Incipient Faults in Distribution Systems: Experiences, Use Cases, and Case Studies

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Agenda

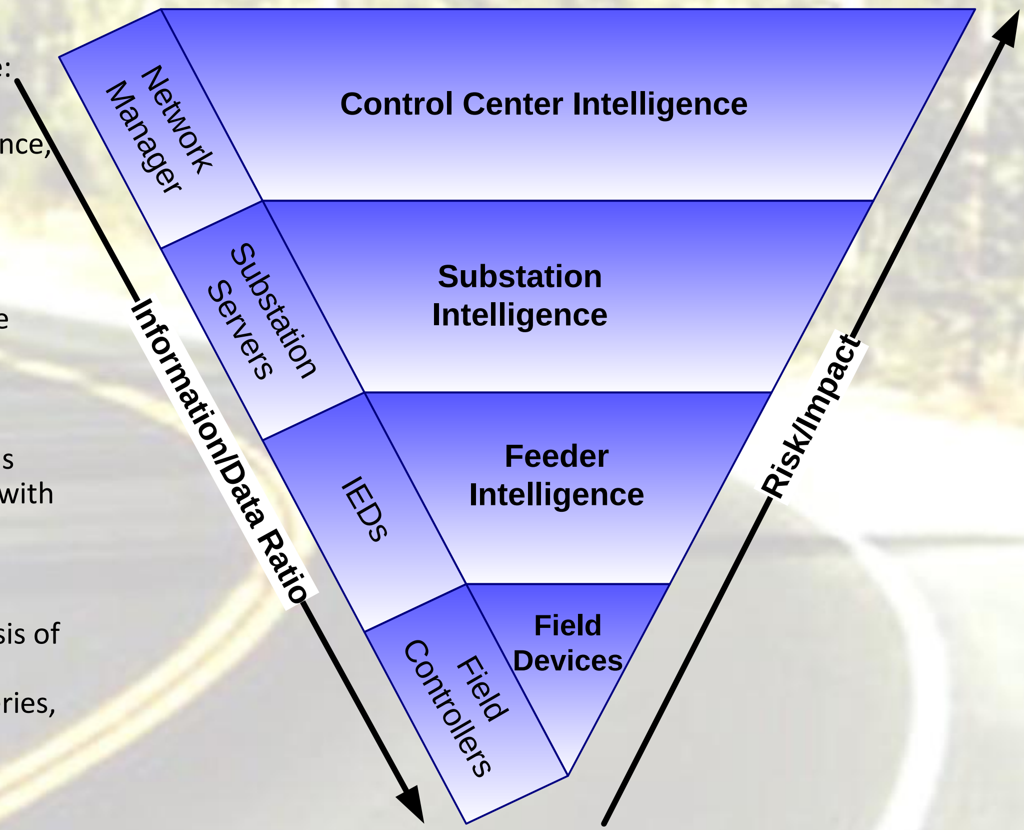
- Introduction
- Incipient fault characteristics with field-recorded illustrations
- Detecting re-occurring incipient faults
- Conclusions

Research Roadmap: Intelligent Solutions

Incipient faults has been an R&D&D topic for many years

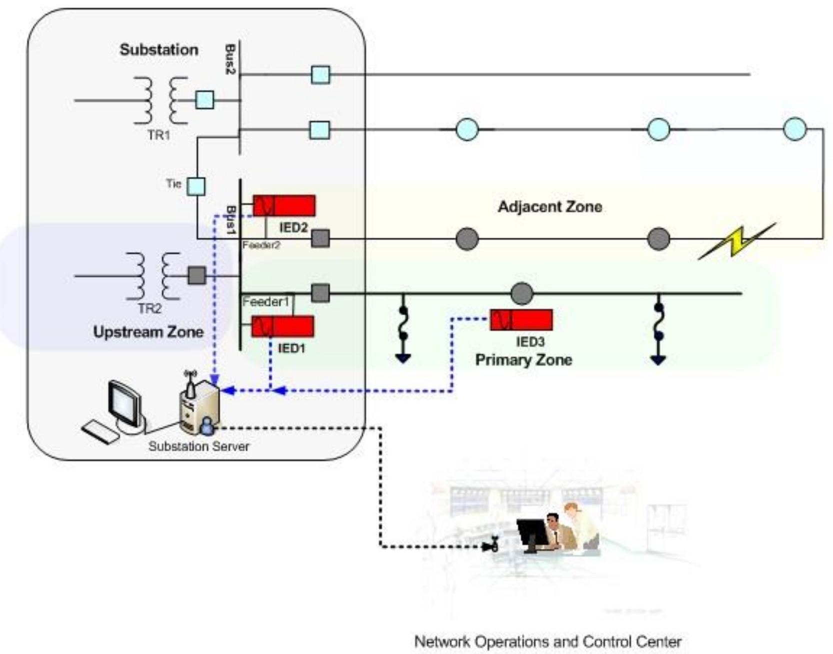
- 2013-2016 (condition-based control applications)
- 2011-2013
  - Time-tagged sensor data and derived intelligence: integration into control center
  - Use of sensor data for real-time feeder performance, asset management, grid analytics, and modeling funded in part by DOE
- 2010-2011
  - Focus on multi-IED feeder and station intelligence applications for substation servers
- 2008-2009
  - Focus on high-end feeder intelligence applications embeddable in IEDs or substation servers in-line with the advent of Smart Grids.
- 2007&prior
  - Focused primarily on low-cost modules for analysis of non-operational data e.g. disturbance data for providing feeder intelligence (e.g. breakers, batteries, lines/cables, IEDs, and feeder components)

