A SERIES OF UNFORTUNATE EVENTS: FAULT DISTURBANCE ANALYSIS OF 345KV LINE TERMINAL BUS INSULATOR FAILURES AND A "HANDTOOL-INDUCED" BREAKER FAILURE EVENT ON NORTHEAST UTILITIES' TRANSMISSION SYSTEM

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Northeast Utilities System

Introduction:

The Northeast Utilities transmission system recently sustained four very similar 345kV line terminal bus insulator failures. These events occurred over the last 2 years during generally cold weather periods. In three of the four events, a line position horizontal bus standoff insulator fractured, causing the section of bus it supported to either fall to the ground or onto adjacent energized equipment. Although the insulator failures were very similar, the faults created by the falling buswork were anything but. Open circuits were typically created, with solid ground faults on one side of the open. During the first event, which occurred on January 22, 2005, the fallen bus created an open phase on a 3-terminal line, which never shorted to another phase or to ground. This open circuit was sensed by a remote terminal relay which tripped the terminal via timed ground directional overcurrent. In another event, which occurred on February 17, 2006, the initial fault was very different from the fault that developed following reclose of the line terminal, owing to the fallen buswork coming to rest across two lower energized bus sections which were not initially faulted.

Analysis of various DFR and relay records helped to determine fault evolution for each event. These analyses provide an interesting and educational perspective on the various ways similar failures can manifest themselves.

This paper also presents a description and analysis of an interesting event that was precipitated by a pair of electrician's pliers falling onto a breaker failure relay.

This paper will provide a detailed description of each event along with the analysis performed and a determination of whether the relay operations were correct and desired.

Brief Summary of Northeast Utilities' Protection Philosophy at 345kV:

Knowledge of applied protection philosophy will help to understand the response of the protective relays to the faults described herein.

Northeast Utilities utilizes two high speed schemes for line protection at 345kV. The primary or system 1 scheme is typically directional comparison blocking (DCB) over power line carrier. The backup or system 2 scheme is typically permissive overreaching transfer trip (POTT) using audio tones over secure phone lines. One of the lines involved in these events (the three terminal 395 line) uses for its primary protection a current differential scheme over a combination of fiber and digital phone lines.

Primary DCB Scheme:

Three zones of impedance protection are used for both phase and ground protection, two forward and one reverse. Zone 1 is underreaching, zone 2 is overreaching and zone 3 is set in the reverse direction to see all faults seen by the remote terminal's zone 2 overreaching element. In typical DCB fashion, the reverse zone starts carrier. Zone 1 is unsupervised and trips instantaneously, while zone 2 is time delayed by a cycle or 2 to allow receipt of a block from the remote end.

We also apply ground directional overcurrent elements to start and stop carrier on ground faults:

Start Carrier and Block: 300A, non-directional
Stop Carrier and Trip: 600A, directional

Ground distance settings are the same as the phase settings.

Unsupervised ground directional overcurrent elements are used as backup for high impedance faults. Instantaneous elements are set for greater than the maximum remote terminal ground fault, while timed elements are set typically for 240-300A and coordinated with remote terminal devices.

Switch onto fault protection is also provided and is enabled for 30 cycles following close of terminal breakers.

Backup POTT Scheme:

Two phase and ground zones are applied, one underreaching and one overreaching. The underreaching zone 1 element is unsupervised and trips instantaneously. The overreaching zone 2 element will trip instantaneously with permission from the remote terminal but can also trip with time delay.

The scheme also uses unsupervised ground directional overcurrent elements set identically to the primary scheme.

A trip issued by a relay (say for a zone 1 instantaneous or 67N trip) will also transfer trip (a DUTT scheme) the remote terminal via a separate redundant communications channel, such as frequency shift carrier.

Switch onto fault protection is provided in the backup scheme, similar to the primary scheme.

Reclosing and Breaker Failure:

These functions are not incorporated into the primary or backup relay schemes and are provided by separate relays. At 345kV, it is important to note that a breaker failure operation will transfer trip the line terminals remote from the breaker.

First Event: Manchester 395 Line Terminal, January 22, 2005

System Operations:

The 395 line is a 3-terminal line with terminals at Manchester, Connecticut, North Bloomfield, Connecticut and Ludlow in Massachusetts (see figure 1). Originally built as a 2 terminal line from Manchester to Ludlow, the autotransformer at North Bloomfield was added at a later date. The line was protected for most of its history with a primary DCB scheme (using an early vintage static relay system) and a POTT backup electromechanical relay system. The relays at all 3 terminals were replaced a few years ago with digital relays, but the primary DCB scheme was modified to a current differential arrangement utilizing a combination of fiber and digital (G.703) phone communications. Backup overcurrent and distance elements were also programmed into the primary relay. The backup scheme remained a POTT scheme using audio tones over telephone lines.

