Investigation and Analysis into the Mis-Operation due to Carrier Holes

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A bus fault event occurred that resulted in mis-operation of two transmission lines. This paper presents a summary of the event utilizing fault records to determine what happened as well as the use of a portable digital fault recorder to verify the proposed solution to prevent this from occurring again. We will first present the investigation, and then the testing and solution that followed. Carrier Holes have been a topic of discussion for eons and tend to be a mystery. Some typical causes will be presented, with suggestions for identification, prevention, and mitigation.

The Event Summary

In January 2006 on a nice clear day, a substation experienced a bus fault, due to an arrestor failure. The bus protection cleared the fault correctly. However, due to an unforeseen issue, two lines out of the station tripped, single ended at the remote ends. Figure 1- System Configuration depicts the simplified configuration. While the bus fault cleared as designed at station B, both Station A and Station C experienced a single-ended line relay trip operation.

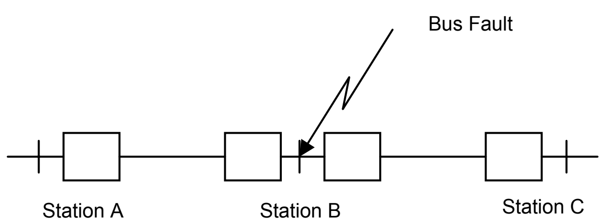


Figure 1- System Configuration

Restoration

The first thing to occur was the system was restored to as normal a configuration as was possible from the control center, until someone arrived on site to access why the bus had locked out.

Investigation

The first step of the investigation was verification of targets and verification of the fault on the bus and its correct isolation. The bus differential scheme had isolated the fault as required. Then the single end trips were quickly reviewed. Targets and Digital Fault Recorder information were reviewed. We monitor Unblock with channels at both locations A and C, which has a channel for UNB SEC which tells us that an unblock trip occurred. This quickly led the personnel to the conclusion that we had some type of incorrect action which came as a result of the bus fault. Since an unblock event was on the DFR a PLC channel issue was the most obvious place to start, see Figure 13 and Figure 14. The lines were restored to put the power system back into its normal configuration.

Targets and fault records were gathered from all devices at station B, as well as from Station A and C to aid in the analysis. These were reviewed by the field engineers responsible for these locations, along with review by the Technical Services Engineers responsible for carrier channel, transmission protection and analysis and others. After review, a plan of attack was reached for testing and further investigation to be done by the field. From the DFR information, Figure 13 and Figure 14, at hand, an Unblock trip occurred on both lines. . An unblock trip is when a fault causes a loss of channel on the Power Line Carrier, the carrier logic will output a trip to give permission to the line relay to trip. This is to allow tripping on an internal line fault which causes the loss of channel. From a reliability point of view, this provides a very dependable system.

The question was what caused it to happen. A carrier hole was verified by SOE Loss of channel from station B. The protection scheme which operated was the secondary scheme, which is redundant and similar to the Primary. These are Directional Comparison Unblock Systems and these particular ones were older solid state protection panels which have no microprocessor relays. So event records were unavailable from them to help try and piece this action together.

We reviewed all the available information we had on the operation, - targets, records from various DFR's, SOE, and SER. We determined that an unblock trip occurred, from the Loss of Channel, at 4.5ms (~¼ cycle) into the fault, thus allowing the Station A and C terminals to trip for the C phase to ground fault at Station B.

We brainstormed as to what the possible problem could have been. The original thinking was, as always a channel issue. But what could it be? Could we have a common failure mode of a module in these older relay panels (circa 1980s) which we had not seen previously? So a plan developed to check the most likely root causes for the failure we saw.

After running through our standard battery of tests – checking levels for transmit level and receive margins, wiring, relays, coax cable, tuning unit gaps, we found nothing obvious as to the root cause. We proceeded to investigate further in great detail to find the culprit that caused this carrier hole (loss of channel).

We started with the carrier system in detail. We left no area untouched, from the transmitter, receiver, cables, (control and coax) the tuner and the ccvt's and traps, to the frequencies used on these lines. First we need to understand what causes carrier holes. Various tests were done from a megger test on the coax to power levels at the transmitter / receiver along with levels taken out at the tuner to verify what was being sent or received made it out into the yard or back to the vault.

<u>What causes carrier holes?</u>

Carrier holes are caused by something flashing over to ground and shorting out the the signal of a channel. Anytime there is a surge on the line (fault, transients due to line switching, a breaker opening, etc.), something is liable to flash-over. Severe RF interference is generated anytime there is slow-speed switching such as a disconnect switch operation. The big question is what this "something" was. It is not just one place, one component or one reason.

The Power Line Carrier channel is made up of the transmission line, the coupling capacitor voltage transformer(s) (ccvt), the line trap(s), the line tuner(s), the lead-in cable, the coax or triax cables, the hybrids and combining filters, and the electronics, see Figure 2. In this path, there are several items that have a potential to flash over, some that are supposed to and some that shouldn't but do. The flash-over will occur at the point in the channel that is the "weakest link" to the transient wave.