Pyramid of Intelligence



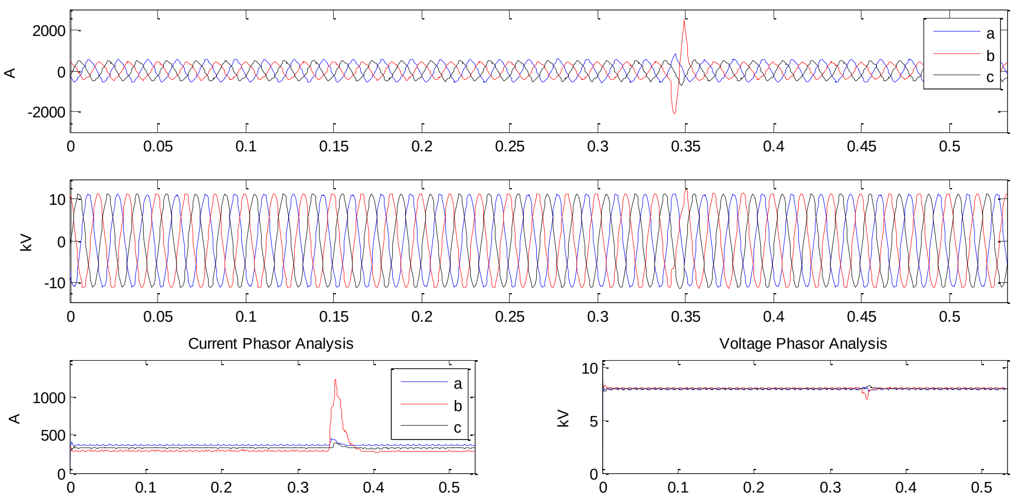
Data Acquisition and Processing Flow

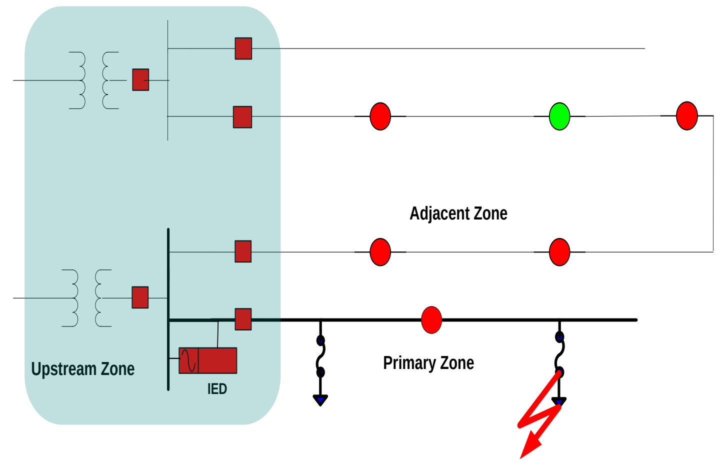
- Taps into available data from IEDs (32 spc min. res.)
- No new sensors/CTs/PTs required
- Real-time and automated analysis of disturbance records from field IEDs
- Detection and Control Center notification within seconds with the end-to-end process fully automated
- End-User value
  - Knowledge: situational awareness (WWWWH)
  - Enables incipient fault/abnormality detection
  - Faster outage detection and notification e.g. fuse-cleared faults
  - Reduces OK-on-arrival truck rolls
  - Confirmation of switching events, power on, and power off
- Field verified and validated algorithms
- Available for pilot deployment in IEDs, substation automation controllers, and integration with control center

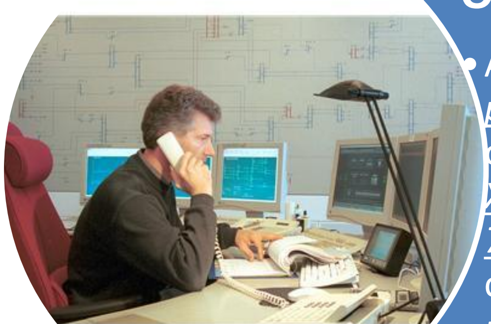


Comprehensive Analysis, Detection, and Assessment

What/When/Where/Why/How (Available in Substation Controller)







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).*

Case # 955 in MDB	DFEVAS	OMS
	Predicted	Actual
Time of Event	12/13/2008, 7:44 AM	12/13/08 8:02 AM
Substation	XYZ	XYZ
Feeder Number	1234	1234
Phase	B	B
Event Classification	Short-duration Feeder Fault (High)	Cable Fault
Infrastructure	UG (80%)	UG
Equipment Category	N/A	Cable
Clearing Device	Fuse	Fuse
Clearing Device Size	[10A,65A] [40A,0.981]	40A
Cause of Failure	N/A	Cable Failure
Location	PMZ, Segment X	Primary Feeder
Time of Restoration	N/A	9:45AM

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

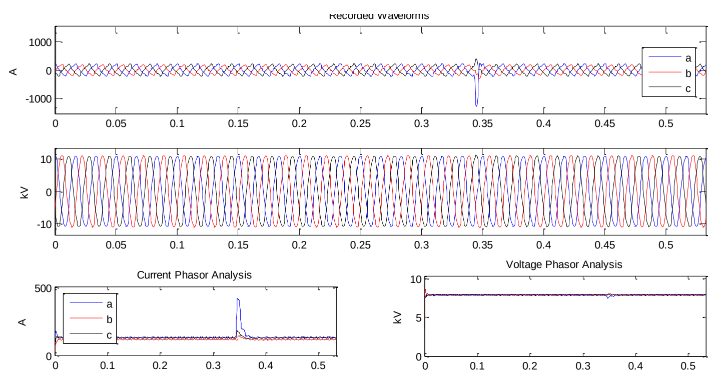
139 Incipient Faults thereafter

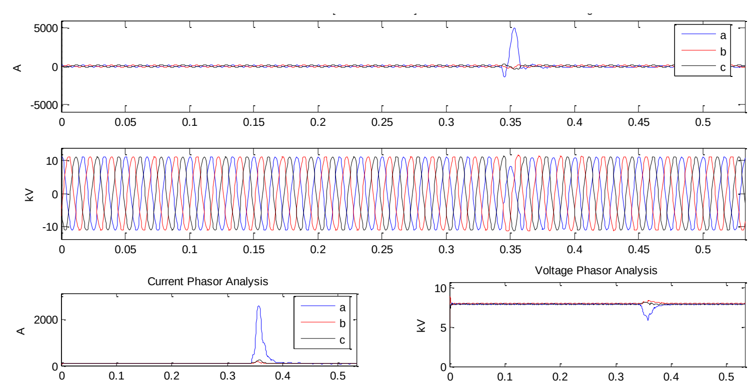
- Ifault = 100's – 1000's A RMS
- Multiple faults per day

Permanent Fault June 14, 2008

12:19 AM

- Ifault = 2626 A RMS
- Customer call



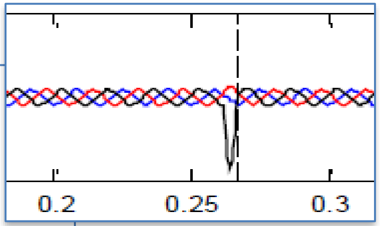


Illustrative Case #2

Incipient fault lasting 3 hours

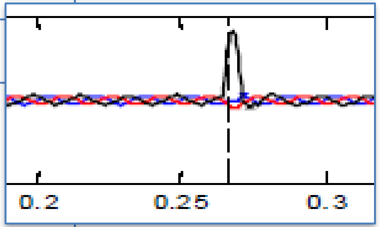
Initial "C" Phase Incipient Fault March 8 at 6:05:55 PM

