Proactive PQ: Enabling Analytics and Initial Successes

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The Imperative for Proactive PQ

Proactive PQ can improve:

- Economic Performance
- Grid Performance Metrics
- Environmental Protection
- Worker and Public Safety
- Customer Satisfaction
- Carbon Reduction and Carbon Neutral Strategies

The aftermath of a (now) readily pre-detectable failure of a substation CCVT sensor
(Source: American Electric Power)

Common Goals for *Big Data* Analytics
(From a PQ perspective)

- Compliance verification
- Performance analysis/benchmarking
- Site characterization
- Troubleshooting
- Advanced applications and studies
- Active PQ management

Resource:

CIGRE/CIRED JWG C4.112 - **Guidelines for monitoring power quality in contemporary and future power networks**
https://e-cigre.org/publication/C4-115_2014-guidelines-for-monitoring-power-quality-in-contemporary-and-future-power-networks--results-from-cigrecired-jwg-c4112

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Common Goals for Big Data Analytics
(From a PQ perspective)

- Compliance verification
- Performance analysis/benchmarking
- Site characterization
- Troubleshooting

Reactive

- Advanced applications and studies
- Active PQ management

Proactive

Reactive Analytics
Primarily Threshold and Limit Based

Harmonics (IEEE 519-2014)

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

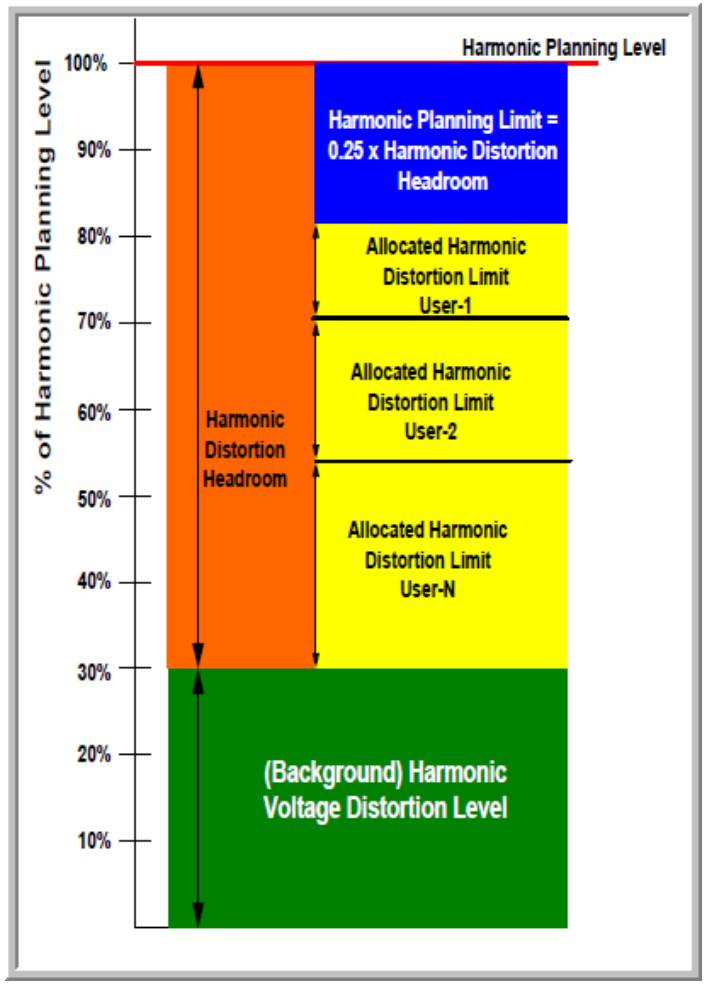
[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Flicker (IEC 61000-3-7)

Table 2 – Indicative values of planning levels for P_{st} and P_{lt} in MV, HV and EHV power systems

	Planning levels	
	MV	HV-EHV
P_{st}	0,9	0,8
P_{lt}	0,7	0,6

Customer Allocation (IEC)



- Standards
  - Designate maximums, not optimums
- Allocations
  - Imply that "below threshold" PQ levels are, by definition, acceptable

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Reactive PQ: Pros and Cons

- Pros
  - Conceptually **simple**
  - Minimal planning and resources
  - Doesn’t need “Big data”

- Cons
  - Little or no anticipation of performance extremes
  - Spawns response only after:
    - Out-of-spec performance
    - Equipment failure/malfunction, and/or
    - Customer complaints occur

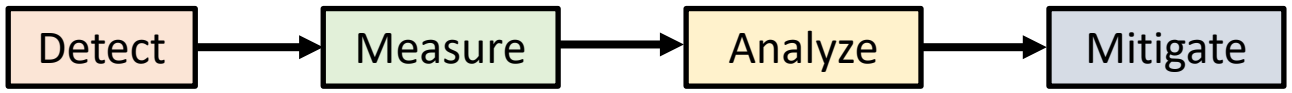
Proactive PQ: Pros and Cons

- Pros
  - Allows assessment of both:
    - Present performance *and*
    - Modeling/prediction of **future** performance
  - Can identify performance changes *before* they become expensive failures
  - Can leverage “Big data” (although it’s not required)

- Cons
  - Conceptually more complicated
  - Software tools required
  - **Significant up-front investment** and management support

Implementing Proactive PQ
General Criteria

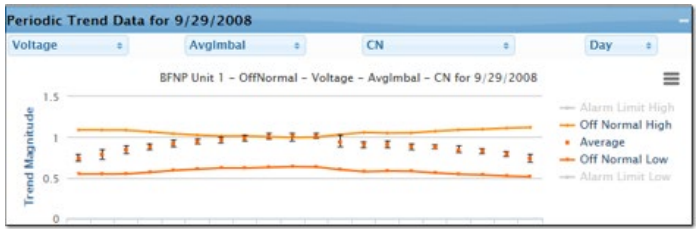
- **Signals**: Indications of declining health or incipient failure are manifested in measurable **voltage and/or current signals**
- **Identification and Analytics**: Enough understanding of those signals exists (or can be created) to **identify these signals** with a high degree of confidence
- **Advanced Detection**: The signals can be detected **far enough in advance** to allow staff to intervene before total or expensive failure



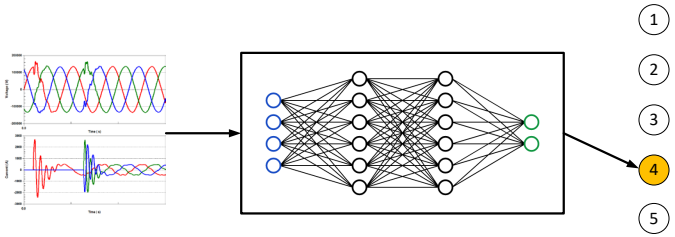
Proactive Use of PQ Data

Continuous tracking of PQ Performance

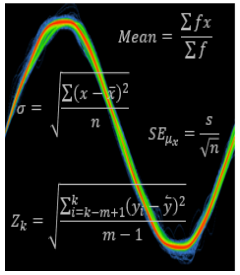
- Monitoring of PQ parameters on a continuous basis rather than only after-the-fact
- Examples:



- Statistical Process Control (SPC)

