Utilizing High-Quality Waveform Data to Detect and Diagnose Protection Misoperations and Anomalies

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Abstract: Power system protection is designed to rapidly clear faults with the aim of improving safety and reliability. While the protection system generally functions as intended, it does fail from time to time. Few oversight systems exist, however, to verify the proper operation of system protection, or help diagnose misoperations when they occur. Researchers at Texas A&M University have developed an automated waveform analytics system which, in addition to other functionality, allows utilities to quickly observe when protection anomalies occur, and obtain information to aid in post hoc investigations.

1. Introduction

Faults are a persistent problem on power systems. Over the past century, engineers have developed a variety of techniques for detecting and clearing faults, improving both the safety and reliability of the electric grid. While system protection generally functions without incident, no system is perfect. Despite this, circuit operators rarely have visibility into or oversight of their protection systems to identify misoperations, let alone aid in diagnosis. This paper will detail multiple instances where advanced waveform monitoring and analytics have aided utilities in detecting and diagnosing protection anomalies.

2. North American Distribution System Overview

While the principles in this paper are generically applicable to distribution systems across the world, it is worth noting that all of the examples contained in this paper are drawn from medium voltage distribution circuits in North America. Because this paper is intended for publication in a European venue and because the authors' experience is that many engineers on both sides of the Atlantic Ocean are unfamiliar with differences in operation between North American and European systems, a brief overview of typical North American practice is included for the reader's benefit [1].

Most medium voltage distribution circuits in North America are operated as radial, four-wire, multi-grounded systems, with typical voltage ranges from 4-35kV. The length of circuits can vary dramatically, from the low tens of circuit-kilometres in urban circuits to over 600 circuit-kilometres in rural areas, with the farthest electrical distance from distribution substation to the end of a branch exceeding 60km. Figure 1 shows a complex North American rural distribution circuit with the substation at the bottom, and three-phase sections of line more heavily shaded. This circuit has approximately 600 circuit-kilometres of conductor exposure, with multiple protective devices.

Unlike in Europe where many customers are served by low-voltage networks, in North America most customers, including in urban and suburban areas, are served directly from a medium-voltage transformer within sight of their meter. For example, in a typical North American neighbourhood, it is common to have multiple houses (e.g., 4-8) served directly from the secondary of a single transformer (generally 15-75kva, depending on the number of houses and required load). The transformer secondary is generally 240V with a centre-tapped neutral, delivered to the residence via a "triplex" cable bundle with two insulated hot cables wrapped around a bare neutral messenger run directly between the transformer and customer's weatherhead. Larger installations requiring three-phase service are generally served from delta/wye or grounded-wye/grounded-wye transformers ranging from 75kva to 2,500kva, depending on the load requirement.

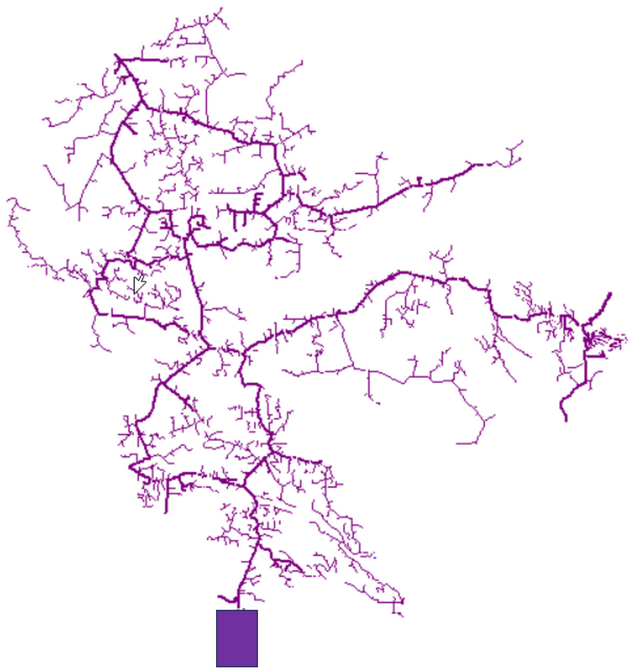

Figure 1: *Complex rural North American Distribution Circuit*

With over a thousand distribution utilities in the United States alone, variations in practice do exist regarding

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the generalities discussed in the previous paragraphs, both between and within companies. The centres of many medium and large cities are served by extensive meshed, low-voltage networks delivered at 120/208V (e.g., New York City is served by dozens of networks, many of which individually have peak load of hundreds of MW); some unusually large single-phase transformers (e.g., 300 kva) exist; some rural systems supply three-phase service with only two phases, some utilities operate three-wire uni-grounded systems, etc. The intent of this section is not to cover all possible variations within North America, but to highlight key differences between systems the audience may be more familiar with and systems commonly in use in North America.