- 1108A RMS
- No outages or customer calls



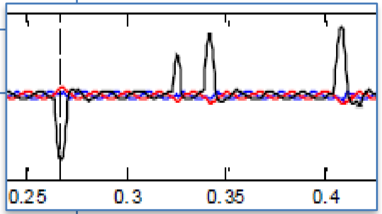
6 Single blips thereafter

- 1600 – 2438A RMS
- Generally less than ½ cycle



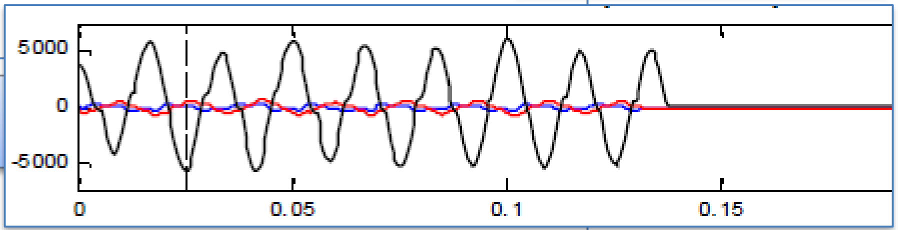
9 Multiple blips thereafter

- 2776-4274A RMS
- Over a few non-contiguous cycles



Permanent fault captured
March 8 at 9:07:53 PM

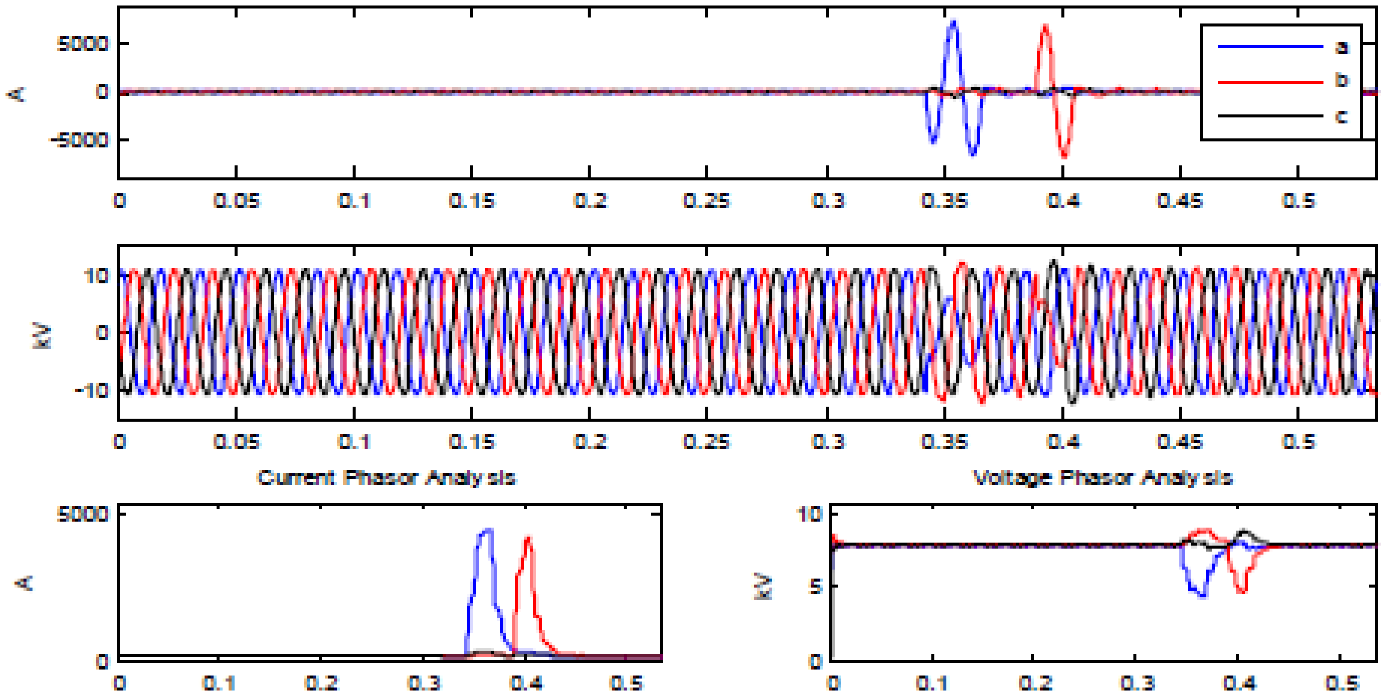
- 4077A RMS followed by a customer call



Illustrative Case #3

Primary zone: Evolving fault

- A phase-A fault evolves into a phase-B fault
- No OMS data!

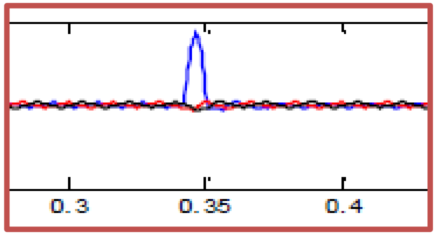


Illustrative Case #4

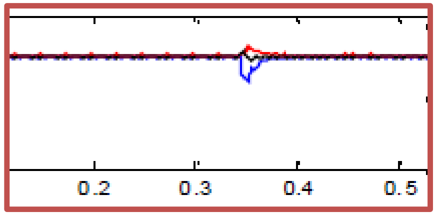
Incipient Fault leads to a Permanent O/H Fault

"A" Phase Fault on Jan 31 @ 12:04:59 AM

- 2564A RMS
- No outages reported around that time
- Cause was tree inside maintenance Corridor
- Feeds traffic and street lighting