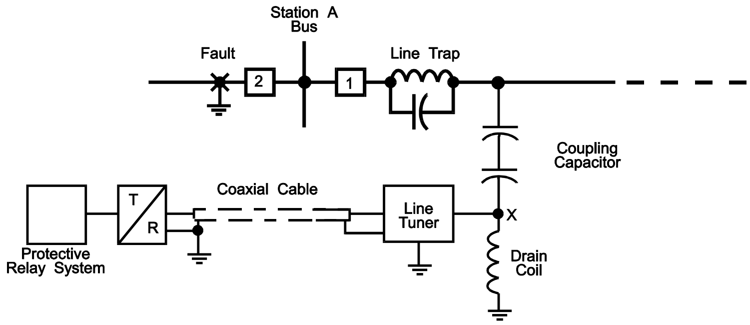


Figure 2 Basic Power Line Carrier Channel (single end)

As coax ages, the insulation begins to break down between the braided shield and the center conductor. Many utilities direct bury the coax in the substation yard, which can add to the aging process. The Power Line Carrier Guide (Reference 5) suggests testing the shield-to-ground insulation for deterioration periodically. The PSRC special report (Reference 6) suggests a more detailed test for checking out the coax cable. The use of triax cable will mitigate this area as a possible flash-over since it has an additional braided shield. However, for these shields to do their jobs, they must be grounded properly. The coax should ONLY be grounded in the control house and the inner shield of the triax should only be grounded in the control house with the outer shield grounded every where there is break in the shield. Once the insulation breaks down enough, a flash-over will occur and result in a carrier hole.

The lead-in cable connects the line tuner to the base of the ccvt. This cable is insulated, unshielded single conductor and rated for 5kV. It should be rigid and supported on insulators so that it doesn't touch the substation steel, and must not be installed in a metal conduit. Should this cable come too close to the steel, it may flashover, resulting in a carrier hole. We place this cable in PVC conduit so as to limit exposure in any way to the elements.

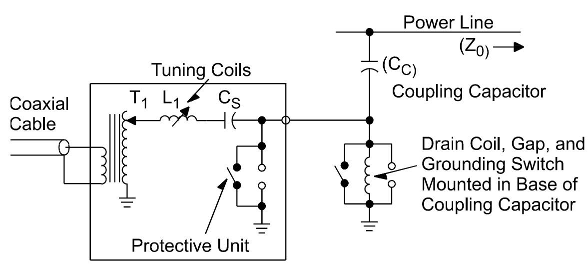


Figure 3 CCVT and Line Tuner Protective Gap

In the ccvt and in the line tuner, there are protective units, made up of protective air gaps (spaces electrodes), gas tube or other limitation devices, and an RF grounding switch. In the ccvt, the protective unit is across the drain coil. The line tuner may also have a secondary drain coil, in which the protective unit is across that as well, but otherwise, the protective unit is still there, along with an RF grounding switch. See Figure 3. The protective gaps serve to provide a low impedance path to ground for surges due to transients, thereby preventing high level surges from getting into the electronics of the PLC channel as well as protecting the drain coil in the ccvt. The goal of the protective gap is to arc over quickly and "seal-off" or extinguish the arc expediently. The gap should arc and seal-off within 1 to 2 milliseconds, so fast that the transmission line protection relay has not had time to process the fault data and take action for the fault. These surges are also limited by the substation lightning arresters. The flashover point is defined in the ANSI C93 standards (References 1, 2, 3, and 4 to be above 2.5 kV RMS at power frequency voltage and below 85% of the BIL rating of the device (10 kV for Line Tuners, ccvt's).

Other areas of concern may be what occur during a ground potential rise caused by the fault, what about Transient Voltage Recovery capacitors, what about series of shunt capacitors and their interaction with the ccvt's capacitance? There may be other areas to consider.

It would appear that there is an increase in the occurrence of "carrier holes", but it is probably more due to the increase of information that is now available with the micro-processor-based devices and the ability to obtain sequence of events out of these devices. DFR's also provide SER / SOE data to help dissect relay actions in question. The Digital fault recorders are no longer the 16 or 32 channel machines from days gone by. These new machines can monitor a Station, along with have the SER / SOE functions available.

Nothing really pointed to why we lost signal after the fault started. We used a fault tree analysis to aid us in the search for our root cause, see Figure 4**Error! Reference source not found.**. A Cause Effect Analysis was also done for Loss of Guard and "Carrier Hole", these both pointed us in the same direction. Gaps came up in several places as a possible reason for the loss of channel. From the investigation done on site within a few days of the fault, we reviewed the tuning unit's gap measurements and found them within specification. The one area left untouched at this time was the ccvts. In order to investigate, this would require a line outage – meaning coordination of crews and time to organize it.

In the mean time, research was done as to what vendor, type, age, and anything we knew about them from previous experience. We had a past experience with gaps being an issue in ccvt's. This being the case we had along time ago standardized our gap setting values and coordinated them with the tuning units gaps, which is part of Reference 1.

