Complex Faults: Using High-Quality Waveform Data to Understand Faults That Misbehave

presented to the

74th Annual Conference for Protective Relay Engineers
Texas A&M University, College Station, Texas USA
Tuesday, March 23, 2021, Distribution Session 1

by

Dr. B. Don Russell, Distinguished Professor
Carl L. Benner, Research Professor
Dr. Jeffrey Wischkaemper, Asst. Research Professor (presenting)
Dr. Karthick Manivannan, Asst. Research Professor
Department of Electrical and Computer Engineering
Texas A&M University, College Station, Texas 77843-3128 USA

Complex Faults: Not that simple.

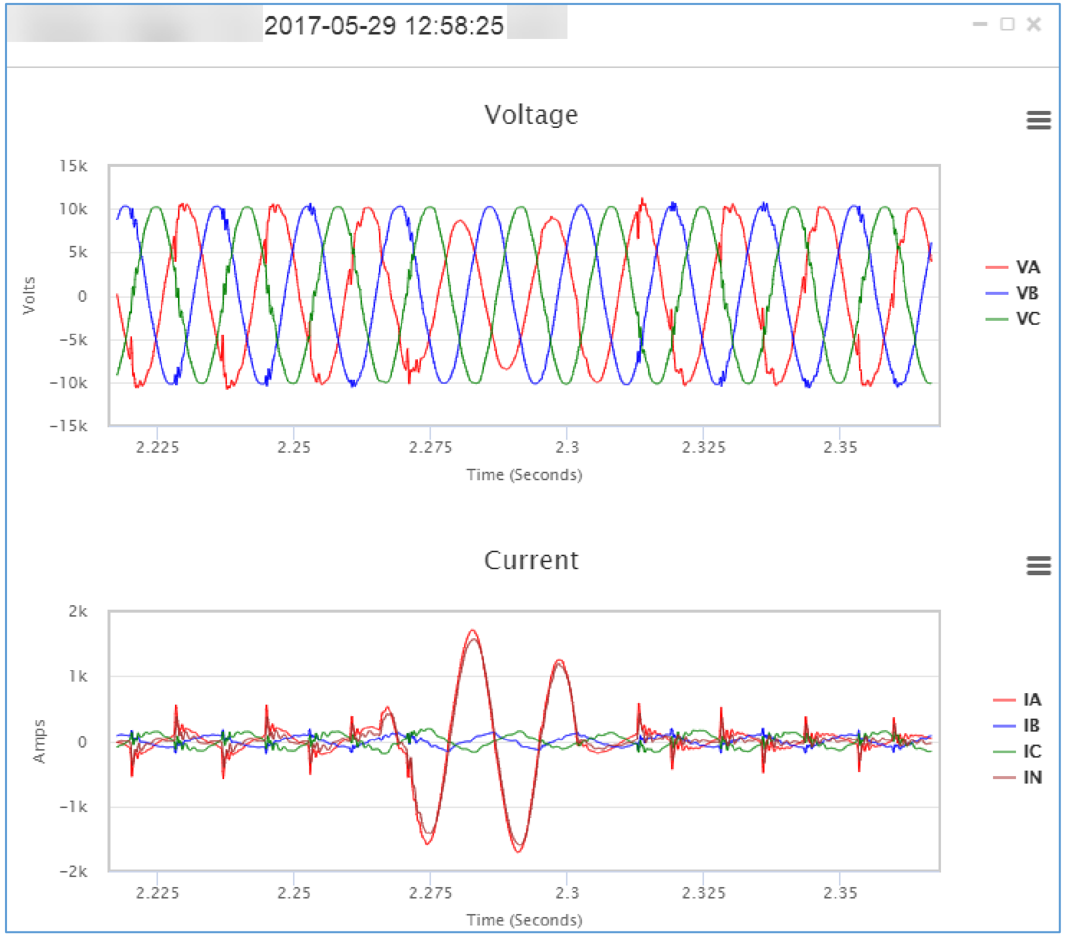
- Conclusions about the root cause of faults on distribution circuits are often incorrect.
- The absence of high-fidelity, long-duration data recordings hinders the investigation of complex faults, and often requires engineers to "guess" about what may have occurred.
- Decisions about root-cause failures based on incomplete information often lead to incomplete remediation of the true root cause.
- Examples in this presentation are real-world events recorded during routine utility circuit operations.
- Examples are not staged, and data is not simulated.

Data Source

- Texas A&M Engineering developed DFA technology which monitors CT and PT signals at the substation head of distribution circuits (feeders). That hardware/software monitor provides all data in this presentation.
- The monitor triggers sensitively and makes long recordings, starting at ten seconds and extending up to 60 seconds if complex events cause re-triggering. All recordings are retrieved to a central server automatically.
- All recordings have 18+ bits of resolution and a sample rate of 256 samples/cycle for 3 voltages and 3 currents plus a calculated 3Io.
- For extended-duration recordings, viewing RMS values (1/cycle) first provides the "big picture," before drilling down into waveform details. The viewer provides high-speed V&I, RMS V&I, P&Q, etc.
- All recordings are from circuit CTs and bus PTs at the substation.