3. Distribution Protection in North America

As a result of the large numbers of transformers on North American systems, fuses are the most common protective device on a typical circuit. Most distribution transformers in North America are protected on their high side with a fuse (usually rated from 2-65A, depending on the kva rating of the transformer and voltage level, though higher values are often required on transformers over 1,000 kva), and unprotected on the secondary. A typical North American medium voltage circuit would have hundreds or likely thousands of fuses protecting individual loads.

Given the large number of fuses and the radial topology of most distribution circuits in North America, almost all distribution protection is based on 50/51 (instantaneous overcurrent and/or time-overcurrent) schemes. The most common protection arrangement on a North American circuit would be a reclosing circuit breaker at the substation, with one or more reclosing circuit breakers along the circuit at major three-phase branches, with single-phase laterals protected by large fuses or, in some cases, a single-phase recloser. Figure 2 shows a different North American rural circuit, this time with approximately 225 circuit-kilometres of overhead exposure. The green boxes in the figure are the locations of line reclosers. Astute readers may note that the circuit in question uses a combination of single-phase, two-phase and three-phase reclosers.

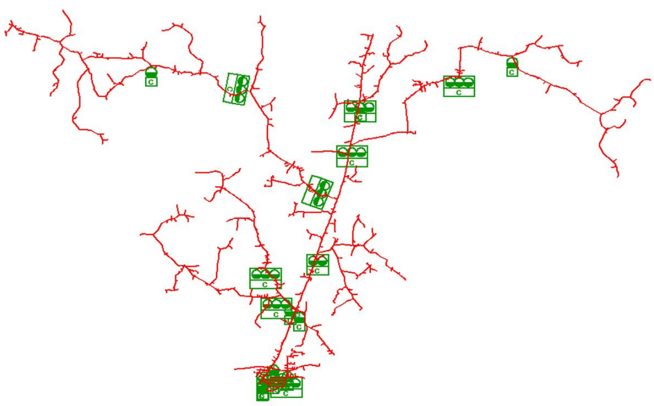

Figure 2: *Recloser locations on rural circuit*

In general, reclosers are coordinated such that the device closest upstream of the fault operates first, though on long and complex circuits it is not always possible to perfectly coordinate between devices. While many utilities have begun the process of modernizing their recloser fleet, many non-communicating hydraulic reclosers are still in service in North America, and indeed many utilities continue to refurbish and replace existing hydraulic reclosers. Even where utilities have substantially more modern protection schemes (e.g., Fault Location, Isolation and Service Restoration, or FLISR) in place, single-phase lines or non-tie three-phase branches may be protected by legacy hydraulic reclosers.

4. Distribution Fault Anticipation

For over two decades, researchers at Texas A&M University have engaged in projects with utilities and other circuit owners to characterize transient electrical behaviour on medium voltage distribution systems. This work, which known as Distribution Fault Anticipation (DFA), has produced the largest-known database of waveform oscillography from in-service medium voltage distribution circuits, including normal and abnormal operations of various circuit apparatus.

The DFA project uses specialized data collection devices, applied on a one-per-circuit basis, to sensitively monitor bus voltage (a.k.a. potential) transformers (VT/PTs) and circuit current transformers (CTs). In contrast to more conventional devices which produce waveform oscillography, DFA Devices trigger far more sensitively to record minor transients which may contain signatures of incipient failures. Each DFA Device contains online waveform analytics, at the edge, which attempt to determine the underlying cause of waveform recordings based on knowledge acquired from confirmed events investigated during the DFA project. At the time of publication, the DFA project monitors approximately 650 circuits in 4 countries and has a historical record of over 2,750 circuit-years of exposure. The full operation and scope of the DFA system is not the primary focus of this paper, but interested readers can consult other publications to learn more about the monitoring hardware, capabilities, and operational philosophies behind the technology [2-10].