Current waveforms



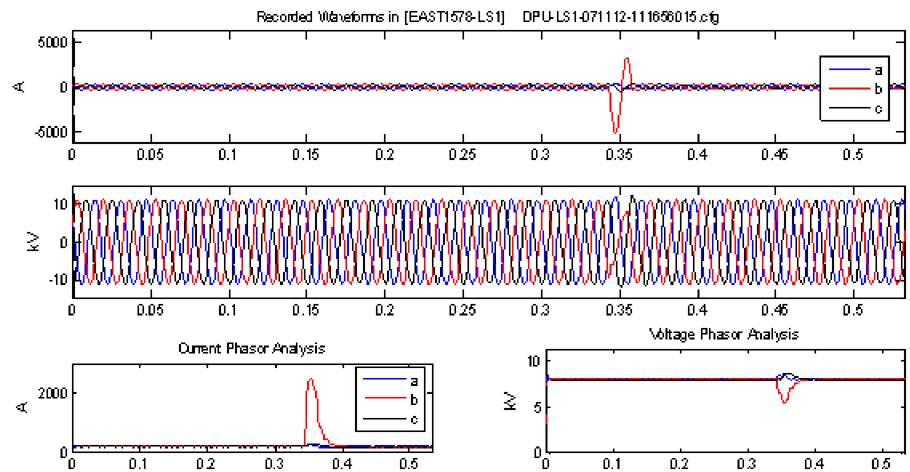
Voltage waveforms

Outage registered 7:41AM

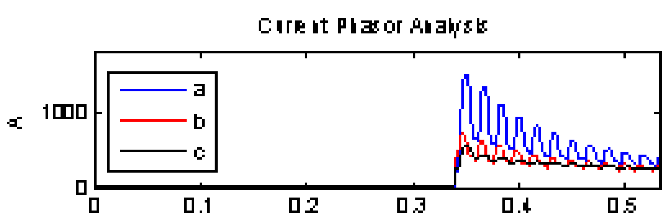
Opportunity to fix the problem before an outage call

Avoiding False Positives

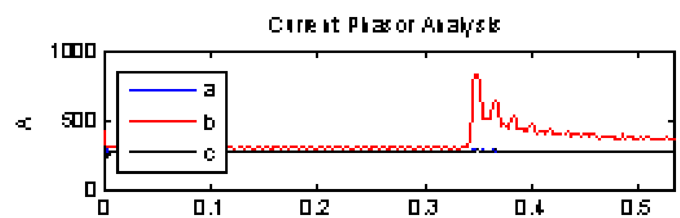
- Example of proper cable fault detection



- Examples of 'false positives'
  - Inrush



A



B

Incipient Fault Characteristics

Solidly-grounded Circuits

Common Characteristics: magnitude, duration, inception angle, harmonics, long and short term trends (not exhaustive)

- Do not draw sufficient current for O/C protection
- Do not last sufficient enough for coordinated O/C protection
- Fault duration on an average less than half a cycle.
- Peak fault current could be multiple times the RMS load current
  →Harmonic analysis not necessarily required.
- Increasing trend in the normalized instantaneous peak fault current towards eventual fault time
- Increasing trend in 0^{th}, 2^{nd}, and 3^{rd} harmonic.
- Fault inception angle close to 0 degrees w.r.t. voltage peak
- Intermittent on/off behavior
- Could persist for as little as hours

Illustrative Example: Splice failure

Recording begins on August 19

- First case of incipient fault recorded on September 11
- Current Peak- 1287A Duration- 0.22 cycles
- No Records on Utility Outage System

After 139 repetitive incipient faults over 9+ months!

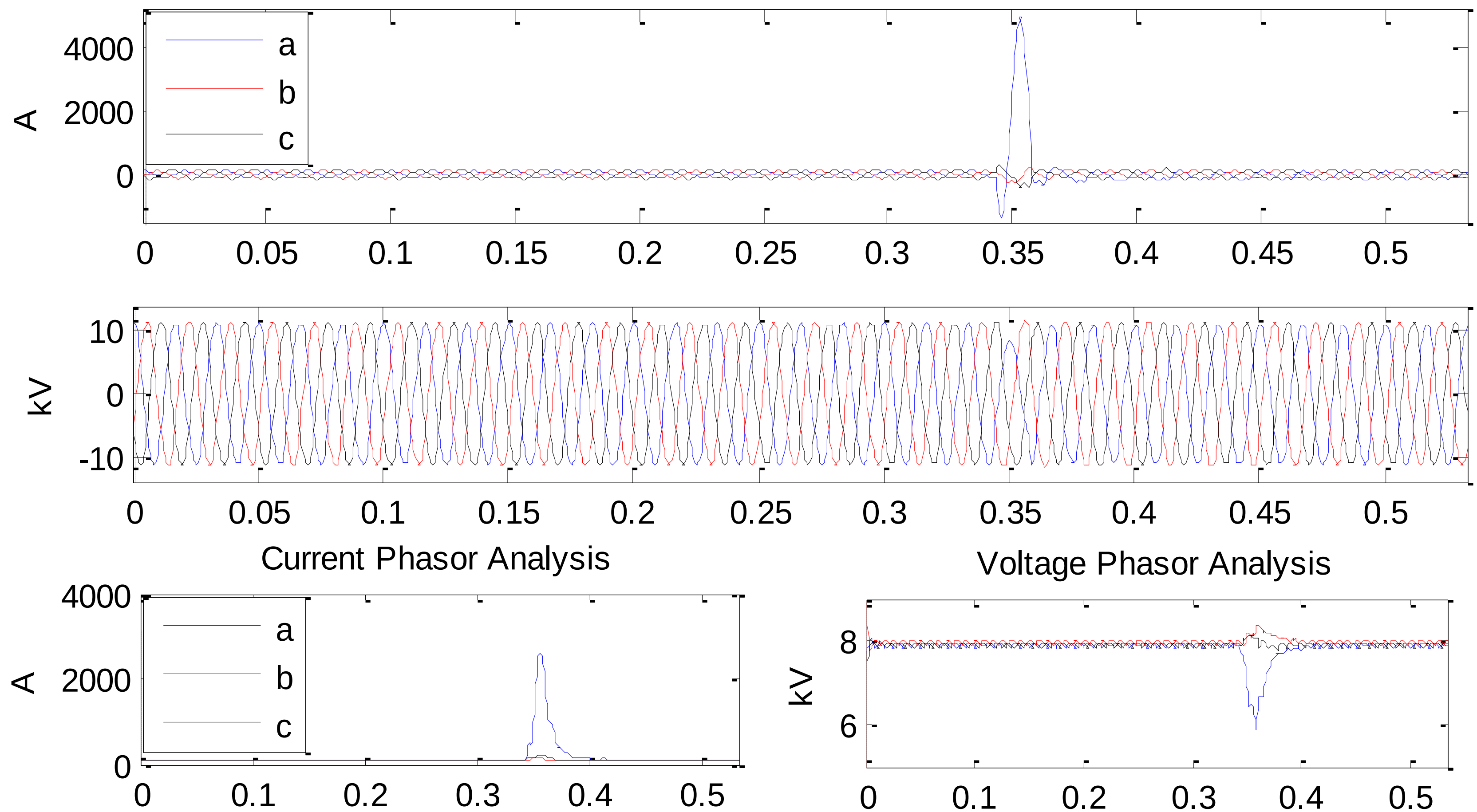
- A catastrophic failure occurred on June 14
- 65 A Fuse blown
- Peak Current – 5000A

