High Impedance Fault Detection and Backup Protection – A Case Study

Ian T. Riensche, P.E., *Relay Application Innovation, Inc.*
John P. Merrell, P.E., *Tacoma Power*

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Abstract

In 2007, a rural Tacoma Power customer snagged an overhead service wire with his trailer, damaging the conductor and causing a high impedance fault. After a significant delay, during which the pole-mounted transformer fuse serving the customer's property did not blow, the high impedance fault detection feeder relay at the substation operated, tripping and locking out the feeder. Following the event, a conversation arose as to whether it was appropriate for a substation relay to lock out a distribution feeder for a fault on the customer side of a service transformer. This paper is a case study of that event and the final conclusions of the discussion regarding remote backup protection.

I. Introduction

In 2005, Tacoma Power completed a relay upgrade project at its rural Lacamas Substation, replacing the legacy, electromechanical overcurrent feeder relays with multifunction, high impedance fault detection relays. Due to its numerous trees and long, overhead, radial feeders, the Lacamas service area was considered a prime candidate for high impedance fault detection technology. Lacamas was the first Tacoma Power station to have this functionality installed and put in service.

Less than two years later, a rural customer about three miles from Lacamas Substation ran into his property's overhead service wire with his "fifth wheel" travel trailer, damaging the conductor and causing a high impedance, single-phase fault. The 8T high-side fuse on the pole-mounted service transformer did not trip; 27 seconds later the high impedance fault detection feeder relay at the substation operated, causing the feeder breaker to trip and lock out. Below is a sketch of the circuit, from the substation to the customer.

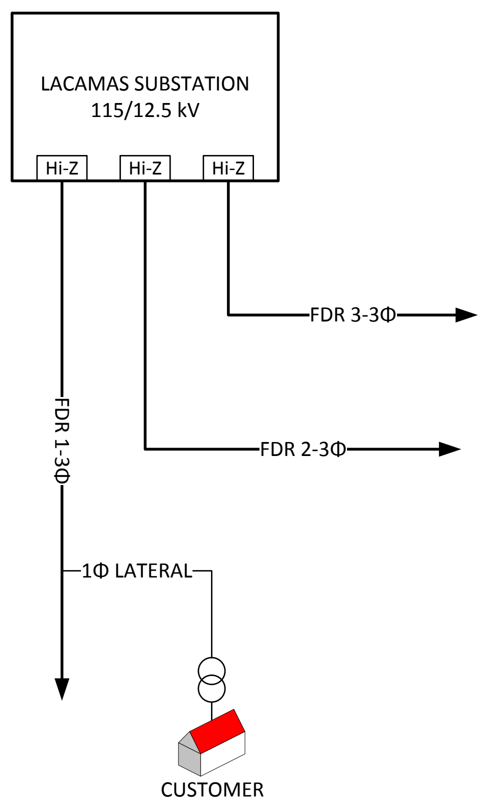

Figure 1: Lacamas

The photograph below is of the 7.2 kV/240 V/120 V pole-mounted transformer serving the property. In the upper left region of the photograph is the 8T fused disconnect that did not operate.

Figure 2: Pole-mounted service transformer

Figure 3 is a photograph of the travel trailer that contacted and damaged the service conductor. The service conductor can be seen just behind the trailer; it is indicated by the two arrows.

Figure 3: Travel trailer with service conductor in background

Not surprisingly, this event triggered an internal philosophy discussion regarding remote backup protection. There were some that believed that a substation feeder relay should never lock out an entire distribution feeder for a fault on the customer side of a service transformer. On the other hand, there were those that maintained that the relay operation constituted remote backup protection and that the scheme performed as designed. One could also contend that the high impedance fault detection element in the substation relay was in fact primary protection for a high impedance fault—even if that fault was miles away on the customer side of a residential transformer.