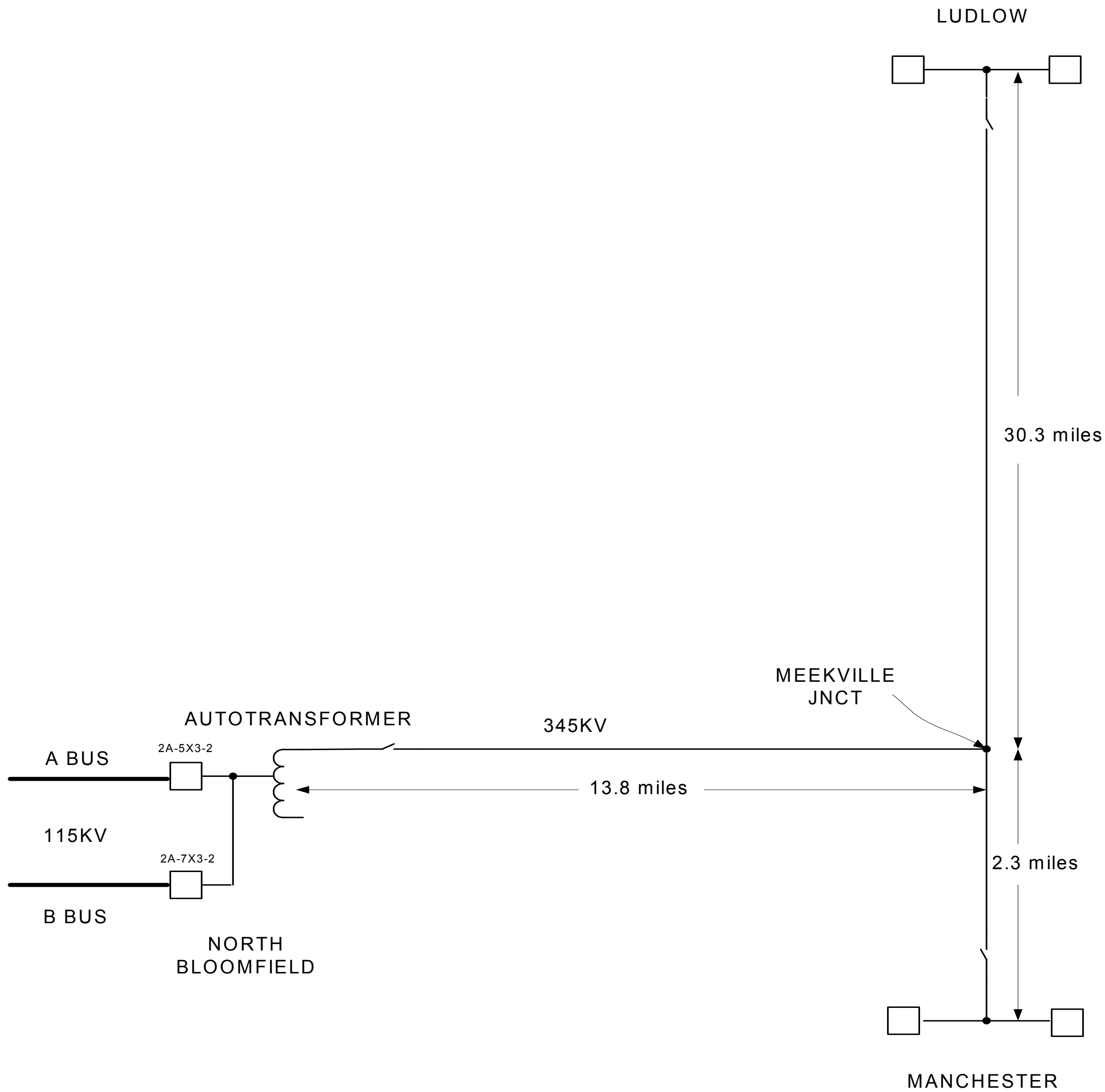


Figure 1: The 395 Line

Early on the morning of January 22, 2005, the North Bloomfield terminal of the 395 line tripped. Breakers 2A-5X3-2 and 2A-7X3-2 (low side 115kV breakers) tripped and reclosed live-live in about 10 seconds per design (see sequence of events below in Table 1). Both breakers opened again approximately 13 seconds later. Since the reclosing relays have a 15 second reset time, the terminal did not reclose again. At about 3 minutes into the event, CONVEX (Connecticut Valley Electric Exchange, our System Operator), issued a remote (SCADA) close of the 5X3 breaker. The breaker successfully closed, but again tripped in about 10 seconds, reclosed and tripped again. No further attempts were made to remotely close the North Bloomfield terminal.

TIME	STATION	ID	DEVICE	OPERATION
1:20:15.282	North Bloomfield	2A	2A-5X3-2	Open
1:20:15.282	North Bloomfield	2A	2A-7X3-2	Open
1:20:25.012	North Bloomfield	2A	2A-5X3-2	Closed
1:20:26.267	North Bloomfield	2A	2A-7X3-2	Closed
1:20:38.376	North Bloomfield	2A	2A-5X3-2	Open
1:20:38.377	North Bloomfield	2A	2A-7X3-2	Open
1:23:22.980	North Bloomfield	2A	2A-5X3-2	Closed (SCADA)
1:23:32.943	North Bloomfield	2A	2A-5X3-2	Open
1:23:44.645	North Bloomfield	2A	2A-5X3-2	Closed
1:23:54.621	North Bloomfield	2A	2A-5X3-2	Open

Table 1: SOE For 395 Line Event

Analysis:

Test personnel traveled to the North Bloomfield substation and found a primary relay target indicating ground directional overcurrent trip (element 51G made directional by 32GF), but it was not immediately obvious what physically had tripped the terminal (see Figure 2 for primary relay plot). Our Massachusetts Test supervisor was able to observe remote Manchester currents on the primary relay at Ludlow, and direct personnel to the Manchester terminal. It would be a few hours before test personnel visited the Manchester terminal and discovered the culprit (see Pictures 1 thru 3). They observed that the A phase line terminal bus horizontal standoff insulator had broken, allowing the bus to separate away from the line terminal without touching another phase or ground. The North Bloomfield primary relay responded to the neutral current created by the unbalanced phase currents.

We questioned why was it that only the remote North Bloomfield terminal tripped for this condition. A review of the relay settings revealed that the North Bloomfield relay was set more sensitively than the other terminals due to the fact that this terminal is a weak source. The North Bloomfield relay was set for 240A, while the other 2 terminals were set for 600A. Roughly 290A of neutral current flowed from the North Bloomfield terminal for a time period sufficient for the timer to time out. Reviews of the relay record at Manchester indicated that the neutral current exceeded 600A for short time intervals, but never long enough for the timed element to trip (see figure 4). Overall we considered this a correct and desired relay operation.

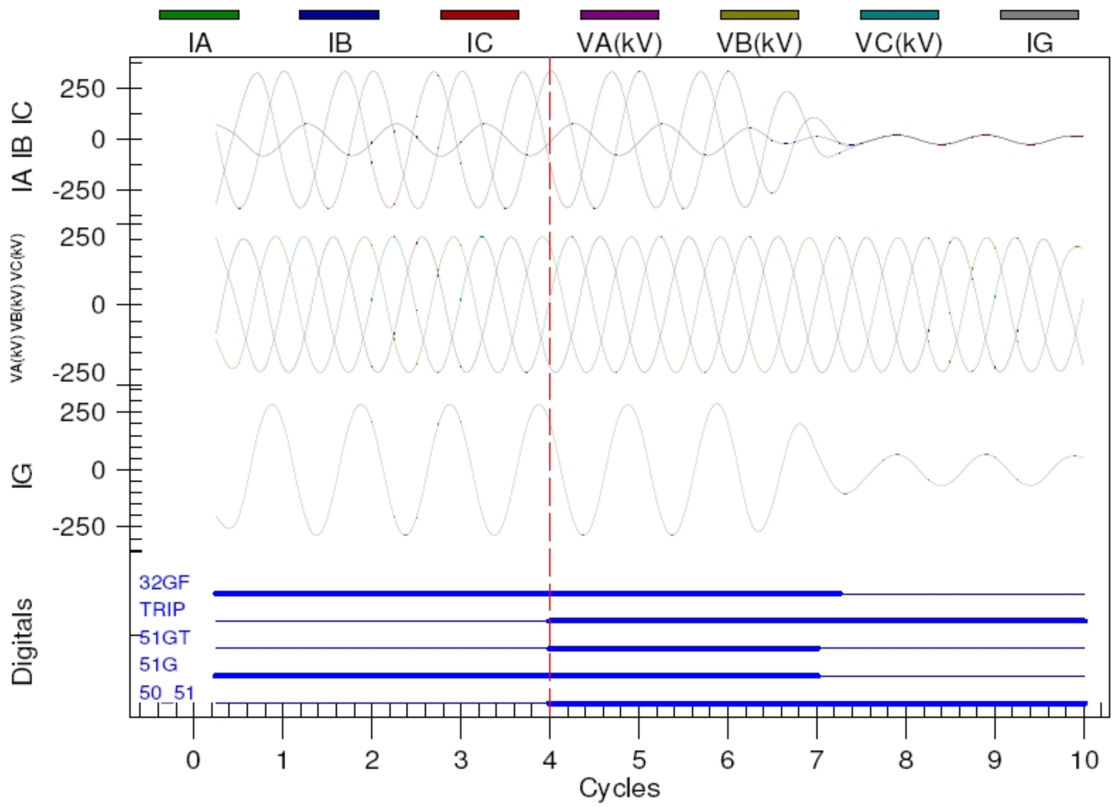


Figure 2: Primary Relay Record for First Trip at N. Bloomfield
Time – 1:20:15.253