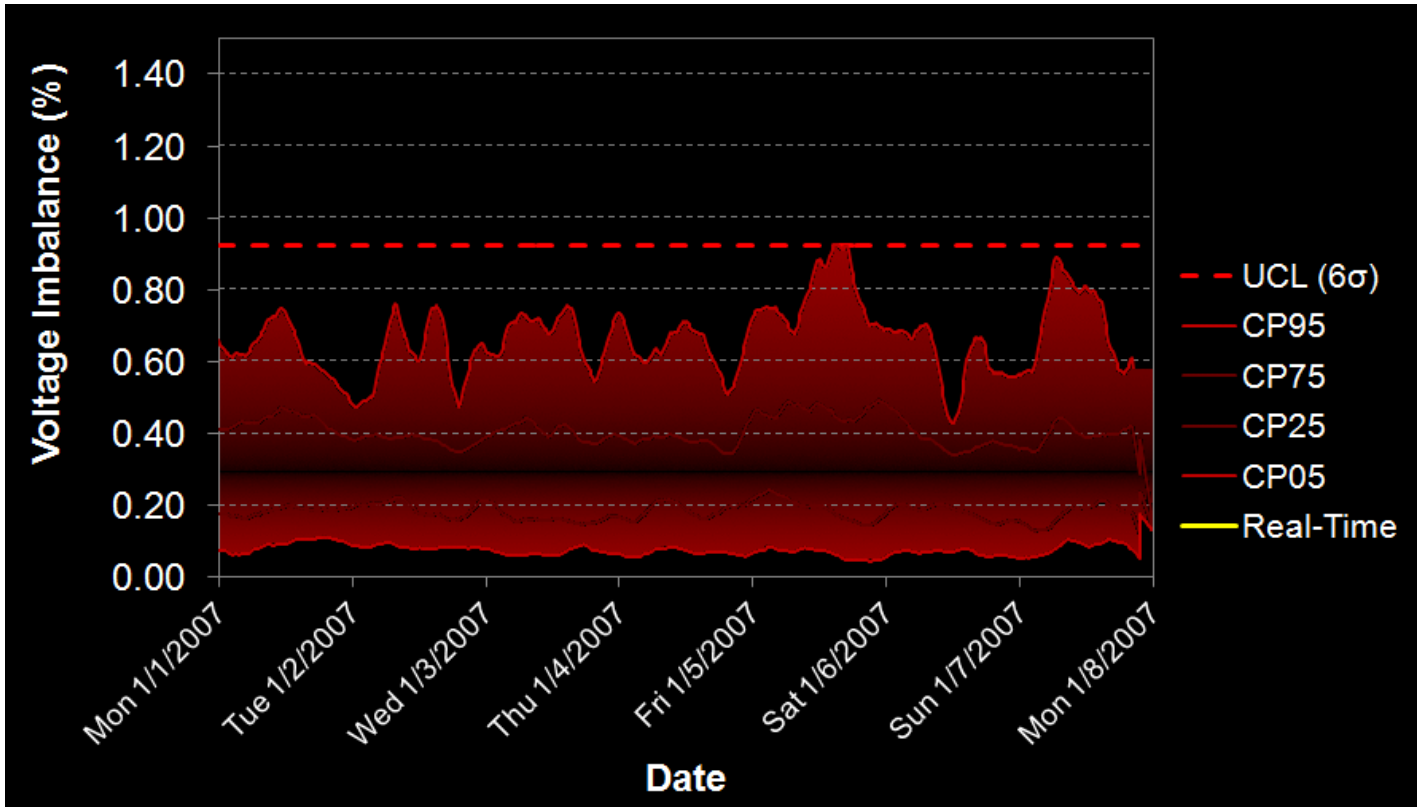


- AI/ML Techniques



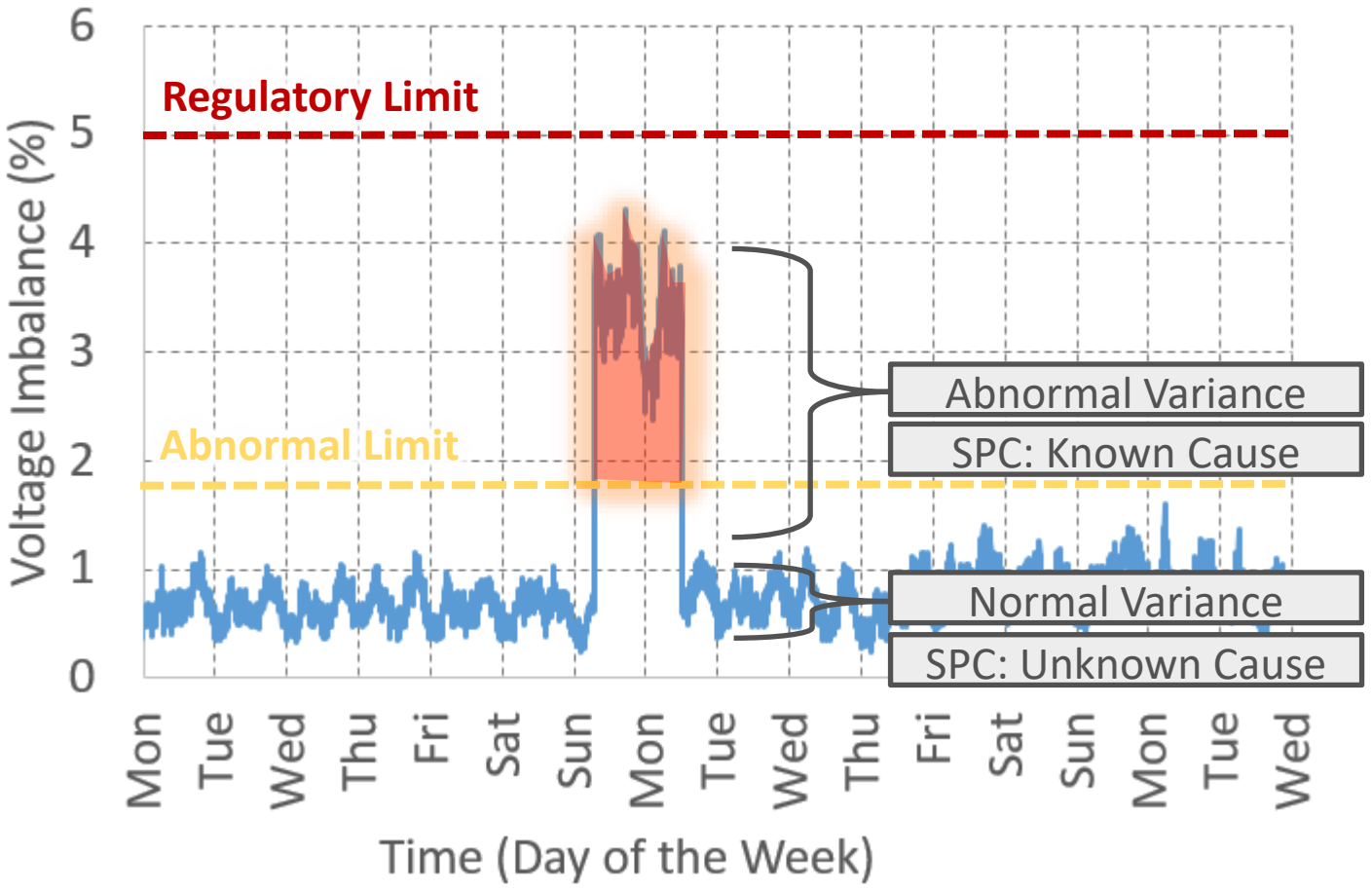
- Full Waveform Analysis

Proactive PQ Analytics using SPC



Importance of Creating Limits for PQ Trend Data

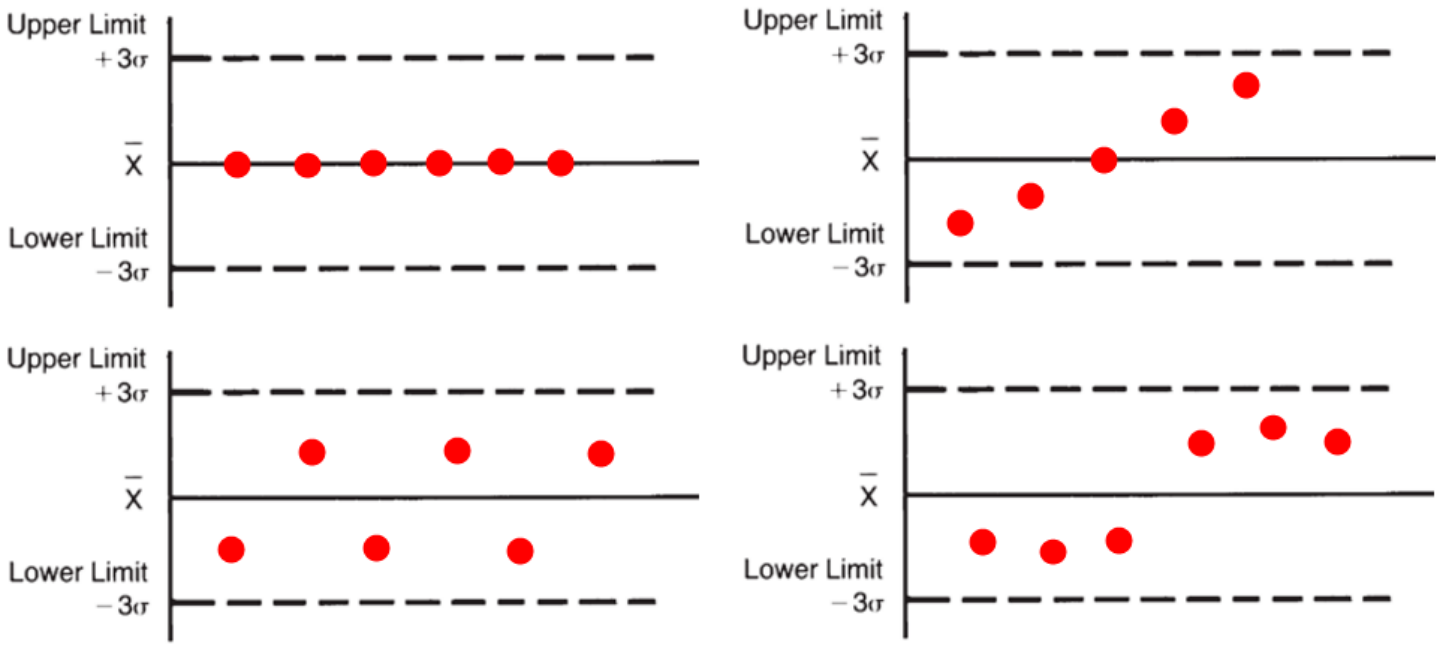
- Alarming on Damaging PQ Levels
- Alarming on Abnormal Variance
- Needed to Automate Detection of Excursions
- SPC is an Established Method for Detecting Abnormal Variances without having to visually inspect the data



Statistical Process Control for PQ

Detecting problems/issues before they become expensive

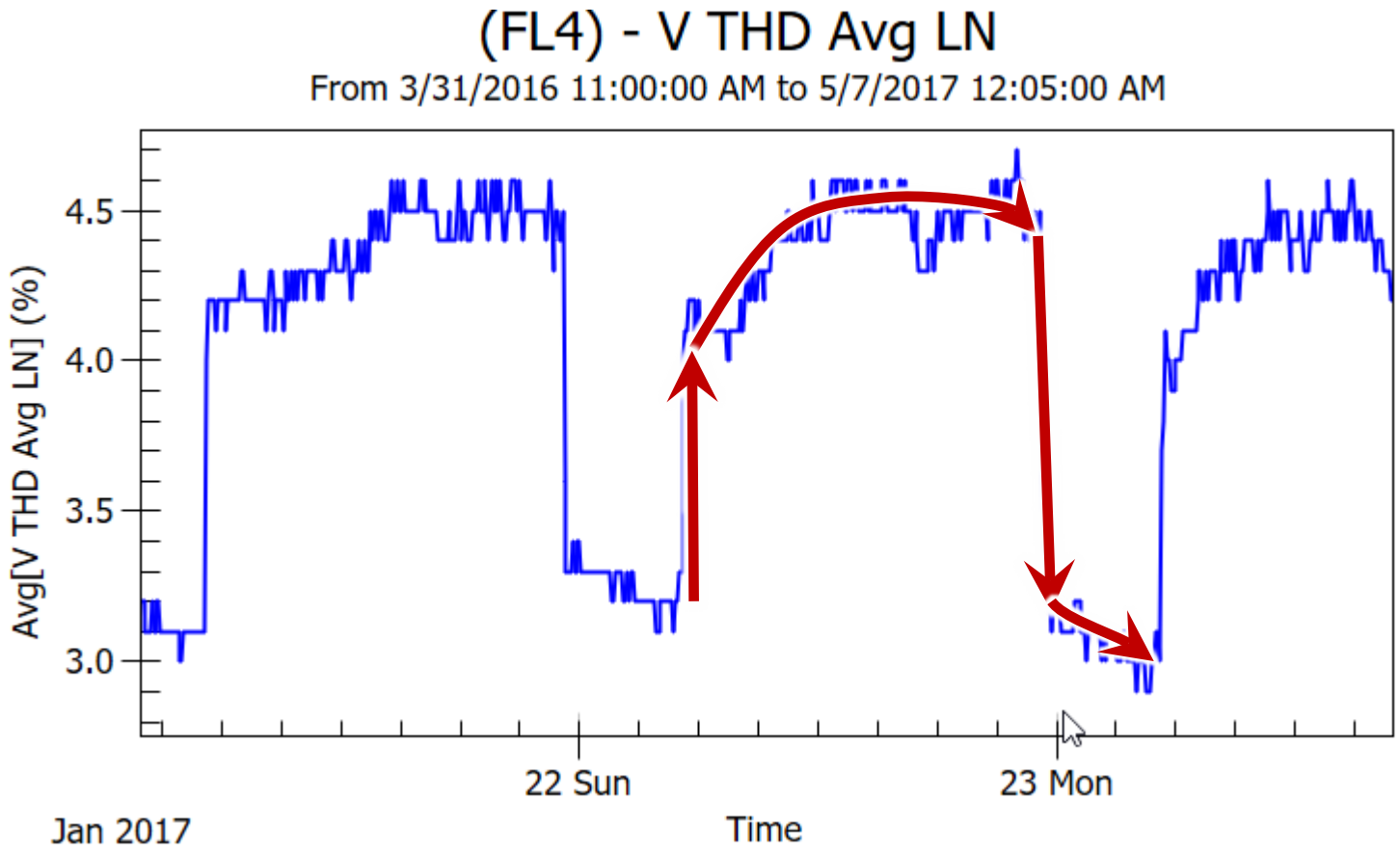
- In addition to continuous tracking of PQ, SPC techniques allow detection of a very wide range of issues that aren't normally flagged



SPC for PQ

Dealing with the Challenge of Cyclical Behavior

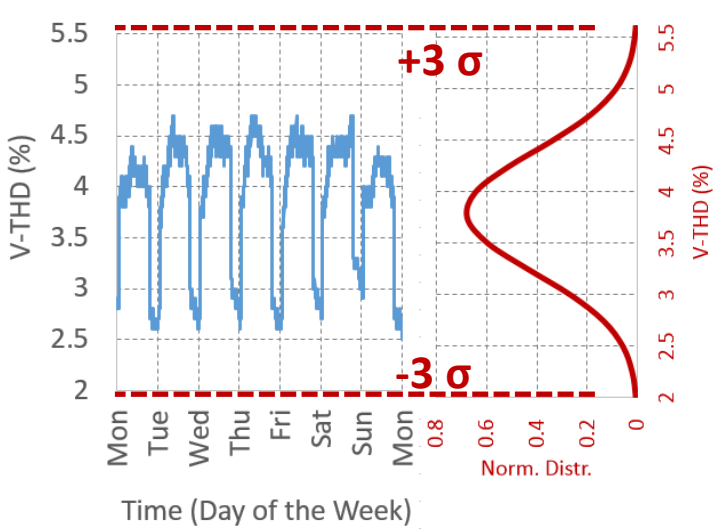
- Daily Trend (Known Cause)