II. Fault Calculations

As the reader is aware, the inherent problem with high impedance faults is that traditional overcurrent protective devices have difficulty detecting them due to the low magnitude of fault current resulting from relatively large impedance in the faulted circuit path. We know this from Ohm's Law, which defines an inversely proportional relationship between resistance and current flow through a circuit. As impedance increases current decreases, and *vice versa*, assuming a constant voltage level. Equation 1[1] is an example of a fault calculation when the incipient voltage, Thevenin impedance and fault impedance are known:

$$I_{fault} = \frac{V_{fault}}{Z_{Thevenin} + Z_{fault}} \qquad \text{Eq. 1}$$

The reader can see that as the denominator increases, the quotient decreases. As an example, let's reconstruct the event discussed in this paper. Based on the event data and dispatcher's report, we know that it was a single-phase fault on phase B. Using system data provided by the utility, we are able to calculate the approximate current contribution from the high impedance fault.

Because our goal is to estimate the level of current seen by the transformer high-side fuse, we will stay in the phase domain for these calculations, rather than work in the zero-sequence domain. The figure below is a single-line diagram of the circuit that illustrates the impedances used in the fault calculation.

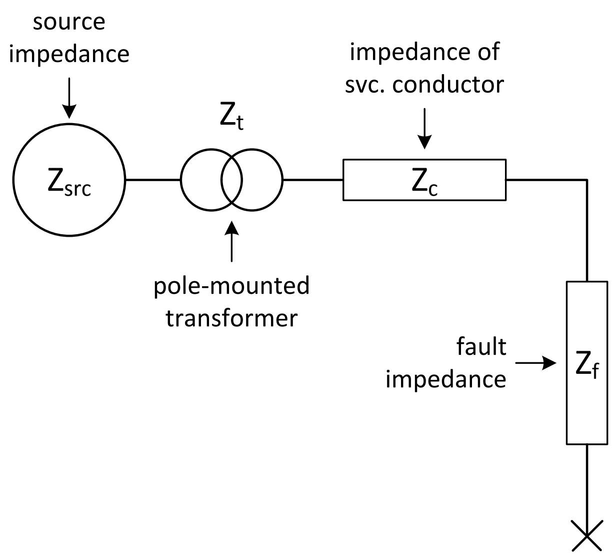

Figure 4: Single-line diagram of circuit

Impedances from the above diagram:
Z_{src} (source imped., from utility) = (3 + j4) Ω
Z_t (imp. of 7.2kV/240V/120V, 25kVA transformer) = 2.1%
Z_c (imp. of 4/0 AWG Al @ 75°C) = (0.1157 + j0.1053) Ω[1]
Z_f (fault resistance, estimated) = 20 Ω

$$Z_{base(12kV)} = \frac{12.5kV^2}{25kVA} = 6250\Omega \qquad \text{Eq. 2}$$

$$Z_{src(\Omega)} = 3 + j4\ \Omega \qquad \text{Eq. 3}$$

$$Z_{src(pu)} = \frac{Z_{src(\Omega)}}{Z_{base(12kV)}} = 0.00048 + j0.0064\ pu \qquad \text{Eq. 4}$$

[1] Impedance of 4/0 Al from AlCan conductor properties table.

$$Z_t = j0.021\ pu \qquad \text{Eq. 5}$$

$$Z_{base(120V)} = \frac{3\cdot(120V)^2}{25kVA} = 1.728\Omega \qquad \text{Eq. 6}$$

$$Z_{c(\Omega)} = 300ft \cdot \frac{0.1157 + j0.1053\ \Omega}{1000ft} = 0.035 + j0.032\ \Omega \qquad \text{Eq. 7}$$

$$Z_{c(pu)} = \frac{Z_{c(\Omega)}}{Z_{base(120V)}} = 0.02 + j0.018\ pu \qquad \text{Eq. 8}$$

$$Z_{f(\Omega)} = 20\Omega \qquad \text{Eq. 9}$$

$$Z_{f(pu)} = \frac{Z_{f(\Omega)}}{Z_{base(120V)}} = 11.57\ pu \qquad \text{Eq. 10}$$

$$I_{base(12kV)} = \frac{25kVA}{\sqrt{3}\cdot 12.5kV} = 1.2\ A \qquad \text{Eq. 11}$$

$$I_{sc(pu)} = \frac{j1\ pu}{Z_{src(pu)} + Z_t + Z_{c(pu)} + Z_{f(pu)}} = (0.086\angle 89.8°)\ pu \qquad \text{Eq. 12}$$

$$I_{sc(12kV)} = I_{sc(pu)} \cdot I_{base(12kV)} = (0.099\angle 89.8°)\ A \qquad \text{Eq. 13}$$

