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

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***Abstract*—Oscillography provides users data which can be used to analyze fault behavior. In digital relays, fault recording is often an "add-on" function that supplements the core mission of protection, rather than an integral component. For well-behaved faults, recordings from relays may provide sufficient information to determine a reliable sequence of events. Many faults, however, are not well-behaved, and it is these faults which are often the most important to analyze. It is not uncommon for faults on distribution systems to show substantial dynamic behavior over many seconds, including significant changes in fault current magnitude and/or phase involvement. In these cases, fault recordings from relays often have severe limitations in their ability to help utilities diagnose the root cause of underlying events and/or determine a reliable sequence of events.**

Keywords—faults, waveform analytics, protective devices

I. Introduction

The development and widespread application of digital protection devices for distribution circuits provided engineers the opportunity to record and analyze data concerning the behavior of faults. Analysis of data after fault events helped engineers develop a broader understanding of fault characteristics, dynamic behavior, and parameters such as magnitude and clearing time [1-2].

The use of relay and recloser platforms for data collection does have limitations. The data requirements for protection are not burdensome, allowing for, as an example, low sample rates. Parameters such as signal conditioning, filtering, and data capture duration-per-event are typically and appropriately optimized for the protection function. After all, the purpose of a recloser or relay is to clear a high magnitude fault; it was not designed for the primary purpose of data collection [3].

Researchers at Texas A&M University have documented tens of thousands of fault events over a period of two decades using specialized data recording equipment data at higher fidelity and with longer duration than typical relays. This ongoing research program has monitored over 300 circuits at more than 30 utility companies, totaling over 1,500 circuit-years of exposure on operational distribution circuits as of the writing of this paper. Analysis of events collected as part of this research has shown that the complexity and behavior of distribution faults over longer time periods is more complex than previously understood.

Many faults are well behaved and are cleared quickly and appropriately by system protection. Other faults are more complex, with dynamic behavior that may persist over many tens of seconds. In some cases, faults are preceded by low-magnitude transients which may offer clues as to the root cause of the fault. In other cases, fault magnitudes may vary substantially over the length of the event. Other faults evolve from single-phase to multi-phase events, or vice-versa. Researchers have documented multiple cases showing complex and unusual fault progressions. For example, in one case a distant phase-to-phase fault caused a mid-point recloser operation, which in turn caused conductor motion upstream of the recloser, resulting in a second fault. The arc energy from the second fault then rose into an over-built parallel distribution circuit, which caused a fault on the second circuit. While typical recordings from relays may be useful in the analysis of common faults, in all of these cases and others, short duration, low-fidelity recordings can pose an impediment to complete analysis of the root cause of the event.

In practice, the biggest limitation in analysis of most complex fault events using records from protective relays is the duration of recordings. While state of the art relays have increased their recording lengths and record retention substantially over previous generations, they are often still limited to tens-of-cycles of continuous recording with only a handful of records before memory is overwritten. For complex fault events spanning multiple seconds, this arrangement at best results in multiple fault recordings that must be manually pieced together. Even in this best-case, however, there are often gaps in the data where engineers are forced to "guess" about what may have occurred during missing sections. In many cases, relays may record only the cycles adjacent to initiation of the high-current fault and the cycles adjacent to protection tripping. Based on comparisons of data from the same event collected from high-fidelity monitors and traditional relays, analyzing fault events using relay data from complex faults often results in *limited* information, and in many cases it results in *misleading* information. Limited and/or misleading information from fault records can and often does cause investigating engineers to make incorrect determinations about the root cause of events on their system, leading to improper remediation or even completely missing the true root cause of the problem.

This paper presents several examples of real-world events recorded over the course of two decades of research at Texas A&M. The examples are were recorded during routine utility circuit operations. No data was staged or simulated. In each case, the source data was obtained from monitors developed for the Texas A&M Engineering DFA platform, which monitors feeder CT and bus PT signals at the substation. The DFA monitor triggers sensitively and generates long waveform recordings – 10 seconds at minimum – with the ability to record continuously for tens of hours during periods of frequent transients. All recordings have 18+bits ENOB at a sample rate of 256 samples per cycle for three voltages, three currents, and a calculated 3 I_0.

II. Case Studies

A. Example 1 – Capacitor arcing causes an MOV failure

Figure 1 shows a fault which caused a fuse to blow. A resulting patrol identified a failed MOV lightning arrester downstream of the fuse. The two cycle, 1KA fault would have been recorded by many conventional digital protection devices. High-fidelity, high-bandwidth recordings, however, show repeated high frequency transients both before and after the fault blew the fuse. This raises an important question: If the transients were caused by the failure event, how could they persist after the fuse operated?

