Protection Based on Dynamic State Estimation (a.k.a. Setting-less Protection): Status and Vision

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History of Developments
History of Developments


Distributed State Estimation (2009-13, DoE) (COLLABORATORS: USVI-WAPA, NYPA)


The Substation of the Future
PSERC Project 2007-08
Overall Approach

From This

To This

UGPSSM
Universal GPS
Synchronized Meter

Redundant Local Area Network

Redundant GPS Timing Signals

Control House

PC
Basic Questions

- Does it make sense to have separate SCADA system and Numerical Relays?
- Does it make sense to continue designing relays that rely on (typically) three currents and three voltages?
- Is it necessary for each relay to be equipped with data acquisition systems? Should DAQ be separate from relays?
- Present Systems and Technologies are Digital – They Provide Tremendous Flexibility – Are the capabilities of the technology used or we simply mimic E/M relays?
- Is the technology available to move from zone protection to subsystem (such as substation) protection?
- How do we deal with Increased Complexity?
Traditional Component Protection

• Monitor Specific Quantity or Quantities (current, differential current, distance, voltage over frequency, etc.) and Act When the Quantity Enters a Specified Locus (settings).

• The Traditional Protection Approach Exhibits Limitations for the Simple Reason that the Specific Quantity that is Monitored Does not Always Represent the Condition of The Component Under Protection.

• NERC: #1 Root Cause of System Disturbances is Protection Relaying
Complexity, Gaps & Challenges

A Modern Substation May Have Tens of Numerical Relays, each relay has an average of 12 protection functions. Coordination of all these relay functions is quite complex. Experts (humans) and Expert Systems (computers) are needed…

Tools to validate coordination of complex protection schemes are at best inadequate.

Protection Gaps: HIF, Down Conductors, Faults Near Neutrals, Inverter Interfaced Generation, Faults in Series Compensated Lines, etc. etc.

Protection Gaps Result in Fatalities…
The Setting-Less Protection Method
In Search of Secure Protection

Setting-less Protection can be viewed as Generalized Differential protection

Differential Protection
(Monitors KCL Only)

Setting-less Protection
Monitors All Laws Applied to the Device
(KCL, KVL, Thermal Mechanical, i.e. Complete Device Model)

Analytics: Dynamic State Estimation (systematic way to determine observance of physical laws)
The Zone Setting-less Protection Approach

- Measure/Monitor as Many Quantities as Possible and Use Dynamic State Estimation to Continuously Monitor the State (Condition, Health) of the Zone (Component) Under Protection. Identify bad data, model changes, etc.

- Act on the Basis of the Zone (Component) State (Condition, Component Health).

  **Advantage**: No need to know what is happening in the rest of the system – no coordination needed.
Key Elements of Approach

• “Digitization” Separate Data Acquisition from logic devices (relays, recorders, etc.) – Merging Unit Approach

• “Objectify” the model and measurements of each component: Starting Point: component physical model.

• “Interoperability” at all levels
  
  • Each logic device (IEDs) performs:
    
    Protective functions for the component
    Validate the “model object”
    Perform parameter identification, if necessary
    Transmits model objects to any other stakeholder

• Extent this structure to the control center
"Objectification": The SCAQCF Model
(State & Control Algebraic Quadratic Companion Form)

Compact Component Physical Model
Set of Algebraic & Differential Linear & Nonlinear Equations & Inequalities

Quadratized Model

\[ i(t) = Ax(t) + B \frac{dx(t)}{dt} + C \]
\[ 0 = Dx(t) + E \frac{dx(t)}{dt} + x^T(t) \langle F \rangle x(t) \]

State & Control Algebraic Quadratic Compact Form
(SCAQCF)

\[ i(t) = f_1(x(t), x(t_m), b_1(t-h)) \]
\[ 0 = f_2(x(t), x(t_m), b_2(t-h)) \]
\[ i(t_m) = f_3(x(t), x(t_m), b_3(t-h)) \]
\[ 0 = f_4(x(t), x(t_m), b_4(t-h)) \]

Addition of State Variables
Quadratic Integration
“Objectification”: Measurement Model

Actual Measurements
\[ z_i(t) = h_{i1}(x(t), x(t_m)), \sigma_{meter} \]
\[ z_i(t_m) = h_{i2}(x(t), x(t_m)), \sigma_{meter} \]

Derived Measurements
\[ z_j(t) = h_{j1}(x(t), x(t_m)), \sigma_{meter} \]
\[ z_j(t_m) = h_{j2}(x(t), x(t_m)), \sigma_{meter} \]

Pseudo-Measurements
\[ z_k(t) = h_{k1}(x(t), x(t_m)), \quad \sigma = \text{large} \]
\[ z_k(t_m) = h_{k2}(x(t), x(t_m)), \quad \sigma = \text{large} \]

