Incipient Fault Detection Using IEDs and Real-Time Substation Analytics

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Tuesday Panel Session 1PM-3PM
IEEE PES General Meeting
National Harbor, MD, July 27-31, 2014
DOE Feeder Health and Performance Management Project

- Objective: research, develop, and demonstrate a real-time distribution feeder performance monitoring, advisory control, and health management system for enhanced asset utilization and grid reliability.

- **Enhance Grid Reliability** by virtually extending SCADA beyond the substation fence and in part by incorporating advanced fault detection, notification, and localization techniques which will ultimately help reduce the frequency and duration of unplanned outages.

- **Enhance Asset Utilization** by enabling condition-based maintenance, prognostics concepts, and incorporation of real-time asset information derived from the automated analysis of sensor and IED data in the operation and asset management decision making processes.

- *This presentation originates from a multi-year pilot project between ABB and Xcel Energy (2006-present), the last Phase of which was funded in part by DOE under DE-OE0000547.*
Acknowledgement and Disclaimer

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• The authors gratefully acknowledge the support of the Xcel Energy Next Generation group as well as the operations and engineering personnel for their hard work on the field installations and assistance with the data collection and validation.

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Outline

• Background
• Automation system overview
• Application overview
• Demonstration and case studies
• Summary
Service Reliability and Restoration

Challenges

Permanent Faults
- Have DMS/OMS but desire faster outage response times
- Appreciate a “heads-up” time
- Fix the problem before the customer knows about it
- Identify outage cause
- Identify faulted lateral segment(s), etc...
- Better info, timely delivered, and in the right format

Feeder Events and Incipient Faults
- Have or enhance situational awareness
- Ability to anticipate problems
- Detect incipient and self-clearing faults
- Reduce OK on arrivals, etc...
- Better info, timely delivered, and in the right format

Do more with less cost-effectively!
- Leverage existing CTs/PTs/sensors
- Leverage multi-functional IEDs
Addressing New and Emerging Challenges

Opportunities

- Leverage existing information and communications infrastructure
- Tap into the abundance of grid data
- Leverage grid analytics and big data
- Break silos of automation and information
- Convert data into actionable knowledge/information
The Big Picture
End-to-End Grid Analytics System
Objective and Architecture

Leverage substation automation system (SAS) to detect incipient and/or self-cleared fault events and determine faulted segment(s) in real-time independently and ahead of OMS/AMI/Customer calls.
Predictive Grid Analytics

Enhancing outage management, incipient fault detection, and situational awareness

- Primary value: Knowledge
- Event X-rays → Event MRI

Dispatchers will know what they didn’t previously know when a feeder fault/abnormality occurs that is either self-clearing, incipient, or are cleared by a non-communicative device, e.g., reclosers or switches, or unintelligent device, e.g., fuse

- Knowing beforehand assists utility in reducing “D”uration
- Will know substation, feeder, phase, magnitude, type, zone, segment, date, and time information
- Able to detect 24/7/365 momentary, incipient, and permanent faults on overhead and underground lines
- Do it all from inside the substation taking advantage of the data infrastructure already in place and potentially reducing or eliminating feeder sensor installations.
Real-world deployment
Real-time detections and notifications

- Established robust, reliable real-time notification solution
- Thousands of records retrieved, analyzed, and OMS confirmed.
- Early notifications some hours ahead.
- Some late notifications due to the cloud!
- Few missed notifications initially
  - Setup issue resolved via remote access

Substation deployment
March 2011

Incipient fault
May 7, 2011
Permanent fault
May 27, 2011
Technical Approach

- Based on statistical decision theory, machine learning, and signal processing techniques.
- The main technical challenges are in the design of algorithms, signal modeling, and discovering a few informative features for representing patterns while optimizing for dimensionality. Dimensionality is characterized by the number of features used in the classifier design.
- Development involves a 5 step cyclical model
- Both supervised and unsupervised approaches are utilized. The unsupervised design is favored from the configuration/parameter settings point of view.
- Optimized solution where the classifier accuracy is maximized but the complexity is minimized to meet platform requirements.

Mathematical expression:

\[ Q_x = \Pr(S > S_x) \]

\[ = 2(2\pi r_1)^{-1} \int_{x_1}^{\infty} \exp\left(-\frac{r_1^2}{2\sigma_x^2}\right) dr \]

\[ + \left[ \int_{x_1}^{\frac{N}{2}} \int_{-\infty}^{\infty} \exp(-x) dx \right] x_1 = \frac{S_x}{2\pi} \]
Tech. Approach: Probabilistic Classifiers

- The length of transient spectrum is 130. This potentially gives rise to 130 dimensions!!
- PCA reduces that dimensionality to 2.
- The first two PCs account for over 95% of variability in patterns.