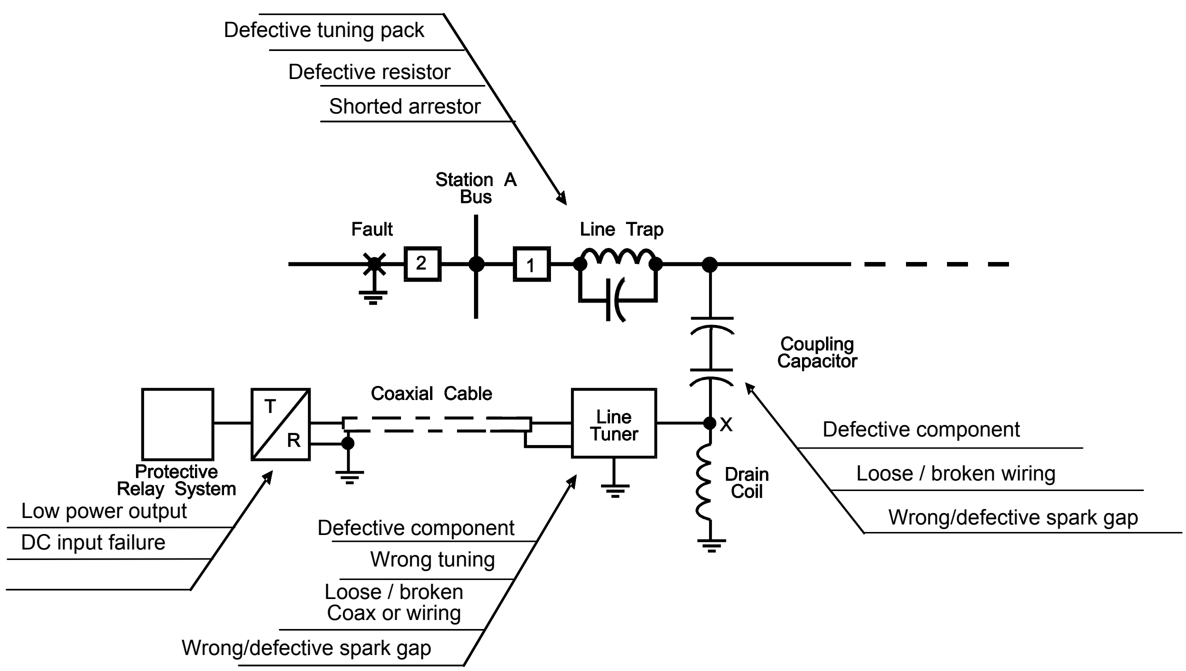


Figure 4 - Root Cause Analysis

We coordinate our gaps for our tuning units and ccvt's since we can easily verify gaps are correct at ground level without a line outage, the ccvt's are set larger than our tuners. Setting the tuner gaps to flashover at lower voltage levels than the ccvt's gaps allows them to thereby operate more often and quicker.

After bringing all the data together it was found that the lines which tripped incorrectly were all the same type of ccvt.. Our specification calls for only adjustable gaps in our ccvt's and tuning units but had previously accepted units with non-adjustable gaps. The change to specification was about the time these line terminals were built.

Due the desire to "coordinate" the gaps in the ccvt with the line tuner, it is preferable for the protection devices in the line tuner to be adjustable air-gaps, not sealed gaps. If the gap in the ccvt is set at a higher flash-over point than the gap in the line tuner, then the line tuner will experience most of the flashovers. Addressing the line tuner gap does not require access to the EHV potential, but care should be taken to check the integrity of the drain coil prior to any work inside the line tuner. More frequent checks are possible in the line tuner, than the ccvt.

Once an outage was allowed, the ccvt's were found to have a fixed non-adjustable gap. There were signs that they had flashed-over and some were dark looking, like they had been firing, and been hot, see **Error! Reference source not found.** Figure 7 - Evidence of flash-over and heat damage**Error! Reference source not found.**. We proceeded to replace these gaps with new adjustable units from the vendor which had previously not been available.

At this point we wondered if the tuning units had fired even though they didn't seem to outwardly show it. There gaps were set as specified for coordination with the ccvt's. A closer look revealed after disassembling them that they had indeed fired but it was not visible unless they were inspected with a mirror or removed. They had fired but not to any great extent, the gap was in very good condition. See Figure 9

We then stepped back and looked at what we had. We found the root cause of this event which now could be put to rest. But had we really stopped the problem from occurring. Carrier Holes have been around forever and we still see them. We have all had this issue and can we work with the vendor to get around this and keep our high speed protection functioning properly.