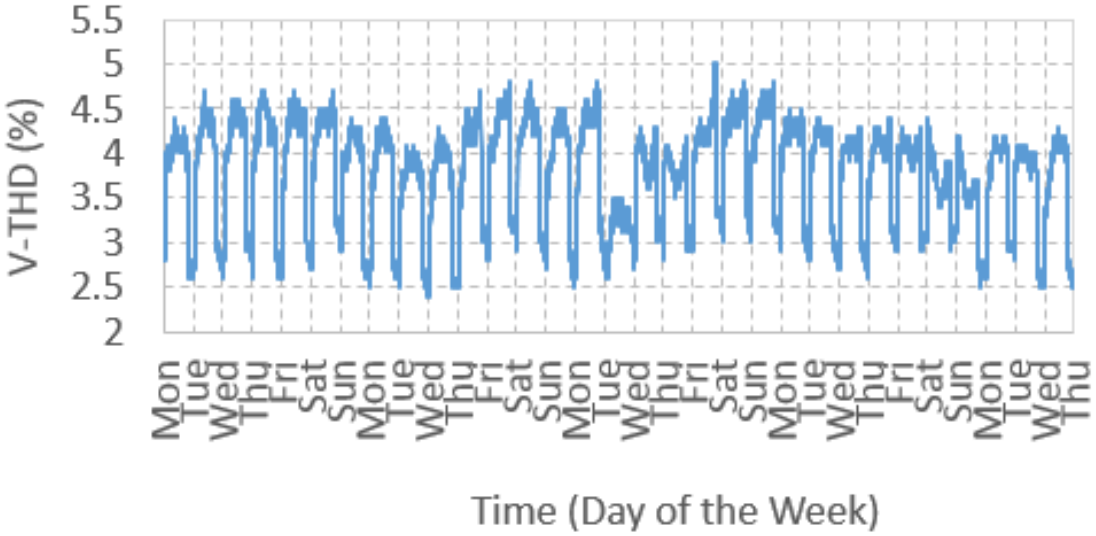


Dynamic Limits are Needed for Trends with Known Repeatable Variance

Calculating SPC Control Limits

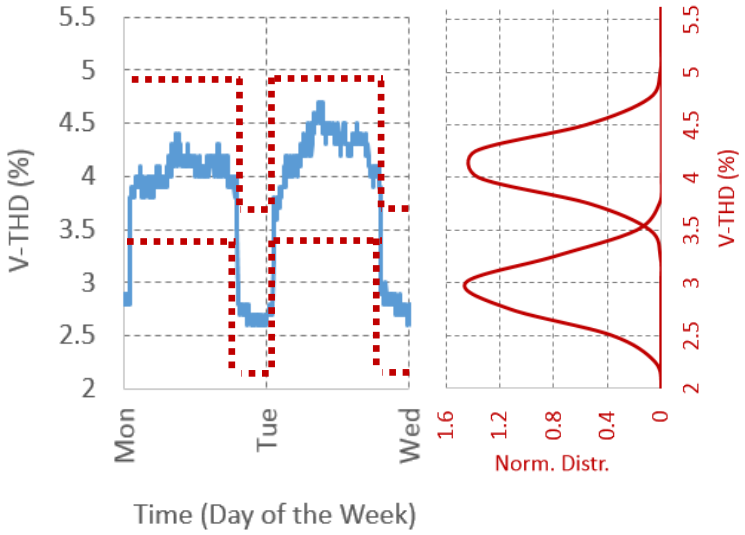
Results based on using original data en masse

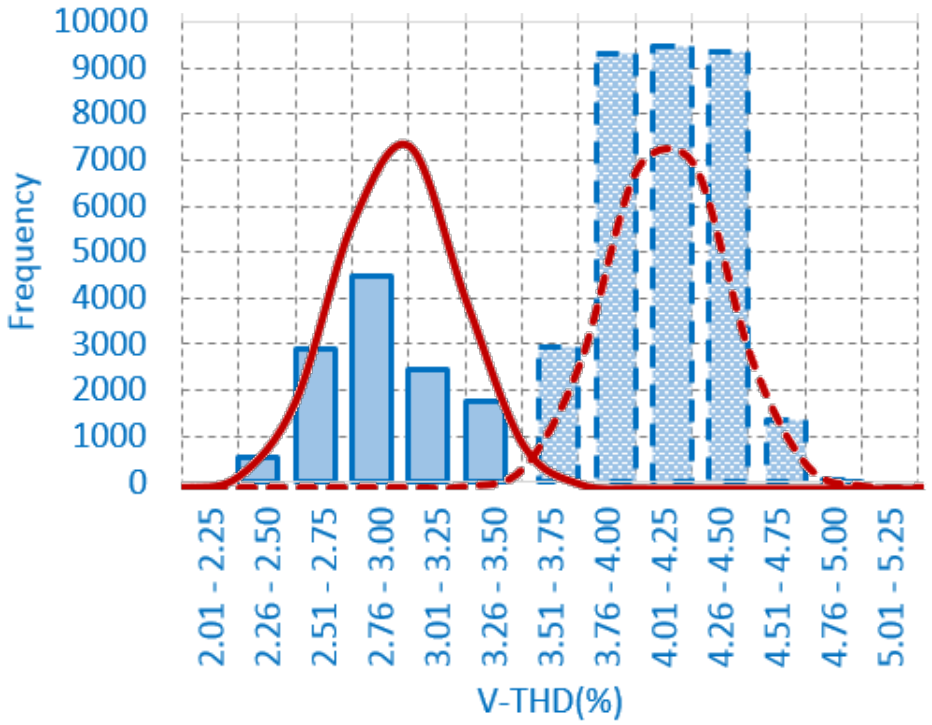




Control Limits calculated based on original data set produces Zero Alarms

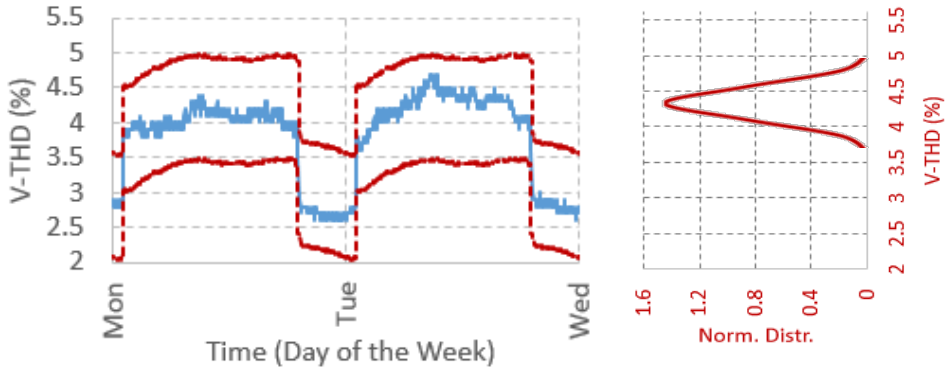
Calculating Dynamic SPC Control Limits

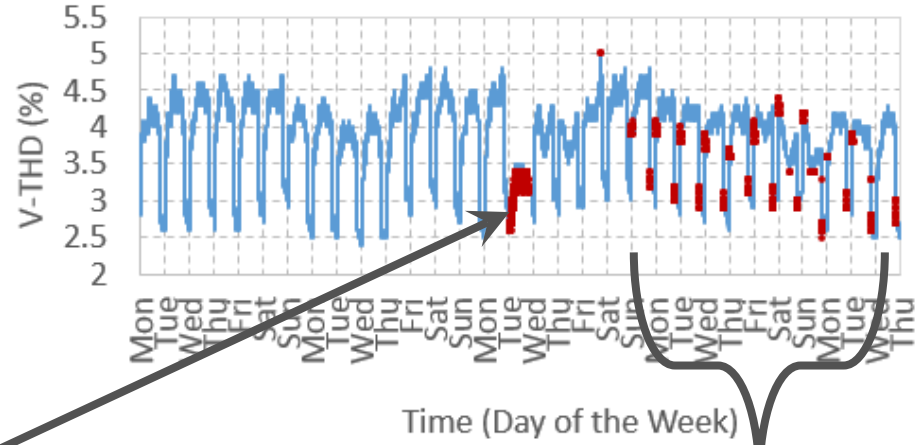


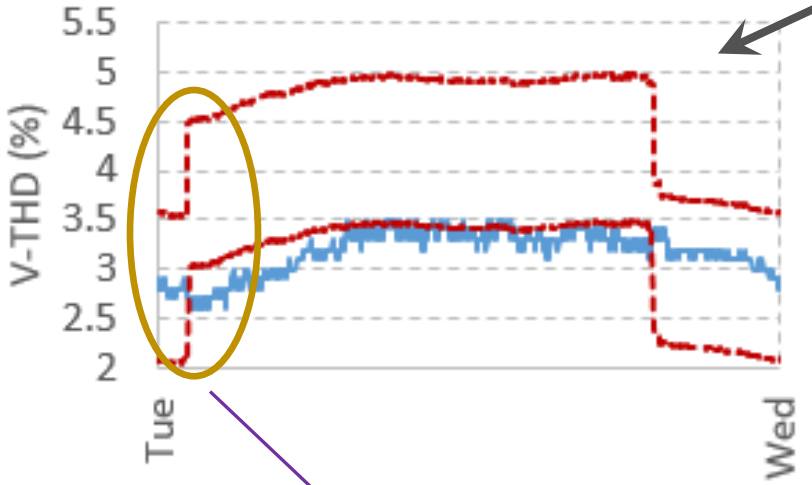


Applying Dynamic Limits Results

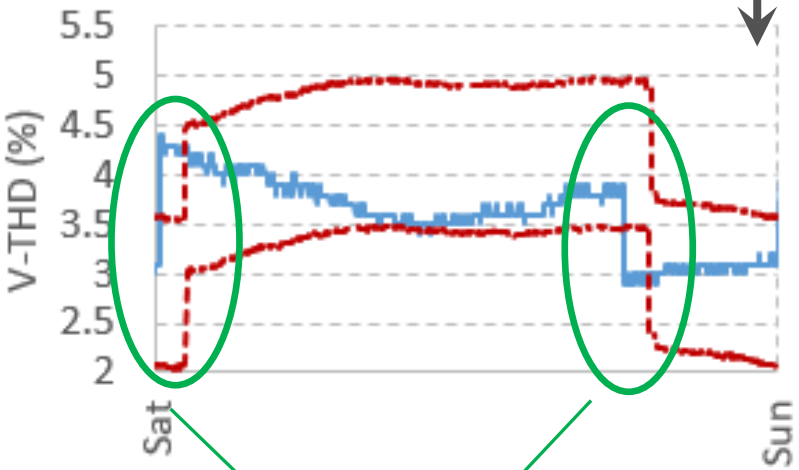
From Zero alarms to multiple alarms with the same data







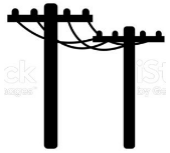
Cap bank failure to energize?



Timing or timestamp error?