Picture 1: Open A Phase on Manchester 395 Line Terminal-Upper Bus End

Picture 2: Broken Bottom Bus at Manchester

Picture 3: Another View of Open Phase A at Manchester

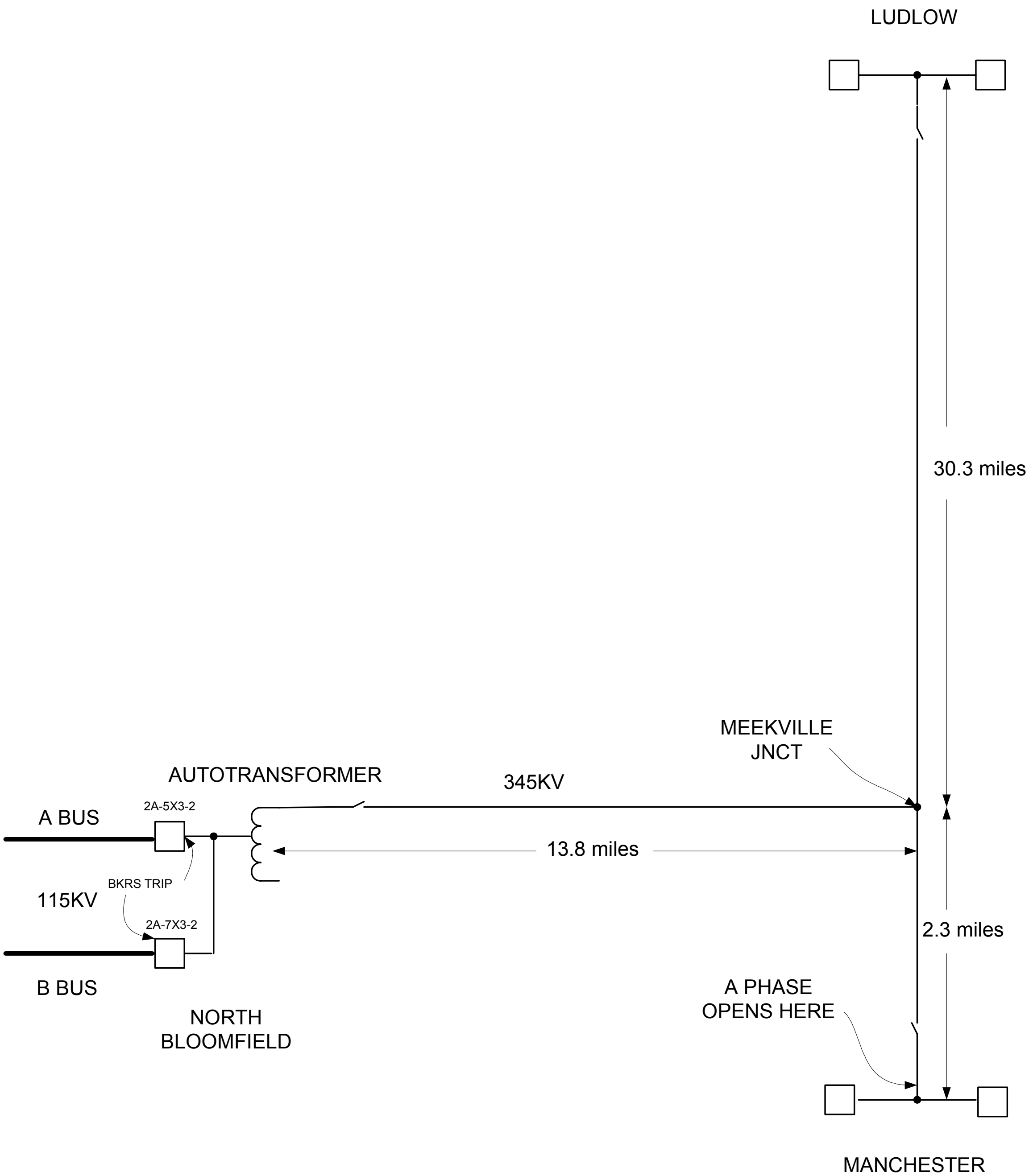


Figure 3: Open at Manchester w/Trip of N. Bloomfield Terminal

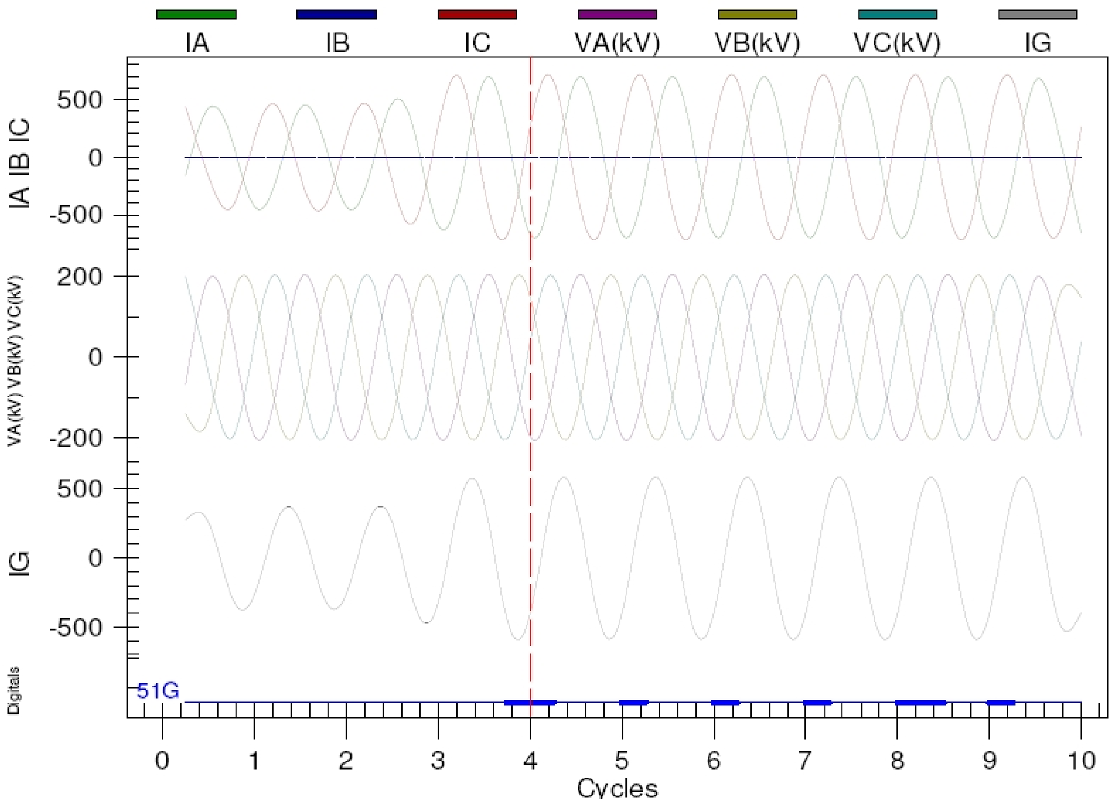


Figure 4: Manchester Relay Record Showing Short 51G Pick Ups

Second Event: Ludlow 334 Line Terminal, April 2, 2005

System Operations:

The 334 line is a short 2-terminal line with terminals at Ludlow and Stonybrook Massachusetts (see figure 5 below). Stonybrook is a merchant generating station, and no relay or DFR records were available from this end of the line. The line is protected by early vintage static and electromechanical relays, with a DCB sheme over power line carrier for primary protection and an audio tone POTT scheme over phone lines for backup. The Ludlow to Northfield 354 line was also involved in this event and was at the time protected by the same relay schemes as the 334 line. The relays and communications systems on the 354 line have since been replaced by modern digital equipment.