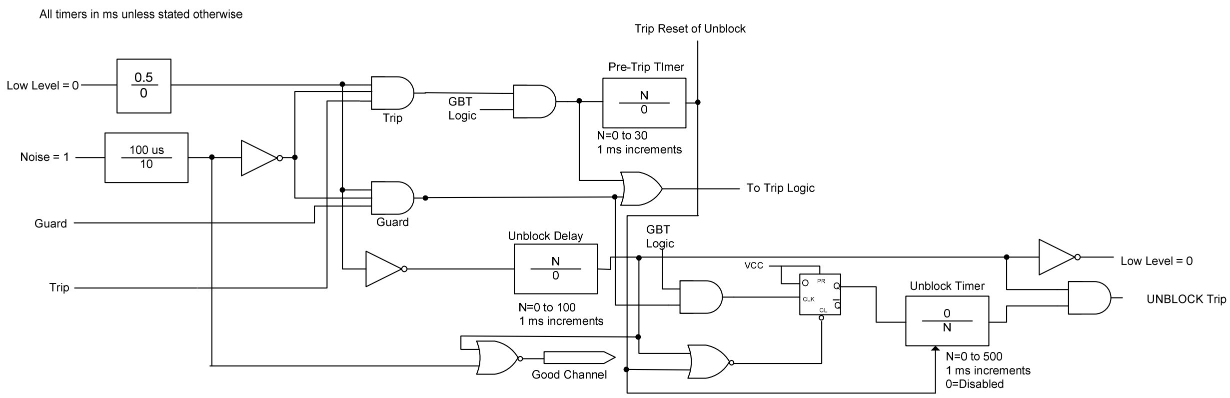
<u>Further Prevention of such misoperations</u>

Even coordination of the gaps will not stop them from firing if a big enough transient occurs; an incorrect operation may then follow if it happens during a fault. We decided to try to see if the carrier equipment we were using from the various vendors could somehow override or ride through this hole and prevent an incorrect operation. These particular systems were all one type along with the carrier sets. We have a lot of these systems still in service so if an answer could be found, it could be used across our system. We also can apply this to our newer microprocessor schemes to improve them.

Historically, an unblock trip is issued immediately after detection of a loss of channel. Meaning a carrier hole would cause an unblock trip to be issued. Previously, the vendor had added additional timers in the receiver logic to delay the unblock output. Using this additional timer, we wanted to test how well the system worked in its new configuration. To do this we decided to use a portable relay test set which has outputs which we could program to operate for different times to operationally test the new timer settings effectiveness in the system.

So a simple setup with a spare carrier set through an attenuator to replicate the line attenuation, was put together to see how it would react to our simulated carrier holes. The carrier holes we simulated to be on the order of 2 to 6 ms, see Figure 16 We used a portable DFR to monitor all aspects of our test. We monitored the pulse from our remote carrier and compared it with the local unit to see how this new logic operated. We were very surprised to find out that the time we chose as the delay we wanted to use on our system was not really working, we were still getting immediate unblock trip outputs. We started seeing a difference when we increased the setting to over twice what we wanted. We found an interesting thing that happened to the local receiver - it would mask any return of signal until after almost 10 milliseconds. We tried many values for our delay setting but until we were above 10 milliseconds we saw really no change and it would still send a trip output. This was unacceptable, the vendor was contacted. With the vendor's assistance, we found that there was a 10 ms dropout delay on the noise circuit to prevent extraneous alarms. See Figure 5.

The delay was reduced in the receiver circuit by the vendor to 2 ms, and we were provided with proto-type receivers to run through our tests again. This time, we accomplished what we had wanted. We are able to put a short time delay on the unblock timer of less than 10 ms. This will give us the ability to ride through short carrier holes on the Directional Comparison Unblock systems, while still maintaining the overall reliability of the relay system. Putting a longer delay on the unblock output was not acceptable to us, as we need to be aware of longer carrier holes that would indicate a significant issue with gaps or other component flashovers.



Unblock Logic

Figure 5 Unblock Logic

Types of Gaps

Over the years, many forms of protective gaps have been used in carrier equipment. These span the technology from a basic spark plug to more sophisticated components such as gas tubes and metal oxide varistors. The basic requirement is that they meet the ANSI C93.4 requirement of flashing over at not less than 2.0 kV rms at power frequency or greater than 85% of the tuner BIL rating at the standard impulse of 1.2 x 50 microseconds.

Below are some of the types of protective gaps we have found on our system.

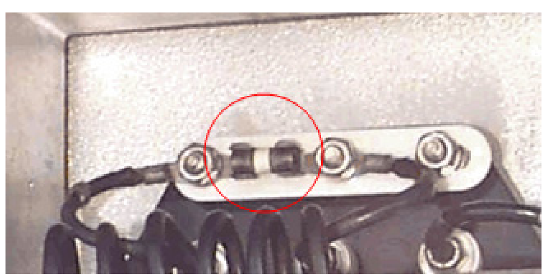


Figure 6 - Non Adjustable Gaps

Figure 7 - Evidence of flash-over and heat damage

Figure 8 - Closer view of non-adjustable Gaps

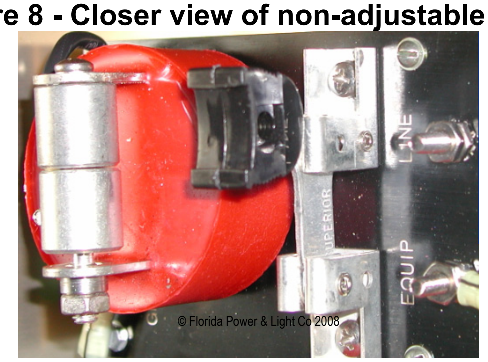


Figure 9-Adjustable Gap Assembly

Note: This was the type which showed no flash marks until disassembled

Figure 10 - Adjustable Gap Assembly

Figure 11 - Obvious Flashover Marks

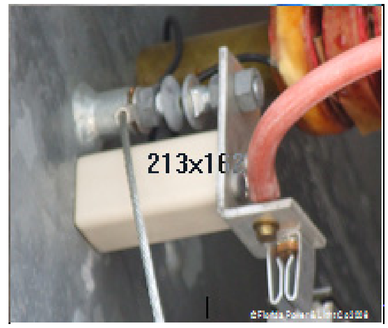


Figure 12 - More Flashover Mark

Review of the remote station DFR records.