DFA Waveform Analytics system is primarily intended to assist circuit owners by providing improved situational awareness as well as detecting and locating incipient fault conditions – in many cases before they result in a protective operation – but an additional benefit of the system is that it can passively detect issues with system protection system and/or assist utilities as they debug potential misoperations. This paper will detail multiple cases where DFA has identified issues with protective device operations, and/or has helped utilities prevent protection misoperations.

5. Case Studies

5.1. Excessive Recloser Operations

As noted in Section 3, most utilities in North America use one or more levels of automatic circuit reclosing on medium voltage distribution circuits. Most faults on distribution systems are believed to be temporary in nature, with many cited sources suggesting that up to 95% of faults can be cleared with three reclosing attempts. (Authors' note: the most recent studies claiming these numbers are forty years old, and only examined substation breakers [11-17]. It is the authors' belief based on 50,000 faults recorded by DFA that the true number of temporary faults is likely substantially less, especially if one considers faults not cleared by substation breakers.)

Reclosing practices vary widely from utility to utility, but a common scheme deployed at many utilities uses “four trips to lockout” – in practice, usually two fast-trip operations followed by two slow-trip operations, at which point the recloser would lockout (i.e., not reclose), leaving the downstream circuit deenergized. Figure 3 shows an example of a fault with three subsequent reclose attempts. Specific timings and numbers of reclose attempts may vary depending on utility-specific factors (e.g., wildfire risk), but in general utilities consider reclosing to be an acceptable trade-off that helps improve reliability while minimizing potential damage to the system and safety hazards to the public.

Figure 3: *Fault with three reclose attempts*

While most utilities would agree that a four-trip-to-lockout scheme is an acceptable trade-off between safety and reliability, few if any utilities audit their reclosers to ensure they are in fact operating as intended. Consider the case of a hydraulic recloser. In most cases, the only diagnostic information available regarding the health of a hydraulic recloser is a trip-counter which may be recorded on a periodic basis. A utility which inspected its hydraulic reclosers annually might know, for example, that a particular recloser tripped 31 times, but it would have no way to know whether those events were 31 single trip-and-reclose events, or one single trip-and-reclose along with 10 instances where the recloser tripped three times before successfully reclosing.

DFA has detected multiple instances where reclosers which were intended to trip four times before locking out in fact tripped six or more times, as shown in Figure 4. It should be noted that this is not merely a case of miscoordination – where one recloser is over-reaching to clear a fault downstream of another. This is, rather a failure of the protection control.

It is obvious that operating two times more than designed can cause unintended consequences, including increased burndown potential at the fault point and premature wear on system components. Far more concerning, however, are multiple observed cases of reclosers operating dozens or hundreds of times over minutes or tens of minutes without locking out. The exact causal mechanism in these cases is not known, but it is assumed to be a failure in the lockout mechanism of hydraulic reclosers.

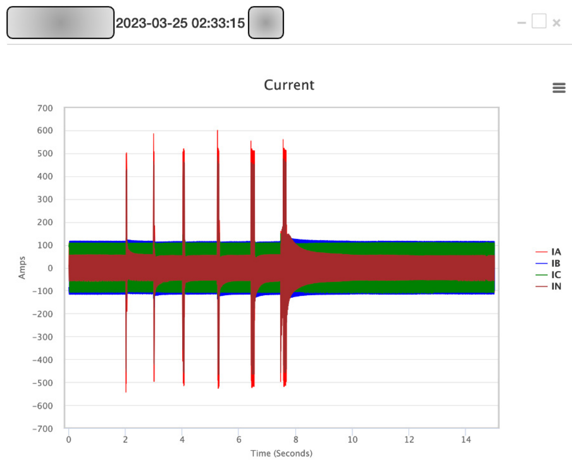

Figure 4: *Six recloser operations before lockout*

Figure 5 shows sixty seconds of waveform oscillography from one of these events. In each case, the recloser successfully interrupts a fault of approximately 1,200 amperes, only to reclose into the fault a few seconds later. It is worth noting that all users downstream of the recloser but upstream of the fault would experience a momentary interruption each time the recloser was open and a brief resumption of power each time the fault current resumed.