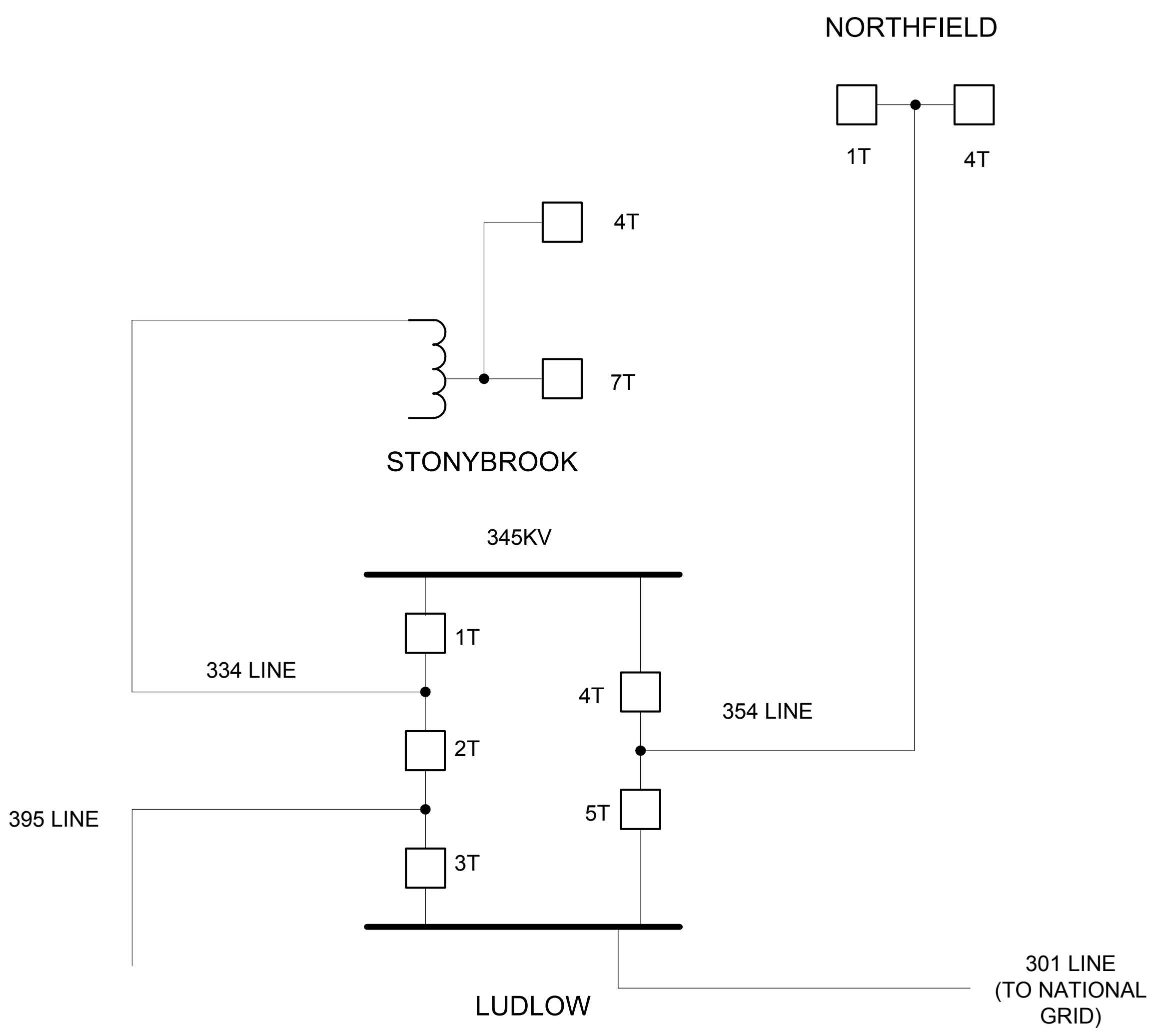


Figure 5: The 334 and Adjacent 354 Line at Ludlow

Both terminals of the 334 line tripped open late in the evening on April 2, 2005 (see abbreviated sequence of events in Table 2 below). Operations at the Stony Brook terminal of the line are not shown due to lack of SCADA there. Terminal breaker 1T reclosed within about 10 seconds per design, and immediately retripped. It's significant to note that 2 overtrips occurred when the 1T breaker at Ludlow reclosed. One overtrip occurred at the Northfield Mountain's 354 line terminal and another at our 115kV East Hartford station, each listed in the SOE. Only the Northfield Mountain overtrip will be analyzed here. Both overtripped line terminals successfully reclosed.

TIME	STATION	ID	DEVICE	OPERATION	NOTES
23:38:12.930	Ludlow	19S	19S-1T-2	Open	
23:38:12.937	Ludlow	19S	19S-2T-2	Open	
23:38:23.196	Ludlow	19S	19S-1T-2	Closed	Reclose
23:38:23.207	Ludlow	19S	19S-1T-2	Open	
23:38:23.219	Northfield Mountain	16R	16R-4T-2	Open	Overtrip
23:38:23.220	Northfield Mountain	16R	16R-1T-2	Open	Overtrip
23:38:23.281	East Hartford	32G	32G-1T-2	Open	Overtrip
23:38:23.295	East Hartford	32G	32G-1X3-2	Open	Overtrip
23:38:23.625	East Hartford	32G	32G-1T-2	Closed	Reclose
23:38:28.380	Northfield Mountain	16R	16R-1T-2	Closed	Reclose
23:38:28.479	Northfield Mountain	16R	16R-4T-2	Closed	Reclose
0:38:34.040	East Hartford	32G	32G-1X3-2	Closed	SCADA Op
3:17:16.435	Ludlow	19S	334-19S-5	Open	SCADA Op
3:17:44.475	Ludlow	19S	19S-1T-2	Closed	SCADA Op
3:17:44.485	Ludlow	19S	19S-1T-2	Open	Oops!
3:17:44.498	Northfield Mountain	16R	16R-4T-2	Open	Overtrip
3:17:44.499	Northfield Mountain	16R	16R-1T-2	Open	Overtrip
3:17:50.094	Northfield Mountain	16R	16R-1T-2	Closed	Reclose
3:17:50.383	Northfield Mountain	16R	16R-4T-2	Closed	Reclose

Table 2: SOE for the 334 Line Event

At about 3:17 on the morning of April 3rd, CONVEX attempted to isolate the 334 line by opening the line motor operated disconnect (MOD) and closing the 1T breaker. The terminal again immediately tripped, and another overtrip of the Northfield 354 line terminal followed with a successful reclose there. No additional automatic recloses or SCADA closes of the Ludlow 334 line terminal were attempted.

Test personnel traveled to the Ludlow substation and found 21N (334 line directional distance ground-phase A) and 21Z1 (334 line directional distance phase zone 1) targets. This time the targets were found on the backup relays and were indicative of a high magnitude close-in fault. Examination of the following DFR traces confirmed this (see figures 6 thru 8).