Virtual Measurements
\[ 0 = h_{v1}(x(t), x(t_m)), \quad \sigma = 0 \]
\[ 0 = h_{v2}(x(t), x(t_m)), \quad \sigma = 0 \]

All h equations are quadratic at most
“Objectification”: Solution Method

Quadratized Model

State & Control Algebraic Quadratic Compact Form (SCAQCF)

Extended Kalman Filter

Unconstrained Optimization

\[ \text{Min } \sum_{\text{Actual/ Derived Pseudo}} \left( \frac{z - h_m(x)}{\sigma} \right)^2 + \sum_{\text{Virtual}} \left( \frac{0 - h_v(x)}{0.1 \times \sigma} \right)^2 \]

\[ \Rightarrow x^{v+1} = x^v - \left( H^T W H \right)^{-1} H^T W \left( z - h(x) \right) \]

Constrained Optimization

\[ \text{Min } \sum \left( \frac{z - h_m(x)}{\sigma} \right)^2 \]

S.T. \[ h_v(x) = g(x) = 0 \]

\[ \Rightarrow \begin{bmatrix} x^{v+1} \\ \lambda^{v+1} \end{bmatrix} = \begin{bmatrix} x^v \\ \lambda^v \end{bmatrix} - \begin{bmatrix} H^T W & G^T \\ G & 0 \end{bmatrix}^{-1} \begin{bmatrix} H^T W \left( h(x^v) - z \right) + G^T \lambda^v \\ g(x^v) \end{bmatrix} \]

Note: For State Estimation the Controls are Treated as Known Parameters
Implementation Issues

• The Component is Represented with a Set of Differential Equations (DE)

• The Dynamic State Estimator Fits the Streaming Data to the Dynamic Model (DE) of the Component

• Object Oriented Implementation
Implementation Issues

Typical Sampling Rates $\rightarrow t_s = 0.1 \text{ ms to } 0.5 \text{ ms}$

Challenges

1. Perform the Analytics at time less than $(2t_s)$
2. Robust Operation of DSE requires accurate zone model
3. GPS Synchronized Measurements simplify Dynamic State Estimation (for linear zones it becomes a direct method)

Example: Data Acquisition is performed 4 ks/s $\rightarrow$ Dynamic State Estimation is performed 2,000 times per sec.
Examples of DSE Based Protection
Event:
- 115 kV, 48 MVAr capacitor bank
- An external single phase to ground fault happened at 2.2 secs and last for 0.5 secs
- Followed by an internal fault in the capacitor bank at 3.0 secs, which changes the net capacitance of phase C from 4.8 μF to 2.4 μF.

List of Measurements:
- Voltage of phase A-G
- Voltage of phase B-G
- Voltage of phase C-G
- Voltage at neutral point
- Current of phase A
- Current of phase B
- Current of phase C
Capacitor Bank

External Fault

Internal Fault

Actual Measurement Voltage CAPBANK A (V)
Actual Measurement Voltage CAPBANK B (V)
Actual Measurement Voltage CAPBANK C (V)
Estimated Actual Measurement Voltage CAPBANK A (V)
Estimated Actual Measurement Voltage CAPBANK B (V)
Estimated Actual Measurement Voltage CAPBANK C (V)

Actual Measurement Current CAPBANK A (A)
Actual Measurement Current CAPBANK B (A)
Actual Measurement Current CAPBANK C (A)
Estimated Actual Measurement Current CAPBANK A (A)
Estimated Actual Measurement Current CAPBANK B (A)
Estimated Actual Measurement Current CAPBANK C (A)

Confidence-Level

Trip

Execution_time_average (s)

No Trip

Trip
Protection of multi-section Lines

Event:
• 500 kV Transmission Line
• An external phase A-C fault happened at 0.5 secs and last for 0.5 secs
• Followed by an internal phase A-G fault in the transmission line at 1.3 secs, which is a 2kΩ high impedance fault.

List of Measurements:
• Three-phase voltages at two sides
• Three-phase currents at two sides
Protection of Saturable Core Transformers

Event:
- 14.4/2.2kV, 1000 kVA single-phase saturable-core transformer
- A 800kW load connected to the system and generate inrush currents at 0.72 seconds
- Followed by a 5% turn-ground fault near neutral terminal of the transformer at 1.52 seconds

List of Measurements:
- Single-phase voltages at two sides
- Single-phase currents at two sides
- Temperature measurements at selected points
Comparison of AQCF Based Solution and Extended Kalman Filter

\[ \text{VoltageDifference (pu)} = \frac{\text{AQCF Estimated Voltage Magnitude Phase A (V)} - \text{EKF Estimated Voltage Magnitude Phase A (V)}}{15000} \]
Laboratory Experimentation
Laboratory Implementation