The above computation tells us that the level of fault current magnitude at 7.2 kV_{LN} is roughly 0.1 A, *assuming 20 Ω of fault resistance*. However, we do not know with absolute certainty that the fault resistance actually was 20 Ω; theoretically, it could have been 10 Ω or 30 Ω or some other value. The value of 20 Ω was chosen based on industry averages. If we assume 10 Ω and recalculate, the fault duty nearly doubles to just under 0.2 A; on the other hand, if we assume 30 Ω and recalculate, the fault duty drops to 0.066 A.

As mentioned earlier, there was an 8T fuse on the high-side of the 7.2kV/240V/120V pole-mounted transformer serving the customer's property. A small fuse like this is normally sensitive enough to adequately protect a small circuit. However, it was nowhere near sensitive enough to detect the high impedance fault discussed here. Please see the figure below of an S&C 8T fuse curve together with a fault plot at the calculated value. The fault locus is at the upper left hand corner of the graph.

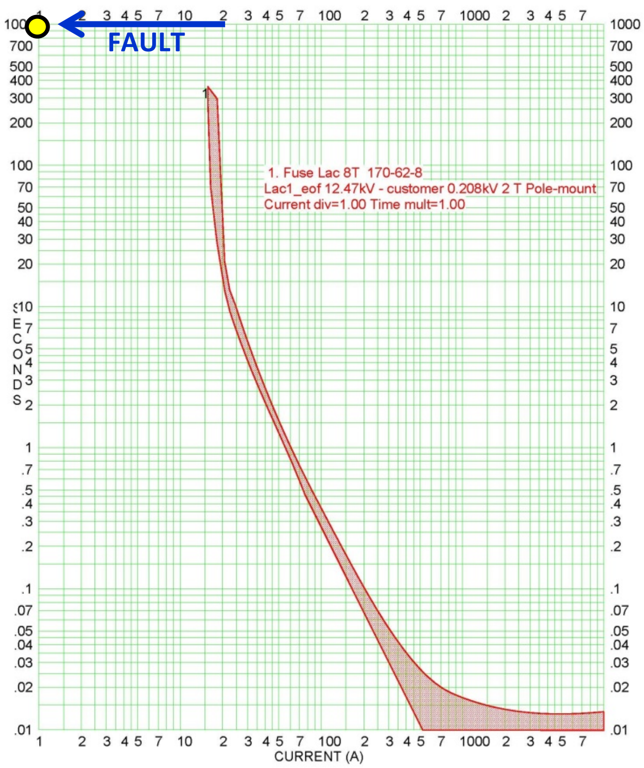

Figure 5: 8T fuse curve and fault mag. seen by fuse

It is apparent from the above plot that the 8T fuse would have never seen the fault, and the conductor would have remained energized until it came into contact with something to cause a solid fault. Also, it is important to point out that we *don't* believe that the aforementioned fuse should have operated for this type of fault. Traditional fuses were not designed to detect high impedance faults; therefore, the non-operation of the fuse did not constitute an equipment failure, and the fuse performed as designed.

III. Event Records

As indicated previously, the pre-fault and fault current magnitudes were nearly identical to each other. Below is an excerpt from the fault report retrieved from the relay that gives the pre-fault and fault values on the faulted phase:

```
Date = 2007/09/28
Time = 19:37:39.693020
[SIGNAL ib]
PrefaultMagnitude = 82.135
PrefaultAngle = 110.6
FaultMagnitude = 82.095
FaultAngle = 110.6
```

The pre-fault and fault current magnitudes were within one-tenth of an amp of each other—well within normal load variation. This is very telling. It reveals that most of the "fault" current magnitude in the report above was in fact load current, and therefore the actual fault current component of the overall waveform must have been small. This condition is verified by the fault calculation in the previous section.

