Learning from Power Signals

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- **Background**
  - Operational Motivation
  - Technical Motivation
  - Approach
- **Distribution**
  - Methodology
  - Results
- **Generation & Transmission**
  - Methodology
  - Results
- **Continuous Waveform Analysis**
- **Future Endeavors**

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Operational Motivation

- **~2,100 Electrical Disturbances (EDs) per month**
  - ***Only 2% analyzed by hand!***
- **"Smart" Devices:**
  - **S&C IntelliRupter® PulseCloser® tech**
  - **APP Engineering Digital Fault Recorder**
- **Needs:**
  - **Classify events to prioritize those needing attention**
  - **Prediction of events before they occur**
  - **Must know "normal" to detect "abnormal"**
- **File formats**
  - **IEEE COMTRADE format** [2]
  - **Comma-Separated Values (CSV) format**
- **Benefits of an automated classification process…**
  - **Saving on *labor costs* and *resource limitations***
  - **Making system improvements**
  - **Identifying and addressing problems that may lead to *asset failure***
  - ***Improving customer service* by making power-quality data available to industrial customers**
  - **Opens the door to future automated analyses such as *alerting engineers before* harmonics reach a harmful level**
  - **Prevent *potentially harmful attacks*, such as directed energy, EMPs, etc.**

S&C IntelliRupter [1]

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Technical Motivation

- **Prior research focused on:**
  - ***Simulated* events** [3] – [7], [19]
  - **Electrical Disturbances (ED):**
    - **Faults: LG, LL, LLG, LLL, LLLG** [3, 4]
    - **Power Quality (PQ): Sags and Swells** [5]
    - **Power Quality (PQ): Sags, Swells, Interruptions** [7]
    - **Power Quality (PQ): Normal, Sags, Swells, Interruptions, Harmonics, Sags with Harmonics, Swells with Harmonics, Flickers, Notches, Spikes, Transients** [6]

- **Feature Space:**
  - **Higher-Order Statistics such as:** [5]
  - **S-Transform** [6]
  - **Discrete Wavelet Transform (DWT)** [7, 19]
  - **Gabor & Gabor-Wigner Transform, Smoothed WVD** [19]

- **Machine learning approaches:**
  - **Digital Fuzzy Logic** [3]
  - **Self-Organizing Maps** [4]
  - **Probabilistic Neural Network** [6]
  - **Support Vector Machines (SVM)** [7]

DATA DICTATES APPROACH!
One size does NOT fit all!

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Approach

Adhere to the K.I.S.S. principle!

- **Develop a hierarchical, automated process to categorize & identify electrical disturbances**
- **Leverages expert knowledge**
  - **Understandable**
  - **Adaptable**
  - **Deployable**
- ***MATLAB code developed to classify events by looking at waveform signature***
  - ***Minimal built-in MATLAB functions … Maintains simplicity***
  - ***Can be compiled into self-contained, executable files***
- ***Executable file reads event COMTRADE/CSV files containing:***
  - ***Time vector***
  - ***Three voltages***
  - ***Three currents***
- ***Analytics for***
  - ***140 distribution events (~23 categories)***
  - ***14 generation/transmission events … 7 more completed, but not presented***
- ***Continuous waveform processing … Enables event prediction & prevention***

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Methodology – Distribution

- Goal: Create a *hierarchical* process
  - Think of each COMTRADE file passing through a funnel

- Each file $\rightarrow 3$ sometimes 4 "checks":
  1. "Valid" data? *"Main Pass 1"*
     - At least one sensor's data has ≥ 100 samples $>$ sensor floor
  2. Switching event? *"Main Pass 2"*
  3. Fault or PQ disturbance? *"Main Pass 3"*
  4. "1 of N" or "X of N"?*

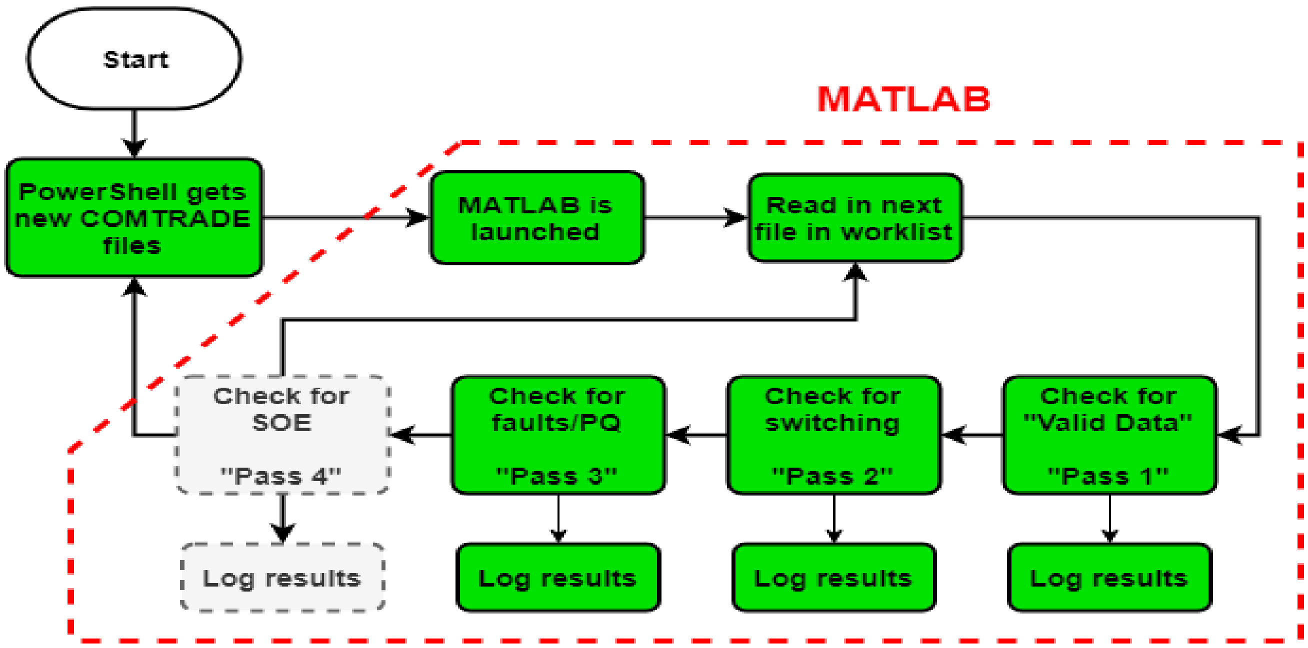
*Sequence of Events (SoE) - Not yet implemented.

Methodology – Distribution

- Events Categorized & Identified:
  - Faults … Single-, double-, or triple-phase
    - Symmetrical faults: LLL, LLLG
    - Unsymmetrical faults: LG, LL, LLG
  - Low-side Fuse Forensics
  - PQ Events
    - Voltage sag & swell
    - Harmonics
  - Switching … Seven main types analyzed
    - Load shifting … increase/decrease in load
    - Return-to-Normal … "normally-closed" or "-open"
    - Energizing
    - De-energizing
    - Source Return … primary or "alternate"
    - Loss of source
    - Return of source

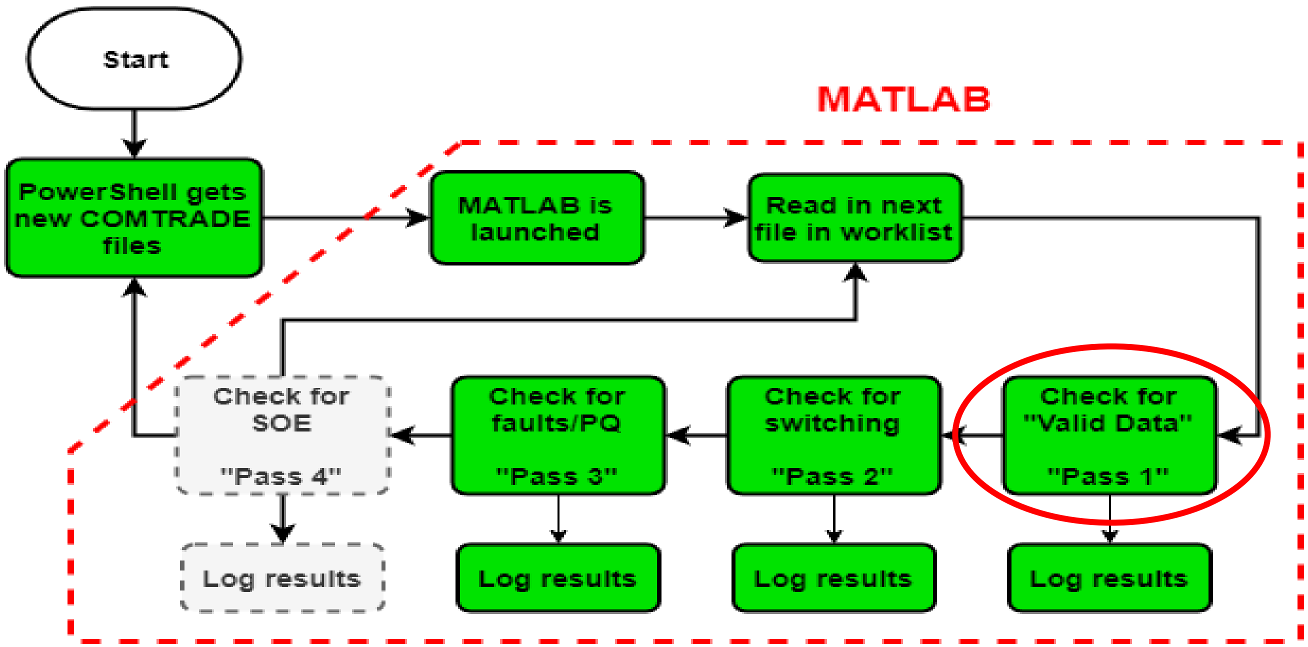
Methodology – Distribution

Overall Process Flow



Methodology – Distribution

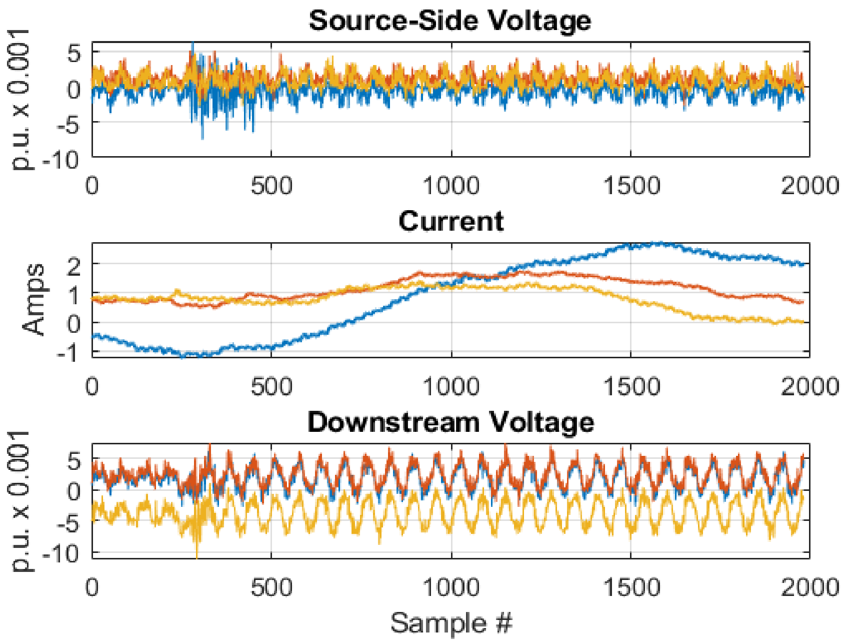
Main Pass #1 - Check for "Valid Data"



