 kV Transmission
- 13 kV Distribution
- Single Generating Plant (RHPP)
- Five Substations (RHPPlant, Long Bay, Tutu, East End, St. John)

- 6 SEL-421 Relays with PMU Capability
- 3 SEL 734 Meters with PMU Capability
- Numerous Areva Relays (P141, P442, P142, etc.)
- There is at Least one PMU at Each Substation
SuperCalibrator Implementation
Substation Configuration – Long Bay – 3D Model
SuperCalibrator Implementation
Substation Configuration – Long Bay
SuperCalibrator Implementation
Substation Configuration – Long Bay

Intelligent Electronic Device

Substation: VIWAPA_LONGBAY

IED
Manufacturer: SEL
Model: SEL421
Name: SEL421/303
Identifier: LB001

Data Type
- Phasors
- Waveforms

Data Source
- Measurement
- Simulation
- Estimate

File Name: undefined

Channel Parameters
- Instrumentation Channels
- Measurements
- View COMTRADE Channels

Show Connections: off
Annotation Font Size: 1.0
SuperCalibrator Implementation
Substation Configuration – Long Bay
SuperCalibrator Implementation
Substation Configuration – Long Bay
SuperCalibrator Implementation
Substation Configuration – Long Bay
SuperCalibrator Power System Model:
Physically Based Three-Phase Model: Example

Physically Based Model

Sequence Parameter Model
Not Used – for Info Only

Cable Sequence Networks

Positive Sequence Network
1.094 + j 0.742
0.509 - j 5259.1
0.509 - j 5259.1

Negative Sequence Network
1.094 + j 0.742
0.509 - j 5259.1
0.509 - j 5259.1

Zero Sequence Network
1.933 + j 0.579
0.649 - j 5259.2
0.649 - j 5259.2

WinIGS-F - Form: GENCABLEPAR1A - Copyright © A. P. Meliopoulos 1998-2007
SuperCalibrator Instrumentation Model: Physically Based Instrumentation Model: Example
SuperCalibrator Instrumentation Model: Physically Based Instrumentation Model: Example
SuperCalibrator Installation: USVI – 5 Substations
The SuperCalibrator Runs 4 Times per Second
SuperCalibrator

Accuracy Assessment
Quantification of SuperCalibrator Output Accuracy

• Chi-Square Test provides a measure of how well the measurements “fit” the model on a probabilistic basis. Equations omitted.

• The SuperCalibrator provides a measure of the uncertainty of the estimated states. Equations omitted.

• The SuperCalibrator provides a measure of Measurement error – to be used for remote calibration. Equations omitted.
Overall Performance Metric
Chi-Square Test

We have introduced the variable $k$

Error = $k \cdot \text{MeterSigma}$

Overall Error is Provided in Terms of the Variable $k$
Performance Monitoring of the SC-Base SE
IEEE-PES General Meeting

Computation of Phase Error

St. Thomas
SuperCalibrator Implementation
Example of Measurement/Pseudo-M Count – Long Bay

Long Bay Substation

Number of Analog Measurements: 318 real
Number of Pseudo-measurements: 72 real

Number of Status Measurements: 15

Future:
Beckwith Relay Measurements: 2

Number of States: 24+20
Long Bay 35 kV Bus: 3 (complex)
Long Bay 13 kV Bus: 3 (complex)
RHPP 35 kV Bus: 3 (complex)
East End 35 kV Bus: 3 (complex)

Redundancy 886%
Syncrophasor Data Processing Example
Voltage Phase Imbalance

Max Phase Imbalance: 0.150 Degrees
Waveform Calculator Formula Example (Phases B and C):
LB001_V_VT1_CN_R LB001_V_VT1_CN_I R2PHAS UNWIND LB001_V_VT1_BN_R LB001_V_VT1_BN_I R2PHAS UNWIND – 120 +
Syncrophasor Data Processing Example
Current Phase Imbalance

Max Phase Imbalance: 8.748 Degrees

Waveform Calculator Formula Example (Phases A and B):

\[ \text{LB001}_C\_3031\_B\_R \ \text{LB001}_C\_3031\_B\_I \ \text{R2PHAS} \ \text{UNWIND} \ \text{LB001}_C\_3031\_A\_R \ \text{LB001}_C\_3031\_A\_I \ \text{R2PHAS} \ \text{UNWIND} - 120 + \]
Max Magnitude Imbalance: 0.122 pu

Waveform Calculator Formula Example (Phases A and B):
LB001_V VT1 BN R L B001 V VT1 BN I R2MAGN LB001 V VT1 AN R L B001 V VT1 AN I R2MAGN – 199.185 /
Max Current Imbalance: 24 A (About 13%)

Waveform Calculator Formula (Phases A and B):

LB001_C_3031_B_R  LB001_C_3031_B_I  R2MAGN  LB001_C_3031_A_R  LB001_C_3031_A_I  R2MAGN –
Syncrophasor Data Processing Example

Computation of Frequency

Note:
Average Frequency 60.0104 Hertz
Average Frequency Difference 45 NanoHertz

\[ f = \frac{\Delta \theta}{\Delta t} \times 360 + 60 \]
Synchrophasor Data Processing Example – Raw Data
1 hour at 1 sample per second
\[ \theta = \text{atan} 2(\text{Im}(V), \text{Re}(V)) \]

Note that the phase discontinuity is an artifact of the arctangent function range limits.
Advantages of the Super-Calibrator Approach

- Utilization of All Data – Relay, SCADA, PMU
- Operates on Streaming Data from ALL DEVICES at the Substation Level – Distributed SE – Generates Streaming State to Other Concentrators (Information)
- **DATA VALIDATION**: Quantifies Data Accuracy – Remote Calibration
- Capable of Storing Data+Model Simultaneously
- Minimizes Data to be Transferred (very important)
  - Communication of Information not Raw Data
  - Improved Latencies