Example 1

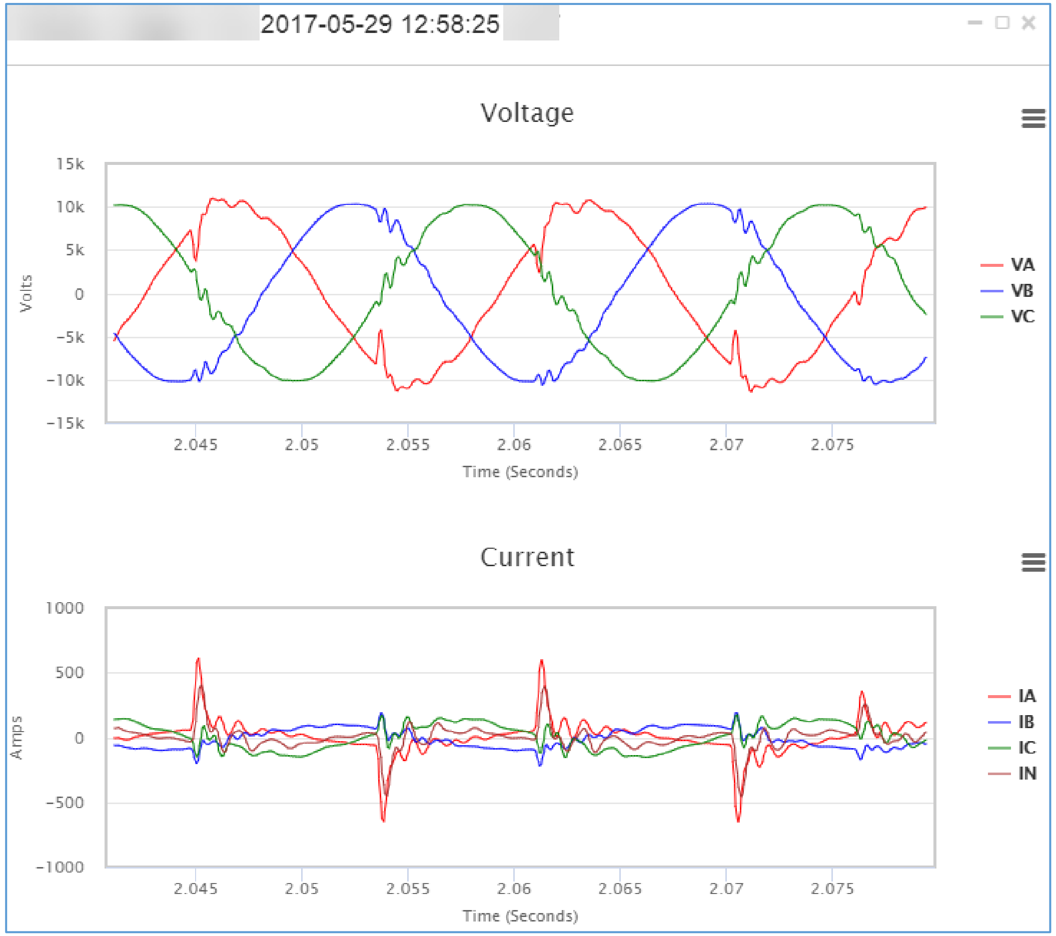
Fault Caused by an Event far Upstream



- A fault caused a fuse to blow, and a patrol identified a failed MOV surge arrester downstream of the fuse.
- The fault recording shows a 2-cycle fault on the order of 1kA.
- But the high-bandwidth recording shows repeated transients, even after the fault blew the fuse.
- How can the transients persist after the fault blew the fuse???