Proactive PQ Analysis using AI/ML

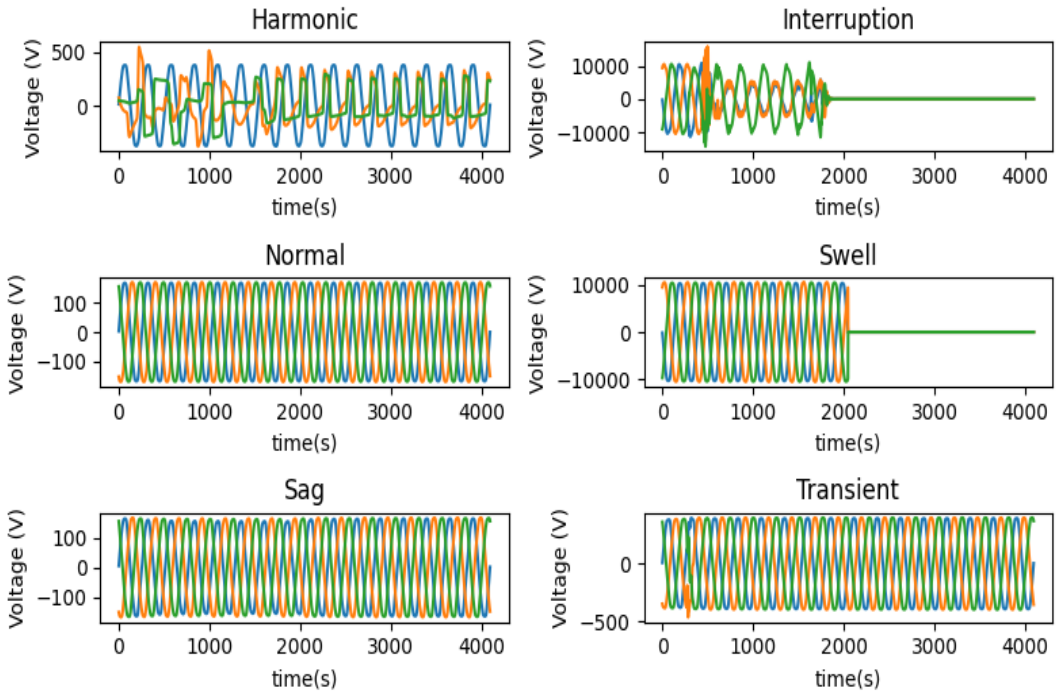
Getting Value from PQ waveform Data



PQ meters in the distribution grid collects periodical data

Too much data

All data are mixed. Hard to identify data of interest

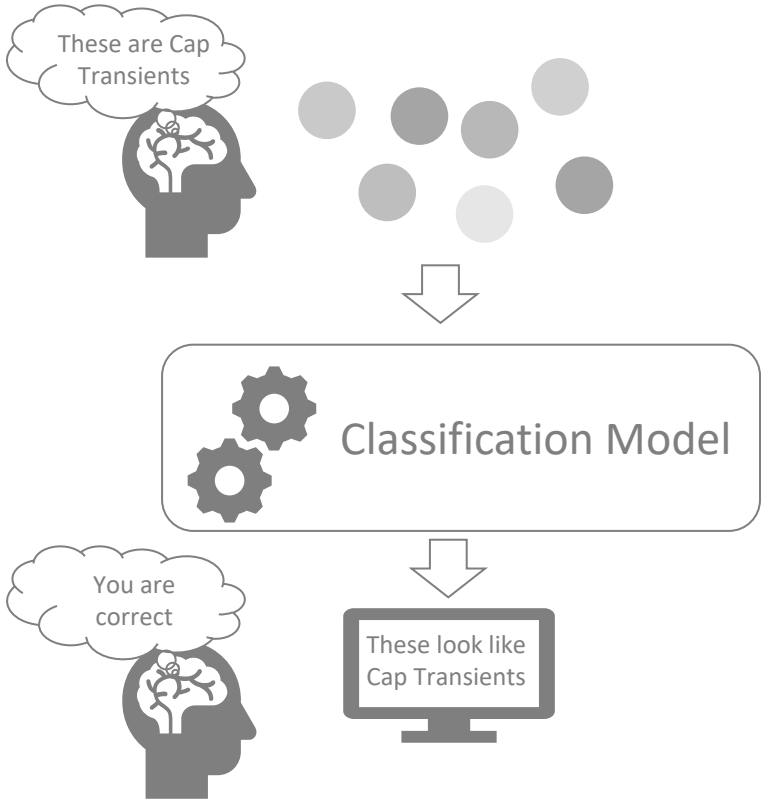


Having to use “educated eyeballs” has mostly limited waveform analysis to reactive, post-mortem cases.

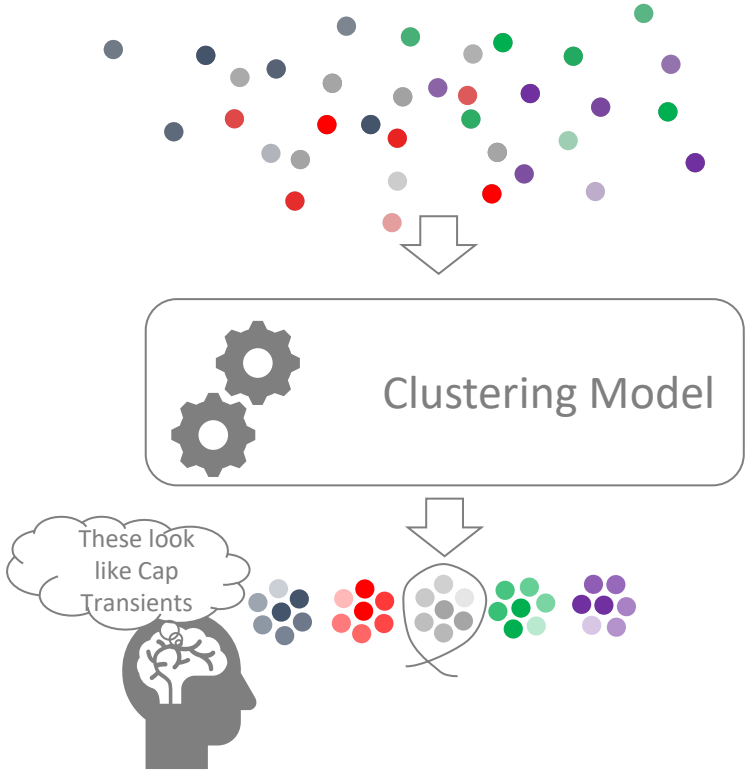
Proactive PQ Analysis using AI/ML

Two Approaches

- With Metadata
  - Classification
    - Human transfer of knowledge
  - Supervised Learning

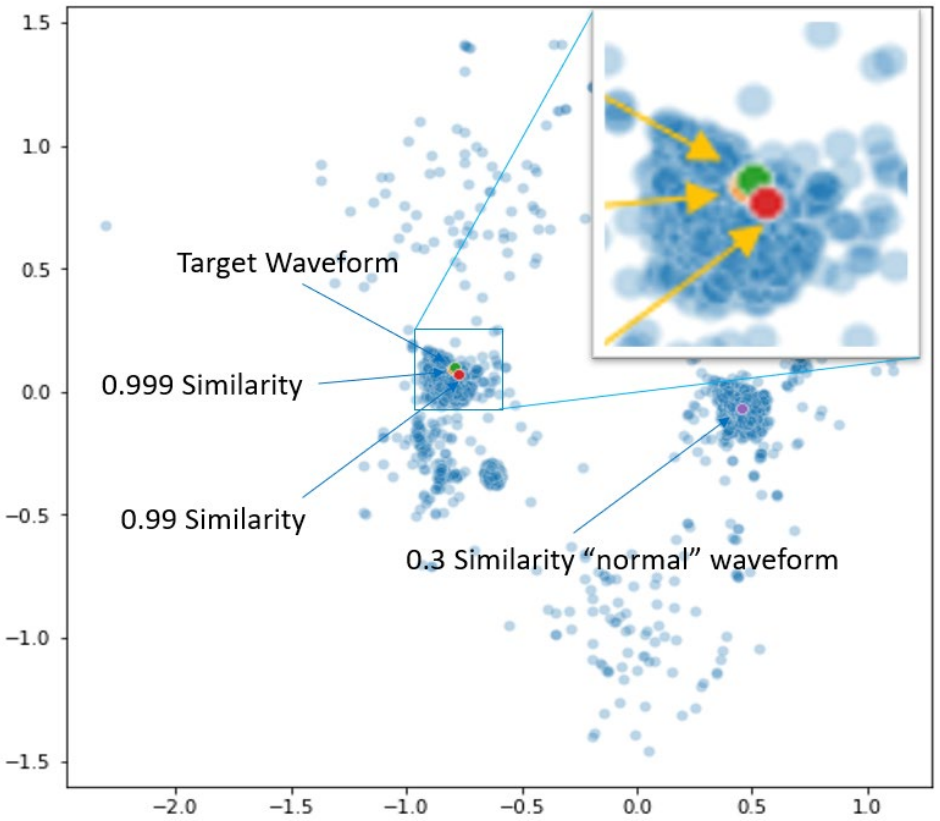


- Without Metadata
  - Clustering
    - Looks for similarities
  - Unsupervised learning

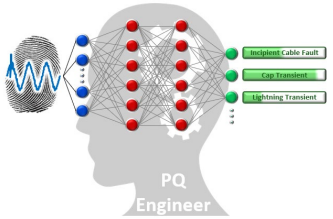


Proactive PQ Analysis using AI/ML

Waveform Signature Clustering

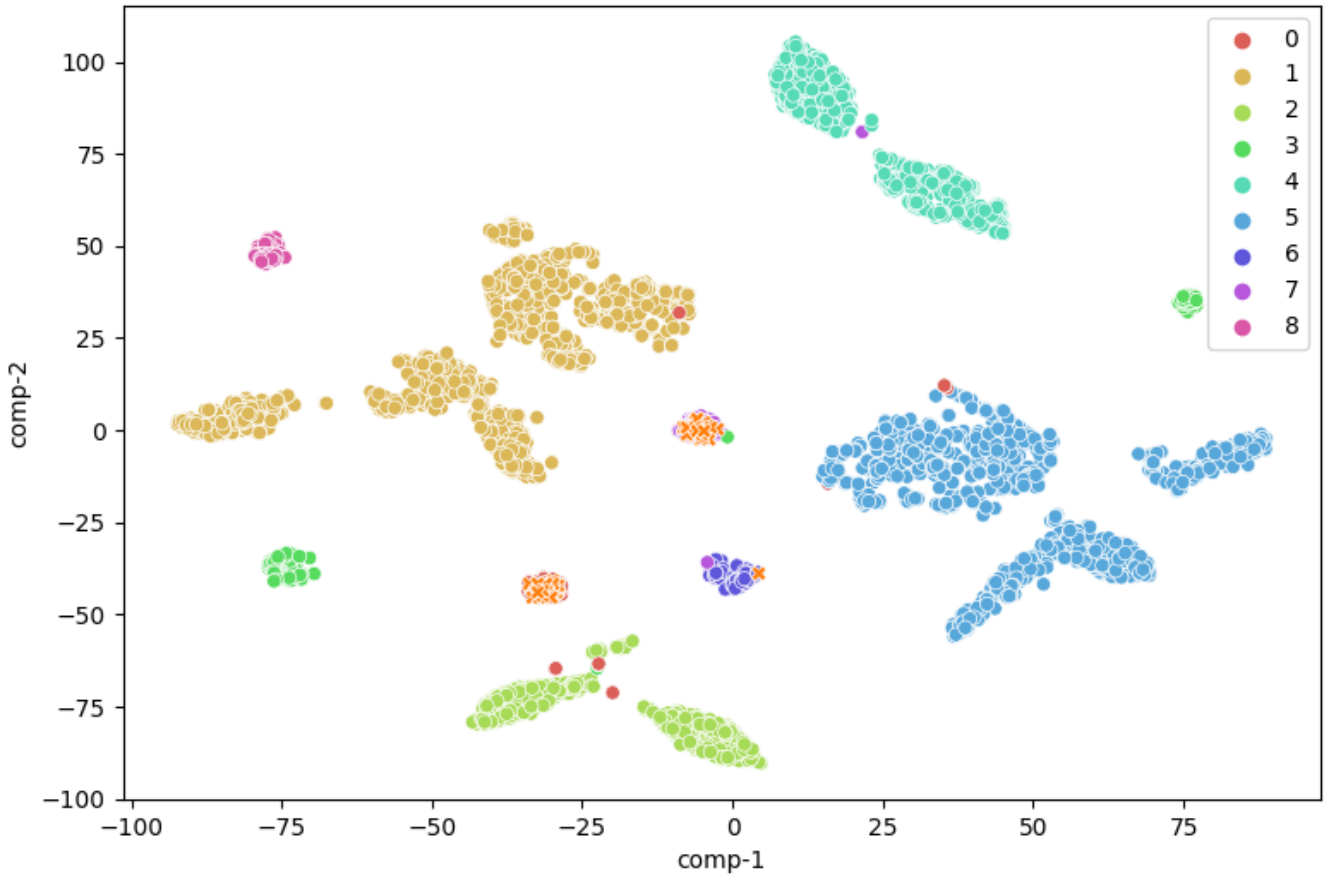


- 1,000 waveforms
  - (existing database > 650K)
- Key:
  - Purple: Normal waveform
  - Green: Target/test waveform
  - Orange: Highly similar
  - Red: Mostly similar
- Vertical and Horizontal scales are unitless/arbitrary