Station A

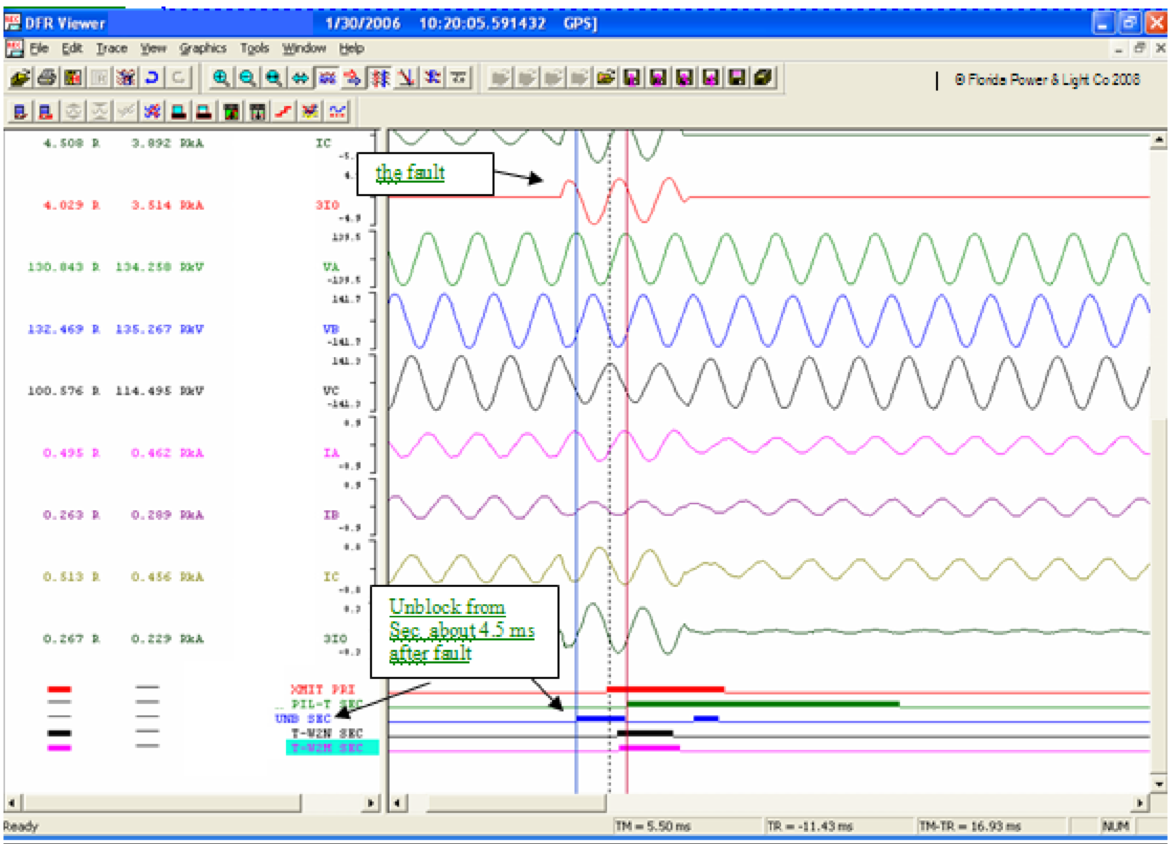


Figure 13 - Event record

Station C

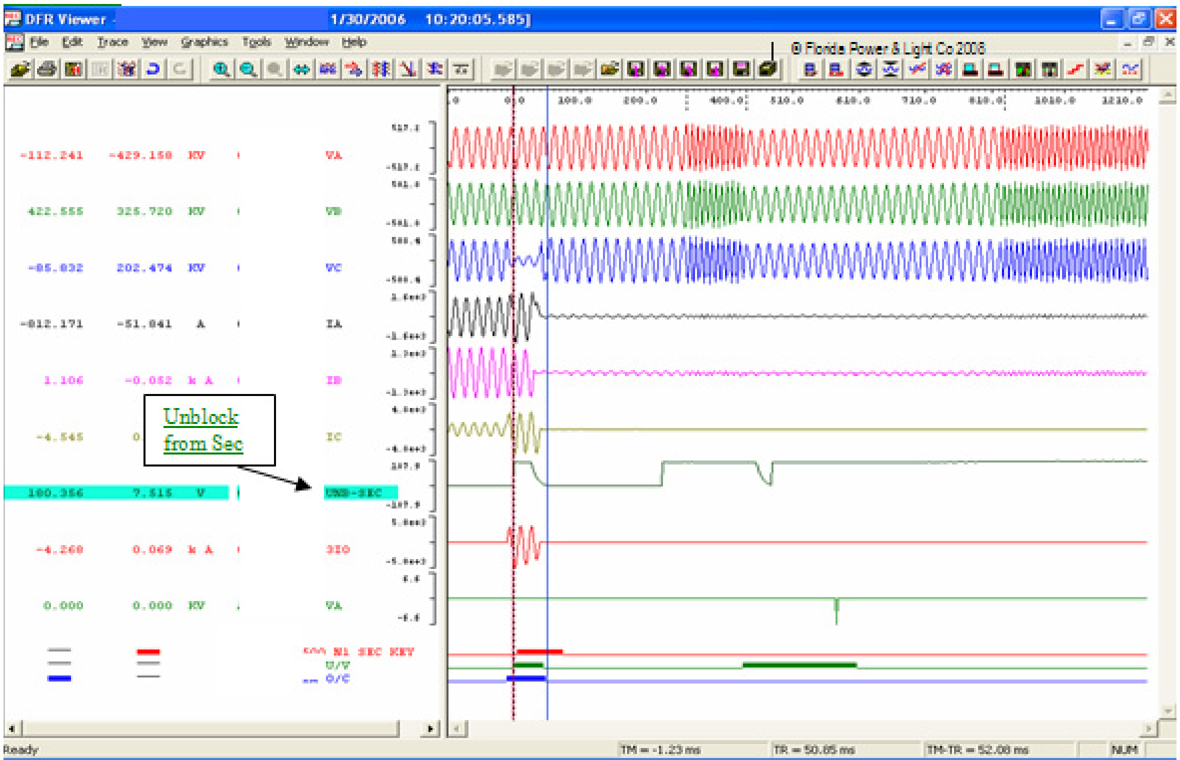


Figure 14 - Event Record

The Test Setup for our portable DFR

Channel:

1	Transmitter output signal (note 1)
8	Unblock output from panel receiver
9	Low Level output from panel receiver
10	Shift High output contact from transmitter
11	Shift Low output contact from transmitter
12	Key unblock input to transmitter
13	Key off input to transmitter

Note 1: the carrier frequency is 315 Khz. This is too high for the DFR (3 Khz). Aliasing causes the signal to show up as a weak negative DC offset. Since the unblock signal is stronger than the Guard signal, a change appears as a magnitude change.

Test with the old Receiver Logic Card

Record Number	Test	Results
591	Loss of Channel	Unblock (UB) after about 8 mS and lasted 150 mS
592	Unblock	UB after about 10 mS
593	4 mS Loss of Guard (LOG)	UB after about 7 mS, lasts about 19 mS
594	10 mS LOG	UB after about 7 mS, lasts about 26 mS
595	6 mS LOG then UB	UB after about 7 mS

Test with new Receiver Logic A card

Record Number	Test	Results