Example 1

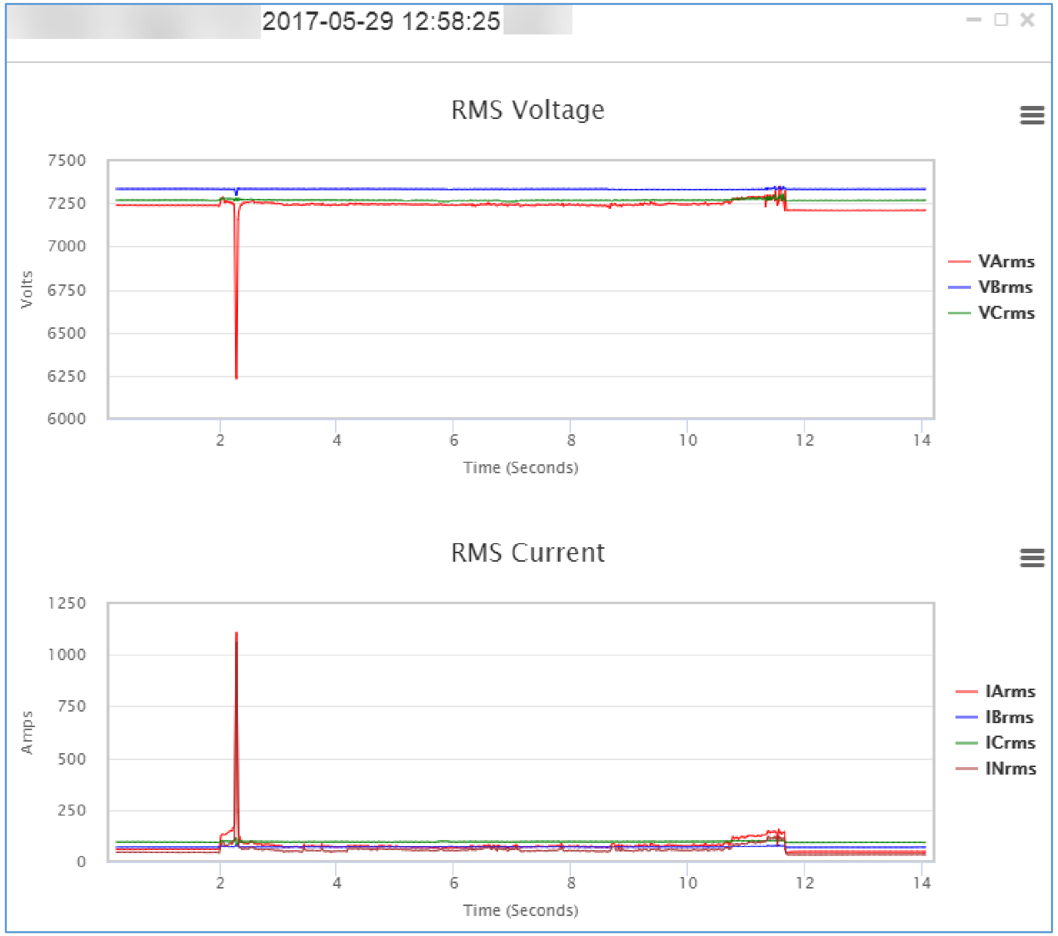
Fault Caused by an Event far Upstream



- Transients before the high-current fault have substantial magnitude but are too time-limited to operate most protection.
- Transients after the high-current fault are substantially the same as before the fault.
- Repeat: How can the transients persist after the fault blew the fuse???

Example 1

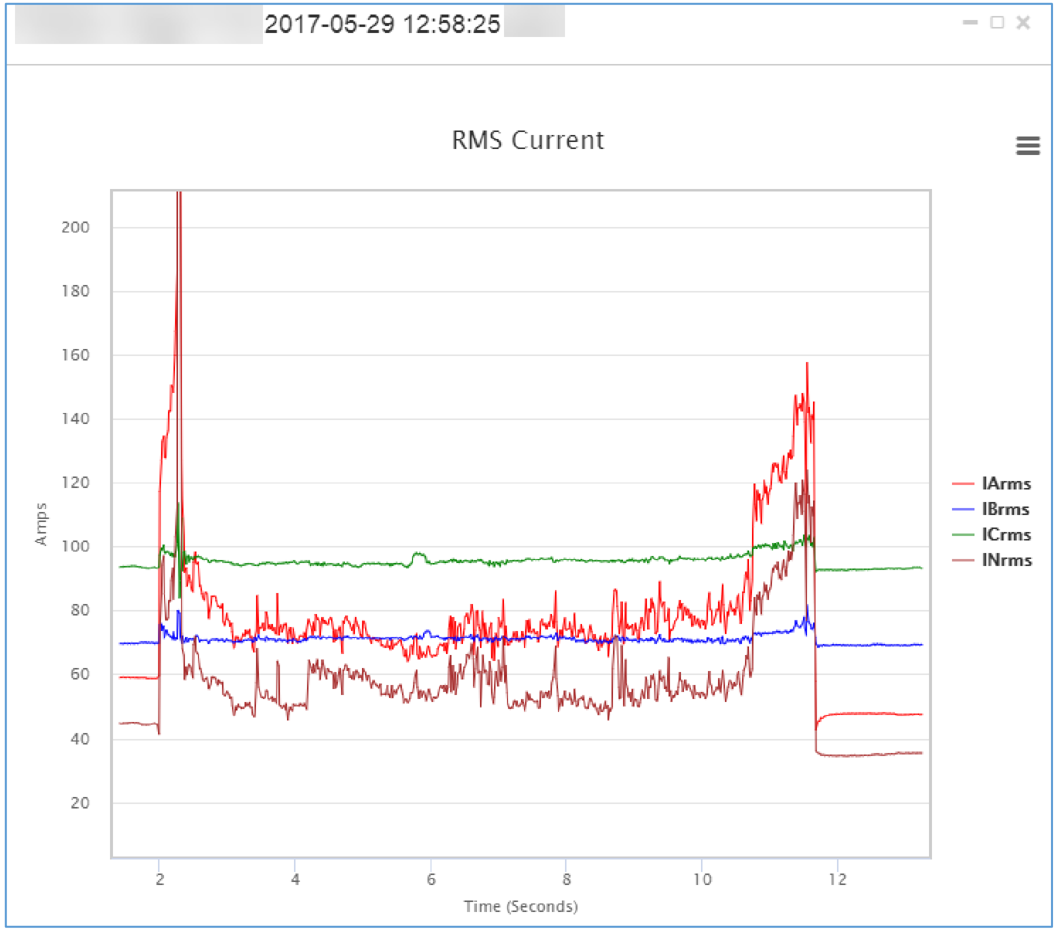
Fault Caused by an Event far Upstream



- The 14-second recording has 256 samples/cycle, but this RMS graph provides optimal big-picture understanding of the event.
- The high-current fault lasted only two cycles, but the full event lasted ten seconds (2s < t < 12s in the graph).
- There is a low-current increase right <u>before</u> the high-current fault, and low-current activity <u>after</u> the fault.
- What could cause this?