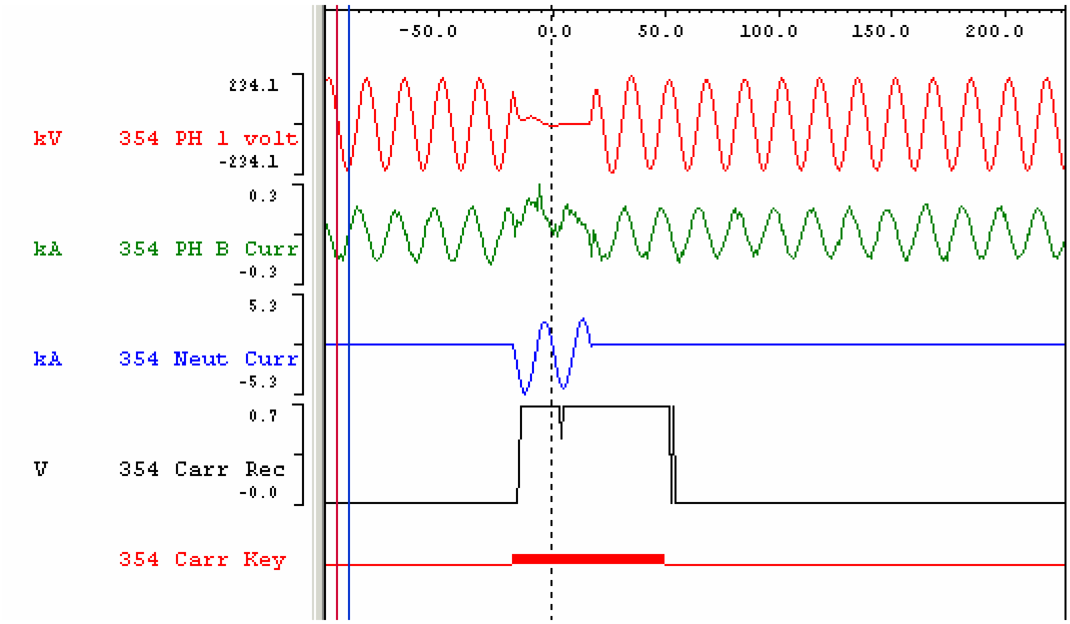


Figure 6: Initial Fault at Ludlow's 334 Line Terminal

Since the 334 line is not protected by digital relays, and DFR traces were unavailable for the 334 line, we had to look at the 354 line DFR traces to do the analysis. Figure 6 shows a 2 cycle clear of the fault on the 334 line. The carrier received trace demonstrates that carrier transmitted is also carrier received at the transmitting terminal. No appreciable holes in carrier were recorded for this initial event. The DFR system at Northfield was inoperable at the time of this event.

Figure 7 is the record generated by the reclose at Ludlow, with subsequent 2 cycle clear again. Figure 8 is the record triggered by the SCADA close of the 1T breaker at Ludlow. These last 2 records show evidence of a hole in the carrier signal which had to have been received by the Northfield terminal, resulting in the overtrip. There was a history of overtrips on this line over the years, but testing could not single out the cause. Vintage relays and terminal equipment on the 354 line were replaced late last year.

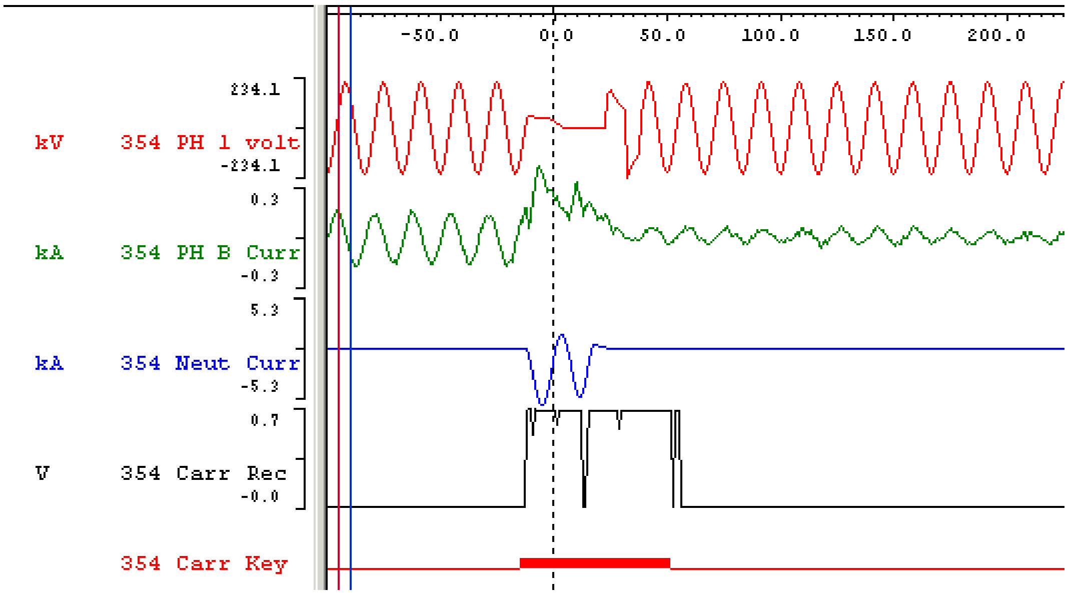


Figure 7: Reclose and Retrip at Ludlow's 334 Line Terminal

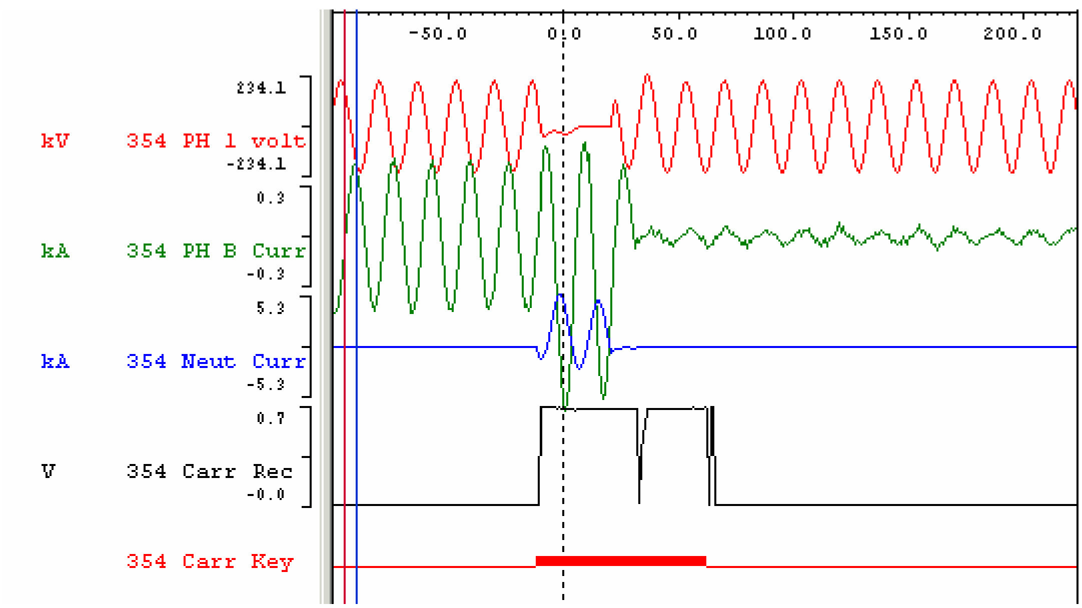


Figure 8: SCADA Close and Retrip at Ludlow's 334 Line Terminal

The damage that occurred at Ludlow as a result of the insulator failure was more severe than what had happened at Manchester on the 395 line. This time, the bus came crashing down to the ground in 2 pieces, coming in contact with grounded and live equipment/structures along the way (see pictures 4 thru 6 below). We considered relay operations on the 334 line to be correct and desired, but operations on the 354 line were incorrect and undesired.