Oscillography

Figure 6 is a load profile retrieved from the relay. It is of a 24-hour period, the day of the event, from midnight to midnight. The top three analog channels (**Hi-Z Ia Mag**, **Hi-Z Ib Mag** and **Hi-Z Ic Mag**) are the RMS calculations of the three phase currents. We can see that over the course of the day, the load was fairly consistent. We can also see that at time = 19:35:00 the breaker tripped and stayed open for one hour and 20 minutes, then after the breaker closed there is the telltale cold load signature for about 30 minutes.

Underneath the analog channels are the digital channels. Surprisingly, none of the Arc Confidence channels registered a change of state during the 24-hour window.

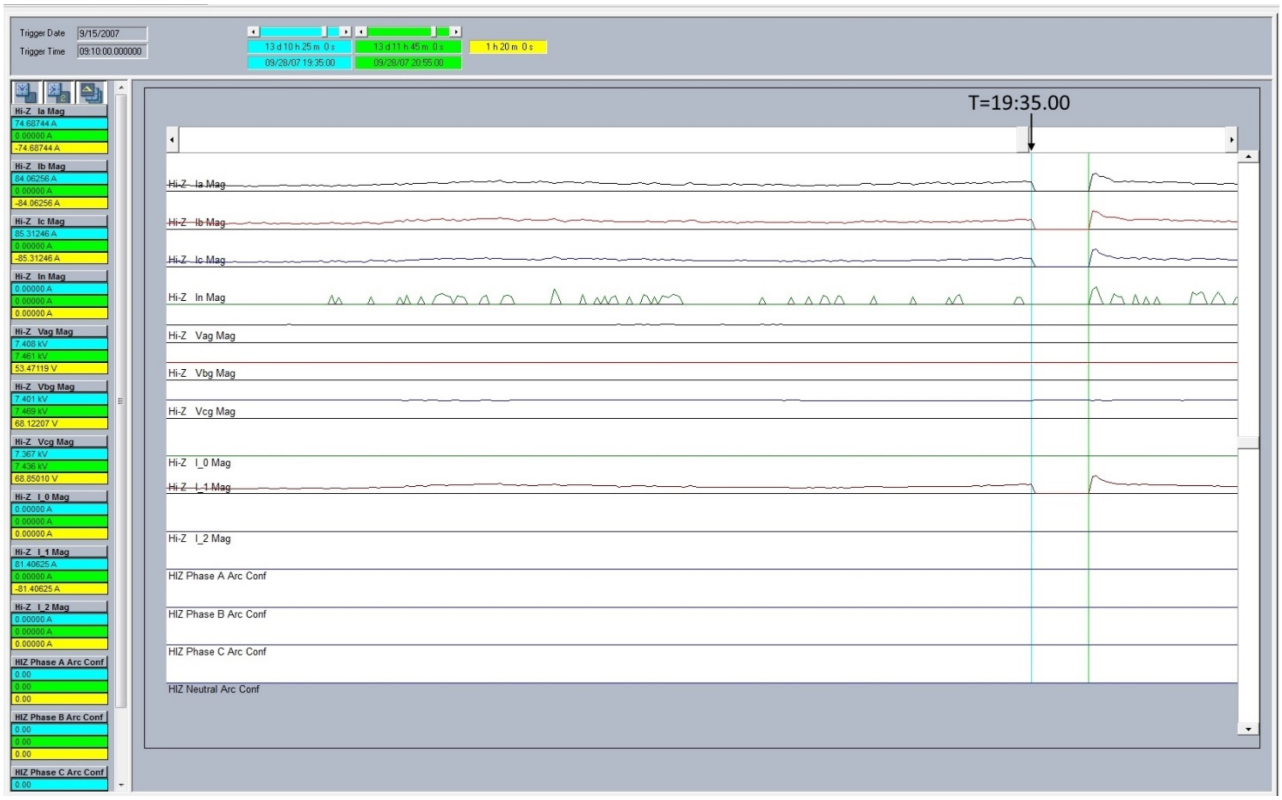

Figure 6: RMS Current, 24-hr Period

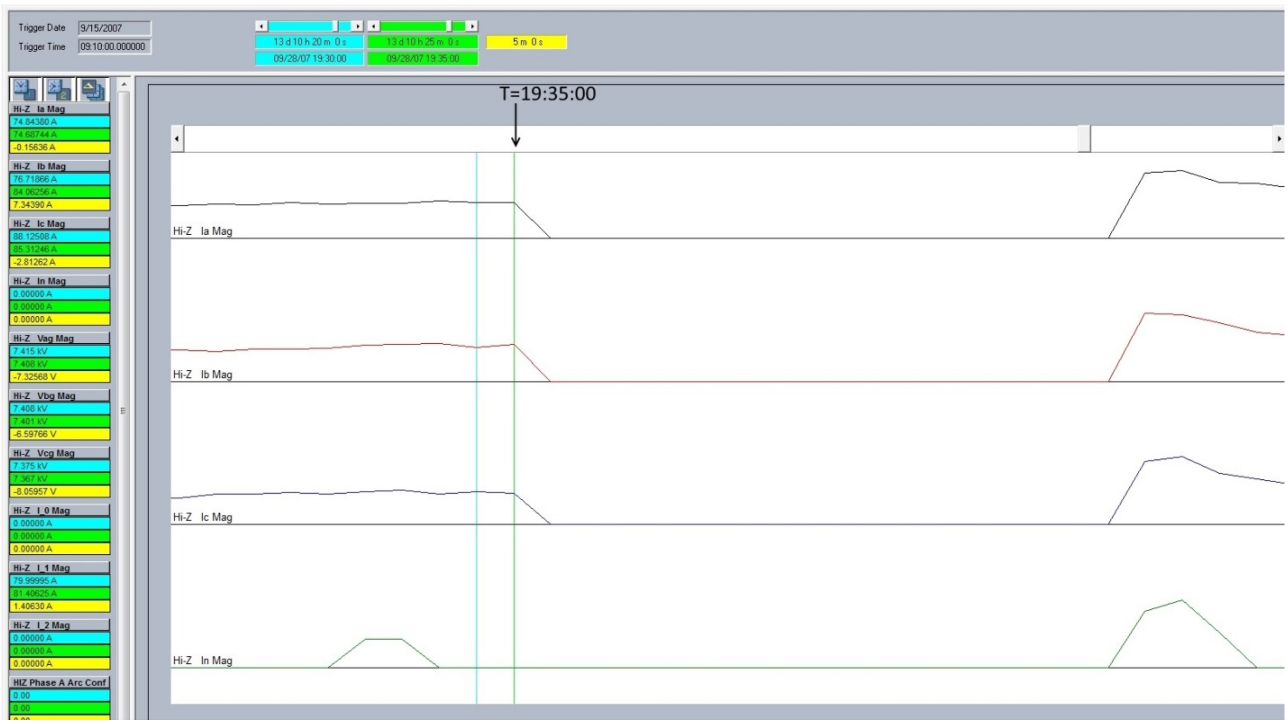

Figure 7: RMS Current, Circa the Event

Now let's zoom in on the time frame right around the fault. Please see Figure 7. Once again, there is balanced load before the breaker opens, and cold load after the breaker closes. However, even zoomed in, we don't see anything indicative of a fault. Granted, these are filtered profiles, so if there was a transient or arcing signature, it has been filtered out. The lack of oscillographic evidence is an example of the insidious nature of high impedance, low current faults; and why, historically, they have been a perplexing phenomenon for protection engineers.