Example 1

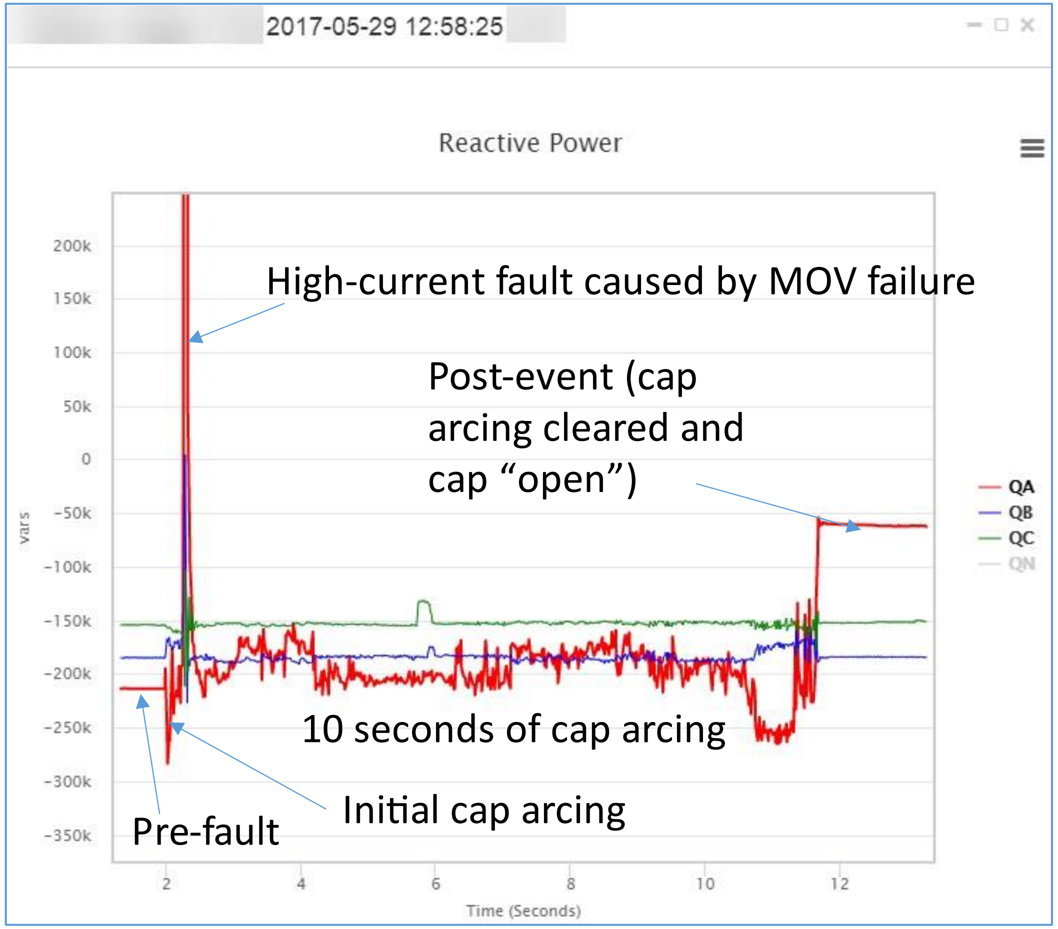
Fault Caused by an Event far Upstream



- The 14-second recording has 256 samples/cycle, but this RMS graph provides optimal big-picture understanding of the event.
- The high-current fault lasted only two cycles, but the full event lasted ten seconds (2s < t < 12s in the graph).
- There is a low-current increase right before the high-current fault, and low-current activity after the fault.
- What could cause this?

Example 1

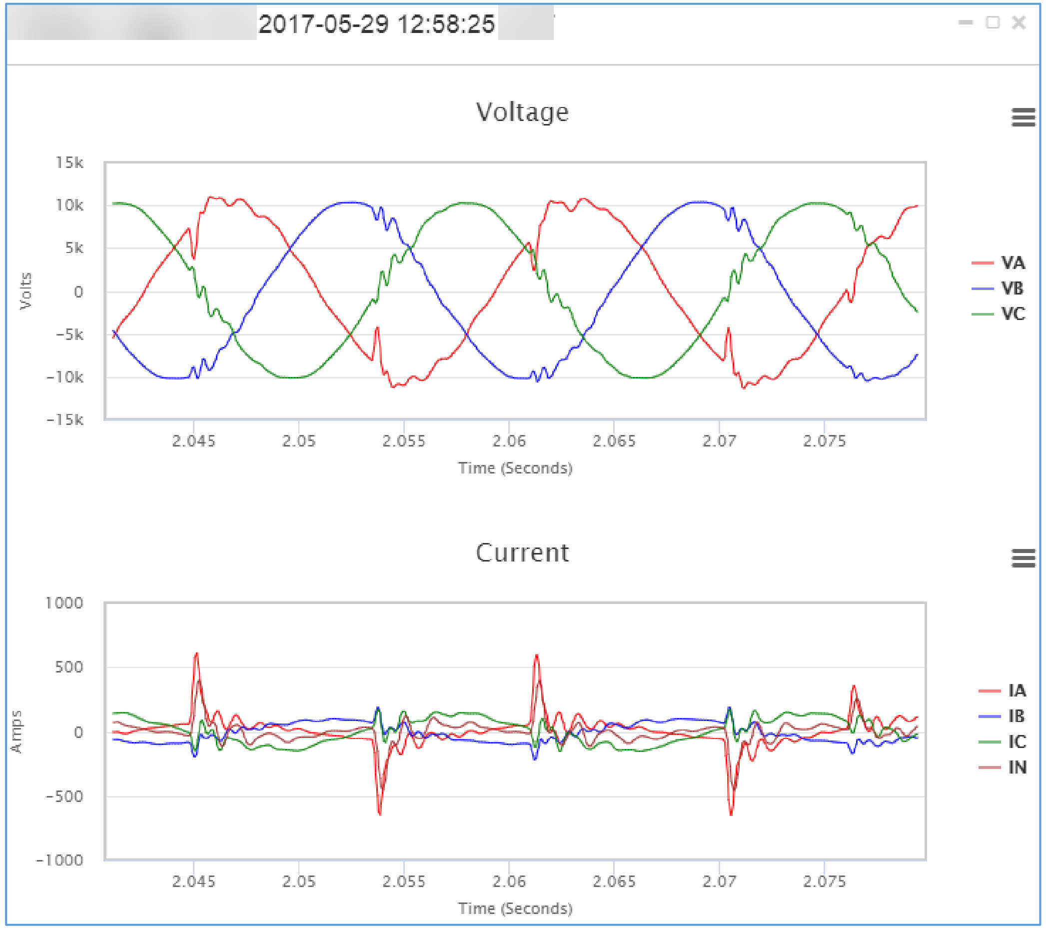
Fault Caused by an Event far Upstream



- Reactive power provides the key.
  - Post-event QA: -62 kvar
  - Pre-event QA: -214 kvar
  - Net increase: 152 kvar
- That change in reactive power is consistent with loss of phase-A of a 450-kvar capacitor bank.
- And the high-frequency transients 2s < t < 12s are consistent with capacitor arcing.
- It is known that capacitor arcing can precipitate MOV failures.