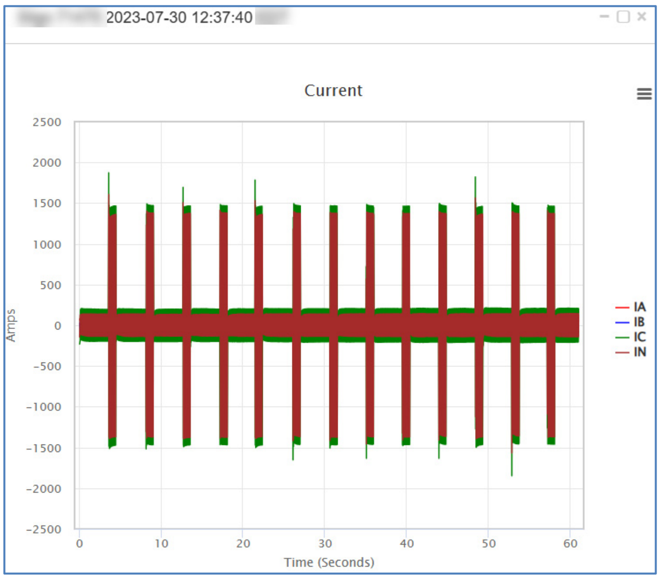

Figure 5: *Repeated faults and recloses from pumping recloser*

In the most extreme case, a recloser on a 25kV circuit operated approximately 1,100 times over 33 minutes. DFA has detected this condition at six utility companies, including both small cooperatively owned utilities and one of the largest investor-owned utilities in the United States. The condition has been detected on ten separate circuits, and in at least two cases, it appears as though the same recloser has “pumped” multiple times. Table 1, below, shows a list of instances where DFA has detected this condition.

It should go without saying that a recloser failing to lock out after dozens or hundreds of trips is a severe problem [18]. Yet in each of the observed cases the utility was entirely unaware of the behaviour, or that reclosers on their circuits were affected. Perhaps shockingly, none of the utilities researchers contacted received a single customer complaint, even though many customers would have experienced momentary interruptions and restoration of power hundreds of times over tens of minutes.

Table 1: *Numbers of counts and minutes for detected pumping recloser events*

Case #	# Auto-reclose operations without lockout	Period spanned by those pumping operations
1	800 operations	24 minutes
2	680 operations	26 minutes
3	107 operations	3 minutes
4	88 operations	2 minutes
5	140 operations	12 minutes
6	120 operations	2 minutes
7	120 operations	6 minutes
8	300 operations	14 minutes
9	740 operations	26 minutes
10	320 operations	22 minutes
11	1100 operations	33 minutes
12	73 operations	3 minutes
Cases 9 and 10, which occurred six months apart, probably involved a single recloser.		
Similarly, cases lines 11 and 12, which occurred three months apart, probably involved a single recloser.		
The twelve cases of pumping involved ten distinct reclosers at six distinct distribution companies.		

There are multiple negative consequences to such events, including but not limited to:

1. Failure to clear faults in a timely manner prolongs safety hazards.
2. Each trip and auto-reclose causes interruptions to all customers downstream of the recloser and upstream of the fault, as well as a voltage sag to all customers on the circuit and adjacent circuits connected to the same bus.
3. Failure to clear the fault in a timely way increases damage at the fault point, likely resulting in catastrophic damage, including the potential to burn down a line and create further safety hazards.
4. All components between the substation transformer and the fault are subjected to thermal and mechanical stresses due to the fault, potentially reducing lifespan.
5. The circuit breaker itself experiences the cumulative stress of interrupting, in a few minutes, more faults than most reclosers experience in decades. Given the nature of the failure, it is also unknown whether the trip counter on such reclosers increments, meaning utilities may be completely unaware that the recloser has operated excessively.
6. Particularly in areas prone to wildfire risk, each fault represents a competent ignition risk. The prolonged series of faults increases that risk, including the risk of a catastrophic failure of the recloser itself. This concern is particularly acute for oil-filled apparatus.

A clear takeaway from these cases is that the phenomenon is not a one-off occurrence. The fact that none of the utilities whose systems experienced these events were aware of them suggests that the condition may be more common than previously known or believed.