Methodology – Distribution

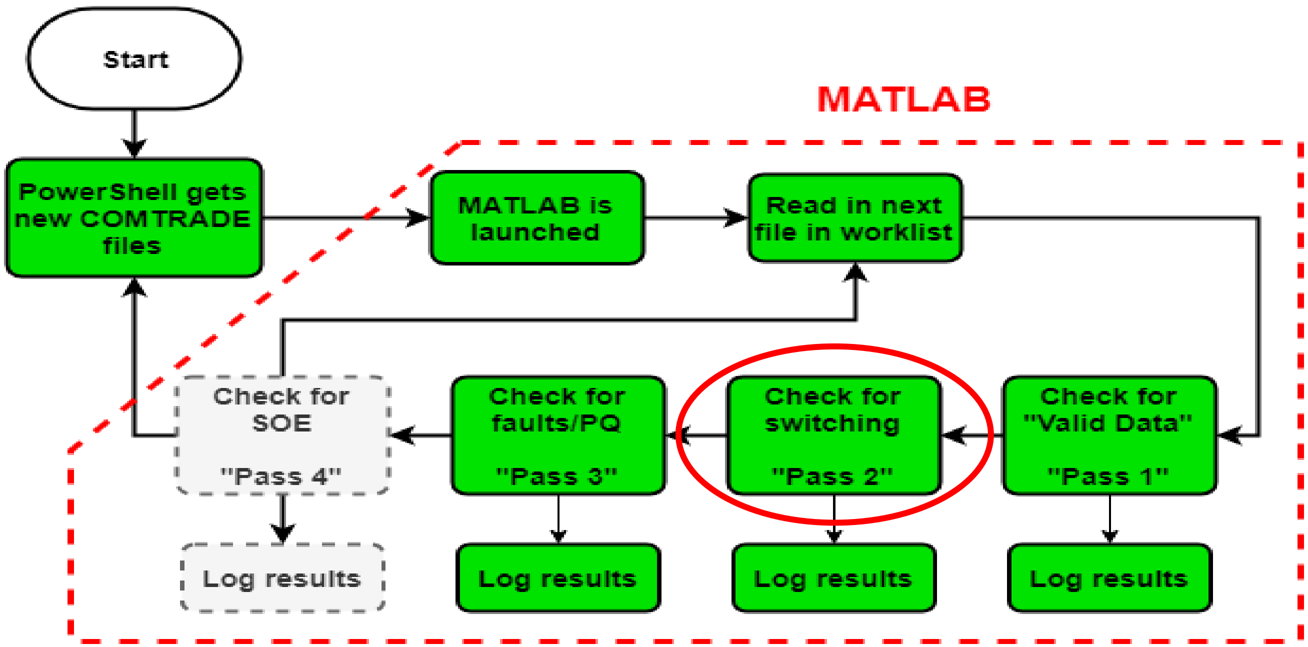
Main Pass #1 - Check for “Valid Data”

Start from main process → Compute RMS Envelopes → If at least one sensor "valid", move on to pass 2 → Return to main process



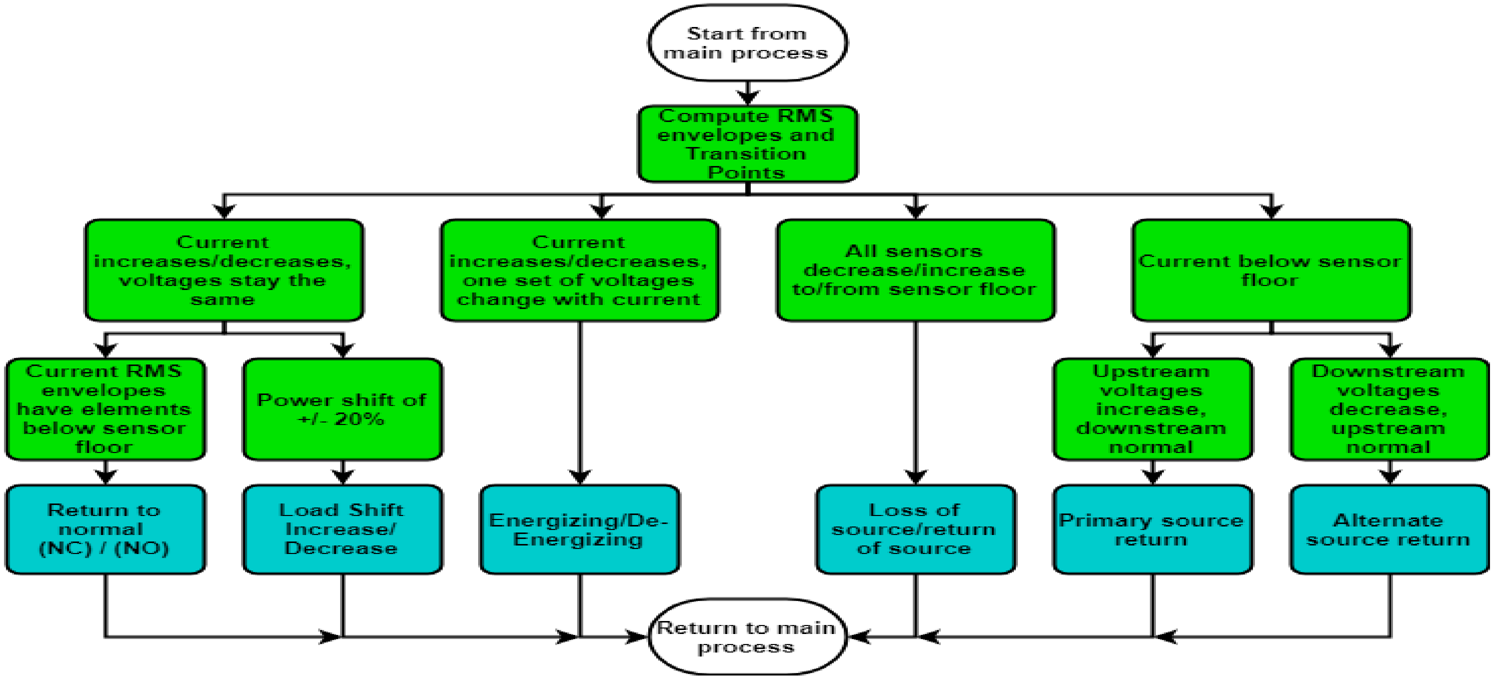
Methodology – Distribution

Main Pass #2 - Check for Switching Events



Methodology – Distribution

Main Pass #2 - Check for Switching Events



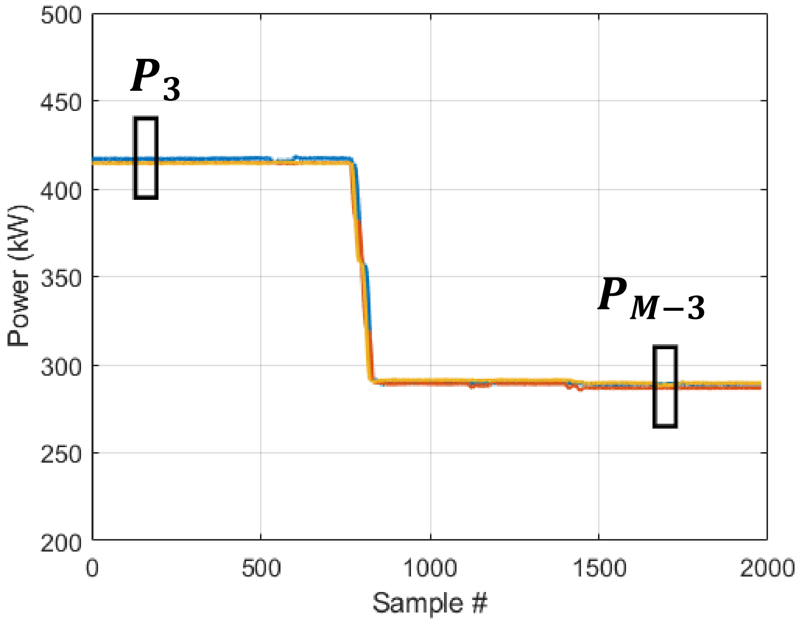
Methodology – Distribution

Main Pass #2 – Load Shifting

- Comparison of "instantaneous power" in 3rd and 3rd-to-last (M-3) cycles

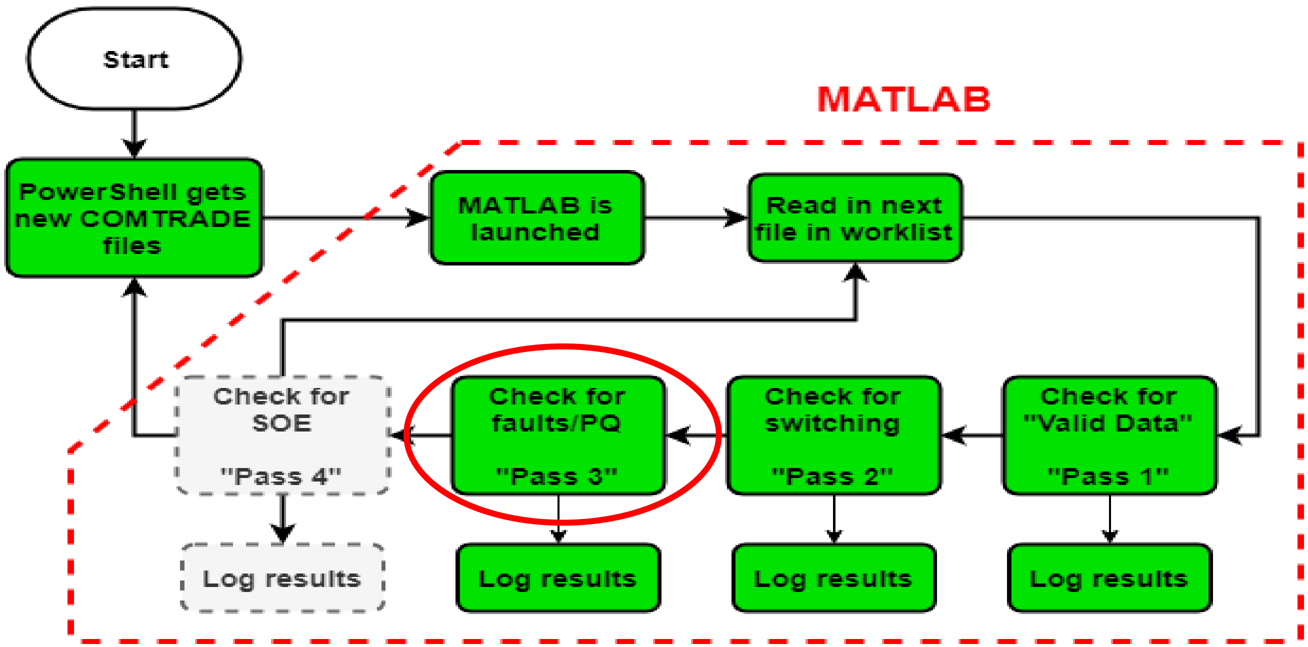
$$P(i) = V_{RMS}(i) I_{RMS}(i)$$

- $P_{M-3} \geq 1.2P_3$ (20% increase)
  - Load increase
- $P_{M-3} \leq 0.2P_3$ (20% decrease)
  - Load decrease



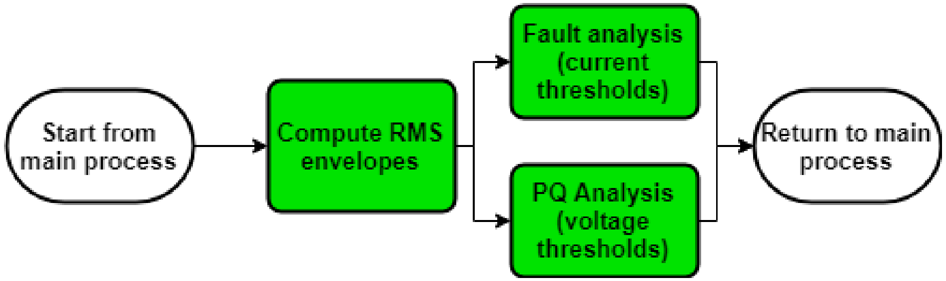
Methodology – Distribution

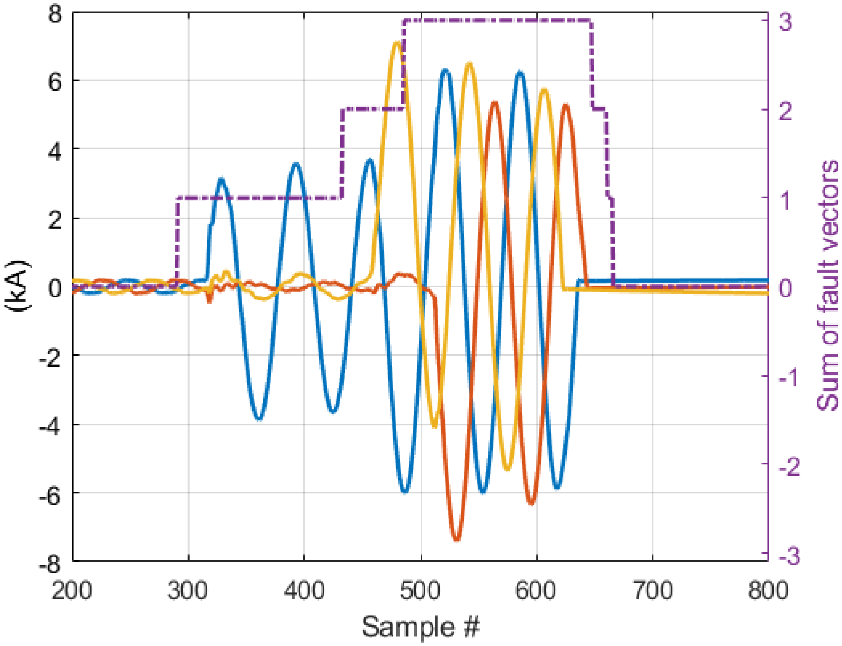
Main Pass #3 - Check for Faults/PQ Events