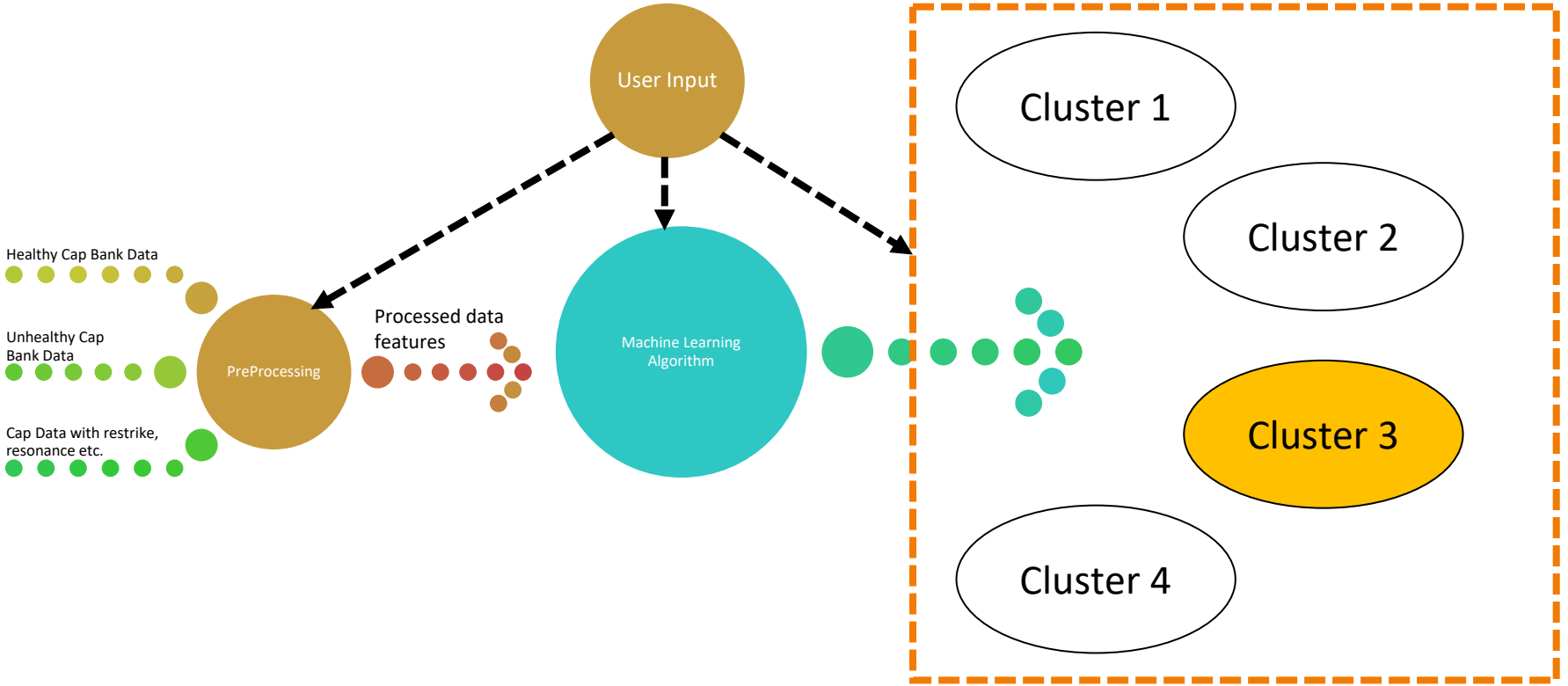
Waveform Clustering using AI
The ‘state of the art’

- Exploring the possibility of using AI and Machine Learning to cluster PQ data.
- Proof of concept was developed by EPRI in 2022.
- Web application currently in development to enable large scale testing.



AI/ML Techniques
What the future is likely to look like

- Let the PQ engineer do the ‘engineering’.
- Let AI do the ‘brute force’ computation.
- Take the ‘big’ out of ‘big data’ using machine learning tools.

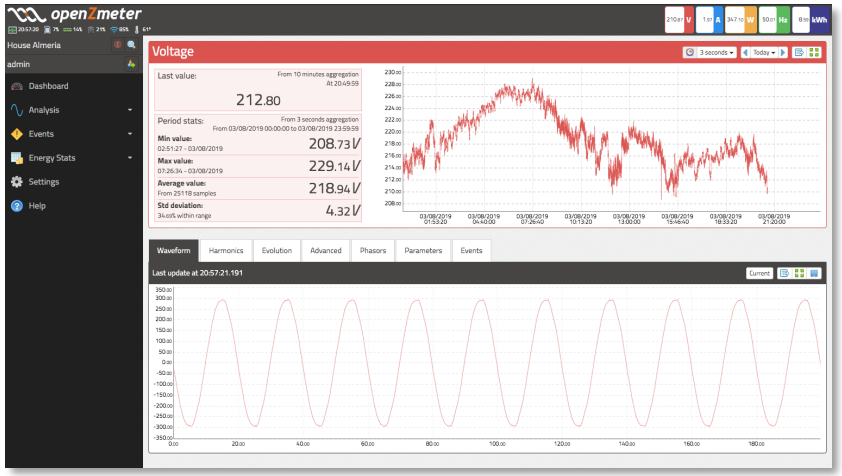


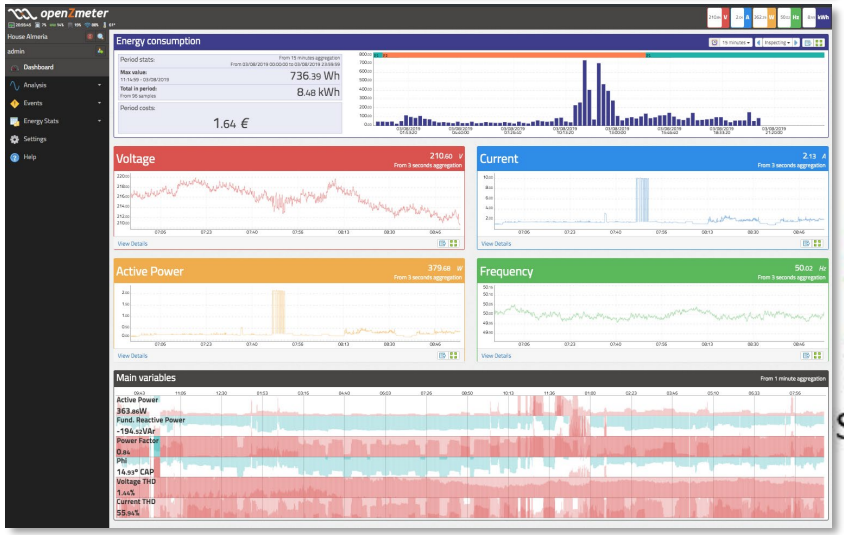
Proactive PQ Analytics using Full Waveform

openZmeter and the Cyclic Histogram

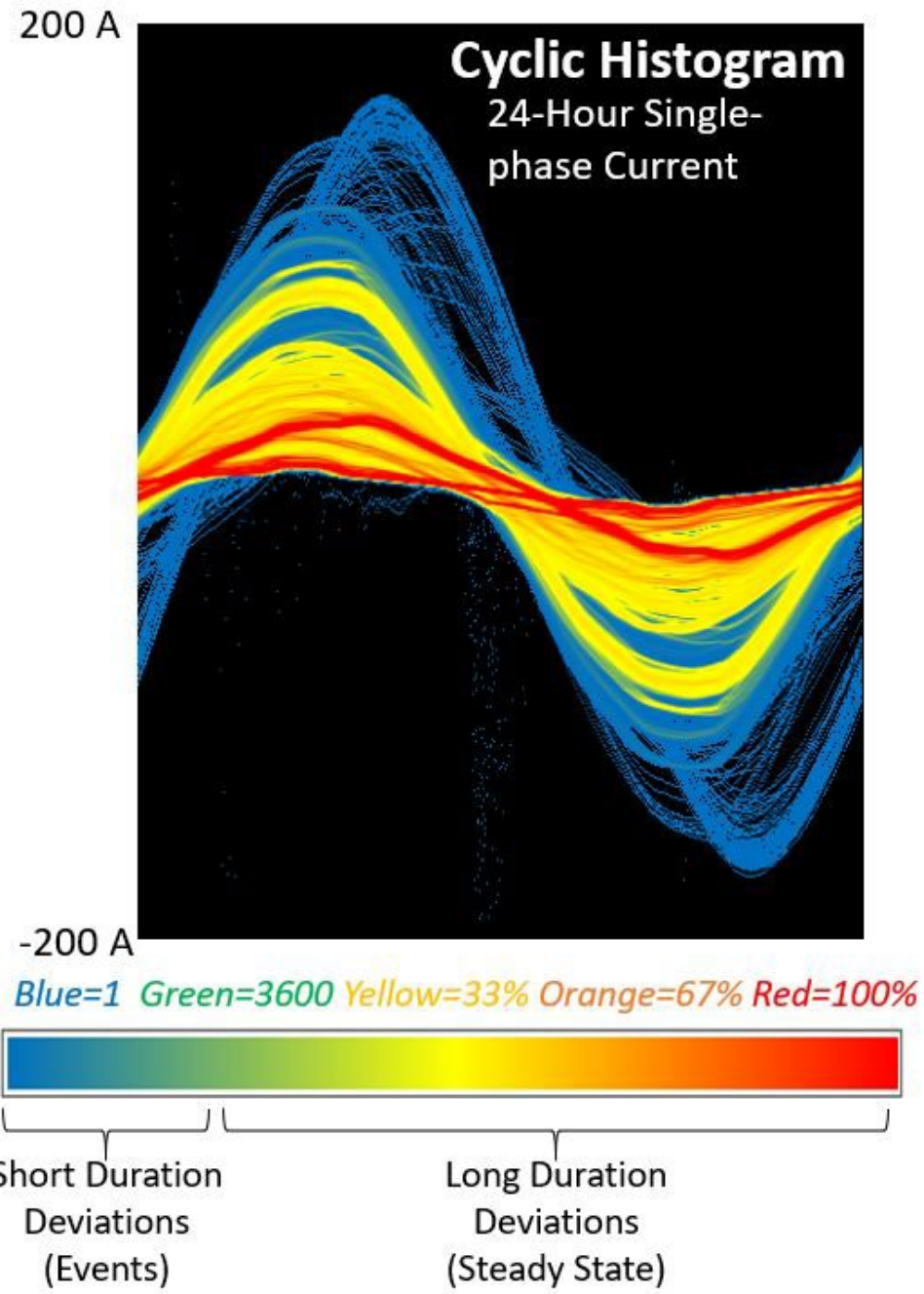
https://openzmeter.com/

Web-based data display





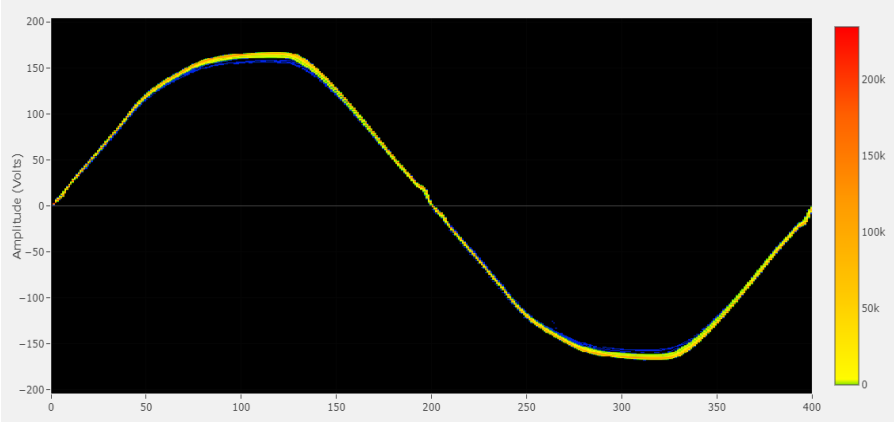
Field installation



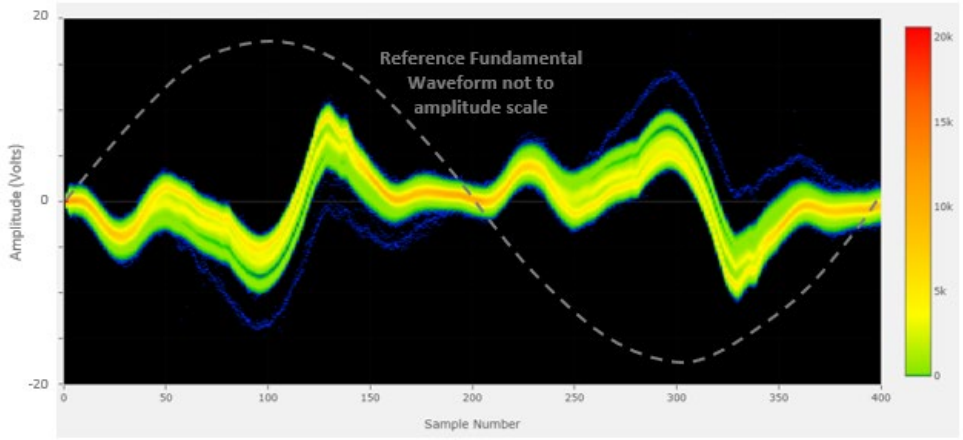
Proactive PQ Analytics using Full Waveform