Example 1

Fault Caused by an Event far Upstream

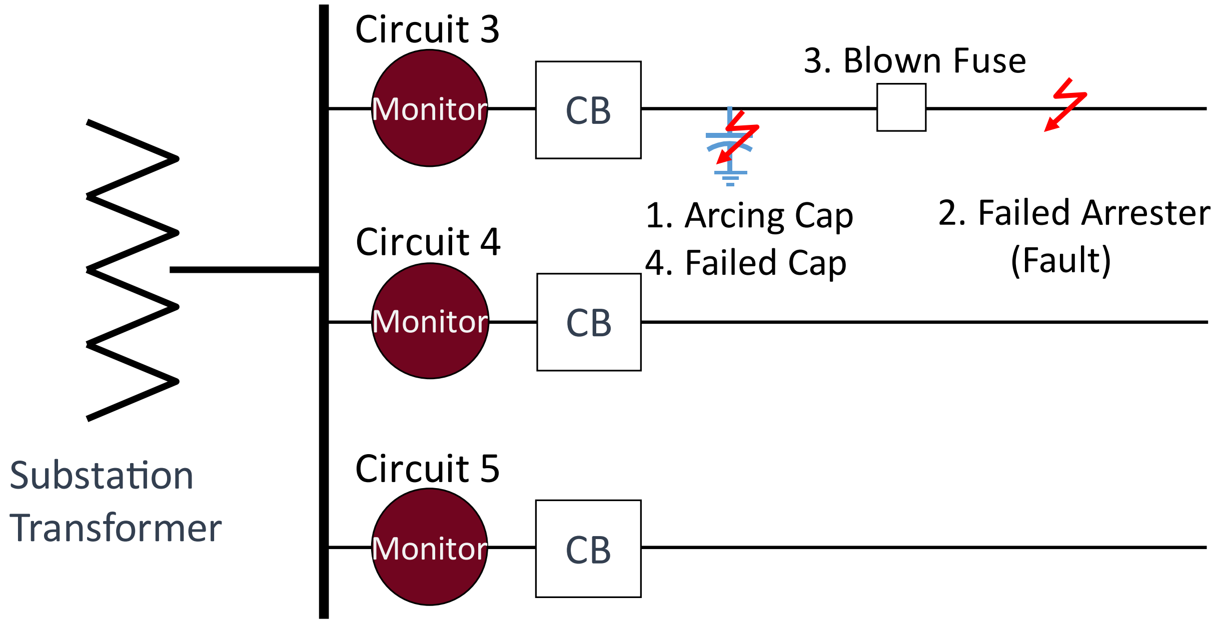


Fact Summary

- Capacitor arcing causes long periods of high-frequency transients.
- Transients from capacitor arcing propagate across entire circuits, even to other circuits, and are known to have precipitated MOV arrester failures, even miles away.
- This event has 1) a blown phase-A MOV arrester and 2) phase-A capacitor arcing.