Experimental Setup

- PC driven D/A Hardware (32 Chan.)
- Omicron Amplifiers (3)
- GE Hardfiber Merging Units (2)
- Reason MU (1)
- Protection PC with Optical Network Interface & IRIG-B Receiver
- Arbiter GPS Clock with IRIG-B output
Laboratory Demonstration (Present Laboratory Capability)

System Under Test consists of:

- Merging units to perform data acquisition
- A process bus, and
- A personal computer attached to the process bus

A personal computer executes the setting-less protection algorithm. The physical system is represented with a simulator, D/A conversion and amplifiers.
Laboratory Instrumentation

Our Setting-less Relay is an 8-core $2k PC
Laboratory Instrumentation

Alternate Configuration

- National Instruments D/A Converter (cDAQ-9168/9264, 32 Channels)
- Omicron Amplifiers
- GE Merging Units
- Process Bus
  - Optical Fiber Patch Box
  - Optical Switch
- Ethernet Hub (Ruggedcomm)
- User Interface
- Test Waveform Generation PC
- Simulator

- GPS Antenna
- GPS Clock (Arbiter 1093)
- Unmodulated IRIG-B
- Relay Algorithm
- PC1
- Ethernet Hub (Ruggedcomm)
- Reason Merging Unit
- Volatges Currents

* CISCO CGS-2520-16S-8PC
  Connected Grid Switch with SFP Optical Ports
Object Oriented Implementation
Instrumentation Verification

Identification of Hidden Failures
- Blown Fuses
- Wrong CT Ratio
- Etc., etc., etc.

Handling of Hidden Failures
- Issue alarms
- Label data as “bad”
Visualizations

Merging Unit Data Concentrator

Measurement Attributes

Name | Phase | Type | Scale | Offset | Instrument Transformer | MU Order | MU
--- | --- | --- | --- | --- | --- | --- | ---
1 | test | A | Voltage | 1000 | 0 | 1.0 V / 1.0 V | 1 | Test GE

Circular Buffer

MU Data Concentrator

Start | Run | Setup
Stop

EBP Relay

CPU Time Usage (%)

Execution Rate | 0.00

COMTRADE Data

Start | Setup
Stop

Reference Clock Settings

Saturday, March 22, 2014
16:04:02.076388

Clock Source

- PC System Clock
- IRIG-b Receiver
- GPS Clock

Status

- Tracking
- Phase
- Frequency
- Intermittent
- Battery OK

Settings

Year | 2014
Local Offset | 4 Hours
Propagation Delay | -5.0 microseconds

Disciplined Oscillator Control Voltage

-5 | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5

Cancel | Apply | OK
Laboratory Results
Technology Issues - MU

• Use of Merging Units is preferable for the Dynamic State Estimation protection because MU data are of better quality and accuracy.

• Interoperability at the Process Bus Level ???

• Data Transmission Latencies may be significant and depend upon communication infrastructure organization and capabilities. Need additional work.

• Transmitted Data Organization Varies among Manufacturers, as IEC68150 does not specify “Application Service Data Unit” (ASDU) format

• The Process Bus implementation details vary greatly among Merging Unit manufacturers (eg: GE vs Reason/Alstom, Siemens, etc.)
Integrated Protection & Control* Vision
Additional Future Plans

Work with forward looking utilities to develop and demonstrate a fully “digital” substation:

• Separated data acquisition systems from logic devices (merging units)
• DSE based protection (both zone and system)
• Integrate Substation Based State Estimation with DSE Protection
• EMS Integration (Seamless applications with SE model → controls → implementation)
• Provide integrated cyber security via the physical system / protection system co-model
Our Vision

Integrate Protection and State Estimation
Perpetual Model Validation
Automated Substation State Estimation
Automated System Wide State Estimation
Perpetual Model Calibration and Validation

A Ubiquitous System for Perpetual Model Validation

Protection is Ubiquitous
- Makes Economic Sense to Use Relays for Distributed Model Data Base
- Capability of Perpetual Model Validation
- Component Real Time Model with GPS Time Stamp – enables distributed approaches
Integrated Wide Area Modeling, Protection, Control and Optimization
Dedicated Laboratory
Laboratory Demonstration
(Present Laboratory Capability)

System Under Test consists of:

- Merging units to perform data acquisition
- A process bus, and
- A personal computer attached to the process bus

A personal computer executes the setting-less protection algorithm. The physical system is represented with a simulator, D/A conversion and amplifiers.
Planned Laboratory Expansion
(Dedicated Lab for Protection, Control & Cyber Security Testing: Continuous Operation of Fully Automated Substation: To Be Used by Multiple GaTech Research Groups)

Configuration is a full replica of the IT infrastructure of a modern substation with multi-vendor equipment.

It will be driven by a high fidelity simulator capable of reproducing real life conditions.

Unique capability for simultaneous testing of protection, control and cyber security.
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