Detecting Small Deviations and Changes in Waveform Shape

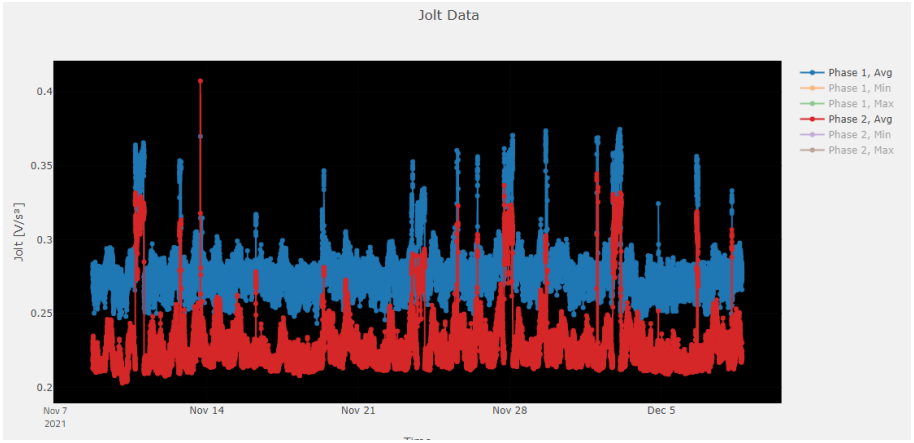
CH Voltage w/Transient Anomaly @ Zero-Cross



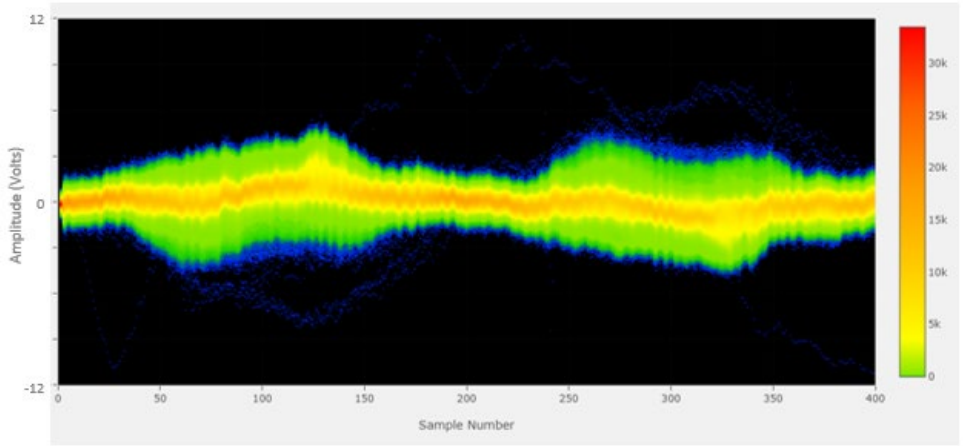
Ideal Filtered Voltage (60Hz Component)



Average Jolt for 30 Days w/increase during Transient



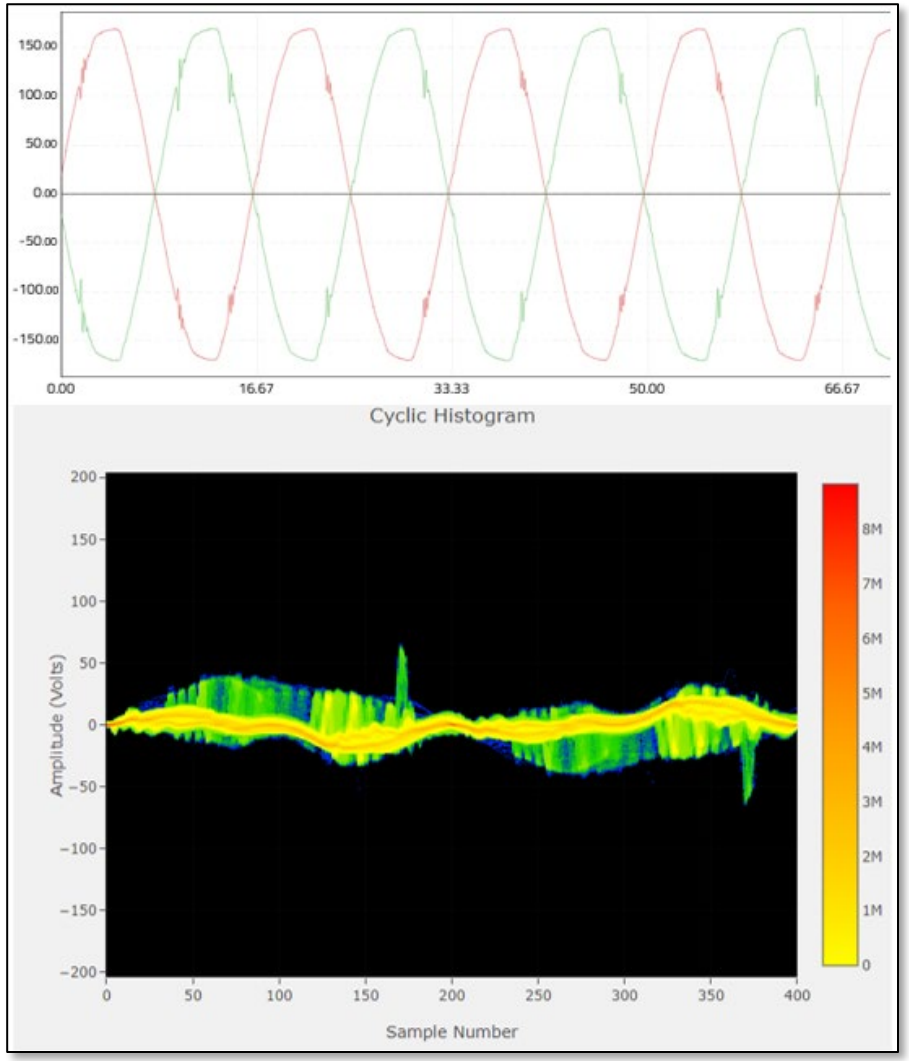
Base Filtered Voltage (Average of 1st 200mS)



Proactive PQ Analytics using Full Waveform

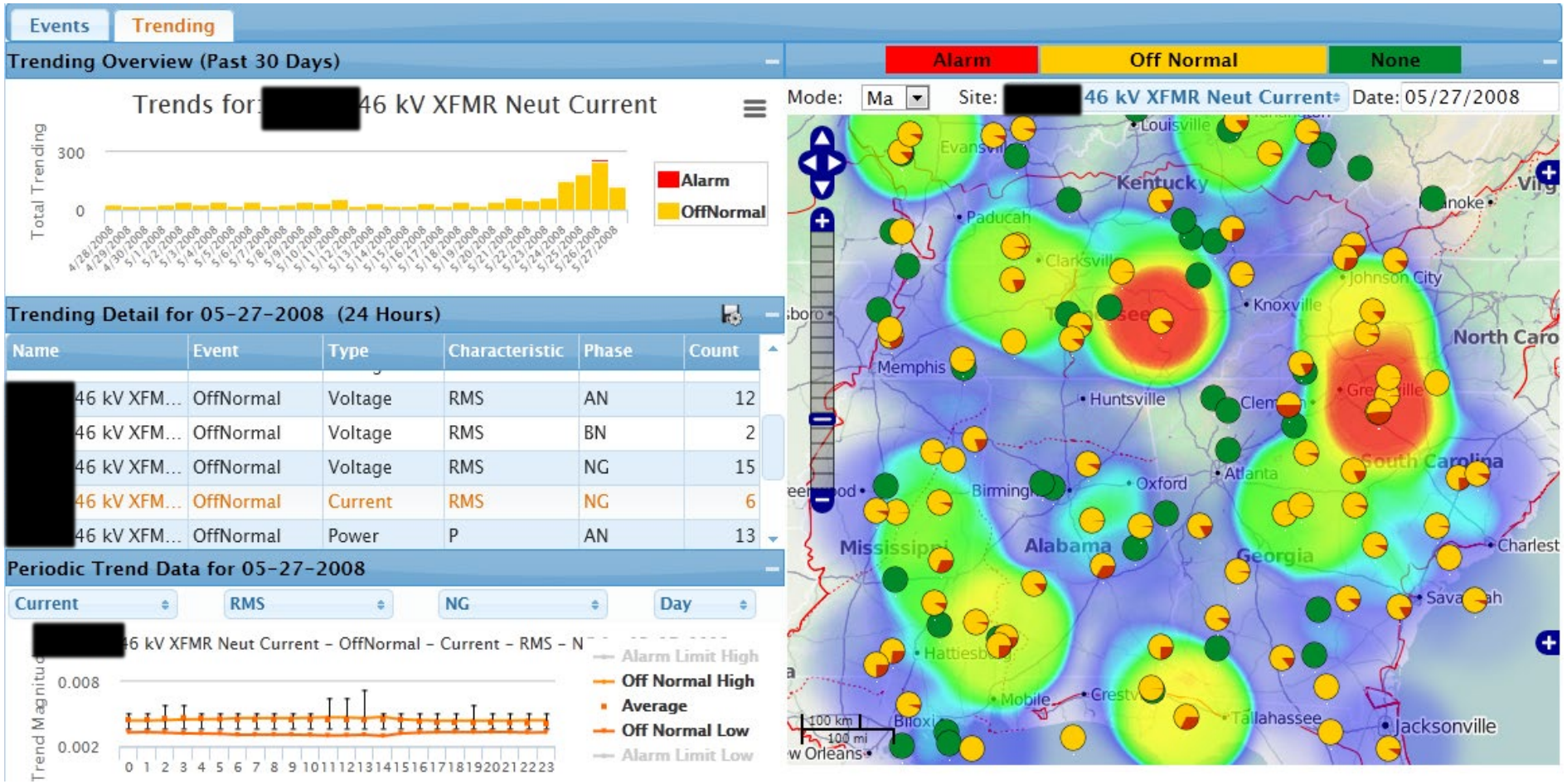
Example: Investigating Light Flicker

- Cyclic Histogram compilation of many cycles
- Filtered deviations now clearly show divergence from normal
- Subtle notching that doesn't exceed a pre-defined threshold or otherwise produce alarms
- Cause: Tankless Water Heater switching / power draw



Proactive PQ Analytics: Implementation

OpenPQDashboard



Resource: Open PQ Dashboard:
https://github.com/GridProtectionAlliance/PQDashboard

Proactive PQ

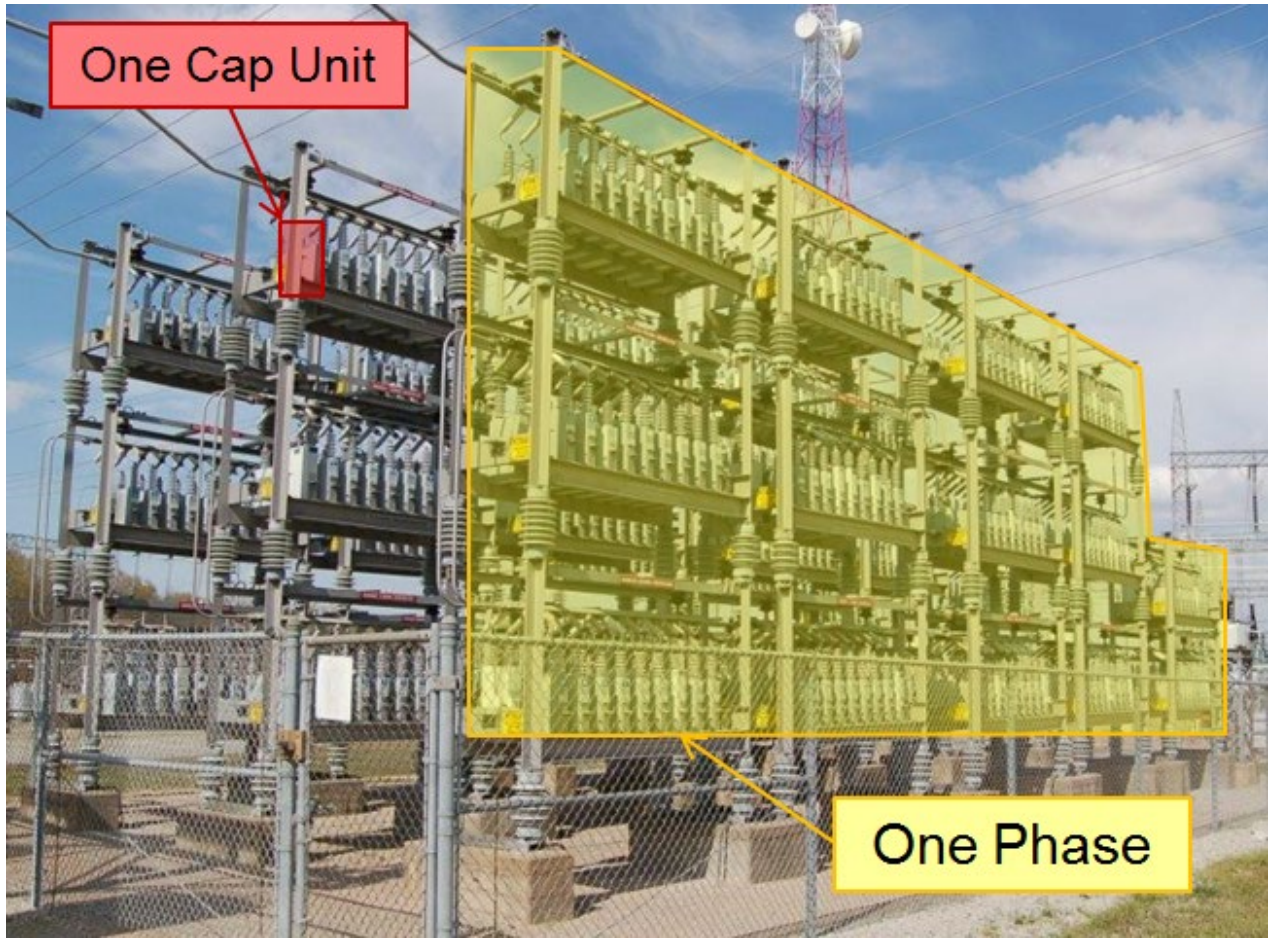
Some Initial Good Candidates for Asset Health