Methodology – Distribution

Main Pass #3 - Check for Faults/PQ Events





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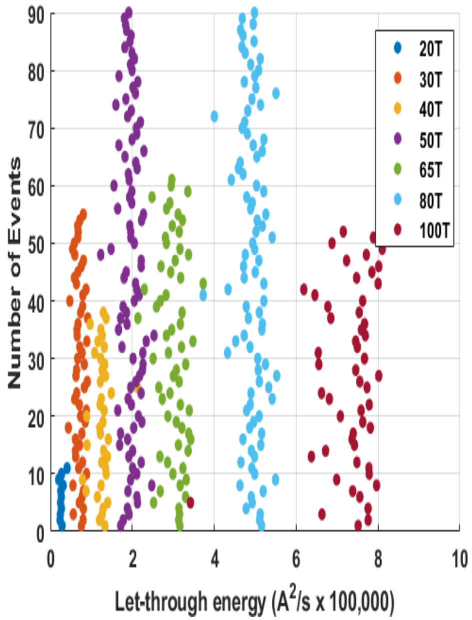
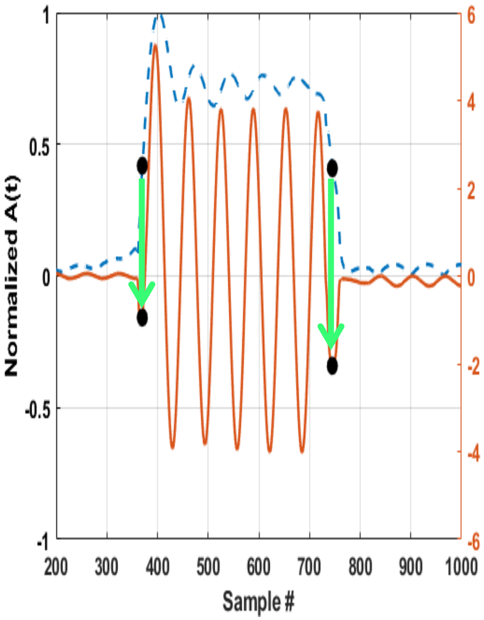
Methodology – Distribution

Main Pass #3 – Fuse Forensics [19]



- Seven fuse sizes (S&C Positrol® "T" Speed)
  - 20T, 30T, 40T, 50T, 65T, 80T, and 100T
  - 397 total events used across all seven classes
- Feature Selection: LTE
- Faulted "portion" of signals isolated via Analytic Signal method
- Naïve Bayes Classifier



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Results – Distribution

Switching Results

	LOS	ROS	RTN-NC	RTN-NO	Total
Correct	1	1	15	16	32
Amount	1	2	18	16	37
Percent Correct	100	50	83.33	100	**86.49**

PQ Results

	Sag	Sag and Swell	Total
Correct	16	10	26
Amount	19	10	29
Percent Correct	84.21	100	**89.66**

Fault Results

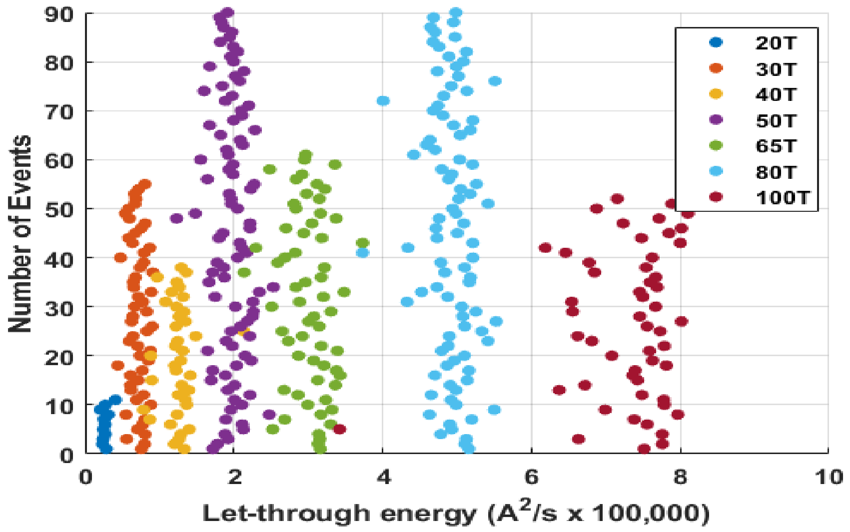
	LG	LL	LLL	Total
Correct	53	11	3	67
Amount	54	11	3	68
Percent Correct	98.15	100	100	**98.53**

Results – Distribution

- **Fuse Forensics**
  - **20T: 11 events …**
    - ➢ **Lower performance**

Percent Correct (%)							
	Predicted						
Actual	20T	30T	40T	50T	65T	80T	100T
20T	**87.5**	12.5	0	0	0	0	0
30T	0	**100**	0	0	0	0	0
40T	0	8.00	**88.00**	4.00	0	0	0
50T	0	0	2.99	**95.52**	1.49	0	0
65T	0	0	0	4.44	**95.56**	0	0
80T	0	0	0	0	1.45	**98.55**	0
100T	0	0	0	0	2.44	0	**97.56**
Average	94.67%						

Fuse Size								
	20T	30T	40T	50T	65T	80T	100T	Total
Amount	11	55	38	90	61	90	52	397



Results – Distribution

- 140 COMTRADE files
  - Contains:
    - 2 Invalid data,
    - 4 Unclassified
    - 29 PQ events
    - 37 Switching
    - 68 Faults
  - Nearly 93% correct

Overall Results

	Invalid Data	Switching	Faults	PQ	Unclassified	Total
Correct	1	33	67	26	3	130
Amount	2	37	68	29	4	140
Percent Correct	50	86.49	98.53	89.66	75	**92.86**

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Generation &Transmission

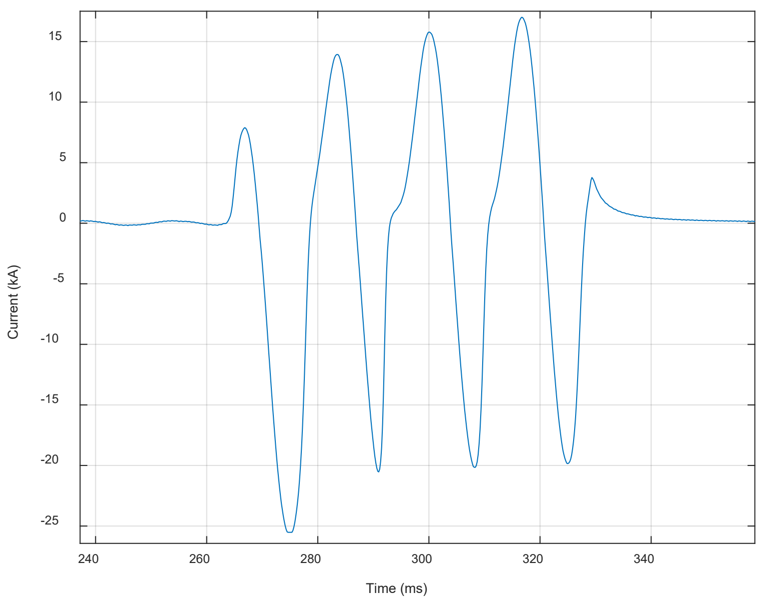
Events Categorized & Identified

- Blown Fuse
- Ferroresonance
- Capacitor Switching
- Lightning
- Harmonic Resonance
- Improper Voltage Transformer (VT) Secondary Grounding
- Incipient Capacitive Voltage Transformer (CVT) Failure
- Current Transformer (CT) Saturation
- Analog-to-Digital (A/D) Converter Clipping
- Induced Transient Noise from Switching
- High-Speed Reclosing with Tapped Motor Load
- DC Offset
- Motor Starting
- Variable Frequency Drive (VFD) Motor Starting

Methodology – Generation &Transmission

CT Saturation

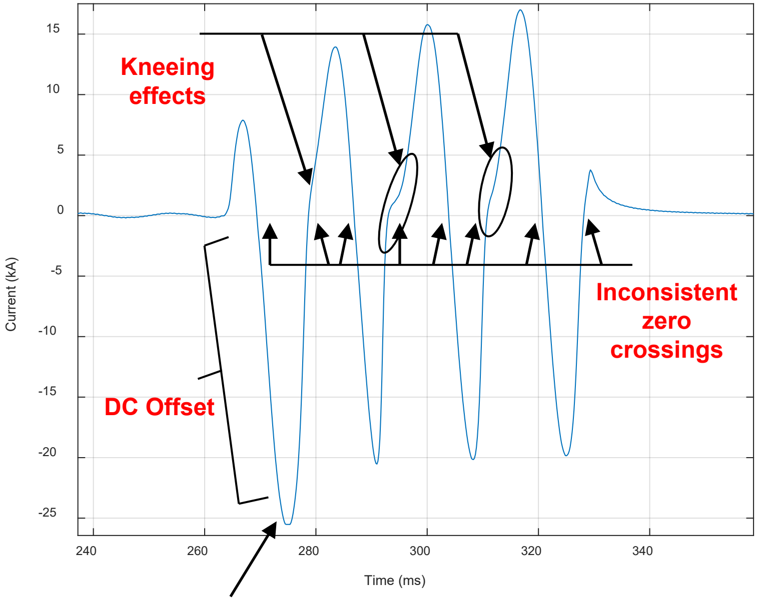
- Current Transformers (CTs) produce low-magnitude currents on the secondary side proportional to the primary side
- Secondary currents used as inputs to relays and meters
- Saturation occurs when the current is so high that it cannot handle any more flux
- Can result in inaccurate secondary currents
  - Could lead to relay incorrect operation
- Produces a waveform with a characteristic "knee"



Methodology – Generation &Transmission

CT Saturation

- Steps:
  - Current exceeds 15 times continuous current of CT
  - Check for DC offset
    - Average positive and negative peaks each half-cycle
  - DC offset returns to normal during fault
  - Inconsistent spacing between zero crossings
  - High 3rd derivative of current
    - Indicates “kneeing” in the curve
  - 2nd harmonic current > 15% of fundamental
  - 3rd harmonic current > 5% of fundamental



25,519 A maximum vs. 1200 A primary CT rating

Methodology – Generation &Transmission

CT Saturation

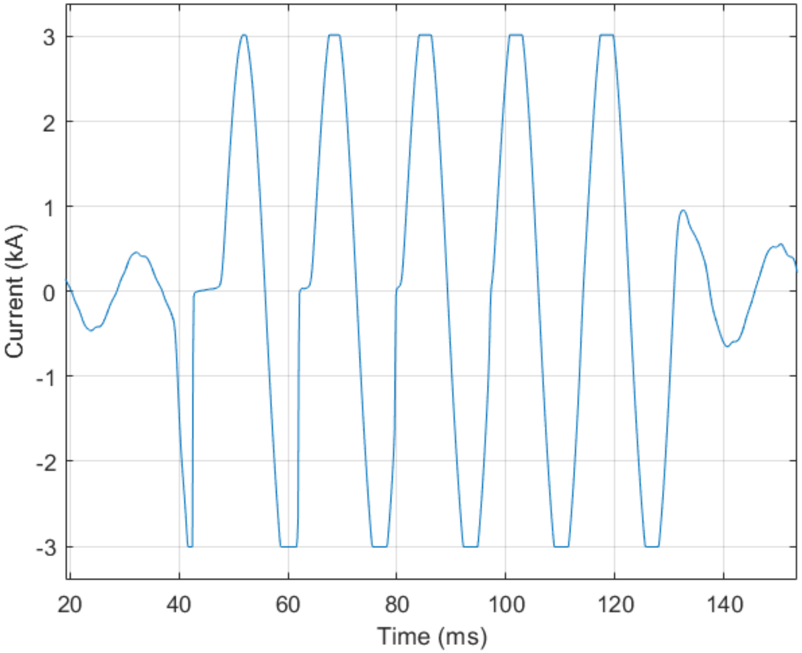
- Checks:
  1. CT primary continuous rating exceeded
  2. 2nd harmonic current > 15% of fundamental
  3. DC offset
  4. DC offset returns to normal
  5. Inconsistent zero crossings
  6. High 3rd derivative
  7. 3rd harmonic current > 5% of fundamental

- High Confidence:
  - #1, #2, & 3 of #3 - #7
- Medium Confidence:
  - #1 & 3 of #3 - #7
- Low Confidence:
  - #2, #7, & 2 of #3 - #6
  - #1 & 2 of #3 - #7