Example 1

Fault Caused by an Event far Upstream

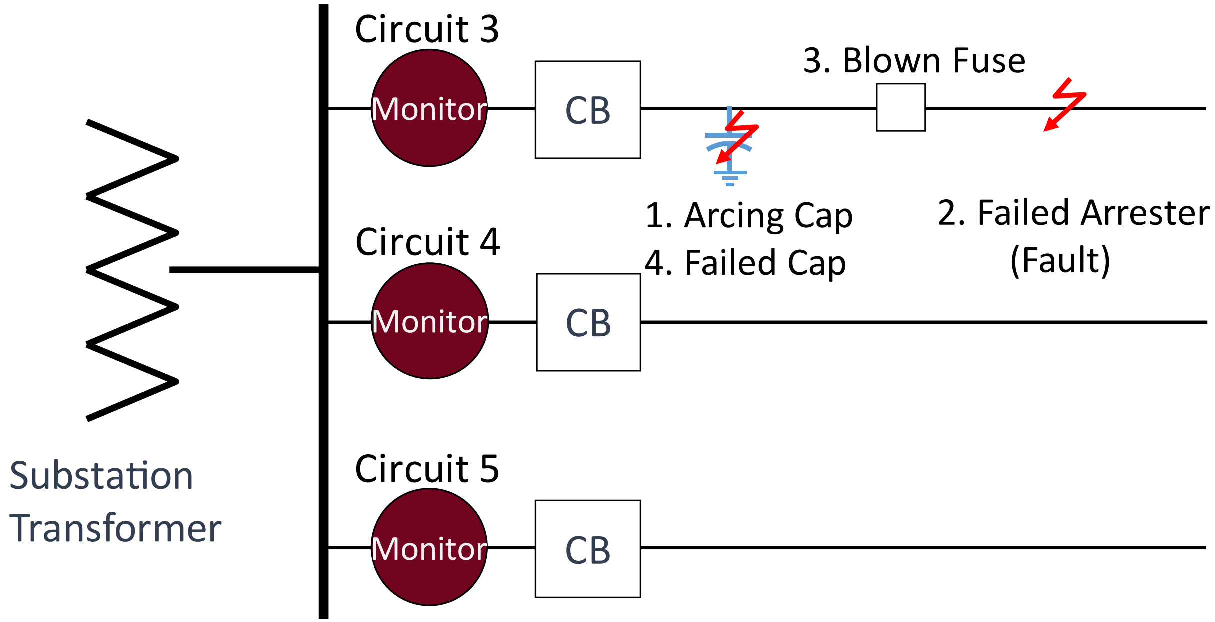


Inferred Sequence of Events

1. Capacitor arcing was the first thing to happen. It caused transients.
2. Those transients caused the arrester to fail (fault).
3. The arrester failure caused the fault that blew the fuse.
4. The capacitor arcing continued for 10 seconds and then failed the capacitor.

Example 1

Fault Caused by an Event far Upstream

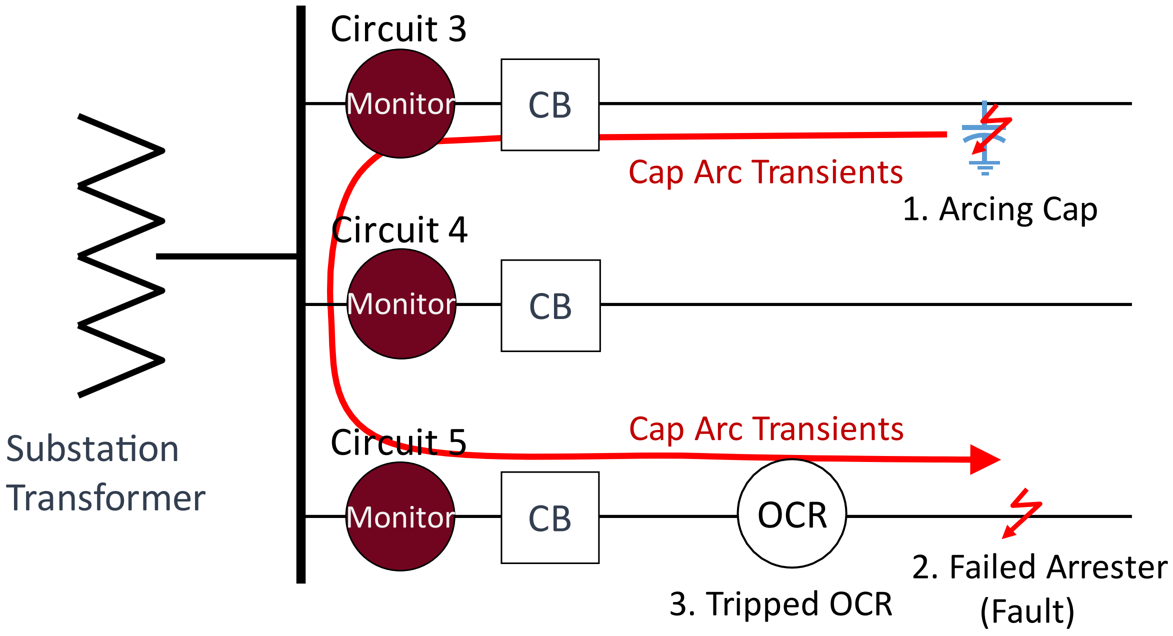


Utility Response

- Based on analysis of the data, the utility knew that phase A of a 450 kvar capacitor bank, upstream of the blown fuse, had failed. Targeted inspection confirmed this.
- They also learned from the data that the capacitor arcing was the root cause of the distant arrester failure and the blown fuse.

Example 1b

Fault Caused by an Event far Upstream

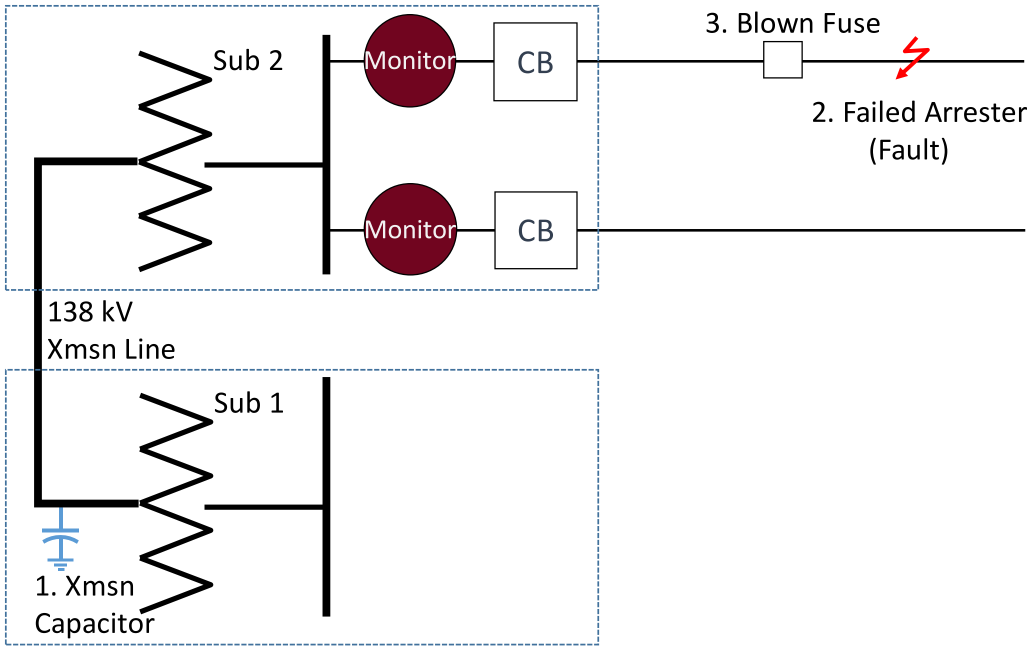


A Similar Case

1. Capacitor arcing on Circuit 3 caused transients on all circuits on the bus. The capacitor arcing (again) was the first thing to happen.
2. Those transients caused the arrester failure on Circuit 5.
3. The arrester failure caused the fault that tripped the OCR.