5.2. Sensitive "Fast-trip" Settings operating on Self-Clearing Faults

In the past several years, multiple utilities in high fire risk regions have deployed aggressive protection settings with the goal of reducing ignition risk. These settings generally involve transitioning from time-overcurrent to instantaneous overcurrent pickup, using tight, definite time coordination between devices, as well as blocking reclosing. Some companies that have deployed these settings have upgraded their fleet of downstream reclosers and can enable such settings for relatively targeted areas more-or-less on demand to balance safety and reliability. The theory behind these changes is intuitively simple: reducing the amount of fault energy that might be proximate to flammable material should reduce the amount of energy available to ignite a fault. DFA is installed broadly at multiple utilities which enable fast trip settings on a temporary basis on some circuits.

DFA has documented tens of thousands of faults on power systems, some of which may draw hundreds or thousands of amperes, but "self-clear" – which is to say extinguish without operating a protective device. While these faults may have sufficient magnitude to operate system protection, they are often quite short, generally less than half a cycle, and therefore do not blow a fuse or trip a time-overcurrent protection element. There are multiple apparatus failures which can cause short-lived faults, but these events are commonly observed during the incipient stage of cable termination failures, such as joints or splices. Over the past three years, DFA has observed multiple failures of cable termination apparatus which produced dozens of fault pulses over months before they either failed, or in some cases were located successfully using DFA and repaired before producing a final catastrophic outage. The waveforms in this section come from a case where a cable termination failure was located and repaired using DFA data.

Figure 6 shows a typical pulse recorded during the incipient failure stage of a particular cable fitting. The graph shows current, recorded at the substation, of 200 amperes (peak) of steady-state load, with a sub-cycle pulse of approximately 400 amperes (peak) of fault current. This failure event was one of dozens recorded during the incipient failure stage.

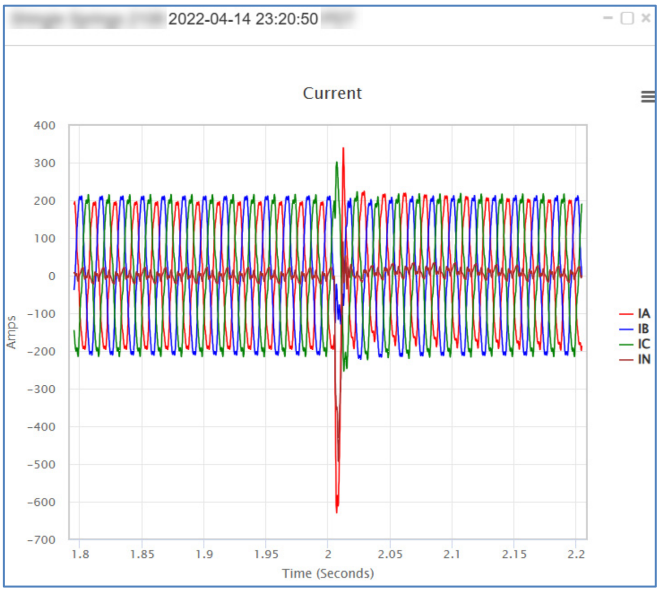

Figure 6: *Typical self-clearing fault produced by cable fitting failure*

Figure 7 shows another fault in the incipient failure sequence. Again, approximately 200 amperes of load current is present at the substation feeder CTs, and again a pulse of just under 400 amperes occurs at just after 2 seconds. Two cycles after the fault self-clears, however, a recloser operates, interrupting load to 1,900 customers. The difference between the faults in Figure 6 and Figure 7 is that in Figure 7 fast tripping was enabled, whereas in Figure 6 it was not. In other words, the 400-ampere pulse activated the recloser's instantaneous trip setting, but the recloser took another two cycles before it was able to mechanically open to clear the fault – only by that time the fault no longer existed.