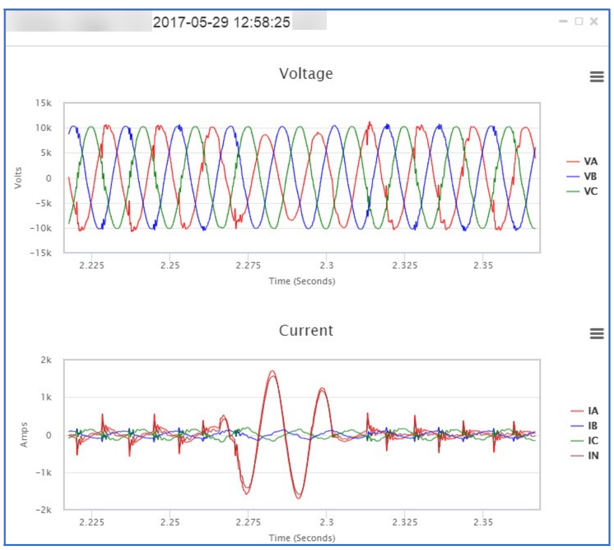

Figure 1: Current and Voltage signals during fault

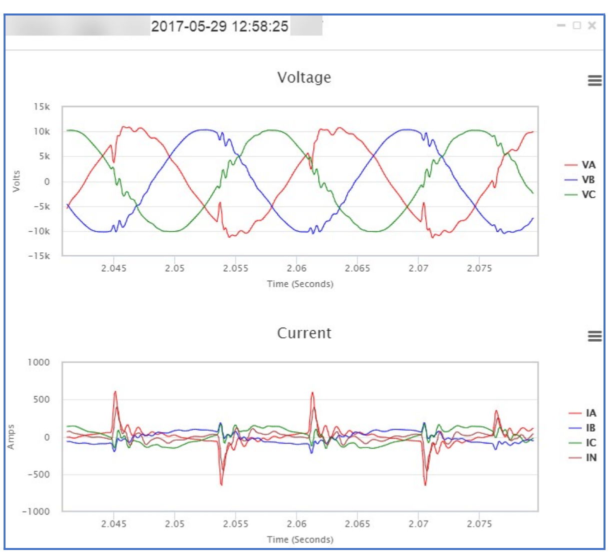

Figure 2: Current and Voltage transients before fault

Figure 2 reveals that the transients before the high current fault have substantial magnitude (almost 600 ampere peaks), but do not have sufficient duration to operate downstream protection. Transients after the high current fault were substantially the same as before the fault. Figures 3 and 4 shows a 14-second recording of the event as RMS graphs. The high current fault lasted only two cycles but the entire fault event lasted 10 seconds including pre-fault transients, the fault itself, and post-fault activity. Note the small current increase just before the high current fault and low current activity after the fault in Figure 4.

Figure 5, a graph of reactive power during the event, provides critical insight to the ultimate root cause. Post-event reactive power was -62 kvar, but pre-event reactive power was -214 kvar; a net change of 152 kvar. That change is consistent with the loss of a single phase of a 450 kvar capacitor bank. The high frequency transients observed both before and after the high current fault are also consistent with capacitor arcing. By analyzing the high-fidelity waveforms shown below, researchers and the utility concluded that capacitor arcing was the initiating, root-cause of the entire sequence of events, including the high current fault. The DFA project has recorded