Example 1c

Fault Caused by an Event far Upstream



Another (Third) Similar Case

1. A transmission capacitor at Sub 1 switched on (normally).
2. Switching transients coupled through 138 kV to Sub 2, through its transformer, and onto the 12 kV distribution circuits.
3. Those transients caused an arrester failure that caused a fault and blew a fuse.

Example 1

Fault Caused by an Event far Upstream

Conclusions

- In these three cases, capacitor-related transients caused far-away MOV failures, which in turn caused faults and protection operations.
- Understanding the root cause required recordings having 1) extended duration (10+ seconds) and 2) high fidelity (bits and sample rate).
- Without adequate data, an incorrect conclusion that the root cause of the fault events was a failed MOV would likely occur.

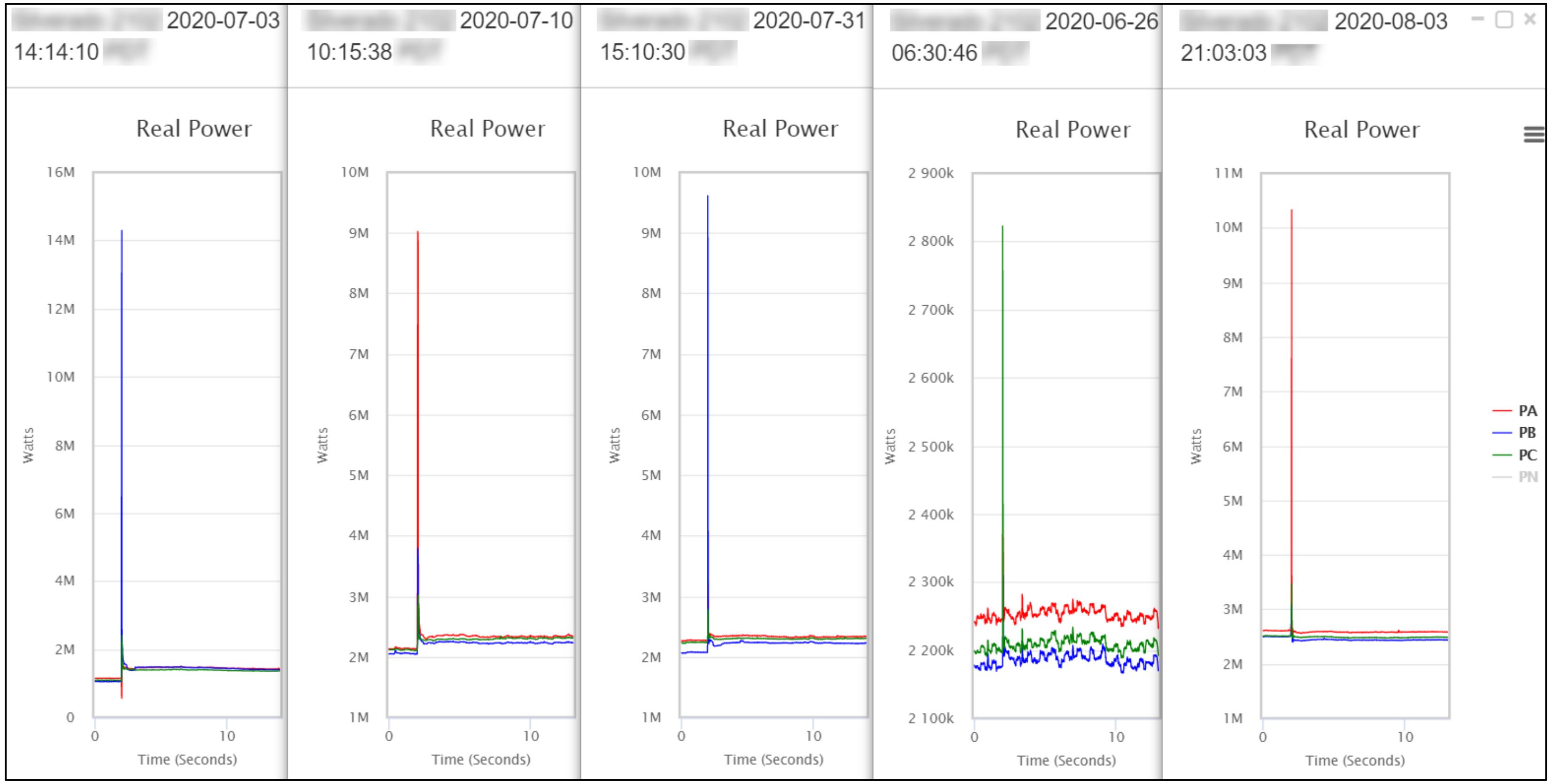
Example 2

Post-Fault Load that Increases?

- Software in the DFA monitoring platform automatically analyzes recordings to characterize faults and other events.
- The software reports multiple parameters, including the amount of load interrupted in response to faults (post-fault minus pre-fault), including those that blow fuses or trip/close unmonitored reclosers.
- For some faults, including those that do not cause protection to operate (either momentary or sustained), post-fault load is observed to increase as compared to pre-fault.