596	Loss of Channel	UB after about 18 mS, lasts about 150 mS
597	Unblock	UB after about 10 mS
598	4 mS LOG	UB after about 18 mS, lasts about 9 mS
599	6 mS LOG	UB after about 18 mS, lasts about 11 mS
600	8 mS LOG	No UB, but did get low level
601	10 mS LOG	No UB, but did get low level
602	12 mS LOG	UB after about 18 mS, lasts about 17 mS
603	14 mS LOG	UB after about 17 mS, lasts about 19 mS
604	10 mS LOG then UB	UB after about 18 mS, off at 33 mS, on at 54 mS
605	16 mS LOG then UB	UB after about 17 mS, off at 39 mS, on at 60 mS
606	8 mS LOG then UB	UB after about 17 mS, off at 31 mS, on at 41 mS

Note: new receiver logic card initially had no output to relays. The old card (circa 1988) has points TB1-6 and TB1-7 internally jumpered together (common). In the new card they were not. After adding external jumper TB1-6 to TB1-7 the new card's output worked

<u>This is a DFR shot from a portable DFR we used for the investigation and analysis of this problem. Channel 1 shows the Loss Of Channel (LOC) and channel 8 shows the unblock from the local receiver 8 mS after the LOC which lasted 150 mS. Other items were monitored for analysis if needed.</u>