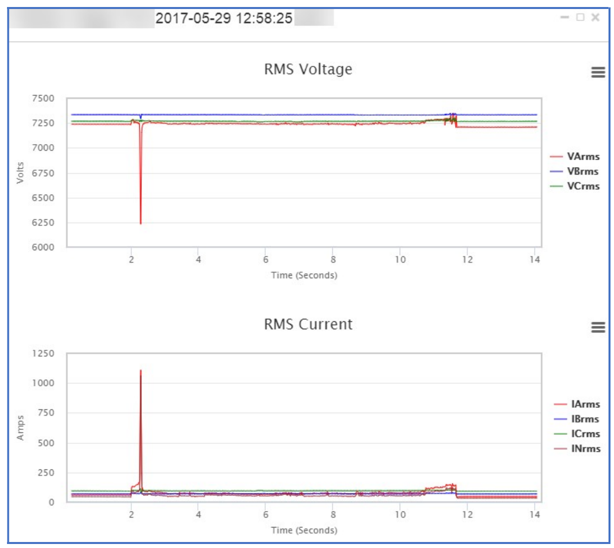

Figure 3: 14-second RMS graph of entire event

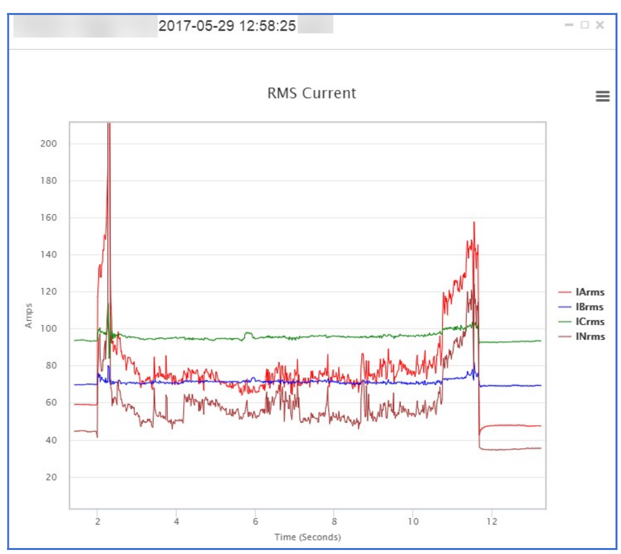

Figure 4: 14-second RMS graph of entire event, scaled to show low-level arcing activity

numerous instances where capacitor activity, including arcing capacitor switches, have precipitated the failure of MOV arresters, even though the arresters may be miles away [4].

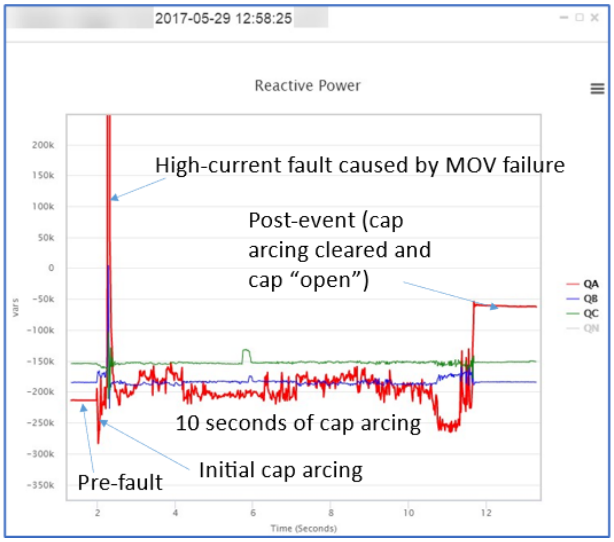

Figure 5: Reactive power before and after event

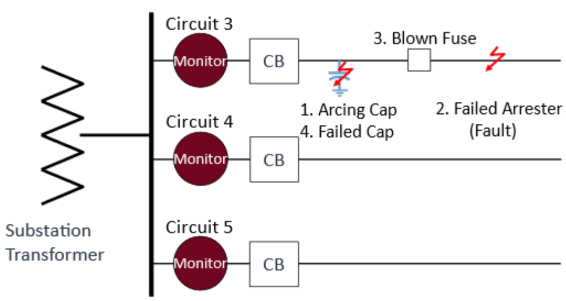

Figure 6: One-line diagram showing sequence of events, 1A

Figure 6 describes this sequence of events. First, arcing began in the capacitor, propagating transients across the bus. As an aside, transients and voltage disturbances produced by capacitor arcing are seen by *all customers on the bus*, including customers on adjacent distribution circuits. In this case, transients from the arcing capacitor caused the MOV arrester to fail – a situation that has been documented multiple times. The arrester failure caused the high current fault, which subsequently blew the fuse. After the fuse blew to clear the failed arrester, the capacitor continued arcing for 10 seconds before a fuse operated to disconnect the arcing capacitor. But only with high-fidelity, extended duration data did the utility learn that incipient capacitor arcing was the root cause of the arrester failure, the fault, the blown fuse, and the capacitor failure.

Figure 7 represents a similar case that occurred in a different event. In this case, capacitor arcing on circuit three caused transients on all circuits tied to the same bus. The transients produced by the capacitor on circuit three were the root cause of an arrester to failure on circuit five. The arrester failure resulted in a high-current fault that tripped an OCR on circuit five. Again, the utility was only aware of the true root cause and sequence of events – that is to say, that the capacitor