View of the catastrophic failure

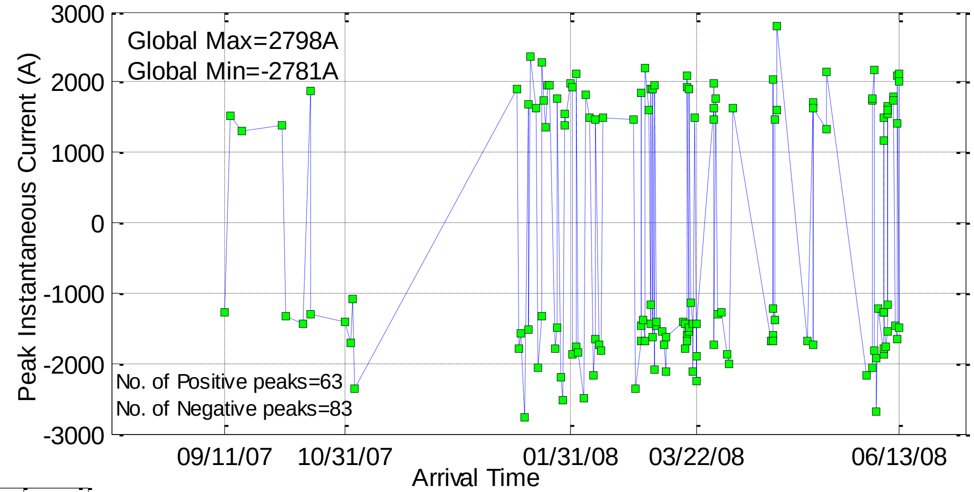
Close-up view of erosion of splice body

The center splice body is a non-faulted splice from the same location on different phase, this splice is in good condition.

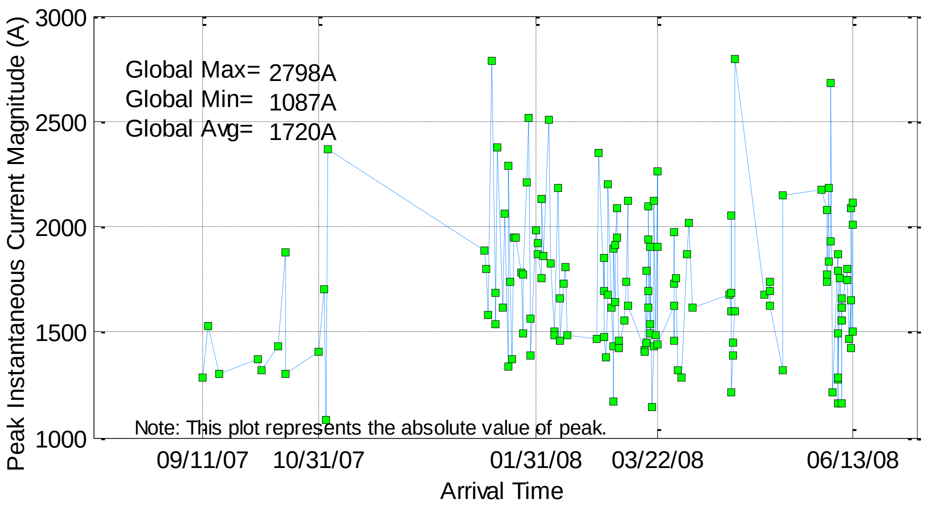
View of the catastrophic failure



Time Domain Analysis



Peak FAULT CURRENT by Polarity



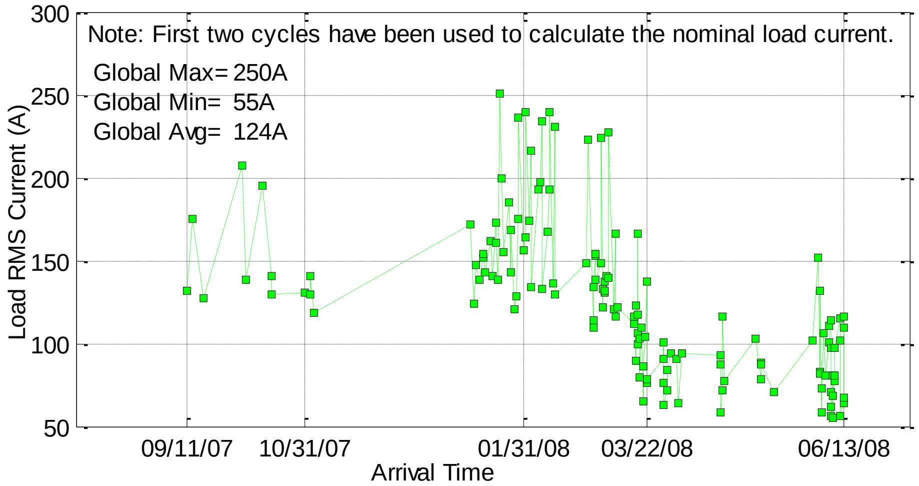
Peak Abs. FAULT CURRENT

Polarity not a significant determining factor for fault initiation.

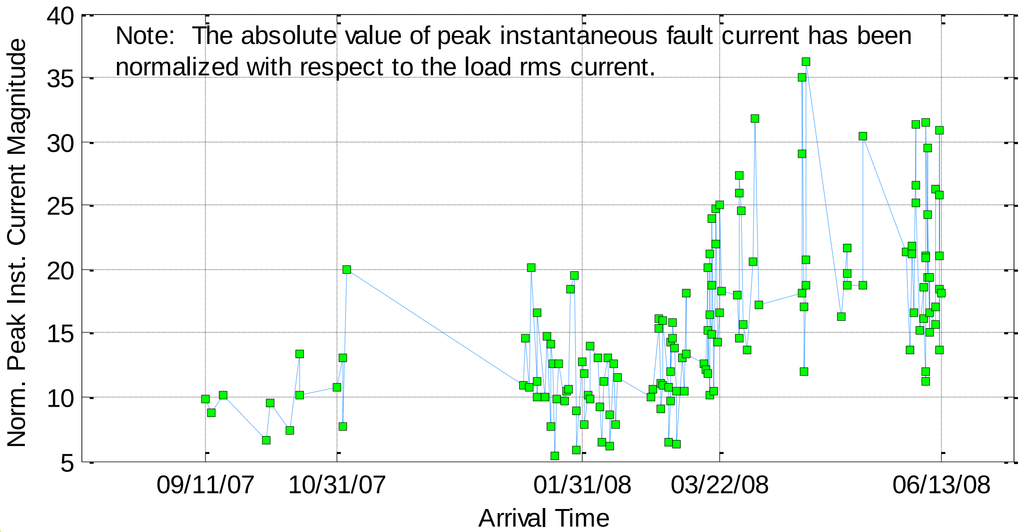
Time Domain Analysis

RMS LOAD CURRENT

• Peak fault current is 5-6 times the RMS load current



• Normalized instantaneous peak fault current has an increasing trend.