Example 2

Post-Fault Load that Increases?

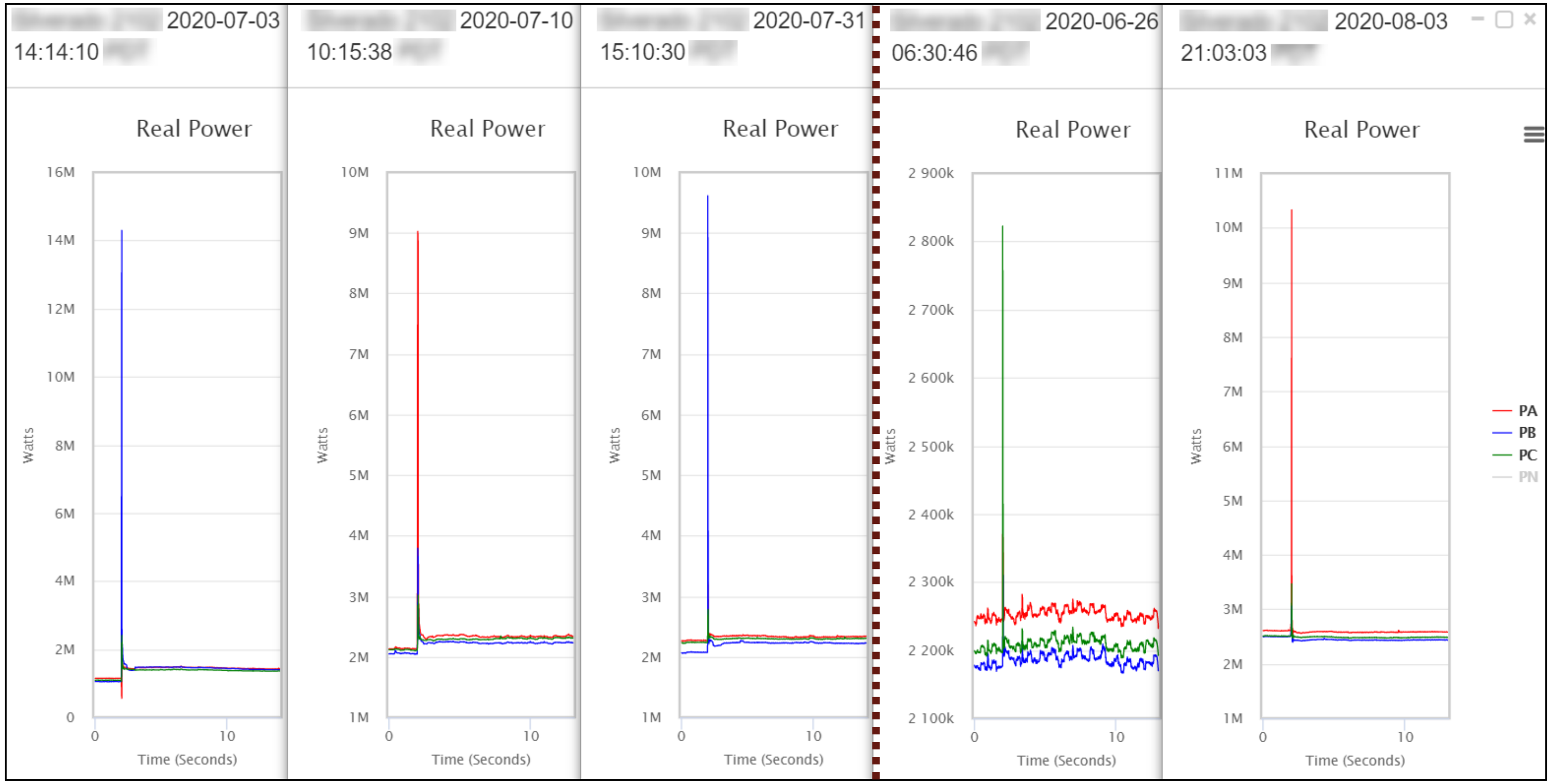


- These RMS recordings show five faults, all on a single circuit.
- Post-fault load increased in three cases and decreased or stayed the same in the other two. Why?

Link

Example 2

Post-Fault Load that Increases?



Three faults during daylight hours

Two faults during "dark" hours

- These RMS recordings show five faults, all on a single circuit.
- Post-fault load increased in three cases and decreased or stayed the same in the other two. Why?
- The key is time of day.

Link

Example 2

Post-Fault Load that Increases?

Conclusions

- On distribution circuits where PV serves a significant fraction of the total circuit load, a circuit may need more substation-sourced power delivery after a fault.
- With the increase in DER penetration, it cannot be assumed that load on a circuit will decrease following faults, with or without operation of overcurrent protection!
- Even momentary voltage sags (1-2 cycles) apparently cause PV inverters to separate from the circuit for a few minutes, even if the circuit has no O/C protection operation. PV separation results in increased current required from the substation. Newer PV inverters may provide more ride through.

Conclusions of Presentation

- A conundrum:
  - A short recording is adequate for understanding well-behaved faults, but well-behaved faults seldom need extensive analysis.
  - Faults requiring special investigation often require investigation specifically because they are not well-behaved and cause complex outcomes.
- Some faults have root causes far from where you find the “broken thing.”
  - Faults induced miles from the source of capacitor arcing.
  - Fault-induced conductor slap, which creates a second fault miles from the initial fault and results in apparent (but not truly) protection miscoordination.
- Long recordings are invaluable for understanding the big picture.
- High fidelity (bits, sample rate) is necessary for understanding complex behavior and transients.