Methodology – Generation &Transmission

A/D Converter Clipping

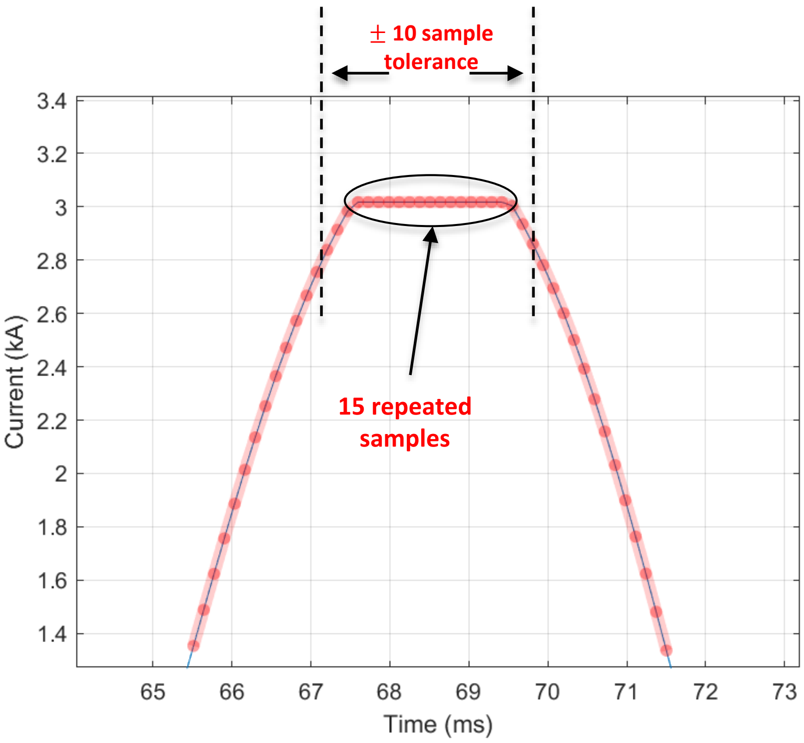
- Analog-to-Digital (A/D) converter translates analog signals into binary code
- Range is restricted by power supply rail voltage
- Digitized signal will be "flat-topped" if range is rail voltage is exceeded
- Usually occurs in current signals during faults
- Can occur in voltage signals as well
- Characterized by repeated samples of equal value at maximum or minimum



Methodology – Generation &Transmission

A/D Converter Clipping

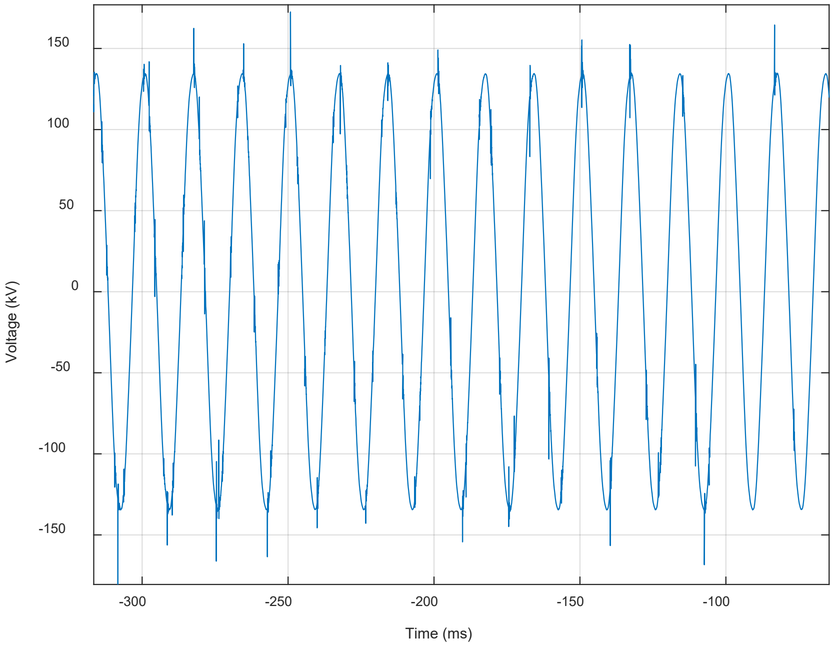
- **Steps:**
  - **Extract tolerance of 10 samples on each side of the maximum**
  - **Repeated samples occur where first derivative is equal to zero**
  - **Clipping occurred if number of repeated samples exceeds a threshold (e.g., 4 samples)**



Methodology – Generation &Transmission

Induced Transient Noise from Switching

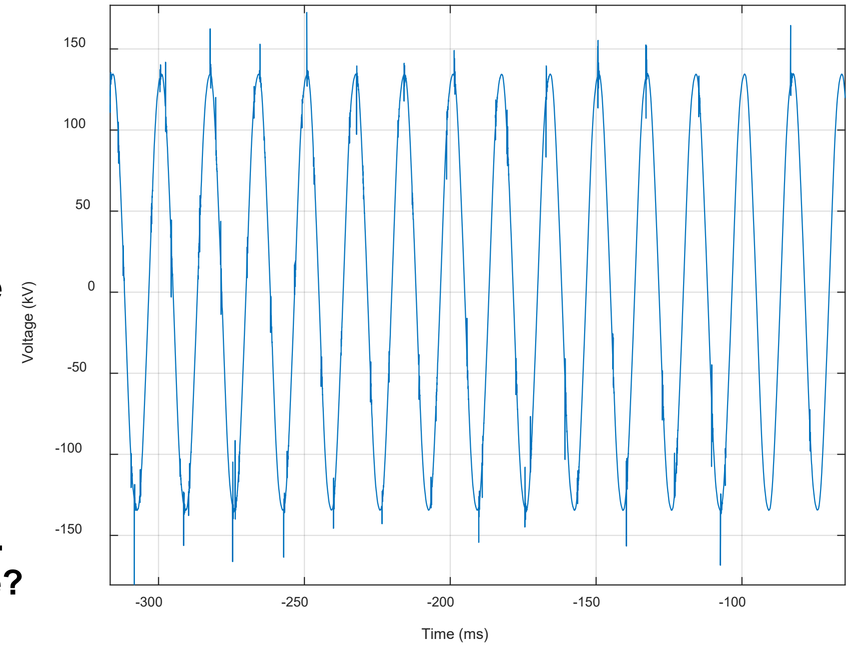
- **Opening of high-voltage devices like air-break switches can produce high-frequency noise**
- **Noise can become induced onto voltage or current signals of measuring equipment**
- **Identifying these events allows us to determine if the following should be checked:**
  - **Signal chokes**
  - **Shielding**
  - **Ground bonding**
- **Characterized by small random spikes throughout voltage or current signal**



Methodology – Generation &Transmission

Induced Transient Noise from Switching

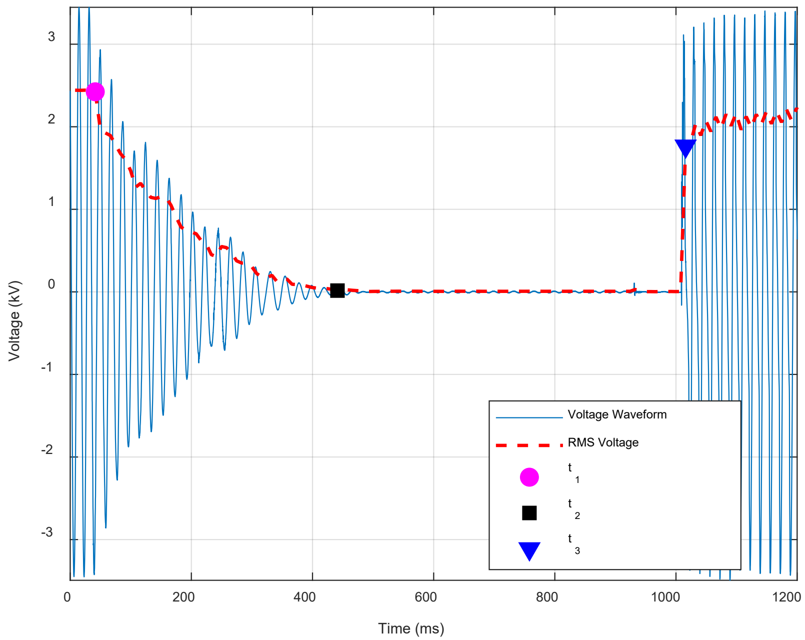
Steps:
- **Was the disturbance as compared to nominal relatively minor?**
- **Were there significant spikes in the first derivative that would indicate noise was present?**
- **Did the noise span at least 5 cycles?**
- **Does the noise occur at least every cycle on average?**
- **Are there at least 20 instances of noise?**
- **For highest confidence, are there at least 5 single-sample spikes that occur above the nominal value?**



Methodology – Generation &Transmission

High-Speed Reclosing with Tapped Motor Load

- High-speed reclosing is common for transmission lines
- Lines often serve large motors tapped on the line
- During a fault, residual voltage may remain on the line due to the motor still spinning
- Results in failed reclose attempt by breaker
- High-speed reclosing should be disabled on these lines
- Algorithms should identify where high-speed reclosing is enabled



Methodology – Generation & Transmission

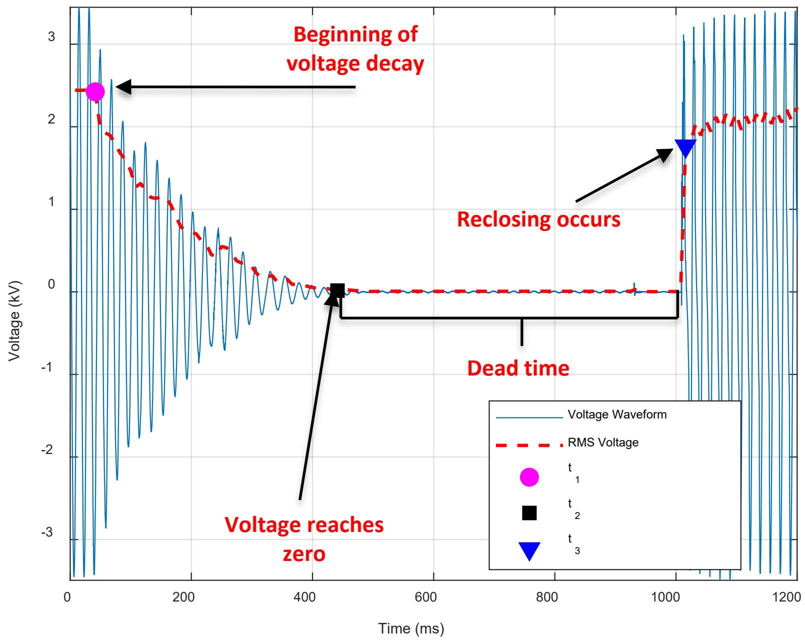
High-Speed Reclosing with Tapped Motor Load

Conditions:

- **RMS voltage decayed to under 0.5 pu**
- **RMS voltage decayed gradually in steps less than 50% of nominal peak value**
- **A 50% voltage step of peak value occurred at reclosing**
- **Find the three points t_1, t_2, and t_3**

High-speed reclosing occurred if:

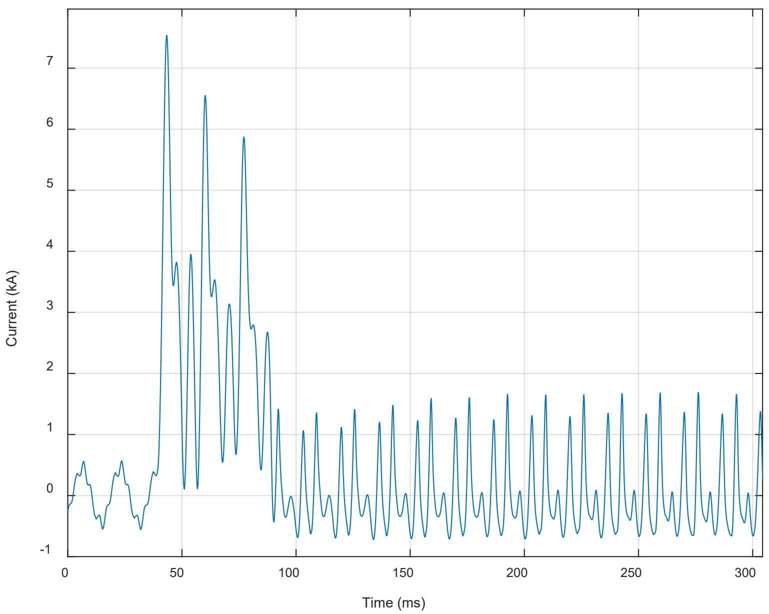
- **Voltage was ~0 kV for shorter than a certain threshold time (100 ms)**