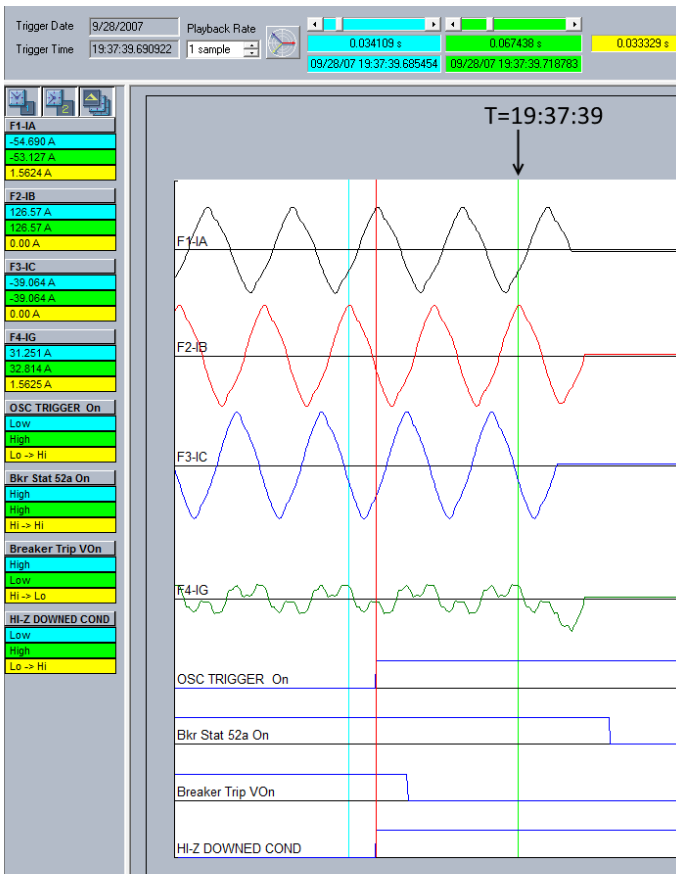

Figure 8: Hi-Z Event Oscillography

Figure 8 is another oscillography from the same event. This one displays the waveforms of the three phase currents, as well as the residual ground current. Obviously, the time window here is much smaller than in Figures 6 and 7—approximately six cycles. As the reader can see, the waveforms simply look like balanced, three-phase load. This also is confirmation that the fault current component was very small.

If the reader examines the waveform closely, it appears to be skewed slightly. But the skewing is fairly even across all three phases, and therefore can't be attributed to the high Z event, which was limited to phase B. So it is unclear where the harmonic is coming from, especially given that this is a rural, residential feeder. But this part of Tacoma Power's system does happen to be nearby an industrial area known as Frederickson (fed by different substations). Therefore it is possible, though not conclusive, that the harmonics are coming from that area.

Continuing the analysis of Figure 8, underneath the analog waveforms are the digital channels. As one would expect, the **HI-Z DOWNED COND** bit shows up. It asserts at time = 19:37:39.690922, and is the only component of this oscillography that gives away the fact that there was a high impedance event.

Finally, Figure 9 is another perspective on the same event. The waveform in this oscillography is from a special set of Hi-Z CT inputs on the relay that measures the current at a different sampling rate. Again, examination of the analog waveform doesn't reveal anything out of the ordinary (other than the current spike when the breaker trips). But the same digital elements change state as in Figure 8's oscillography: **OSC TRIGGER** (0 to 1), **Bkr Stat 52a** (1 to 0), **Breaker Trip V** (1 to 0), and **Hi-Z DOWNED COND** (0 to 1).