Picture 4: Ludlow 334 Line Bus on Ground

Picture 5: Ludlow 334 Line Bus Touching Live Parts and Ground

Picture 6: Missing Bus on Ludlow 334 Line Terminal

Third Event: Northfield 312/393 Line Terminal, February 17, 2006

System Operations:

The 312/393 line is another 3 terminal line similar to the 395 line from the first event. It runs from Northfield to Berkshire, both in Massachusetts, and continues into New York, terminating at National Grid's Alps substation (see figure 9 for simple 1-line). An autotransformer taps into the line at Berkshire. Electromechanical relays at Northfield and Berkshire substations were replaced with modern digital relays in 2005. Carrier and audio tone transceivers were likewise upgraded.

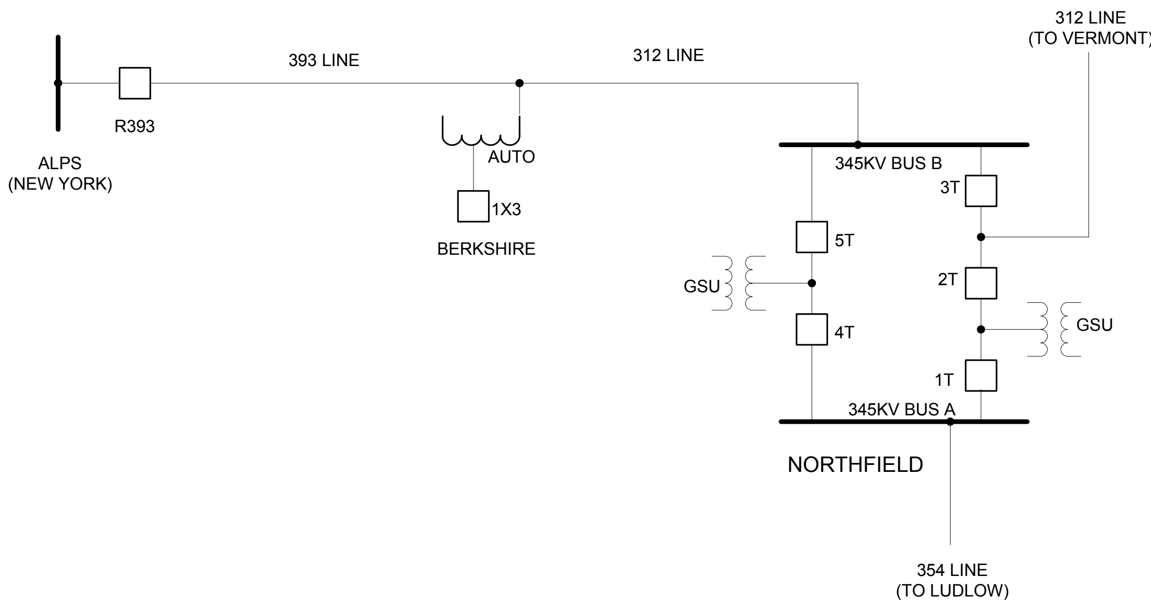


Figure 9: Basic 1-Line of 312/393 Line

All three terminals of the 312/392 line tripped open on February 17, 2006 at about 11:37AM (see table 3 for abbreviated SOE). The SOE does not show operations for the Alps terminal. The Alps terminal took the lead to reclose the line in 30 seconds, but immediately tripped open and locked out. Incidentally, this event causes yet another overtrip, this time of the *Ludlow* 354 line terminal, which successfully recloses.

Time	Station	ID	Device	Operation
11:36:58.308	Northfield	16R	16R-5T-2	Open
11:36:58.310	Northfield	16R	16R-3T-2	Open
11:36:58.322	Ludlow	19S	19S-4T-2	Open
11:36:58.322 (?)	Ludlow	19S	19S-5T-2	Open
11:36:58.344	Berkshire	18C	18C-1X3-2	Open
11:37:04.731	Ludlow	19S	19S-5T-2	Closed
11:37:05.821	Ludlow	19S	19S-4T-2	Closed

Table 3: SOE for 312/393 Line Event

Analysis:

Primary and backup relay targets at Northfield were recorded, indicating ground phase A (yet again phase A!) instantaneous zone 1 trips. No relay targets were found at Berkshire or Alps for the initial fault. However, relays at the Alps terminal recorded targets following the reclose of that terminal; these targets at Alps would cause some confusion during subsequent evaluation of this disturbance.

The primary relay at Northfield triggered a record for the disturbance, shown here in figure 10.

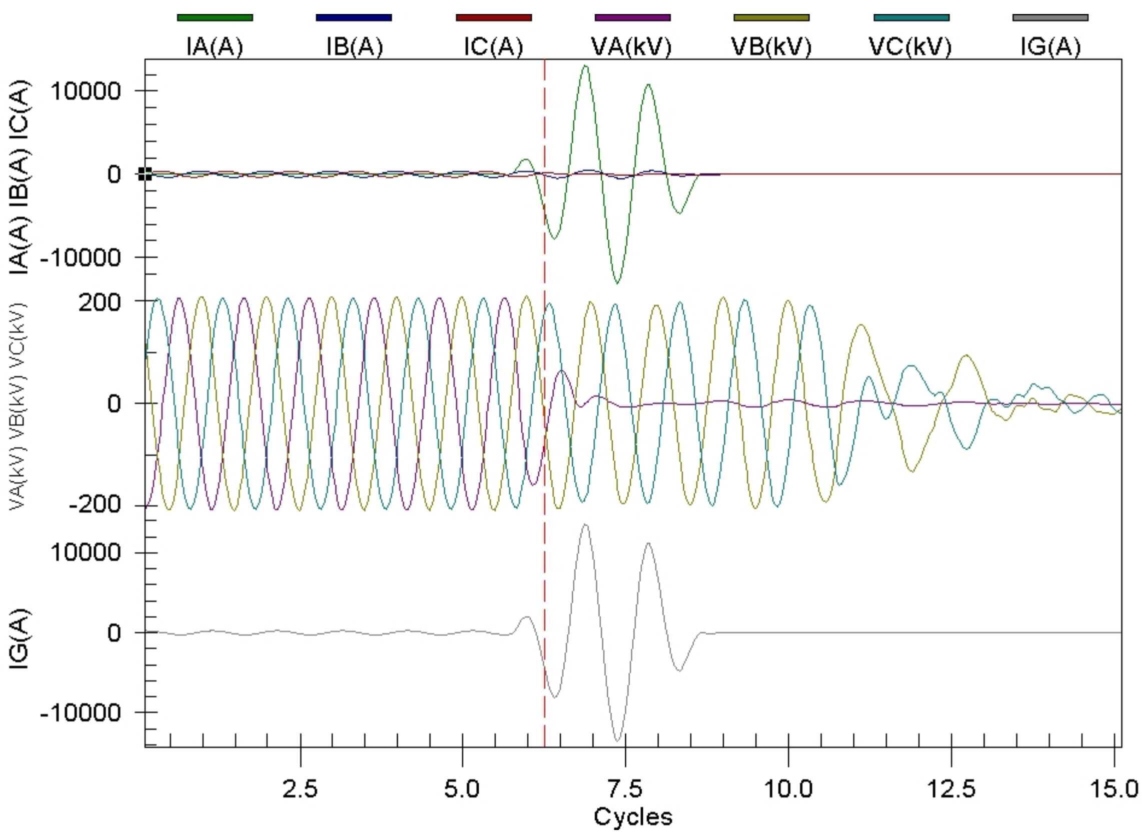


Figure 10: Northfield Primary Relay Record for Initial 312/393 Line Event

The backup relay record for the initial fault is shown in figure 11.