Methodology – Generation &Transmission

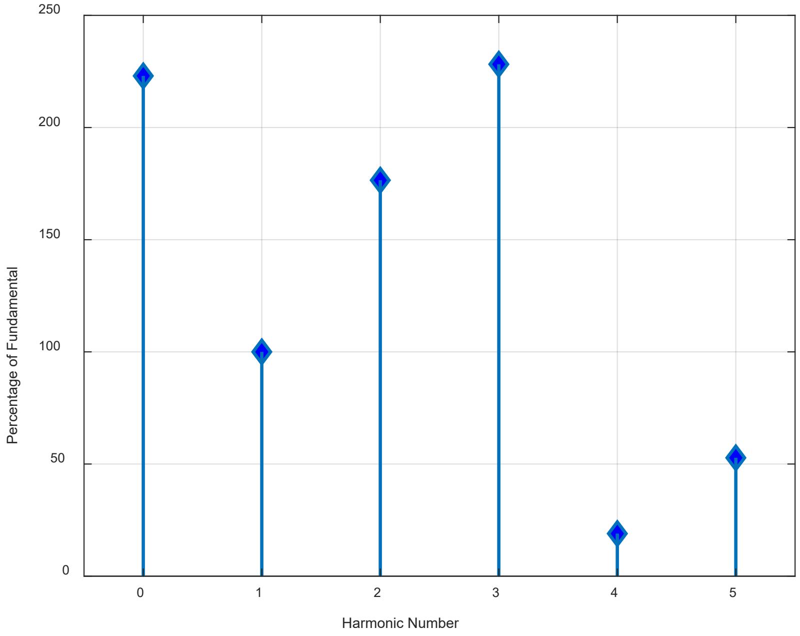
DC Offset

- Common issue in analog DFR channels
- Large offsets impact RMS calculations of signals
- Need to identify offsets to calibrate devices
- Characterized by asymmetry between positive & negative half cycles



Methodology – Generation &Transmission

DC Offset



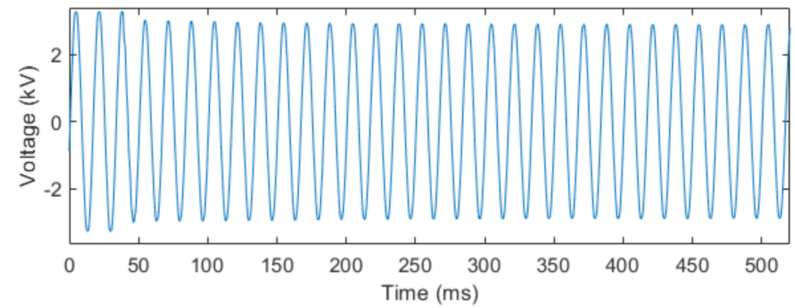
Steps:

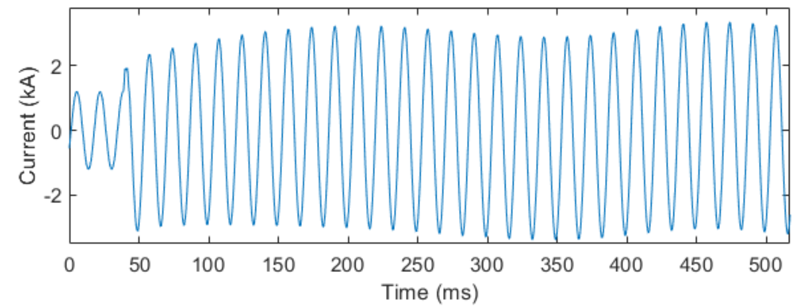
- **Check for zero frequency magnitude greater than 50% of fundamental magnitude:**
  - $\frac{H_0}{H_1} > 0.5$
- **Check for cycles with non-zero mean**
- **Flag event if cycle mean is greater than 50% of nominal peak value**
- **Look at voltage and current signals**

Methodology – Generation &Transmission

Motor Starting

- Large motor starts can cause sudden current increases of 5 to 6 times rated value
- Voltage becomes depressed
- Setting relays to not trip for motor inrush is challenging
- Assumption is made that relays are set correctly
- This event is for classification purposes only



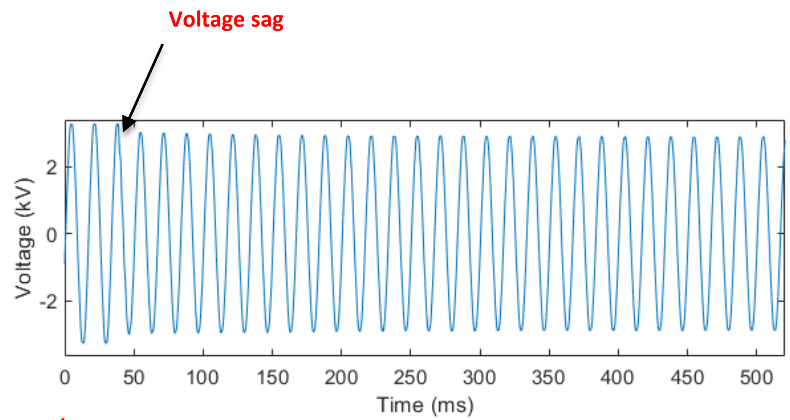


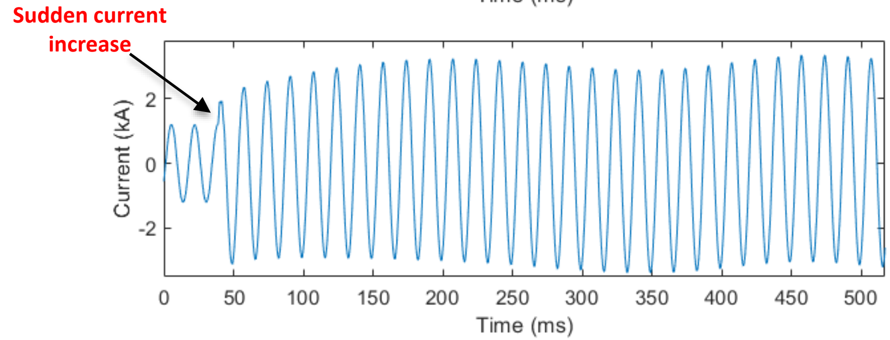
Methodology – Generation &Transmission

Motor Starting

Conditions:

- **Voltage stayed depressed below 95% of nominal value for at least 10 cycles**
- **Current stayed above CT-rated value for at least 10 cycles**
- **Not rich in harmonics (<15%)**
- **Conditions occur across all three phases**

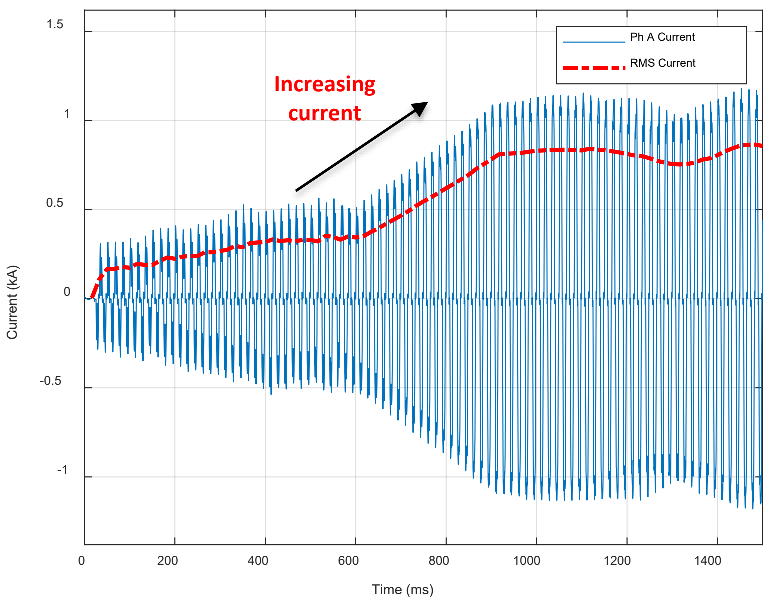




Methodology – Generation &Transmission

Variable Frequency Drive Motor Starting

- Some motors have electronic starting like variable frequency drives (VFDs)
- Used to bring motor up to speed while limiting disturbance to the voltage
- Characteristic harmonics are produced
- Analytics for this event are for classification purposes only



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Methodology – Generation &Transmission

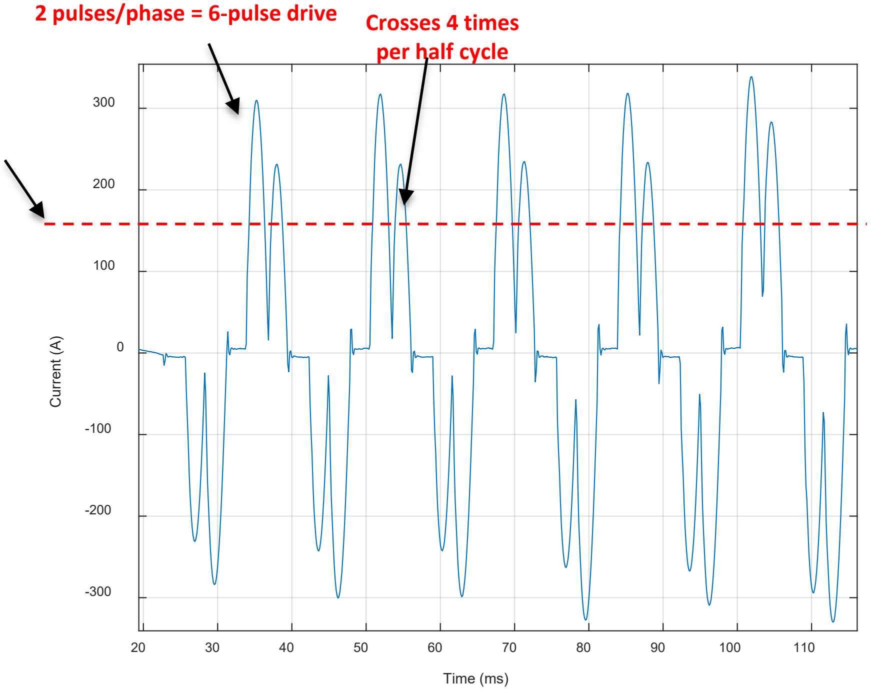
Variable Frequency Drive Motor Starting

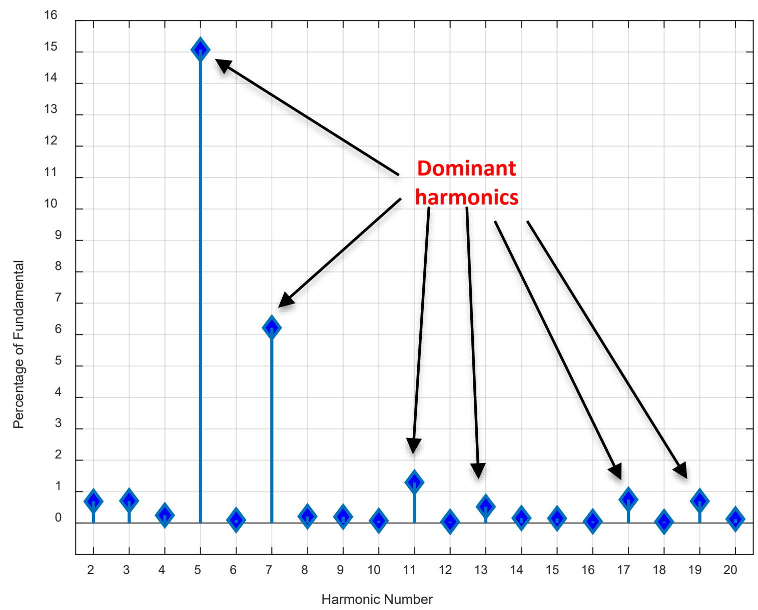
Steps:

- Check that current steadily increases
- Calculate how many times current crosses 50% of cycle max each half cycle
  - $\#\ \text{pulses} = \frac{3}{2} \times 4 = 6$

Steps (Cont'd):

- Calculate harmonics of current signals
- Dominant harmonics are either side of integer multiples of the number of pulses
- Conditions occur across all three phases

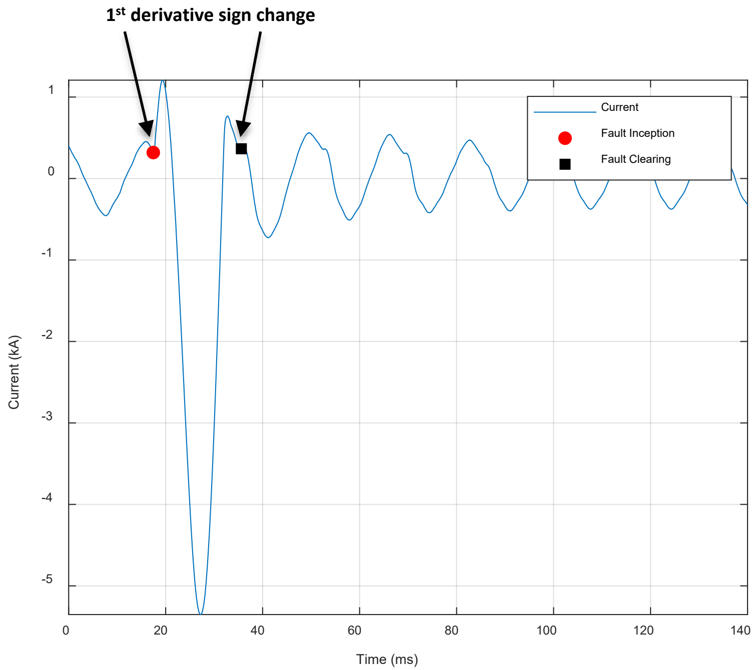




Methodology – Generation &Transmission

Blown Fuse

- Blown fuses require personnel to physically replace the fuse
- Useful to distinguish from breaker trips
- Fuses clear much faster than breakers (<2 cycles)