Figure 9: Hi-Z Analog & Digital Channels

Sequence-of-Events

Printed below is the sequence-of-events from the feeder relay (the event order reads chronologically from the bottom up):

```
509 Sep 28 2007 19:37:44.440400 Trip Indicat Off
508 Sep 28 2007 19:37:43.940457 Breaker Trip Off
507 Sep 28 2007 19:37:43.940457 TRIP Off
506 Sep 28 2007 19:37:43.698817 AR 1 ENABLED
505 Sep 28 2007 19:37:43.690483 LO Alarm Off
504 Sep 28 2007 19:37:43.690483 Downed Cond Off
503 Sep 28 2007 19:37:43.690483 Close Inhib. Off
502 Sep 28 2007 19:37:43.690483 LOA Off
501 Sep 28 2007 19:37:43.690483 BLOCK 79 Off
500 Sep 28 2007 19:37:43.690483 OSC TRIGGER Off
499 Sep 28 2007 19:37:43.690483 HIZ EVENT Off
498 Sep 28 2007 19:37:40.657481 HI-Z DOWNED COND
497 Sep 28 2007 19:37:39.740920 TCM DPO
496 Sep 28 2007 19:37:39.734511 Bkr Stat 52a Off
495 Sep 28 2007 19:37:39.707588 TCM PKP
494 Sep 28 2007 19:37:39.699256 AR 1 DISABLED
493 Sep 28 2007 19:37:39.693020 FAULT RPT TRIG
492 Sep 28 2007 19:37:39.690922 LO Alarm On
491 Sep 28 2007 19:37:39.690922 Downed Cond On
490 Sep 28 2007 19:37:39.690922 Trip Indicat On
489 Sep 28 2007 19:37:39.690922 Close Inhib. On
488 Sep 28 2007 19:37:39.690922 Breaker Trip On
487 Sep 28 2007 19:37:39.690922 OSCILLOGRAPHY TRIG'D
486 Sep 28 2007 19:37:39.690922 LOA On
485 Sep 28 2007 19:37:39.690922 BLOCK 79 On
484 Sep 28 2007 19:37:39.690922 OSC TRIGGER On
483 Sep 28 2007 19:37:39.690922 HIZ EVENT On
482 Sep 28 2007 19:37:39.690922 TRIP On
481 Sep 28 2007 19:37:39.657597 HI-Z DOWNED COND-B
480 Sep 28 2007 19:37:25.640045 HI-Z LOSS OF LOAD-B
479 Sep 28 2007 19:37:19.640673 HI-Z LOSS OF LOAD-B
478 Sep 28 2007 19:37:12.601295 HI-Z LOSS OF LOAD-B
```

The reader can see that the first three entries (478, 479, 480) are Hi-Z loss of load on phase B. Then the relay declares a downed conductor on phase B (entry 481). Subsequently, several relay bits assert in the same processing cycle (entries 482 – 492), including various instances of trip, lockout alarm and oscillography trigger. Finally, there are follow-up bits that assert, such as FAULT REPORT TRIGGER and AUTO RECLOSE DISABLE (entries 493 – 509).

The instruction manual states, “A downed conductor is indicated only when a precipitous loss of load or an overcurrent condition precedes arcing detection.” We see evidence of this in the SOE with the loss of load triggers. There isn’t an arcing detected indication in the list, but there is precipitous loss of load indicated by the **HI-Z LOSS OF LOAD-B** flag. Events were enabled in the Hi-Z settings, therefore we know that all the Hi-Z bits were available in the SOE list.

The important thing to note from this SOE report, besides the type of Hi-Z event, is the length of time that passes from the first event log entry (19:37:12.601295) to the trip command (19:37:39.690922): 27.1 seconds. From this we can be reasonably certain that the relay waited a sufficient period of time—allowing downline protection time to operate, satisfying its Hi-Z algorithms and building up the required confidence level—before issuing a command to trip and lock out the distribution feeder.

IV. Relay Settings

There have already been several excellent papers written on the science of high impedance fault detection, so we don’t need to delve into that here, but we will touch on some aspects of the technology at a more end-user level.

The manufacturer’s instruction manual[2] lists 11 algorithms that drive the high impedance fault detection element in the relay used in this case. In fact, one might think of it more as a family of elements that work together to resolve into either an operate or restrain decision. The eleven algorithms are:

1. Energy
2. Randomness
3. Expert Arc Detector
4. Load Event Detector
5. Load Analysis
6. Load Extraction
7. Arc Burst Pattern Analysis
8. Spectral Analysis
9. Arcing-Suspected Identifier
10. Even Harmonic Restraint
11. Voltage Supervision

There are 14 relay settings used to control various aspects of the high impedance fault detection sensitivity and confidence levels. The relay was set as shown below (values in brackets are settings ranges):

Arcing Sensitivity:	7 [1 - 10]
Phase Event Count:	20 [10 - 250]
Ground Event Count:	20 [10 - 500]
Event Count Time:	15 min [5 - 180 min]
OC Prot Coord Timeout:	10 s [10 - 200 s]
Phase OC Min Pickup:	1.88 pu [0.01 - 10 pu]
Neutral OC Min Pickup:	0.47 pu [0.01 - 10 pu]
Phase Rate of Change:	150 A/2cyc [1-999 A/2cyc]
Neutral Rate of Change:	150 A/2cyc [1-999 A/2cyc]
Loss of Load Threshold:	5 % [5 - 100 %]
3-Phase Event Threshold:	25 A [1 - 1000 A]
Voltage Supv Threshold:	5 % [0 - 100 %]
Voltage Supv Delay:	60 cycles [0 - 300 cyc]
Even Harmonic Restraint:	20 % [0 - 100 %]

Even though there are sections in the relay manual on the theory of operation and settings philosophy, they are mostly narrative descriptions, and the high impedance settings themselves were somewhat esoteric. Therefore, the settings values were selected with guidance from a factory application engineer.