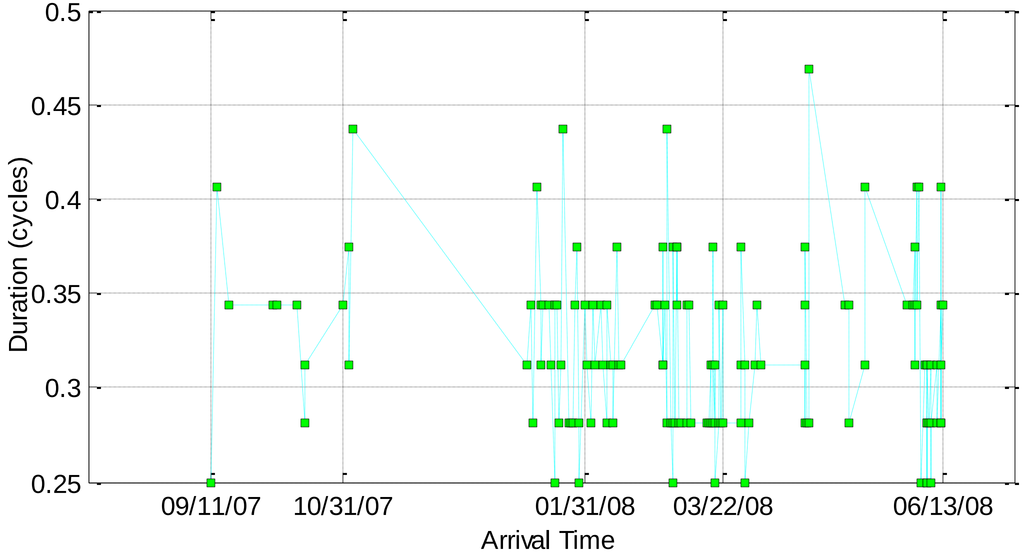


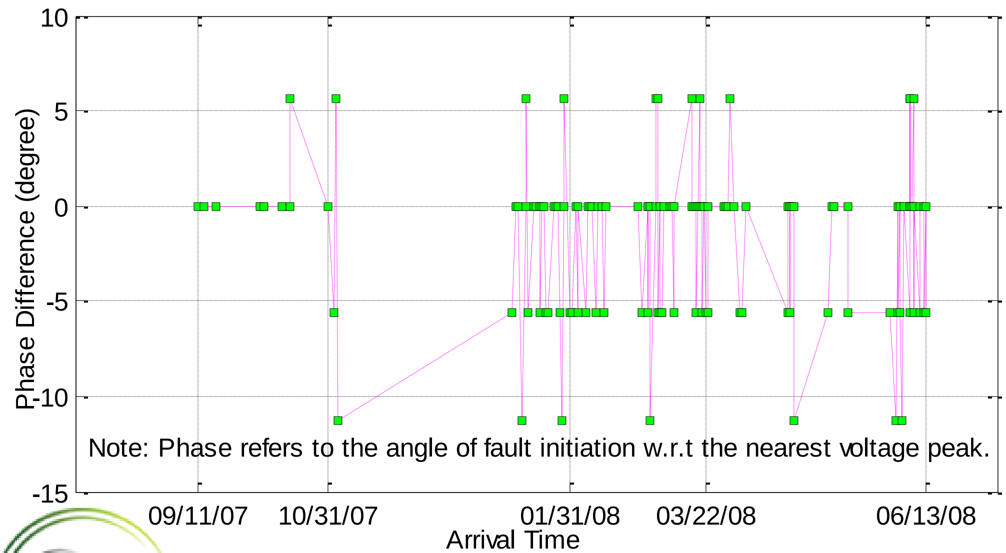
• See progressive trend towards failure
• repeated faults compromise insulation integrity

Time Domain Analysis

DURATION

• Duration lies between 0.25-0.47 cycles- not picked up by conventional relay algorithms.