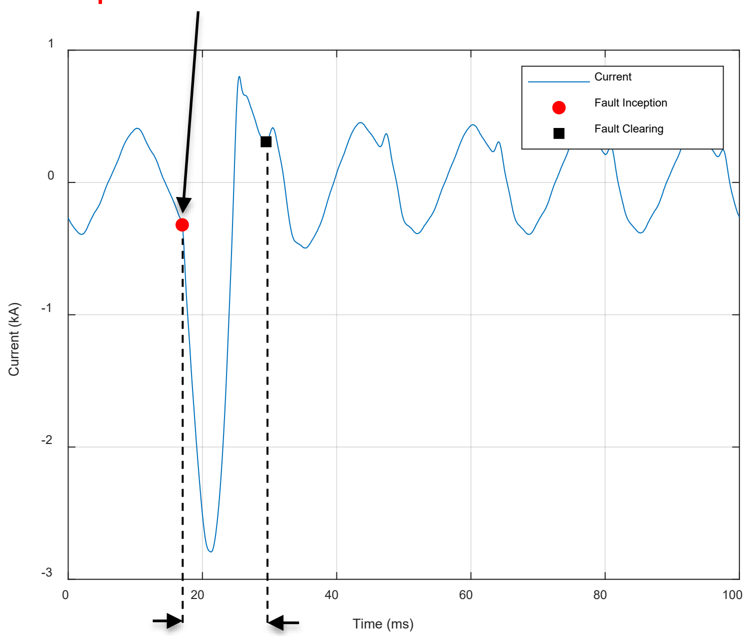
Methodology – Generation &Transmission

Blown Fuse

Steps:

- **Check that fault longer than >0.25 cycles occurred**
- **Find fault inception and clearing points by finding one of the following:**
  - **Sign change in 1st derivative**
  - **Sudden increase in 2nd derivative**
  - **Zero crossings before and after fault**
- **Fuse fault occurred if clearing time is <1.5 cycles**

Spike in 2nd derivative

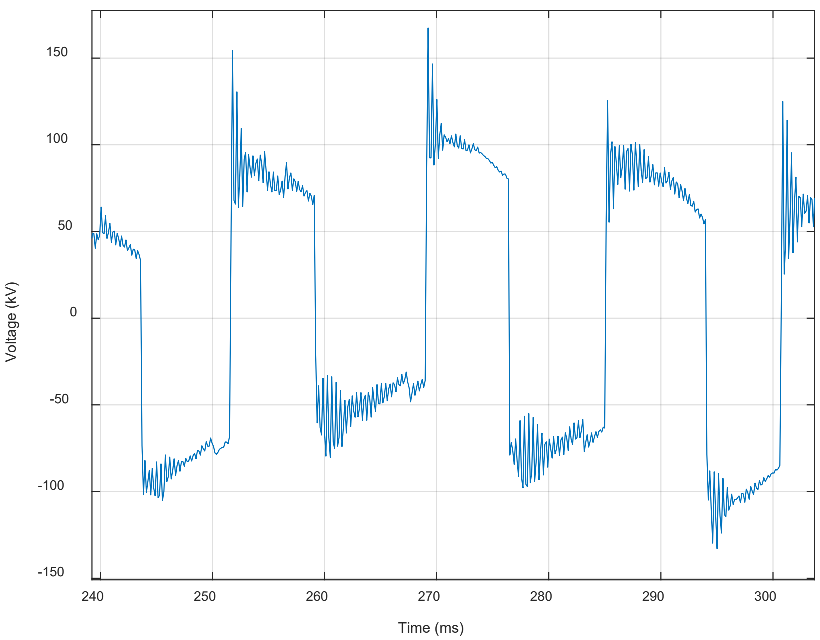


Clearing time = 12.5 ms = 0.75 cycles

Methodology – Generation &Transmission

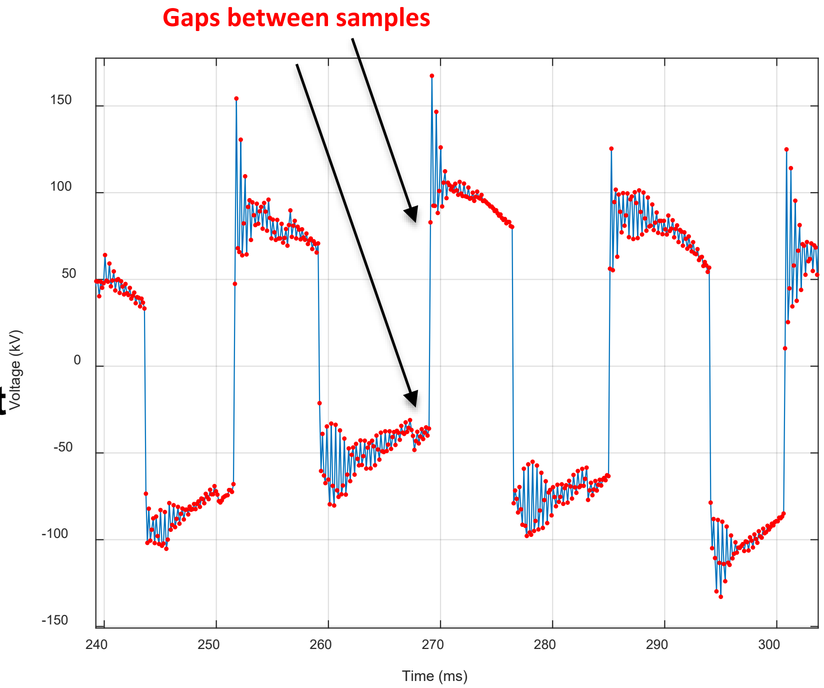
Ferroresonance

- Occurs when circuit containing nonlinear inductance is fed from source having series capacitance
- Ex. Utilizing breakers with grading capacitors to de-energize bus having magnetic voltage transformers (VTs)
- Poses serious safety risk
  - Overvoltages occur when bus is believed to be de-energized
- Voltages exhibit almost square wave
- Current is either zero or sinusoidal



Methodology – Generation & Transmission

Ferroresonance



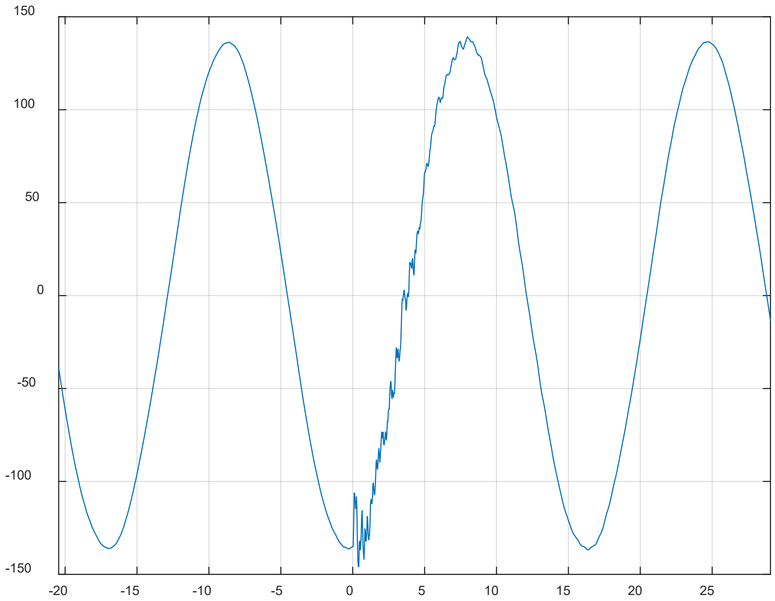
Steps:

- **Check for voltage difference between samples of at least 50% of nominal peak value**
- **Gaps are >1/3 cycle apart and <3 cycles apart**
- **Time between first and last gap is >5 cycles**
- **Sufficient harmonic content is present**
  - **One of 2nd to 50th is >5% of fundamental**
- **Current measured is either zero or nominal sinusoid**

Methodology – Generation &Transmission

Capacitor Switching

- One of the most common events on the power system
- Creates PQ events due to temporary voltage transients
- Voltage transient contains:
  - Quick depression in voltage toward zero
  - Voltage overshoot
  - Decaying ring wave toward steady state
- Algorithm designed for classification purposes only

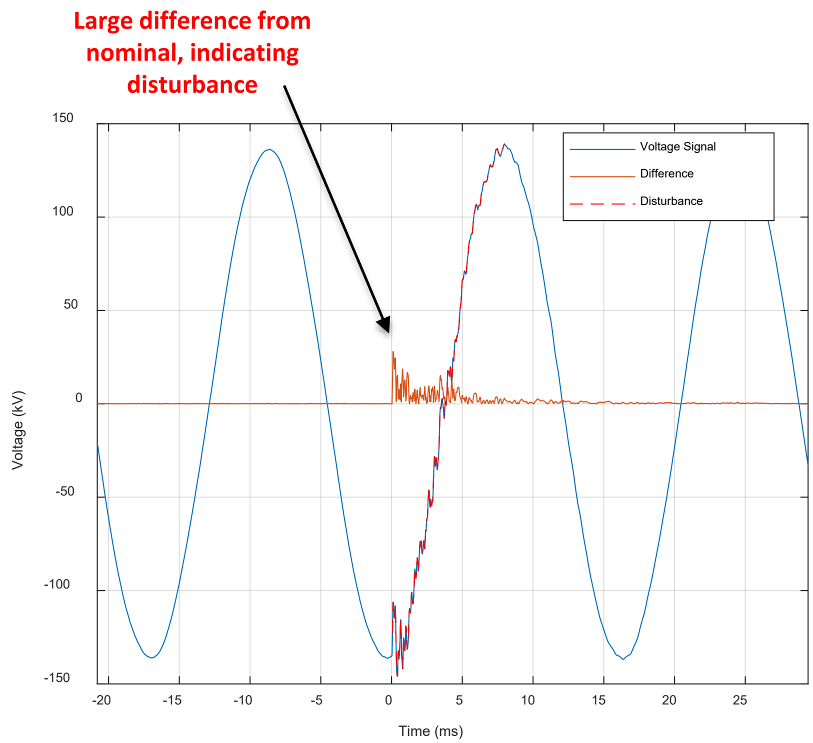


Methodology – Generation &Transmission

Capacitor Switching

To isolate the disturbance in the signal:

- **Select first cycle as reference**
- **Replicate cycle throughout length of waveform to create ideal signal**
- **Subtract ideal signal from actual signal to highlight disturbance**
- **Only continues if length of disturbance is <2 cycles**
- **Some disturbance must occur across all three phases**

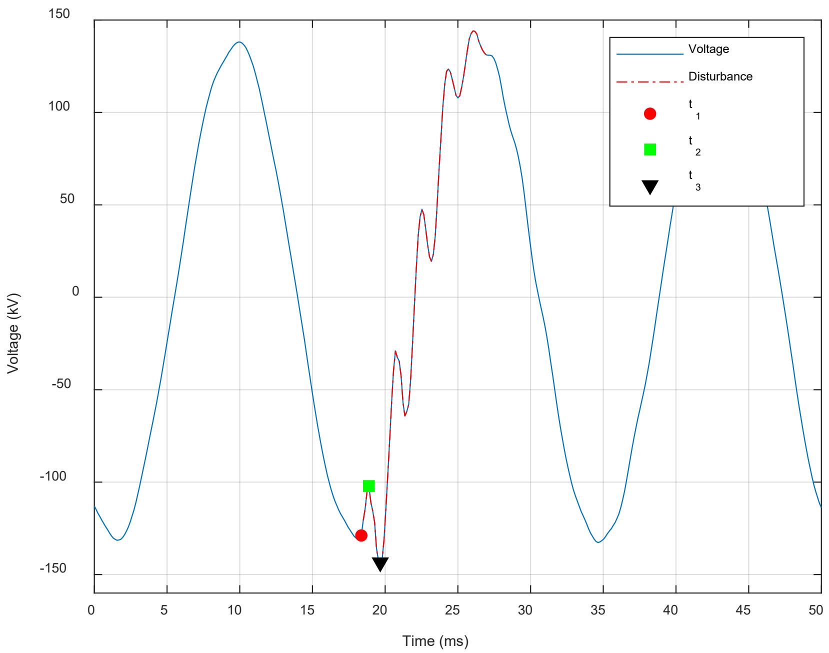


Methodology – Generation &Transmission

Capacitor Switching

Find the three characteristic points on one of the phases:

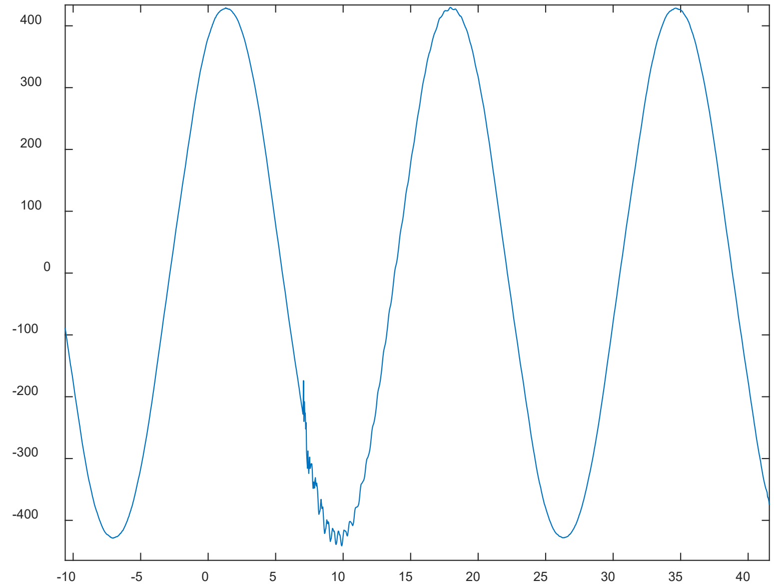
- **Check for voltage peaks 2% above nominal value**
- **No more than 2 peaks can be greater than 10% above nominal value**
- **Place half-cycle tolerance around first overvoltage**
- t_1 **occurs where voltage dropped by 2% in one sample**
- t_2 **occurs where voltage drops below 90% of nominal**
- t_3 **occurs at the overvoltage point**



Methodology – Generation &Transmission

Lightning

- Contain overvoltage transients with rise time in microseconds
- Disturbance is often not fully captured due to:
  - Limitations of instrument transformers to pass high frequencies
  - Limitations in sampling rates of measurement devices
- Algorithm is for classification purposes only

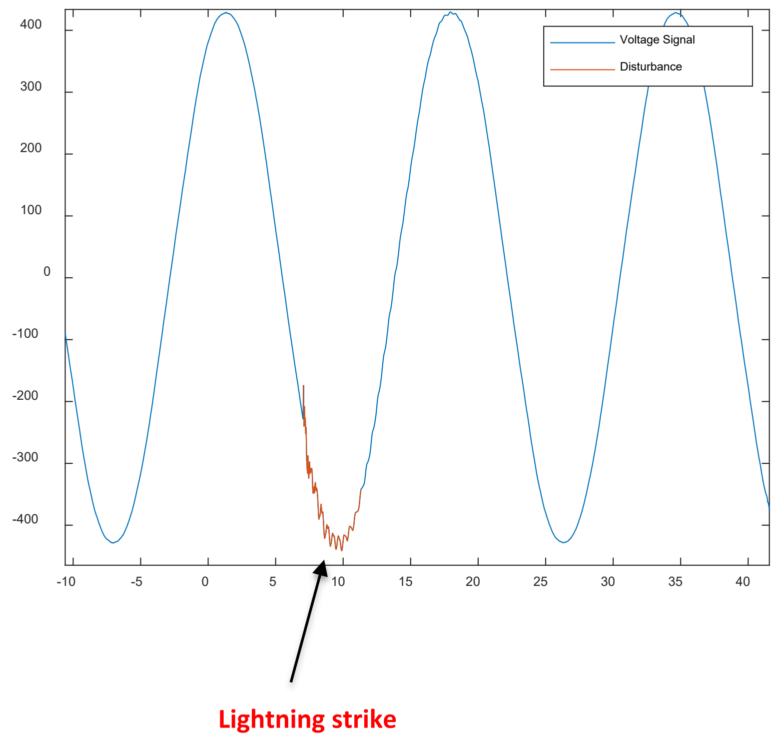


Methodology – Generation &Transmission

Lightning

Steps:

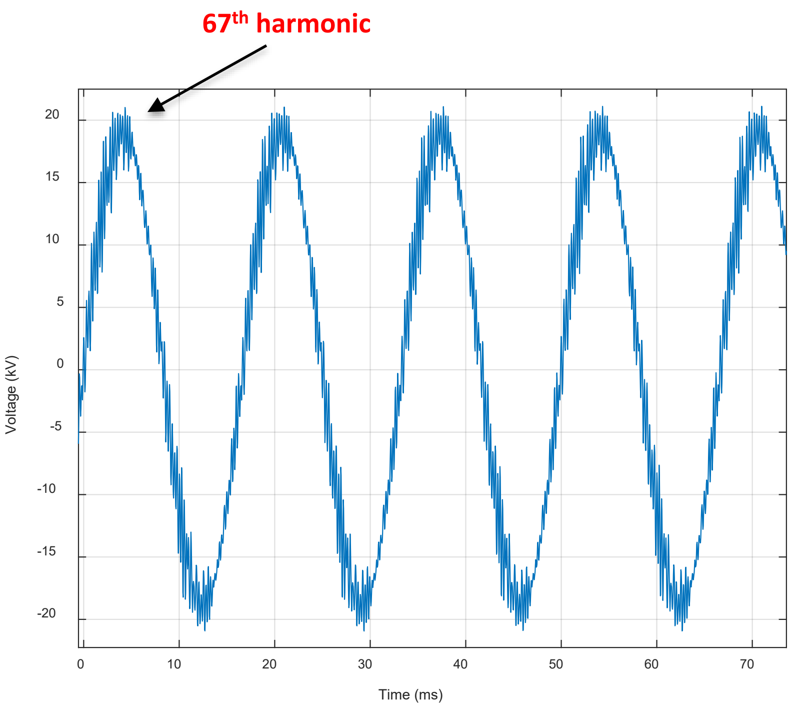
- **Ensure that event is not capacitor switching or a blown fuse**
- **Use first cycle as a reference to isolate disturbance as done previously**
- **Ensure that length of disturbance is <1 cycle**
- **Count number of lightning strikes**
  - **Exclude events with >5 disturbances as indicated by the data**



Methodology – Generation &Transmission

Harmonic Resonance

- Power systems have natural frequencies stemming from their inductive and capacitive impedances
- Non-linear load could generate frequency equal to the natural frequency, creating resonance condition
- Equipment is subjected to overvoltages or overcurrents
  - Could result in equipment failure or mis-operation by relays
- Important to detect resonance conditions quickly

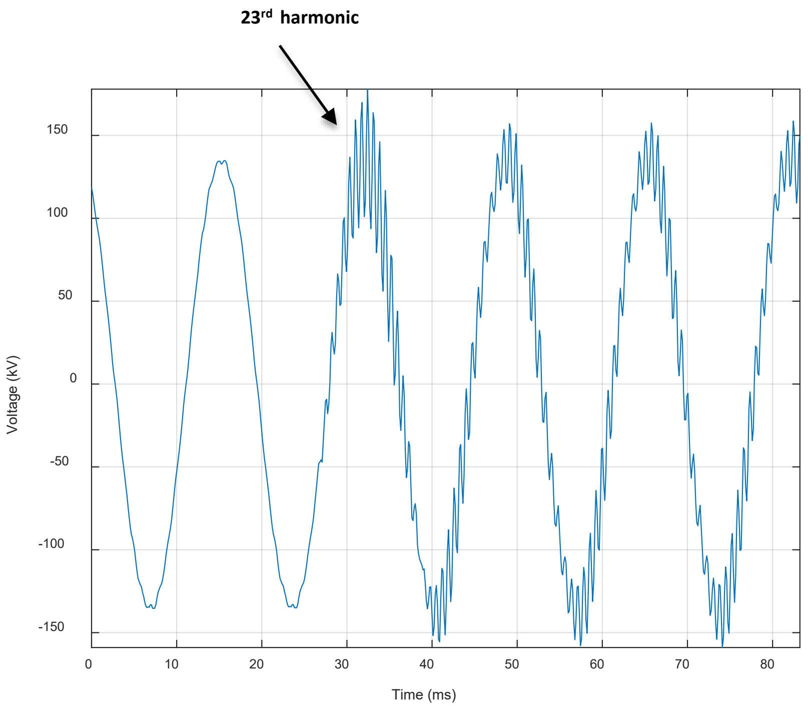


Methodology – Generation &Transmission

Harmonic Resonance

Steps:

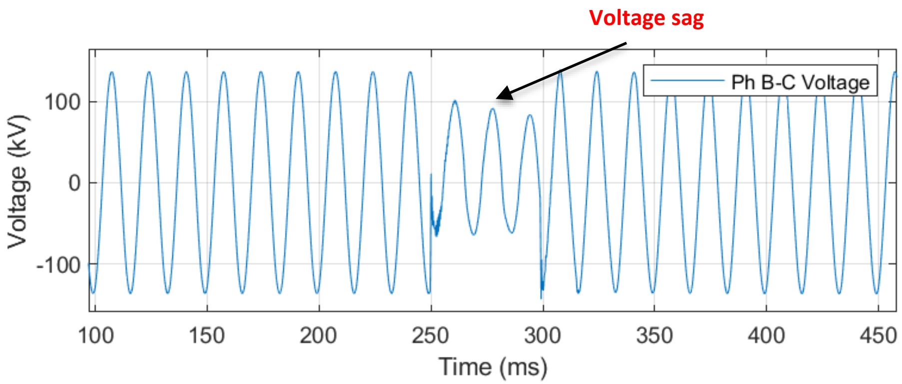
- **Calculate Total Harmonic Distortion (THD) of the voltage signal:**
  - $$V_{\text{THD}} = \frac{\sqrt{\sum_{i=2}^{M} |H_i|^2}}{H_1}$$
- **THD must be >8% of fundamental frequency**
- **Check for one harmonic (above the 5th) that is >5% of fundamental**
- **Number of 1st derivative sign changes must be >10% of the number samples in each cycle**

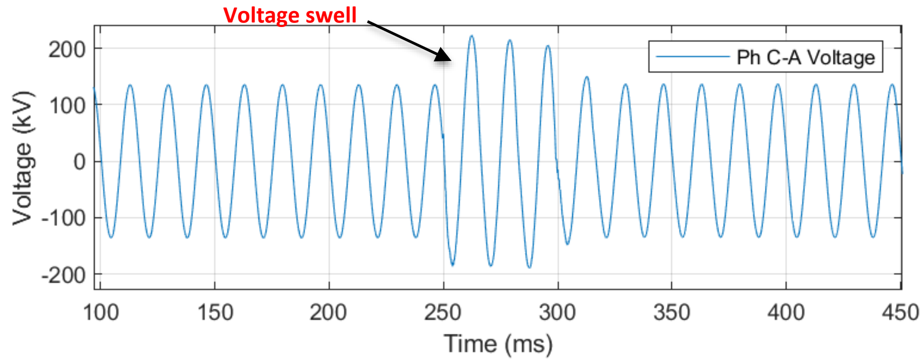


Methodology – Generation &Transmission

Voltage Transformer Secondary Grounding

- Substations should have single and solid grounding on secondary side of voltage transformers (VTs)
- If multiple grounds exist, voltage will be skewed from nominal in both magnitude and phase
- Can lead to mis-operation of protective relays



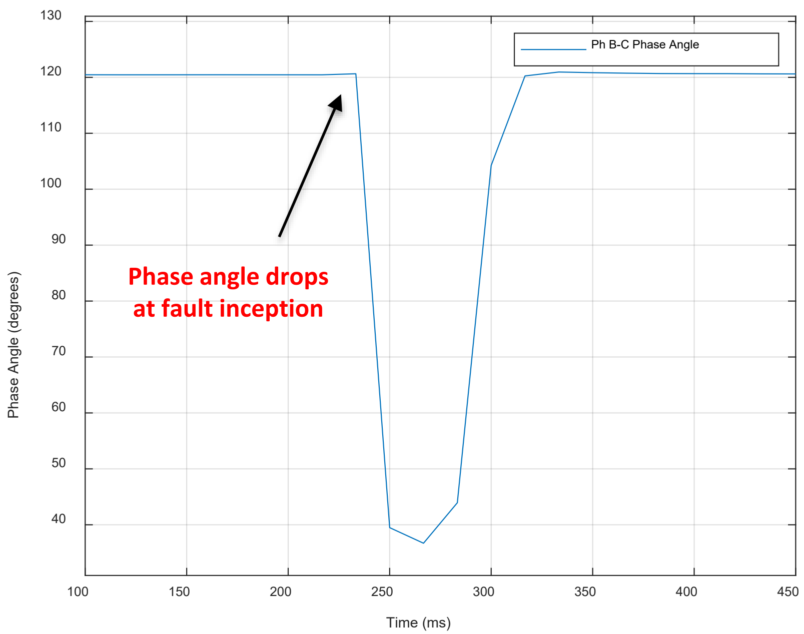


Methodology – Generation &Transmission

Voltage Transformer Secondary Grounding

Steps:

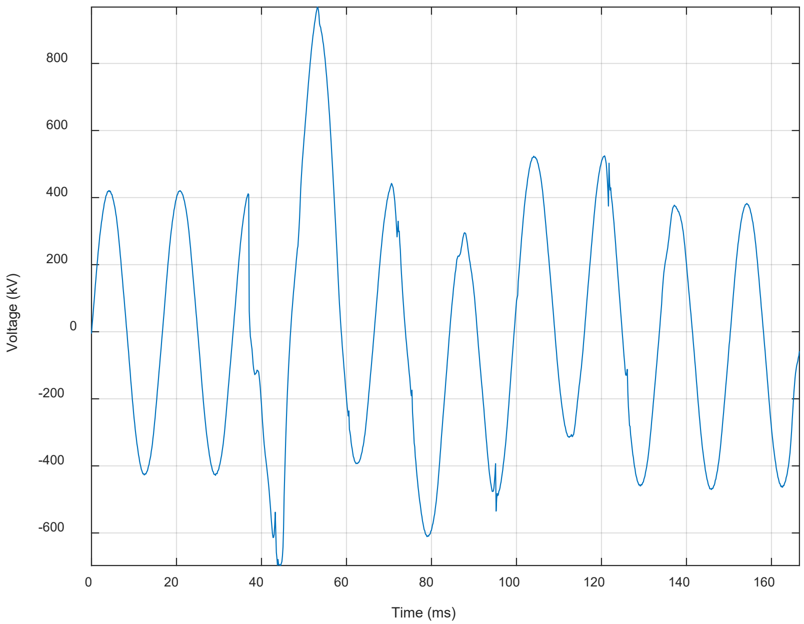
- **Check for voltage sag in one phase and swell in another (above and below 5% of nominal)**
- **Phase angle between voltages is calculated using the definition of dot product:**
  - $$\theta = \cos^{-1}\left(\frac{\vec{V_\alpha}\cdot\vec{V_\beta}}{|V_\alpha||V_\beta|}\right)$$
- **Check that phase angle is >5° different from 120°**



Methodology – Generation &Transmission

Incipient Capacitive Voltage Transformer Failure

- **Capacitive voltage transformers (CVTs) supply voltage to protective relays**
  - **Data measured from CVT must be accurate**
- **For catastrophic CVT failures, relays are equipped with loss of potential (LOP) logic**
- **Relays cannot detect CVT showing early signs of failure**
- **Waiting until failure poses a massive safety risk**
- **We must detect failures before they occur**

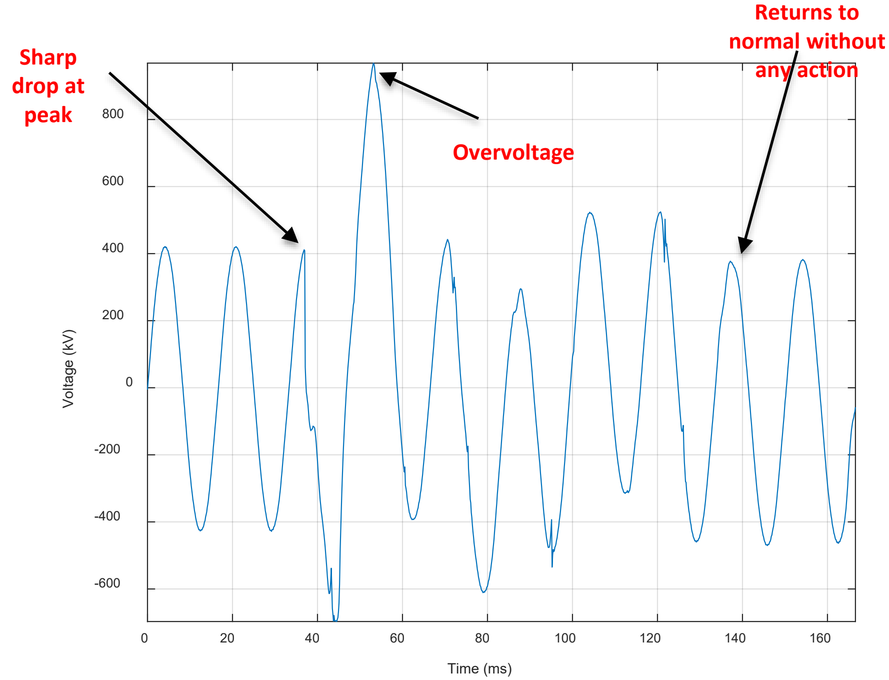


Methodology – Generation &Transmission

Incipient Capacitive Voltage Transformer Failure

Steps:

- Check for overvoltage or undervoltage 10% above or below nominal peak value
  - Must persist for >3 cycles
- Use first cycle as reference check for disturbance in signal
- Only occurs on one voltage phase at a time
- Current should be nominal or zero



- Background
  - Operational Motivation
  - Technical Motivation
  - Approach
- Distribution
  - Methodology
  - Results
- **Generation & Transmission**
  - Methodology
  - **Results**
- Continuous Waveform Analysis
- Future Endeavors

Results – Generation &Transmission

- CT Saturation
  - 464 of 480 … 96.7%
  - Same ratio for all
- A/D Converter Clipping
  - 953 of 960 … 99.3%
- Induced Transient Noise from Switching
  - 477 of 480 … 99.4%
- Incipient Capacitive Voltage Transformer Failure
  - 154 of 160 … 99.3%
- High-Speed Reclosing with Tapped Motor Load
  - 160 of 160 … 100%
- DC Offset
  - 956 of 960 … 99.6%
- Motor Starting
  - 160 of 160 … 100%
- Variable Frequency Drive Motor Starting
  - 160 of 160 … 100%
- Blown Fuse
  - 159 of 160 … 99.4%
- Ferroresonance
  - 476 of 480 … 99.2%
- Capacitor Switching
  - 159 of 160 … 99.4%
- Lightning
  - 477 of 480 … 99.4%
- Harmonic Resonance
  - 480 of 480 … 100%
- Voltage Transformer Secondary Grounding
  - 159 of 160 … 99.4%

- Background
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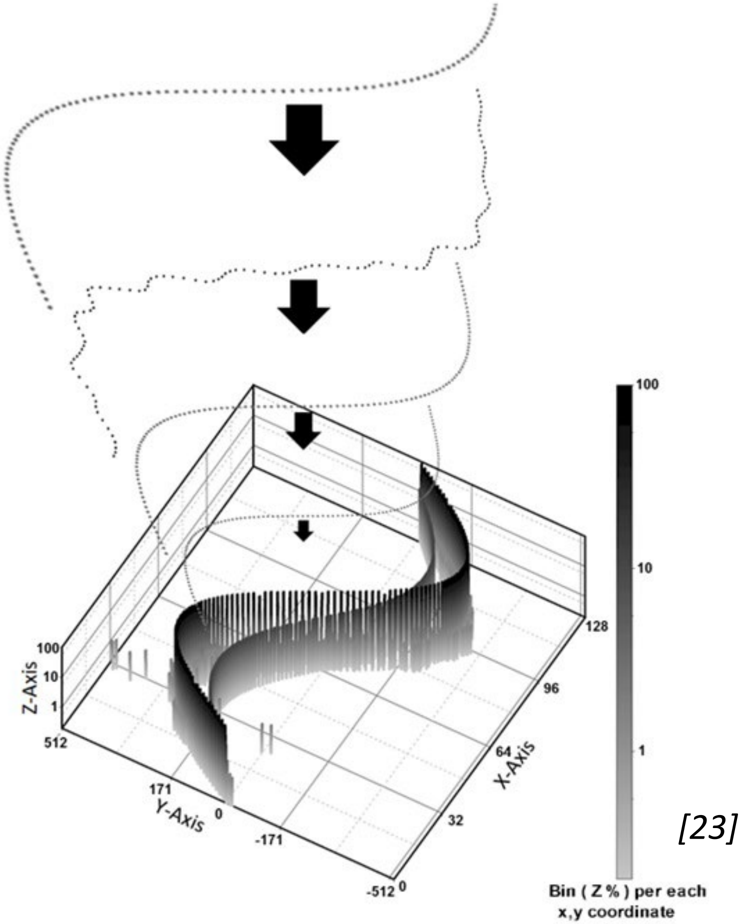
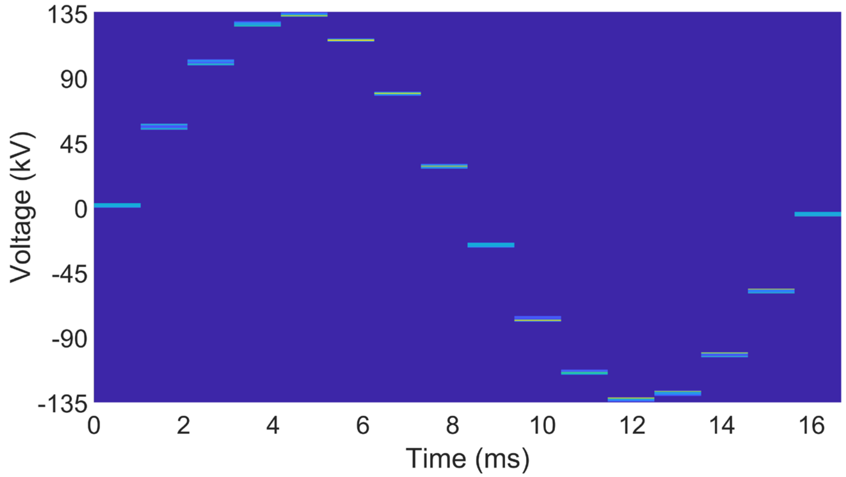
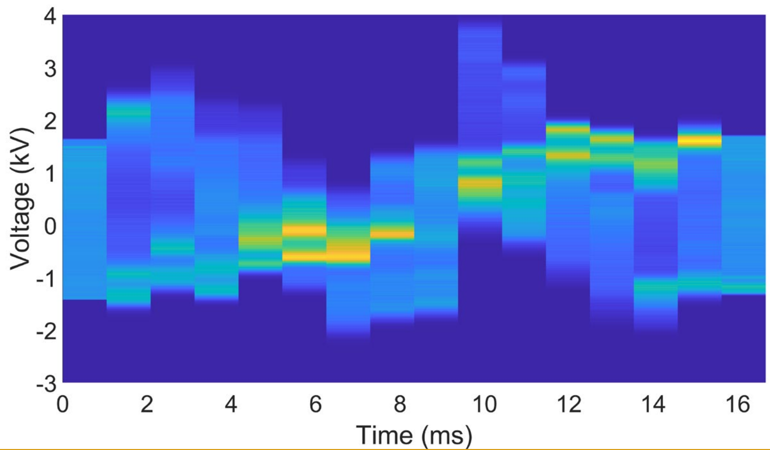
  - Results
- Generation & Transmission
  - Methodology
  - Results
- **Continuous Waveform Analysis**
- Future Endeavors

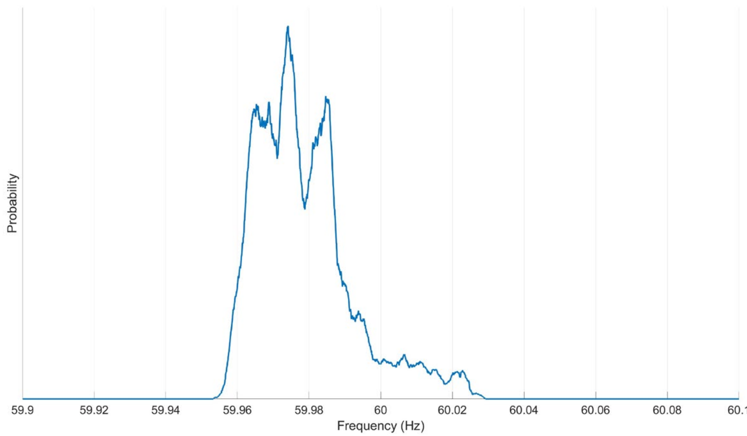
- **Continuous Waveform Analysis**
  - ***Currently***
    - ***Data is not looked at all!***
    - ***Overwritten every two weeks***
  - ***Our approach … Cyclic histogram [23]***
    - ***Ranks probability of data activity***
    - ***Alternative representation for PQ analysts***
    - ***Facilitate incipient fault detection and prediction***
    - ***Reduces storage requirement … Factor of 1,000***



[23]


135
90
45
0
-45
-90
-135
Voltage (kV)
0
2
4
6
8
10
12
14
16
Time (ms)


4
3
2
1
0
-1
-2
-3
Voltage (kV)
0
2
4
6
8
10
12
14
16
Time (ms)


Probability
59.9
59.92
59.94
59.96
59.98
60
60.02
60.04
60.06
60.08
60.1
Frequency (Hz)

- Background
  - Operational Motivation
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- Generation & Transmission
  - Methodology
  - Results
- Continuous Waveform Analysis
- **Future Endeavors**

Future Endeavors

- Address the sequence of events
- Grow the number of events
- Leverage cyclic histogram for event prediction and prevention
- Create & integrate into digital twin
- Transition to utilities
- Expand # of utilities
- Increase the “smarts”

Questions?

Thank You!

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