V. Back-up Protection

Some might argue that a feeder relay should never trip and lock out its breaker in response to an event on the secondary side of a customer service transformer, no matter what type of event. However, what needs to be considered is that this was a case of back-up protection; or more accurately, remote back-up protection. According to J. Lewis Blackburn in "Protective Relaying Principles and Applications"[3], backup protection, "operates independently of specified components in the primary protective system. It may duplicate the primary protection, or may be intended to operate only if the primary protection fails or is temporarily out of service."

In the case of the Lacamas event, the feeder relay was completely independent from the pole-mounted transformer fuse. It operated only when the primary protection failed to operate. Obviously it wasn't a duplicate of the primary protection, since it was a different type of device with completely different technology.

An unpleasant side effect associated with a remote back-up protection operation is that the resulting outage affects more customers than if the primary protection had operated. C. Russell Mason in "The Art & Science of Protective Relaying"[4] writes,

> *"It is perhaps evident that, when back-up relaying functions, a larger part of the system is disconnected than when primary relaying operates correctly. This is inevitable if back-up relaying is to be made independent of those factors that might cause primary relaying to fail."*

That a larger part of the system becomes disconnected when remote backup protection operates is a trade-off that we must live with if we want the insurance of a dependable, alternate line of defense.

Mason goes on to write,

> *"However, it emphasizes the importance of the second requirement of back-up relaying, that it must operate with sufficient time delay so that primary relaying will be given enough time to function if it is able to."*

Mason gives two key requirements of back-up protection: 1) it must be independent of the primary protection so that a failure of the one doesn't lead to a failure of the other, and 2) it must have a sufficient time delay so that the primary protection has a reasonable opportunity to operate first.

The high impedance fault detection relay discussed in this paper conformed to both requirements set forth by Mason. Clearly, there was significant physical and infrastructural separation between the primary and backup protection, and the backup protection delayed 27 seconds before issuing a trip command—plenty of time for the high-side transformer fuse to operate, if it was ever going to do so.

VI. Conclusions

This paper is a case study of a successful high impedance fault detection relay operation. We have presented evidence to demonstrate that the relay behaved appropriately in the given circumstance. It is our belief that, even though the high impedance relay "saw through" the customer service transformer, it operated correctly. Had the high impedance relay not operated, the fault would have persisted unabated until it evolved into a bolted fault.

VII. References

[1] John J. Grainger & William D. Stevenson, Jr., *Power System Analysis*, New York: McGraw-Hill, 1994,.

[2] GE Multilin, *F60 Feeder Management Relay: UR Series Instruction Manual, F60 Revision: 4.6x,* Ontario, Canada, 2005.

[3] J. Lewis Blackburn, *Protective Relaying Principles and Applications, 2nd Ed.*, New York: Marcel Dekker, 1998.

[4] C. Russell Mason, *The Art & Science of Protective Relaying*, New Jersey: Wiley, 1956.

VIII. Biographies

Ian Riensche received his B.S. in Electrical Engineering from Washington State University. He was a Protection Engineer at Tacoma Power for eight years. He currently works for Relay Application Innovation where he has been a Protection Engineer since 2012. He is a licensed Professional Engineer in the states of Washington, Maine and Oklahoma. Ian is a Member of the IEEE and the WPRC steering committee.

John Merrell received his B.S. in Electrical Engineering from the University of Washington. He is presently the Supervisor of the Protection & Controls engineering group at Tacoma Power. He has worked for 10 years as a protection engineer at Tacoma Power and for three years as a new services engineer at Tacoma Power. Previously he worked for two years as a protection engineer at Power Systems Engineering (now PowerStudies.com). He is a licensed Professional Engineer in the state of Washington.