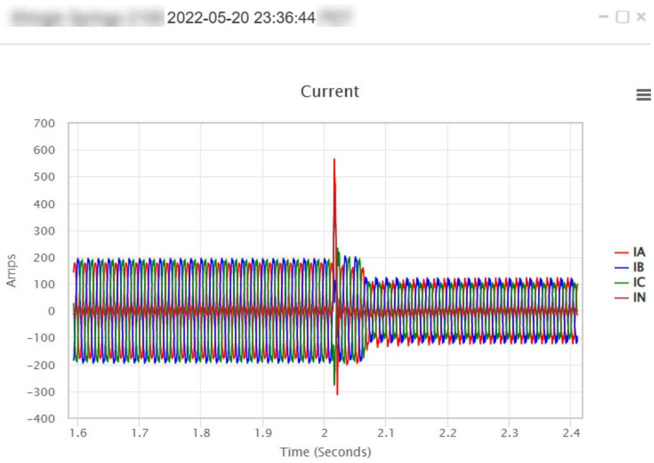

Figure 7: *Self-clearing pulse, followed by fast protection trip*

Recall that the fast-trip protocol is accompanied by blocking of reclosing. Additionally, the utility is required to patrol the circuit before attempting to reenergize. The unfortunate timing of the event (at 23:36) resulted in an extended outage to many customers when the fault itself was already cleared. This incipient event manifested 79 short-lived faults over a 200-day period before utility personnel located and corrected the underlying issue. Three of those faults, including the fault shown in Figure 7 occurred while the fast trip settings were enabled, resulting in an outage to a larger-than-necessary number of customers for a longer-than-necessary amount of time.

5.3. Sensitive Ground Fault Protection False Tripping

Detecting and clearing energized power lines on the ground is a challenging problem. Many developments have occurred in the decades since two of this paper's authors developed the first commercialized downed-conductor fault detection algorithms, and detailing all of them would itself be a meaningful paper. Detecting downed conductors has always involved trade-offs between reliability of operation (i.e., detecting and clearing an energized conductor on the ground when it exists) and secure operation (i.e., not tripping the line when an energized downed conductor does not exist). When considering energized downed conductors, security is often the more difficult part of the problem. As one author of this paper frequently says, "Detecting high-impedance faults is easy. Detecting high-impedance faults without false alarming an unacceptably high number of times is difficult."

Detecting and discriminating so-called high-impedance faults is considerably more challenging than low-impedance or bolted faults, because high-impedance faults may have magnitudes similar to or in some cases substantially less than that of normal system load variations, including routine transients. This is a particular problem on four-wire, multi-grounded systems where loads are intentionally connected phase-to-neutral, making sensitive ground fault protection effectively impossible.

Anecdotally, when developing commercial downed-conductor detection algorithms in the 1990's, the authors were given two key directives from industry: 1) do not false trip, and 2) do not trip too quickly. The authors were advised that even a small number of false trips, across an entire distribution system, would cause a circuit owner to disable the technology, even if it accurately detected most downed lines. Likewise, utilities did not want downed conductor detection to operate too quickly – e.g., on the order of tens of seconds - even if the presence of a downed-conductor was known with 100% certainty so that downstream protection would have opportunity to operate first.

For utilities in high fire risk areas, this calculus has shifted as both ignition risk and the cost of wildfires have increased dramatically. Consequently, many utilities desire faster tripping of energized downed conductors, even though faster tripping inevitably leads to more false trips. At the same time, utilities are increasingly willing to pre-emptively deenergize circuits to avoid starting a fire – an effective 100% trip rate. Given a guaranteed shutoff as the alternative, a modest false trip rate for a downed conductor method may be acceptable. It is worth stating, however, that an increased tolerance for false trips does not imply an infinite tolerance for false trips.

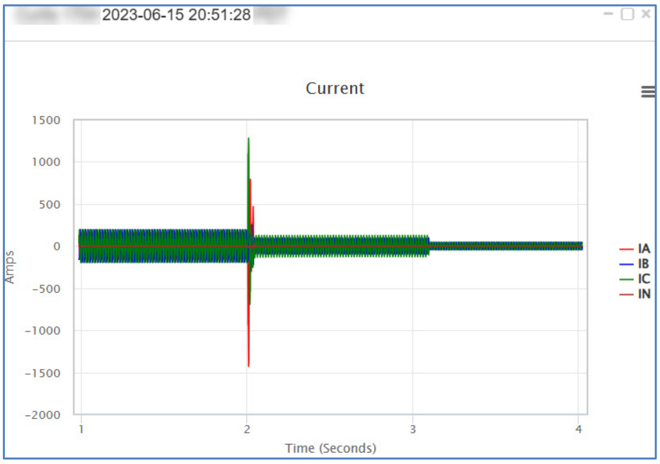

Figure 8: *High-impedance fault false trip*

One utility which uses DFA on many of their high fire risk circuits recently began deploying sensitive ground fault detection from another vendor, with the goal of protecting against energized downed conductors. Without knowing of the deployment, researchers began noticing multiple, unexplained false trips on several circuits, generally after a line recloser operated successfully to clear a fault. Figure 8 shows one such event. In the graph, a line recloser operated to clear a fault at t=2.0s, interrupting approximately 2MW of load. Approximately 1.2s later, another recloser operated, interrupting approximately another 1MW of load.