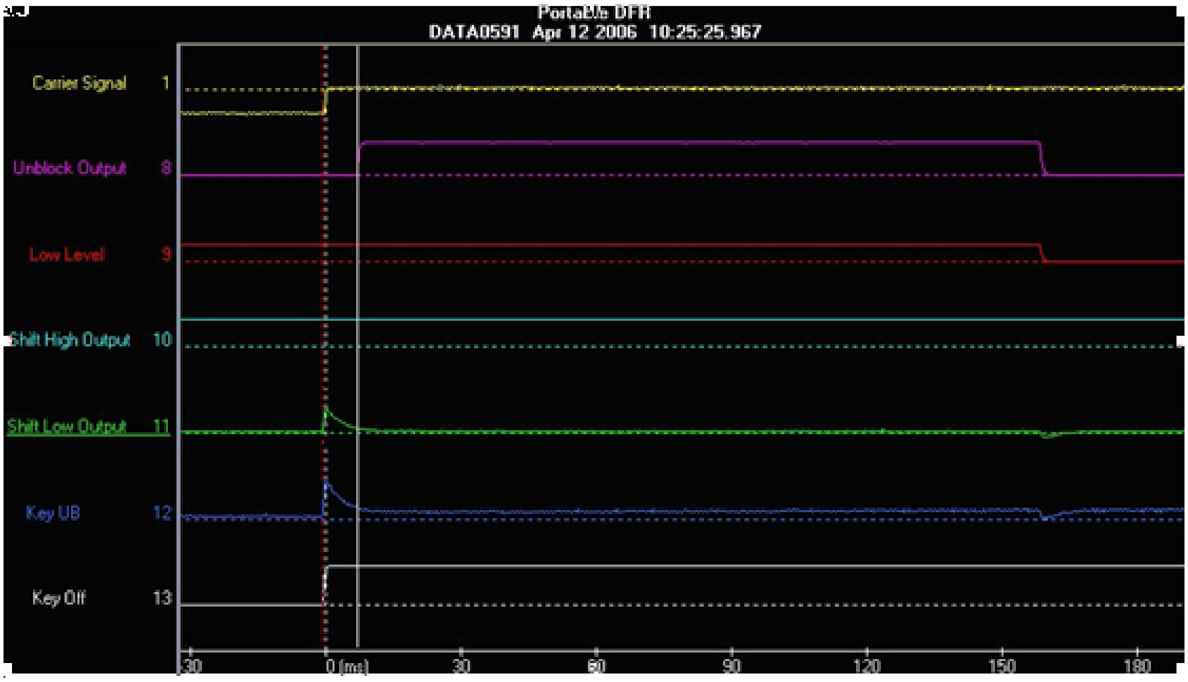


Figure 15– Test DFR Shot before any changes to the logic timers with a loss of channel

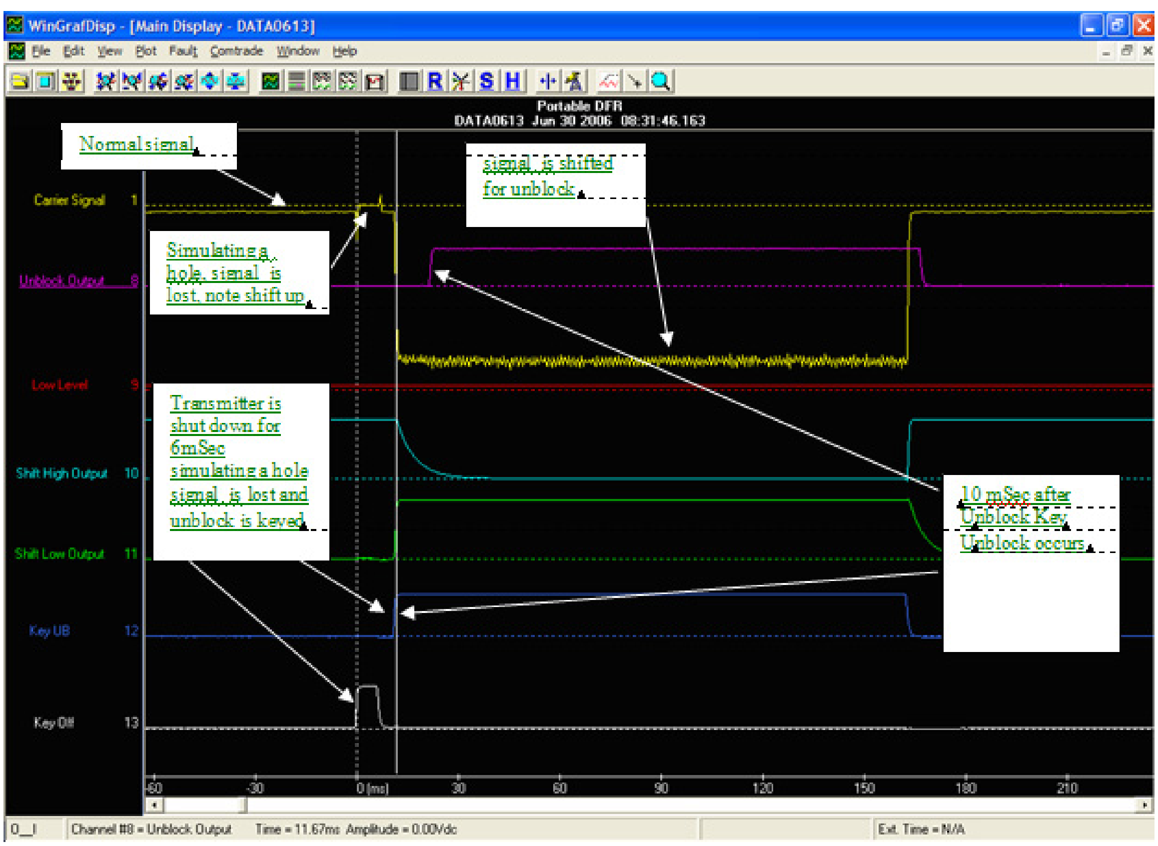


Figure 16 - Test DFR shot with a simulated 6 mS hole from our test setup

Corrective Actions

After all the testing and analysis by both the vendor and us, a way to work through this was reached. A change was made to add an optional time on the receiver module to reduce its dropout time from about 10 milliseconds to 2 milliseconds. This will allow us to still use the setting we think is correct to allow for a loss of channel and still provide a trip for a fault in a time frame which we feel is acceptable.