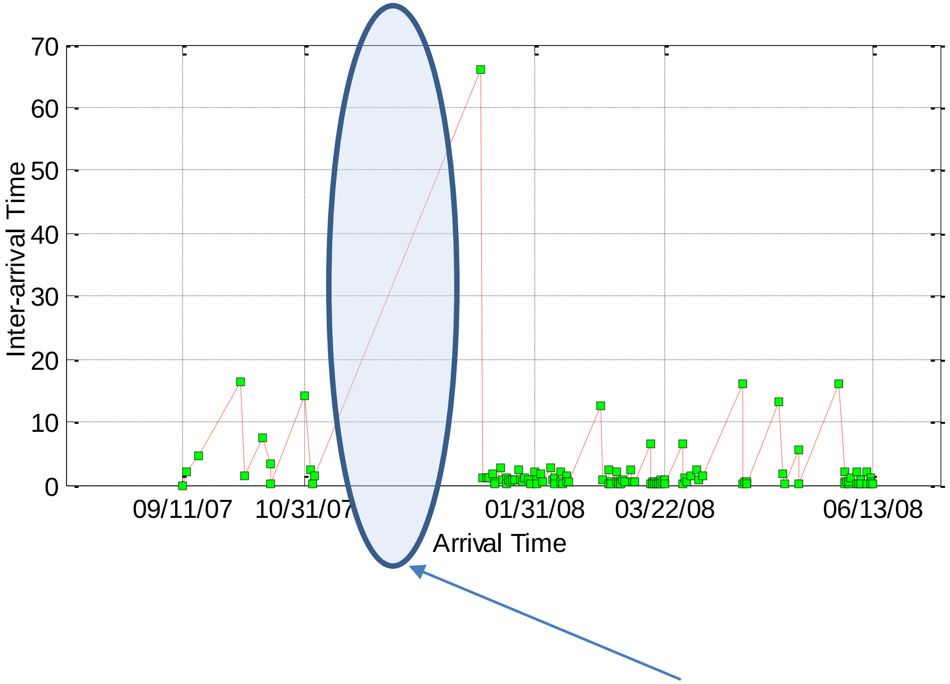


INCEPTION ANGLE w.r.t. voltage peak

Phase difference close to 0, averages around -1.16 degrees

Time Domain Analysis

INTER-ARRIVAL TIME

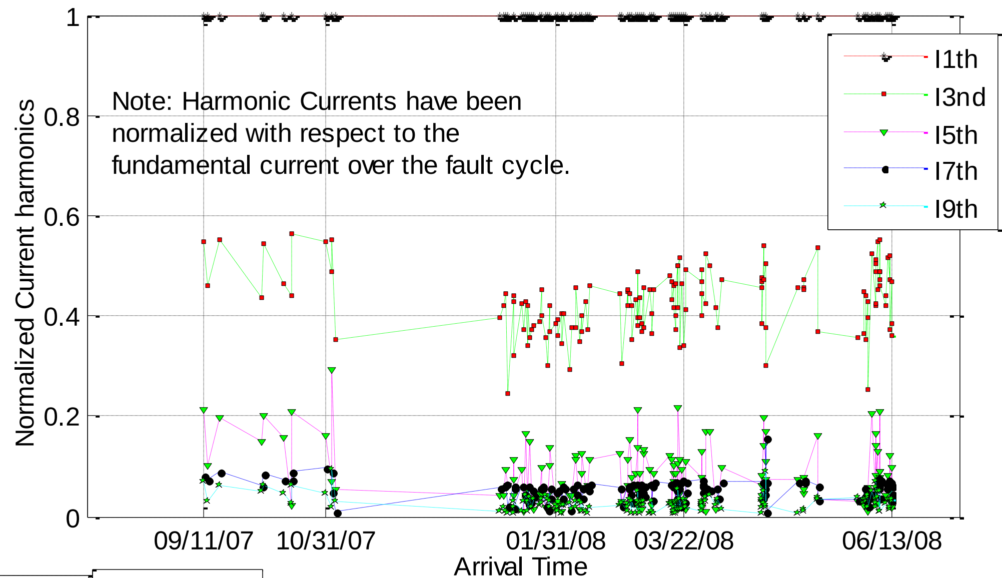


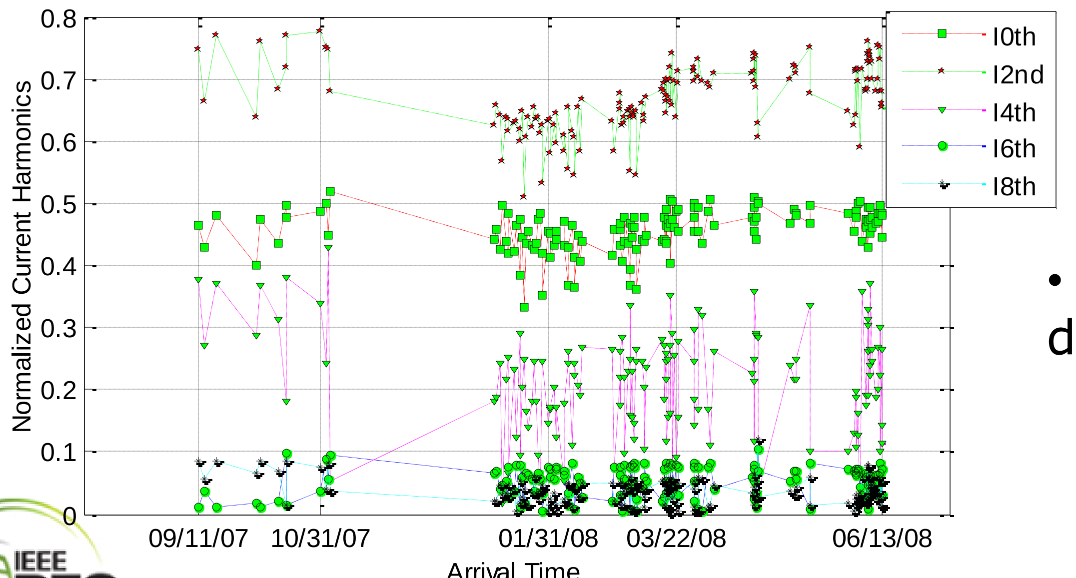
- Inter-arrival Time – demonstrates intermittent on/off behavior

Frequency Domain Analysis

ODD HARMONICS

- Even harmonics generally appear with higher magnitudes than that of odd harmonics – sub-cycle duration.





EVEN HARMONICS

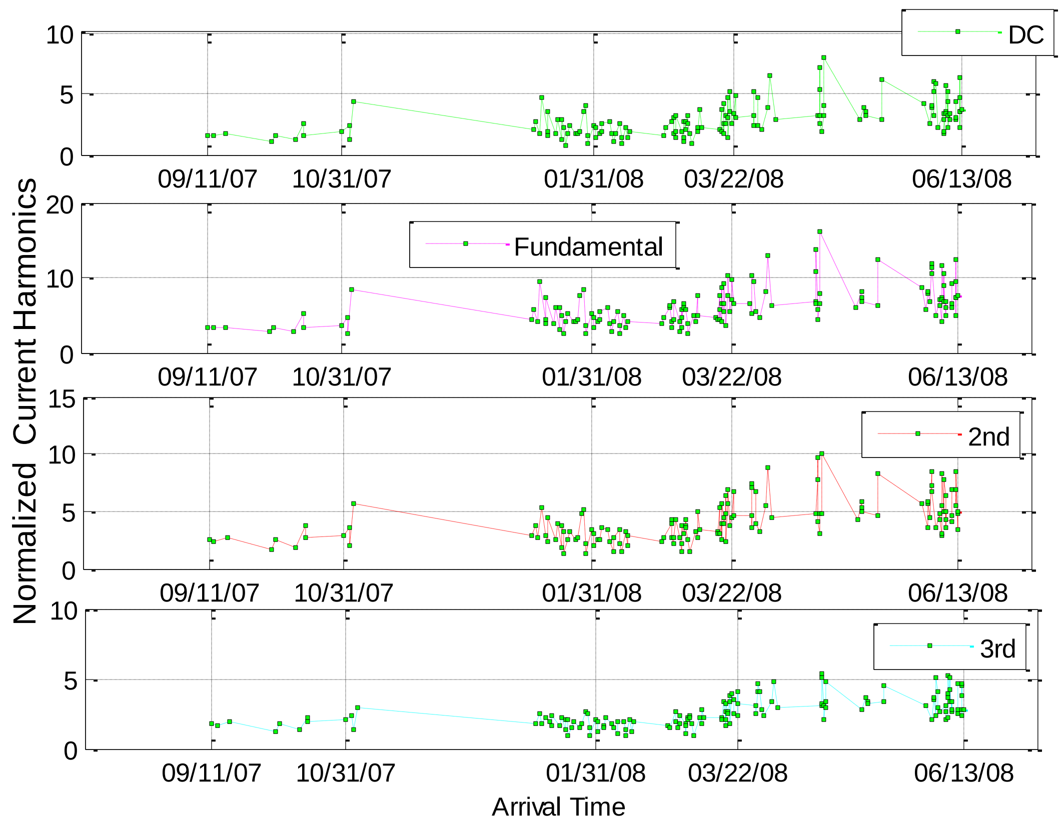
- The 2nd Harmonic is dominant.