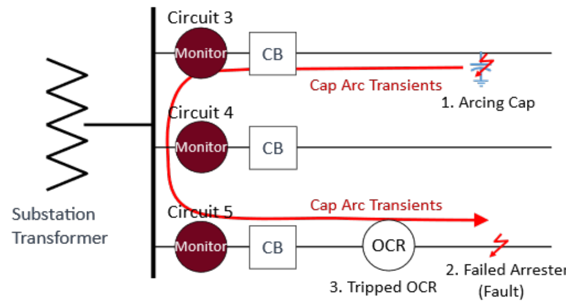

Figure 7: One-line diagram showing sequence of events, 1B

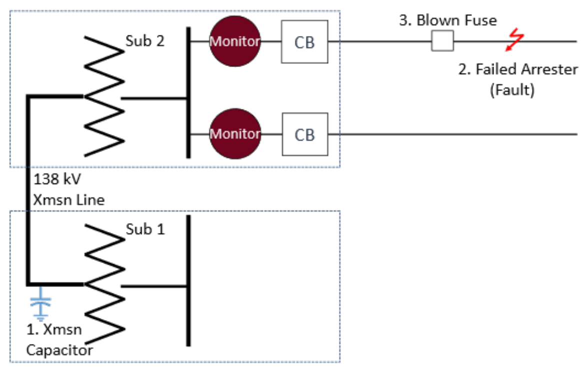

Figure 8: One-line diagram showing sequence of events, 1C

was the initiating root cause – because of high-fidelity waveform data.

Figure 8 shows a third similar case. In this event, a transmission capacitor at Substation 1 switched on normally. Voltage transients from the normal capacitor switch coupled through the 138 kV transmission system to Substation 2, several miles away, and through the substation transformer onto the 12 kV distribution circuits. The voltage transients produced by the normal capacitor switching operation at Substation 1 caused an arrester failure and blown fuse on a distribution circuit served by Substation 2. Again, the utility was only aware of the root cause based on analysis of high-fidelity waveform data.

In each of the above cases, transients from normal and abnormal capacitor operations caused MOV arrester failures which in turn caused faults and resulted in protection system operations. Absent high-fidelity data recordings, the utilities in each of these cases would have reached incorrect conclusions about the true causes of the MOV failures.

B. *Example 2 – Load increase after faults*

High fidelity and long duration recordings often reveal other unusual behavior on circuits. Data on the amount of load interrupted in response to faults and protection system operations is important in understanding some events, and in many cases can be used to help locate faults. Some faults, including those that do not cause protection to operate (either momentary or sustained), show post-fault load levels that are higher than pre-fault load levels.

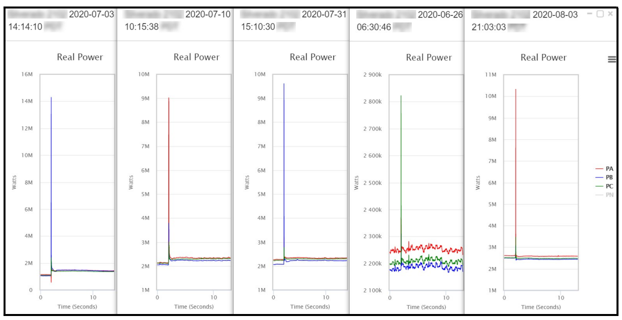

Figure 9: Real power recordings of five faults from the same circuit.

Figure 9 shows recordings of real power during five different faults on a single circuit. In the three cases on the left, post-fault load increases, while in two events the real power decreased or stayed the same. The key in understanding this behavior is time of day: specifically, the faults which show increased post-fault load occur during the day, and those where load decreases or stays the same occur at night. The utility confirmed that the circuit contains a significant amount of distributed PV. In some cases, faults caused the PV inverter undervoltage protection to operate, resulting in the need for additional power sourced from the substation after the fault. Researchers noted that in many cases, load as measured at the substation returns to pre-fault levels within 5 minutes as the DER sources come back online. The critical lesson, however, is that utilities cannot simply assume that load on a circuit will decrease following a fault, with or without the operation of overcurrent protection devices. In fact, even a momentary fault lasting less than two cycles may be enough to cause PV inverters to separate from the circuit. While newer inverters may provide more ride-through capability, this phenomenon may be observed on many existing installations.

In summary, 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, even if there are no protection or sectionalizing actions.

III. Conclusion

While short duration, low-fidelity recordings are adequate for understanding many well-behaved faults, it is often the case that well-behaved faults need no extensive analysis. Faults requiring special investigation or forensic understanding often require study because they are not well behaved, and include complex outcomes that are not easily understood. Some faults have root causes that are far from where you find the "broken thing" that is incorrectly assumed to be the initiating event. For example, faults may be induced miles away from the source of capacitor-related activity. Fault-induced conductor slap creates a second fault that may be miles from the initial fault is often misdiagnosed as a miscoordination of system protection, and occurs frequently on distribution circuits. In complex fault cases, high-fidelity extended recordings are often crucial for understanding the big picture of what has happened. It is often the case that only through such recordings is it possible to find the true root cause and understand the complex, interactive relationships between circuit activity and device operations and failures.

IV. References

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