This new version of the card was produced and tested by the vendor.

Once received by us we reran our test simulations with our test setup to produce holes to the carrier system. This proved to us that with a hole in the channel could be and protect against incorrect operations along with receiving a correct trip as required for true faults on the line.

Lessons Learned and Other thoughts to consider

We found out several things which we feel are worthwhile to pass along.

The first thing would be to bring the vendors in to help with the analysis sooner. Who knows their device better? They also have all of the background on why something is done the way it is in their device. We have to understand that when devices we use and apply daily in performing our jobs in the System Protection field, we need to be aware that things were carried over from older devices. When a new protective or communication device is developed they could be modeled after what we had 10 – 40 years ago. Knowing where you come from can sometimes help in the analysis of where you are.

The second thing would be you can't quit too soon, why it happened is there we just must persist and uncover the problem. You then have to figure out if why it happened is the root cause and can it be fixed 100% or must we go another mile and use our ingenuity to allow us to fix the root cause 85% and make our equipment smarter to cover that last 15%.

In a Directional Comparison Unblock system, use of the time delay on the unblock output rides through any carrier holes shorter than the delay setting, adding security back into the system, preventing mis-operations for an external fault, while not sacrificing high speed tripping for internal faults without a loss of channel. So even if the protective unit or some other devices flashed over for a short period of time, the unblock trip window is delayed for a set period of time to eliminate too quick of a trip during loss of channel.

In a Directional Comparison Blocking system, use caution when applying time delay to receiver output or other carrier-hole logic, so as not to delay high speed tripping should the system be required to trip should the fault become an internal fault. Any delay to the receiver output will delay the overall tripping time of the system.

End to end synchronized relay testing **DOES NOT** test the channel for carrier holes since it is not actively putting transients on the transmission line, but simulating the input into the relays. This only checks the performance of the relay system with an intact channel. Testing for carrier holes will require placing transients on the channel – something not many utilities will do on purpose. Recommendations for testing of coax and other channel tests are explained in the References 5 and 6.

References

1. ANSI C93.1 ANS Requirements for Power-Line Carrier Coupling Capacitors and Coupling Capacitive Voltage Transformers (CCVT)..
2. ANSI C93.3 ANS Requirements for Power Line Carrier Line Traps
3. ANSI C93.4. ANS for Power Systems, Power Line Carrier Line Tuning Equipment.
4. ANSI C93.5 Requirements for Single Function Power Line Carrier Transmitter/Receiver Equipment.
5. IEEE 643 Guide for Power Line Carrier Applications
6. "Special Considerations in Applying Power Line Carrier for Protective Relaying". Working Group (H8) to the IEEE/Power Systems Relaying Committee. (http://www.pes-psrc.org/Reports/SpecialConsiderationsPLC.zip

Biographies

John J Meinardi

A 1981 graduate from Mississippi Sate University with a BS of Electrical Engineering Technology degree and a member of IEEE since 1979, John is a Senior Engineer in the Technical Services Group for Florida Power & Light and employed there since 1981. Areas of responsibility are Fault Analysis, Transmission Line Protection, and Communications, PLC and Fiber Optic systems. He is a member of the Doble PAT committee, along with co-presenting a technical paper at the TAMU Relay Conference in 2004. John also co-authored a recently presented paper at the 2008 TAMU Relay Conference.

Miriam P Sanders

A 1980 graduate from University of NC at Charlotte with a BS of Electrical Engineering, Miriam is a Senior Sales and Application Engineer for AMETEK Power Instruments. With nearly 30 years experience in the relay industry, Miriam has worked with protection channels, transmission pilot relays and distribution relays. Her career started in the Westinghouse Relay Division in Coral Springs, which later became ABB. After nearly ten years there, she returned to her home state of NC to work as a consultant with Booth and Associates, specializing in substation relaying. After returning to ABB at the Transmission Technology Institute in Raleigh, Miriam went to Allentown to work as an application engineer, concentrating on the DPU-2000 Distribution relay introduction and the development on the TPU Transformer Protection relay. In February 1994, she returned to Coral Springs as Product Manager for Power Line Carrier for ABB. As one of the founding stock holders of PULSAR Technologies at its inception on Oct. 28, 1994, she was Product Manager for the Power Line Carrier products prior to its sale to AMETEK Power Instruments.

Miriam is a senior member of the IEEE, presently Vice Chairman of the Power Engineering Society's Power System Relaying Committee, and has held many positions in the organization including, Committee Secretary, and Assistant Secretary, the Standards Coordinator, Chairman of the Transformer Protection Guide, member of the Power Line Carrier Practice Working Group and Transmission Line Protection Guide. She is also active in the PES's Power Systems Communications Committee.

She is a registered Professional Engineer in the states of North Carolina and Florida