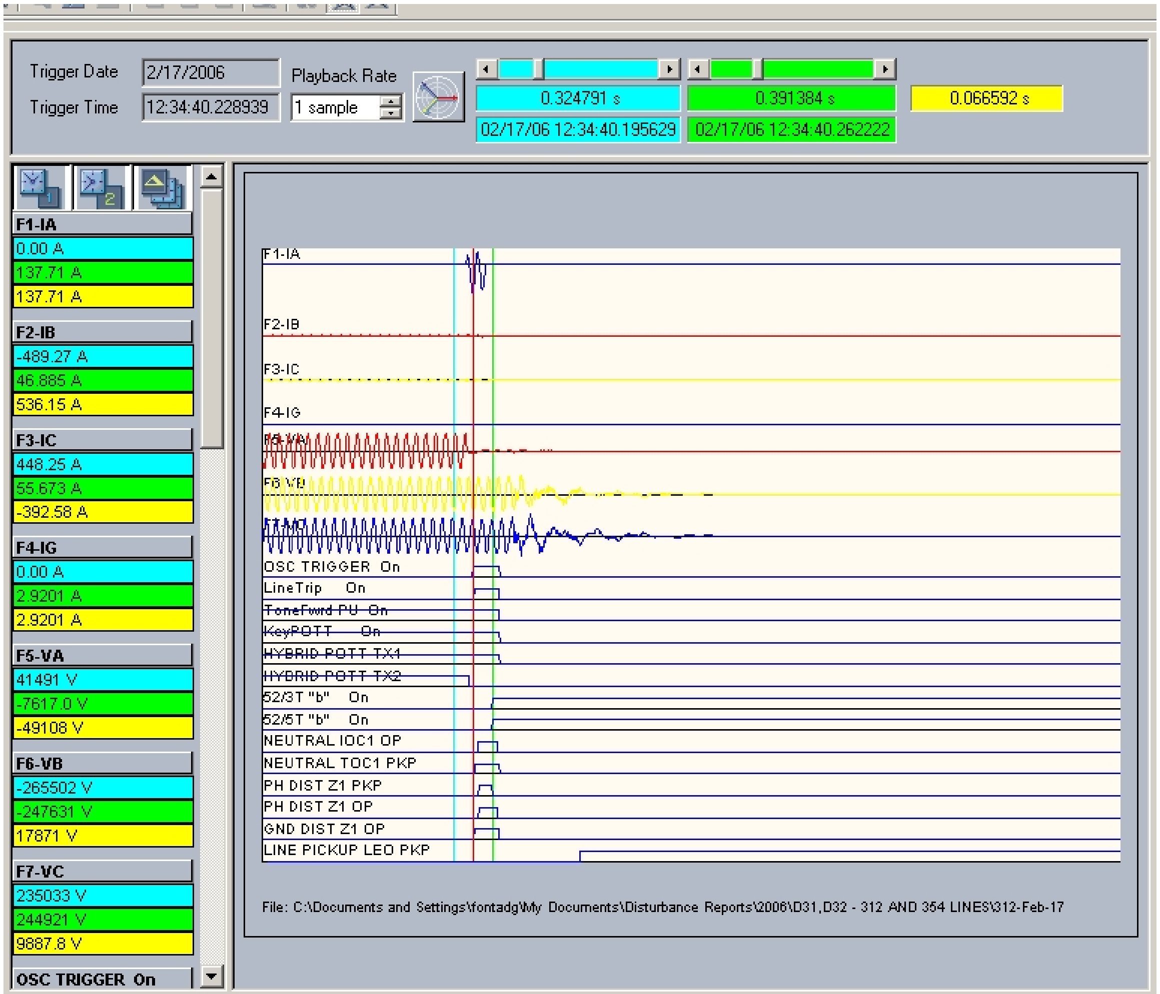


Figure 11: Northfield Backup Relay Record for 312/393 Line Event

One of the many frustrations with fault disturbance analyses is making the physical evidence of the fault (if we can even find this evidence), typically in the form of observed physical damage or a bonafide sequence of operations, agree with what the relay or DFR records tell us. Or, perhaps more appropriately, have the DFR or relay records tell us what happened, and then be able to verify this in the field. We were definitely lucky enough to observe the aftermath of these bus failures, but it was still difficult to determine what exactly transpired after the bus separated from the terminal.

When we examine the attached picture (picture 7) that was taken after the fault occurred, we can see that the bus indeed broke away from the terminal and came to rest on what were then de-energized lower A, B and C phase line terminal busses. When the bus initially fell, it created a phase A to ground fault only on the Northfield side of the open. Since Alps and Berkshire relays did not show any targets for this initial fault, these terminals could only have been transfer tripped by the backup relay at Northfield (in accordance with standard NU practice).

With phase A was now open at Northfield, and the fallen bus resting squarely across the lower busses, the reclose at Alps should have closed into a phase B to C fault.

Picture 7: Northfield 312/393 Line Terminal Following Bus Insulator Failure

National Grid sent us a record they retrieved from the backup relay at the Alps end of the line; this is shown in figure 12. It shows a phase A to C fault, and not phase B to C as had been predicted by the forensic evidence at Northfield.

After much discussion between our Test Department and National Grid, we discovered that the wave traps at Alps were actually located on phase C and not phase B per NU's standard 345kV practice. This led to the discovery that the phases were labeled differently at the 2 substations (see Figure 13) and explained why the phase B to C reclose fault at Northfield was seen as a phase A to C fault at Alps.

Relay operations were correct and desired for this event.