Get tunable parameters for PMZ or AMZ events:
\[ S_{\mu}, P, Par, K, \tau_{\text{min}}, \tau_{\text{max}}, \tau_{\text{tun}} \]

Scale the Park vector of isolated transient
\[ l_n[t] = L_n(t) / (l_0), \ n = 1, \ldots, N, \]

Calculate Hanning window and normalizing factor
\[ w_k[k] = \sum_{n=1}^{N} w_k[k] / 2 \]

Calculate spectrum for the scaled transient
\[ S_k[k] = \text{DFT}(l_n[t] w_k[k]) / \rho, \ k = 1, \ldots, N / 2 + 1 \]

Subtract the parameter "mean spectrum"
\[ S_{\mu}[k] = S_k[k] - \mu \]

Project into principal component space
\[ x = \text{PS}_{\infty} \]

Calculate normalized distances to cluster centers
\[ d = \text{CalcProb}(x, Par) \]

Find closest cluster and distance to closest cluster
\[ k_{\text{min}} = \arg \min_{k} d_k, \ d_{\text{min}} = d_{k_{\text{min}}} \]

Set: Prob='High'
Set: Prob='Medium'
Set: Prob='Low'
Set: Prob='Not found'

Stop
Stop
Stop
Stop

Contours of density function

- Preprocessing
- Feature Computation
- Feature Extraction
- Classification
- Decision making
- Output results
Illustrative Case #1
Incipient fault lasting 9+ months

Initial Incipient Fault
September 11, 2007
02:42 PM
- Ifault = 422 A RMS
- No outages or customer calls

139 Incipient Faults thereafter
- Ifault = 100’s – 1000’s A RMS
- Multiple faults per day

Permanent Fault
June 14, 2008
12:19 AM
- Ifault = 2626 A RMS
- Customer call
Illustrative Case #2
Incipient fault lasting 3 hours

Initial “C” Phase Incipient Fault March 8, 2013 at 6:05:55 PM
- Ifault = 1108 A RMS
- No outages or customer calls

6 Single blips thereafter
- Ifault = (1600 – 2438) A RMS
- Generally less than ½ cycle

9 Multiple blips thereafter
- Ifault = (2776-4274) A RMS
- Over a few non-contiguous cycles

Permanent fault captured
March 8, 2013 at 9:07:53 PM
- Ifault = 4077 A RMS
- Customer call
Illustrative Case #3
Primary zone: Evolving fault

- A phase-A fault evolves into a phase-B fault
- No OMS data!
Illustrative Case #4  
Permanent O/H Fault

“A” Phase Fault  
Jan 31, 2013 12:04:59 AM

- $I_{\text{fault}} = 2564\text{A RMS}$
- No outages reported around that time
- Cause was tree inside maintenance Corridor
- Feeds traffic and street lighting

Outage registered 7:41AM

Opportunity to fix the problem before an outage call
**Operator Message:**

- A **Cable Fault** event on **B phase** has just been detected on **Primary feeder 1234** out of **XYZ substation** on **Dec 13, at 7:44AM** that could have been cleared by a **40A fuse** *(Rel. probability: High).*
Operator Message:

- An **Incipient Cable Fault** event on **B phase** has just been detected on **Primary feeder 1234** out of **XYZ substation** on **Dec 13, at 7:44AM** that could have been cleared by a **40A fuse (Rel. probability: High) in segment x.**
Faulted Segment Identification

Feeder: 1753 line segments
Fault: Nov 22, 2012 @ 09:09:01 PM
4571A peak, 2936A RMS
Confirmed bad B phase cable

Result
7 segments short-listed
Actual faulted segment adjacent
Locating sub-cycle incipient faults challenging in practice!
Summary and Conclusions

• Real-time incipient fault detection and notification are possible using typical substation infrastructure.

• An end-2-end analytics system is required to deliver the value

• Opportunity to optimize field sensor deployment to uniquely identify impacted segment

• Valuable to dispatch for situational awareness and early knowledge of those power system activities previously not known until initial customer call or meter pings
Summary and Conclusions (cont.)

• Be mindful of benefits misalignment if operations are siloed from engineering. Significant value is realized at the company level.

• Over 90% of faults occurred on laterals
  • Detection and location is harder on laterals
  • Do not cause breaker trips
  • Integration with DMS/Control Center is required to make operational impact.

• Sub-cycle and incipient fault location remain an industry challenge!

• Need to deal with feeder modeling inaccuracies
  • Bad connectivity data
  • Incorrect phasing
  • Missing information (conductor length, size, material)
  • As-built vs. as-operated
Thank you for your attention!

Any Questions?

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If you have further questions, please contact me at:

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