When researchers inquired about the unexplained activity, the utility explained that their sensitive ground fault detection scheme was experiencing “a high number of false operations.” The technology was not yet fully deployed, but the initial rate of false trips, extrapolated to the entire system would have resulted in as many as 3-4 false trips per week. As a result, both the utility and the vendor were highly motivated to find the cause of the false trips and develop a fix.

A major limitation in the design of algorithms to detect energized downed conductors is a lack of high-quality data from normal system operations. Laboratory data can be helpful, but staged or otherwise artificial data always have limitations. Particularly for applications like sensitive ground fault detection, there are multiple edge cases, unusual loads, circuit configurations, load interactions, etc., which cannot be simulated or staged in any meaningful way. Additionally, because of the limited data recording capability of most protective devices, it is often challenging to know the actual circuit behaviour in the moments leading up to a fault. This complicates any investigation of why a particular method misoperated in the way it did, often leading utilities and/or vendors to speculate about what might have happened, rather than acting from actual data.

In this case, the utility was able to use data from the DFA system to assess the performance of their sensitive ground fault protection in the field. Moreover, using a DFA Device installed alongside the sensitive ground fault relays in a controlled laboratory environment, the utility was able to quantify differences in characteristics between laboratory staged faults and naturally occurring circumstances on operational circuits.

5.4. Fault-induced Conductor Slap

While not a failure of the protection system per se, fault-induced conductor slap (FICS) is often misdiagnosed as a protection system misoperation, and thus deserves mention in this paper. FICS is a phenomenon that has been observed on dozens of circuits at multiple utility companies, and more importantly has been demonstrated to recur multiple times in the same span over a period of years.

The general behaviour of the phenomenon is as follows:

1. A fault, generally phase-to-phase, occurs downstream of a midpoint recloser.
2. Magnetic forces produced by the fault current push adjacent conductors apart.
3. The midpoint recloser opens, clearing the fault, and removing the electromagnetic force.
4. The upstream conductors, which remain energized, mechanically pendulum back toward each other, and because of a defect or deficiency in the construction of the span, physically contact each other.
5. When the upstream conductors contact, a second, higher magnitude fault occurs closer to the substation which is subsequently cleared either by another line recloser, or in many cases the substation breaker.

Many utilities are unaware that such events are possible, and do not have any process to detect or investigate them should they occur. Consequently, many utilities remain ignorant of the condition, even though, if left uncorrected, it will almost certainly burn the line down over time. In some cases, utilities recognize that *something* went wrong, but frequently attribute the odd-seeming behaviour to miscoordination between two relays. Because the two events occur generally within some seconds of each other, and because many line reclosers do not have accurate timestamps, it is often difficult or impossible to piece the sequence of events together without a third data source to arbitrate. In short, many utilities are unaware of FICS events, and those that are aware often misdiagnose the condition.

By contrast, utilities with DFA-monitored circuits receive an email alert immediately after any suspected FICS event, allowing them to quickly verify whether FICS occurred, and take prompt action. Because FICS is the result of a deficiency of construction rather than a protection system misoperation, the condition will continue to recur, in the same span, causing progressive damage to the conductor until it is either found and fixed, or until the conductor is sufficiently weakened and breaks. High-quality data provides value by confirming that the protection system is, in fact, operating as designed and intended, and that the problem instead is the construction of a specific span on the circuit.

6. Conclusion

Protection against short-circuit conditions is a critical component of any power system. While protection systems are generally reliable, they do fail. In many cases, utilities are only aware of protection failures after they manifest in catastrophic events, sometimes involving the loss of life or property. By contrast, advanced waveform monitoring offers the possibility for utilities to be aware of protection misoperations as soon as they occur, allowing for the possibility of remediation before a final, catastrophic failure occurs.

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