- Substation transformers
- Load-tap Changers
- Measurement devices/sensors (CCVT, MVT, PT, etc.)
- Switch gear
- Capacitor banks

Proactive PQ: Utility Case Study

Transmission Capacitor Banks

- Facts
  - 70 Substations
  - 204 Cap Banks
  - ~32,000 Cap Units
  - ~16,000 Fuses
- Issues
  - An Aging Fleet
  - Nuisance Trips
  - Catastrophic Failures
  - Reportable Mis-ops
  - Out of Service when Needed



Source: Tennessee Valley Authority PQ Team

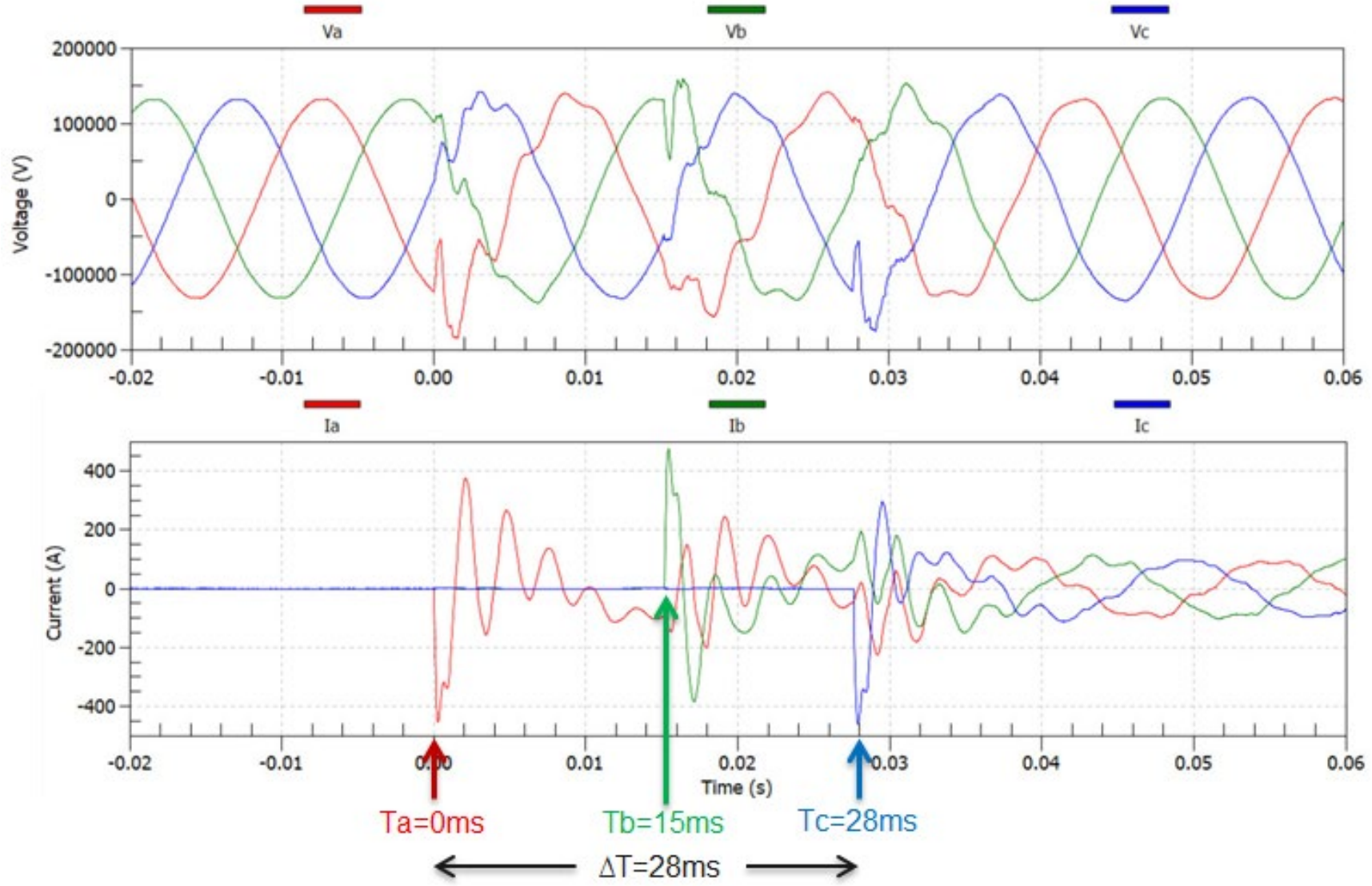
Data Analytics

23 criteria, Some are Complex, but Many are Simple

Analytic	Equipment				
	Circuit Breaker	Circuit Switcher	Bus PTs	Capacitor Bank	Protection System
Timing	X	X			
i^2t	X	X			
Restrike	X	X			
Transient Overvoltage	X	X			
Missing Pole	X	X			
Voltage Closing Control	X	X			
Preinsertion Type	X	X			
Alignment		X			
Loss of Signal			X		
Incipient Failure			X		
Loose Fuses			X		
Chattering Relays			X		
Voltage Step Change				X	
Voltage Regulation				X	
Harmonic Resonance				X	
Current Exceedance				X	
Switching Frequency				X	
Blown Fuses				X	
Shorted Elements				X	
Voltage Unbalance					X
Control Voltage Integrity					X
Disabled Protection					X
Relay Configuration / Readings					X

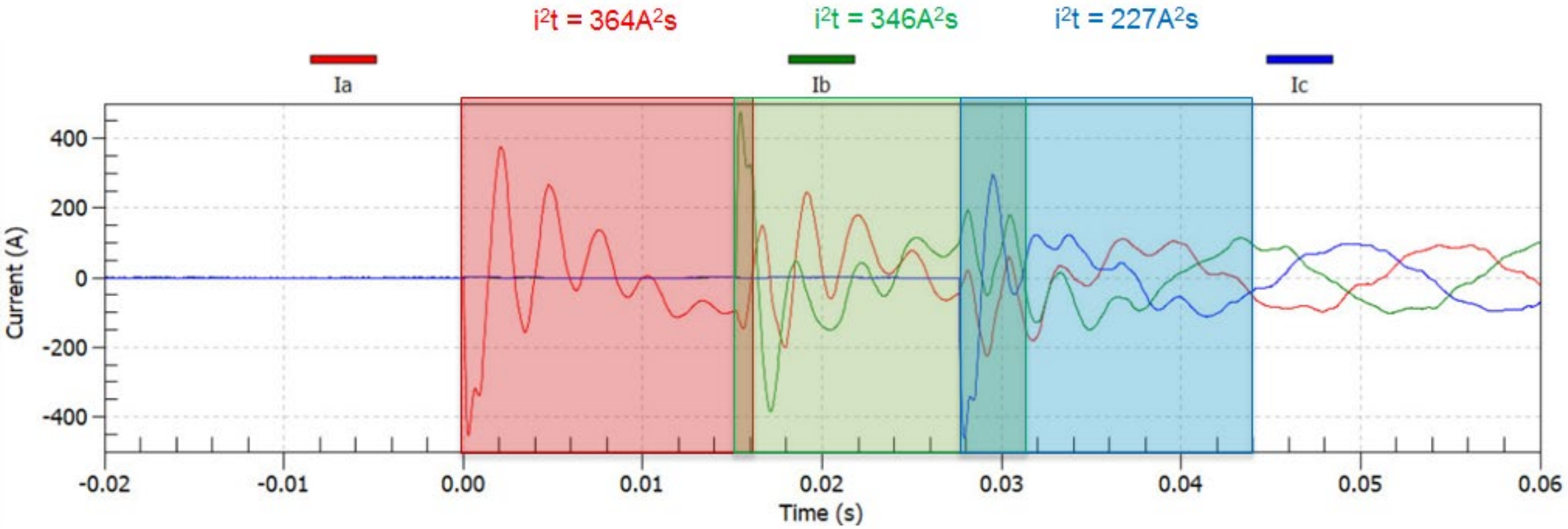
Source: Tennessee Valley Authority PQ Team

Timing of Breakers and Switchers:



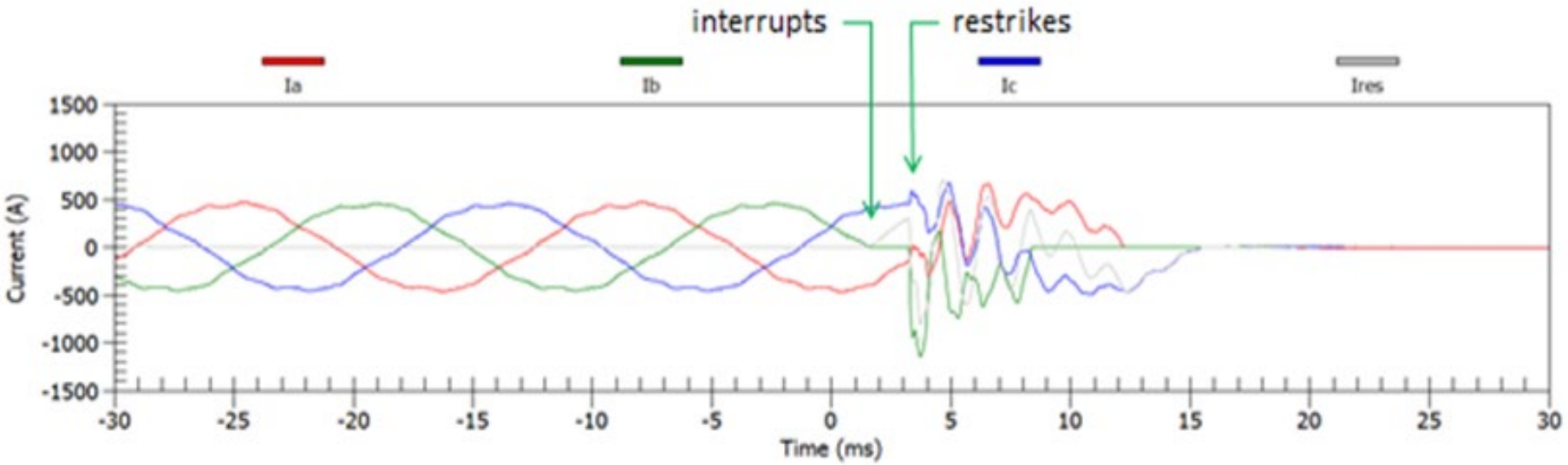
Source: Tennessee Valley Authority PQ Team

i^2t Calculations:

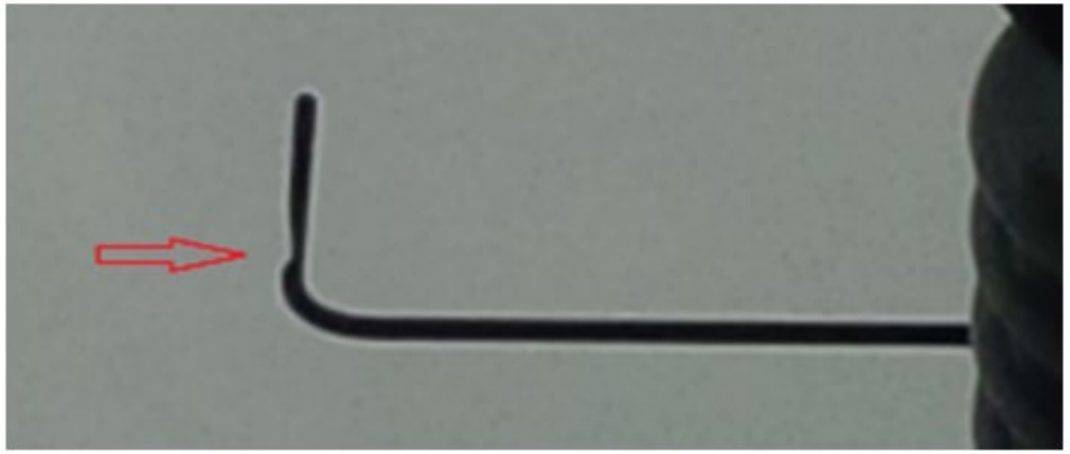


Source: Tennessee Valley Authority PQ Team

Breaker & Switcher Restrikes:



Switcher Arcing Horn Evidenced Pitting



Source: Tennessee Valley Authority PQ Team

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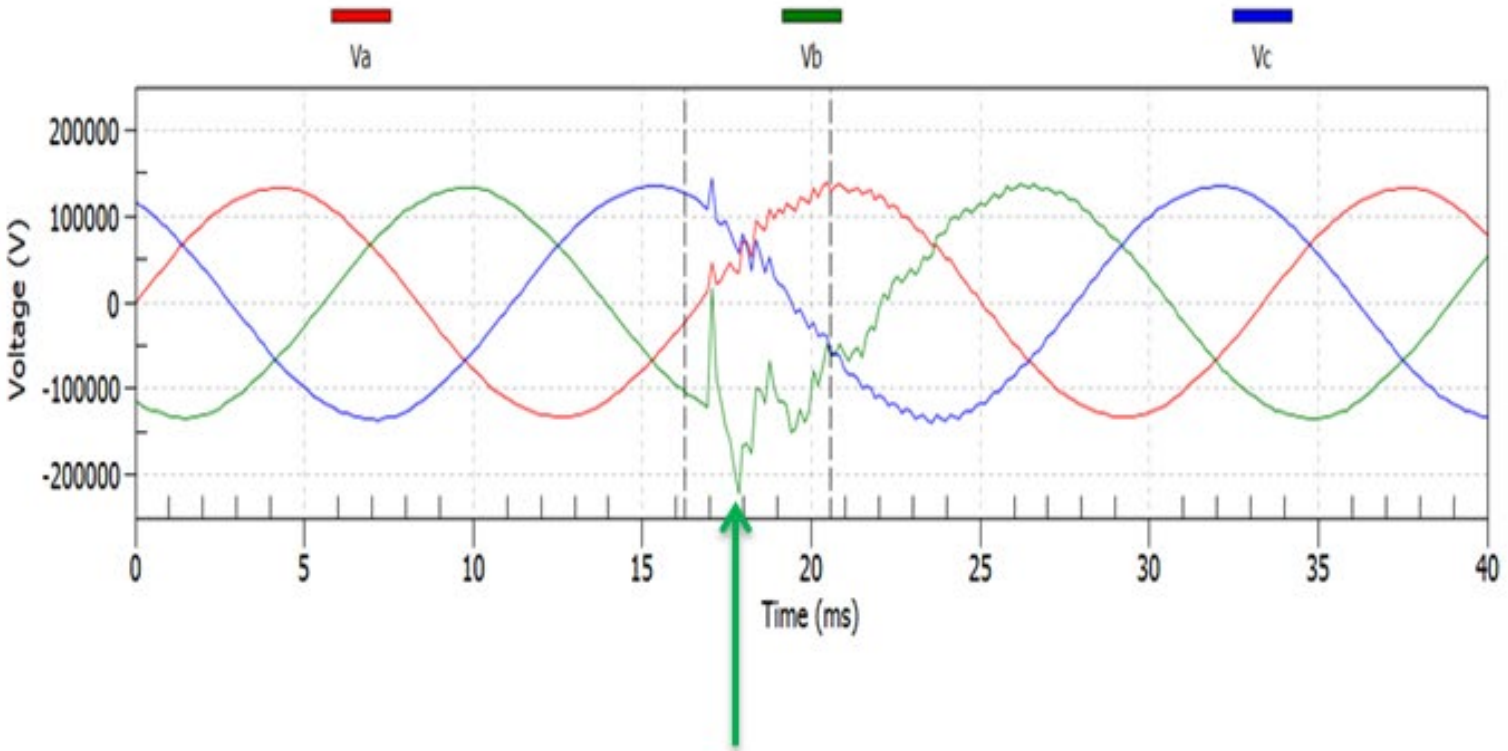
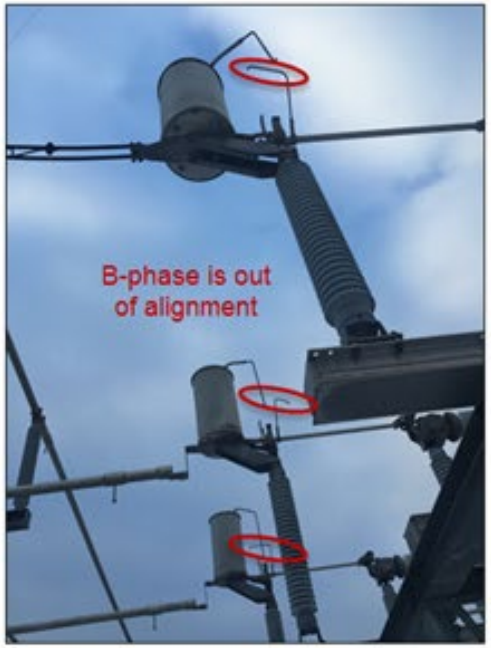
Switcher Alignment Issues:





Source: Tennessee Valley Authority PQ Team

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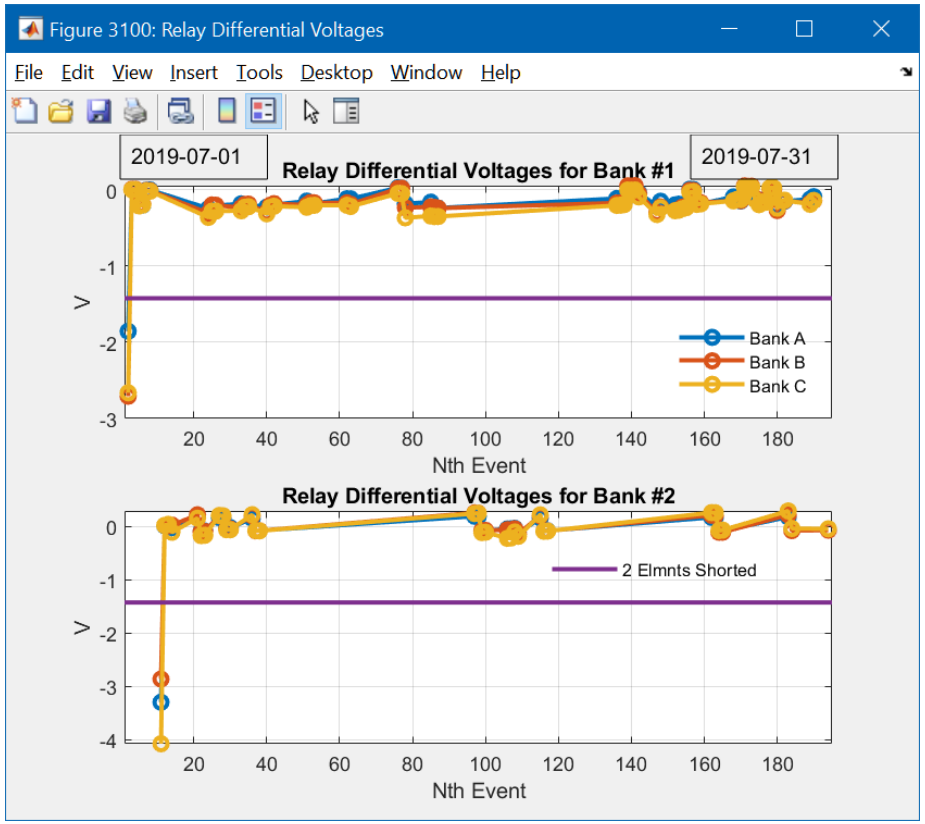
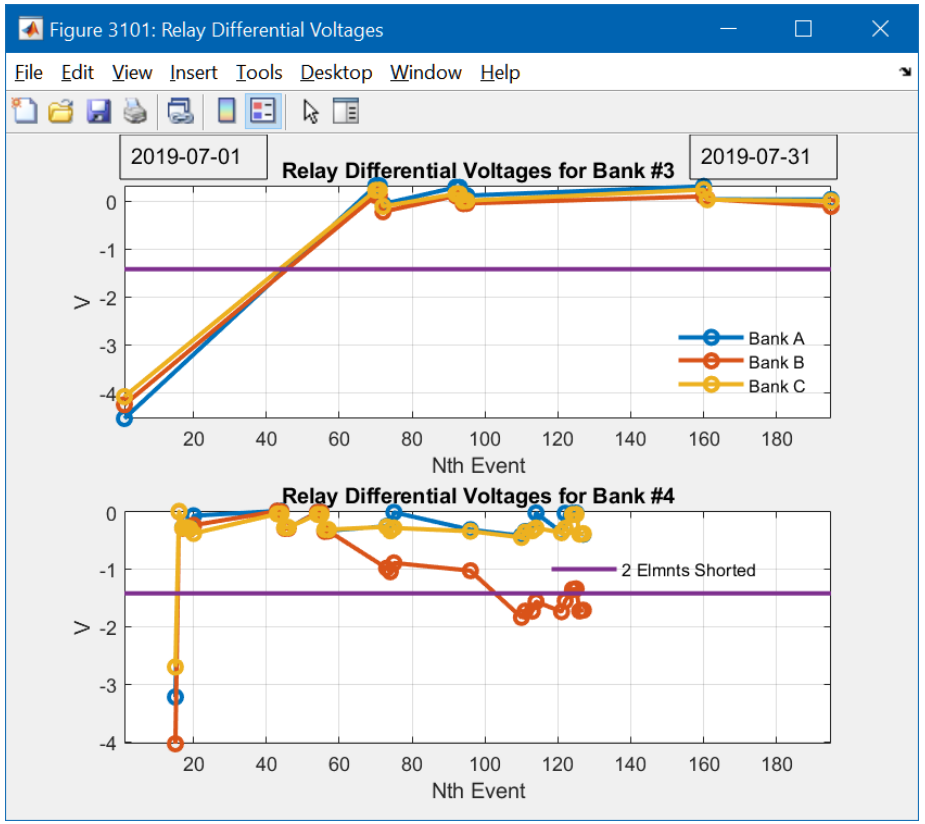
SPC-esque example:

Detecting incremental failure using control limits





Utility case study: Initial Results

Based on Proactive Monitoring of 20 Cap Banks (~7% of fleet)

- **Proactive Detections**
  - Missing poles/phases
  - Sensor malfunctions
  - PT incipient failures
  - Loose and blown fuses
  - Relay chatter
  - Non-synchronized and mis-balanced voltage step change and regulation
  - Harmonic resonance
  - Voltage unbalance
- **Actions**
  - Three (3) of 20 banks immediately removed from service for repairs
  - Prevention from likely eventual unambiguous failure
- **Impact**
  - Estimated ~**US$1million** in initial savings due to less costly repair and cleanup
  - Strong management support for expansion of PQ monitoring fleet across the network
  - Planned expansion to >300 existing capacitor banks
  - Estimated overall cost savings in excess of **US$10million** to date and growing

Power Quality

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International Conference & Exhibition
2023

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