Frequency Domain Analysis

- DC, Fundamental, 2nd and 3rd harmonic normalized currents generally have a positive correlation with the failure.

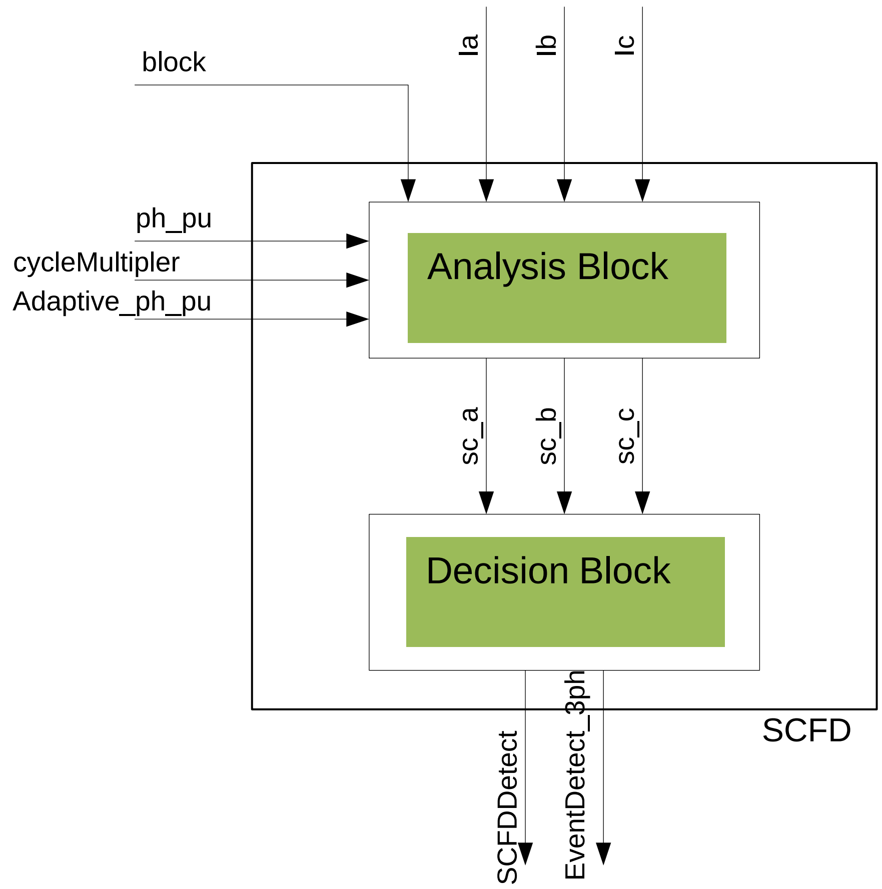
- They may be used as symptom parameters, although implementation details would vary.

- Fundamental suffices in most cases!



Incipient Fault Detection in IEDs

- Available feature in feeder protection IEDs
- Detecting an individual instance of an incipient fault
- Applies to both O/H, U/G, and mixed feeders with incipient, fuse-cleared, or self-cleared faults
- Analog inputs
  - Phase currents – Ia, Ib, Ic
- Logical inputs
  - Block – on/off control of module
- Internal logic
  - Per-phase CFD counters - sc_a, sc_b, sc_c
- Logical outputs
  - Cable fault detection – SCFDDetect
  - Three-phase cable fault event detected – EventDetect_3ph
  - Expanding number of logical outputs
  - Map to trigger DFR



Benefits

- Primary value of incipient fault detection is knowledge, i.e., dispatchers will know what they didn't previously know when a feeder fault occurs that is either self-clearing or are cleared by non-communicative device, e.g., reclosers or switches, or unintelligent device, e.g., fuse
- Algorithm is able to detect incipient and permanent faults on overhead and underground feeders that are solidly grounded (ANSI type)
- High ease of use factor with feature available in feeder protection and control relay eliminating need for extra or unique instrument transformers (CT, VT) or system sensors

Detecting the Long-term Trend

- Incipient faults do not cause outage until they lead to permanent faults
- A series of repetitive occurrences is a major sign of an impending failure
- Detecting individual incidents of an incipient activity is a prerequisite step for alarming (necessary but not sufficient)
- Just-in-time alarming to avoid or manage an unplanned outage requires active monitoring over the activity period
- Could be hours, days, or weeks depending upon many stress factors including thermal and electrical

Detecting The Long-term Trend

Human-in-the-loop Approach

- Keep a daily count of detected incipient activities
- Initiate mitigation plans by intuition after a certain number of occurrences register in a given period
- Pros
  - Simple approach
  - works for one-off situations
  - Lower deployment barrier
- Cons
  - Not scalable
  - Not sustainable due to operator fatigue
  - Prone to operator shift changes
  - Has to be standardized across the system

- *Effective automated techniques are required for just-in-time detection and alarming.*
- *Alarming should be based on risk tolerances (trade-off between missed detection and early warning)*

Gained Experience-Other

- Be mindful of benefits misalignment if Operations are siloed from Engineering/Standards. Significant value for this kind of technology is realized at the company level.
- Over 90% of incipient and permanent faults occurred on laterals
  - Detection and location is harder on laterals
  - Do not cause breaker trips and SCADA alarms
  - Integration with DMS/Control Center is required to make operational impact.
- Sub-cycle and incipient fault location remain an industry challenge although some methods recently have been reported!
- Need to deal with feeder modeling inaccuracies for detection and localization
  - Bad connectivity data
  - Incorrect phasing
  - Missing information (conductor length, size, material)
  - As-built vs. as-operated models

Acknowledgements and Disclaimer

- US Department of Energy

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