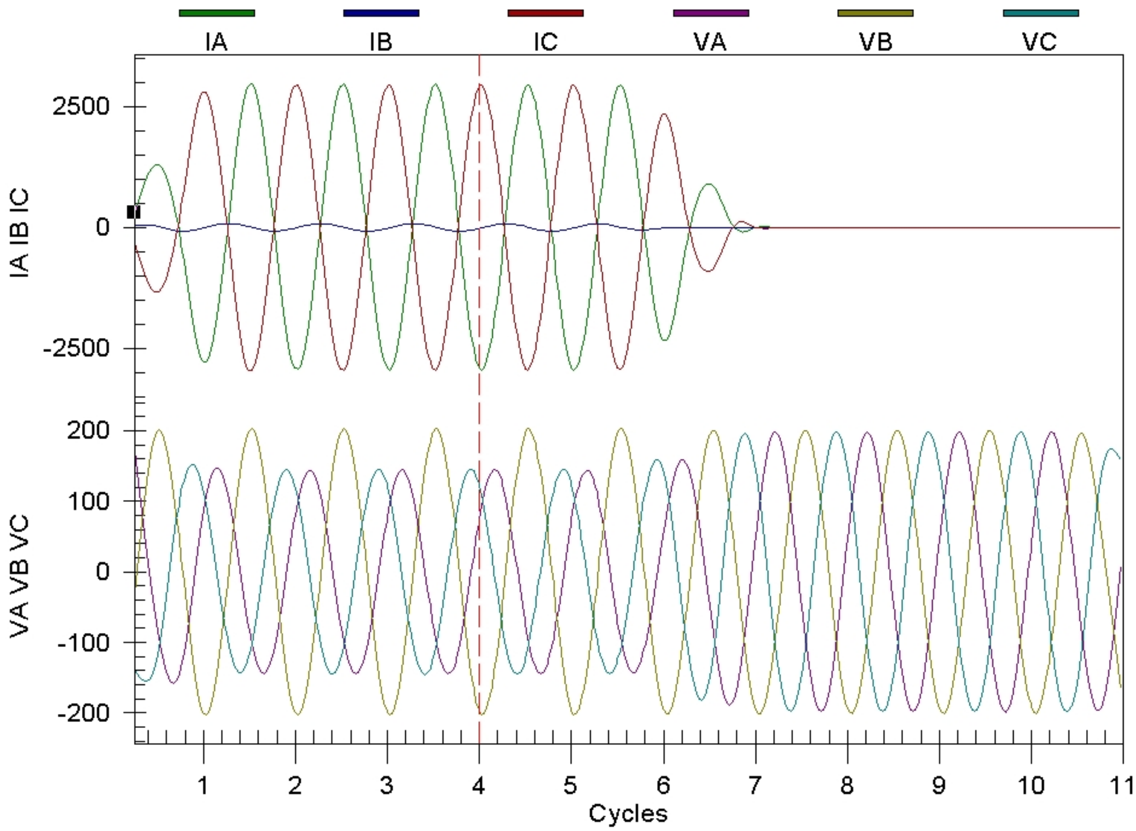


Figure 12: Alps Relay Record Showing Phase A to C Fault

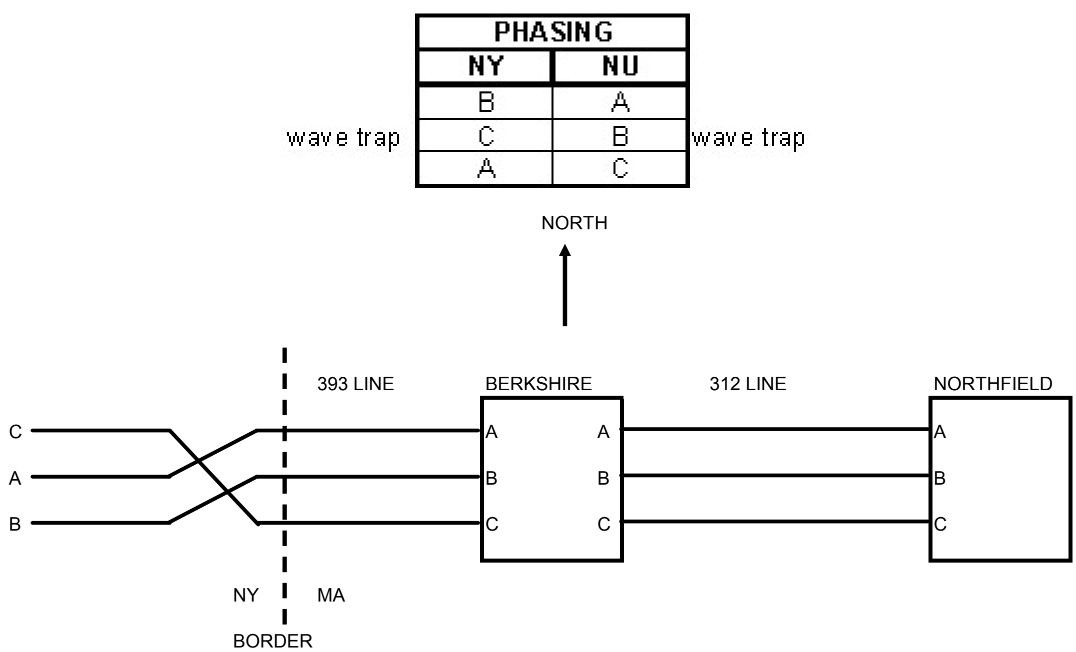


Figure 13: Phase Labels Between Alps and Northfield

Fourth Event: Frost Bridge 352 Line Terminal, March 3, 2006

System Operations:

The 352 line is a 2 terminal line running between our Long Mountain and Frost Bridge substations (see simple one line below in Figure 14).

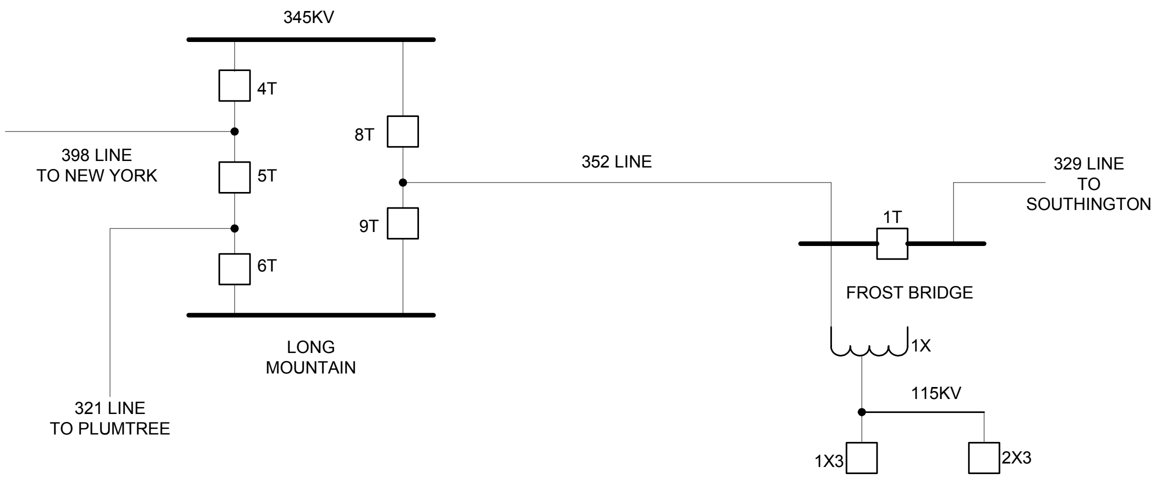


Figure 14: One Line of 352 Circuit

At the time of this event, digital relays protected the Long Mountain terminal of the line, but electromechanical relays were still employed at Frost Bridge. The 1T breaker at Frost Bridge and the 329 line to Southington were out of service prior to the event, so the 1X auto was fed from the 352 line only (recognize that there are weak 115kV sources onto the 345kV system).

Early in the afternoon of March 3, 2006, both terminals of the 352 line tripped. Since reclosing had been turned off due to the 329 line outage, no reclose attempts were taken onto the line, and CONVEX did not attempt a remote SCADA close.

Analysis:

Targets recorded included C (for a change!) phase to ground and overcurrent at Long Mountain and unsupervised instantaneous zone 1 phase and ground distance elements at Frost Bridge. Closer examination of relay records from the Long Mountain relays indicated that the primary DCB scheme tripped the line via its supervised ground directional overcurrent element. Impedance elements did not pick up on the primary or backup relay. So it would appear again that the bus faulted solidly on one (the Frost Bridge) side of the open, but Long Mountain only saw an open circuit on the C phase. So the mystery this time was to determine why the open at Frost Bridge created enough fault current to bring the DCB scheme into play.

Examination of the primary relay record (shown in figure 15) from Long Mountain showed appreciable sustained ground current flowing from that terminal for 4.5

cycles before trip. The record shows that B phase was also involved somewhat in this fault. Note element 67N2 picking up about 1 cycle prior to trip (OUT1 and OUT2 are the breaker trips). Setpoints for carrier stop and trip for this relay are 240A with a 1 cycle time delay. There was more than enough ground current to trip the Long Mountain end of the line.

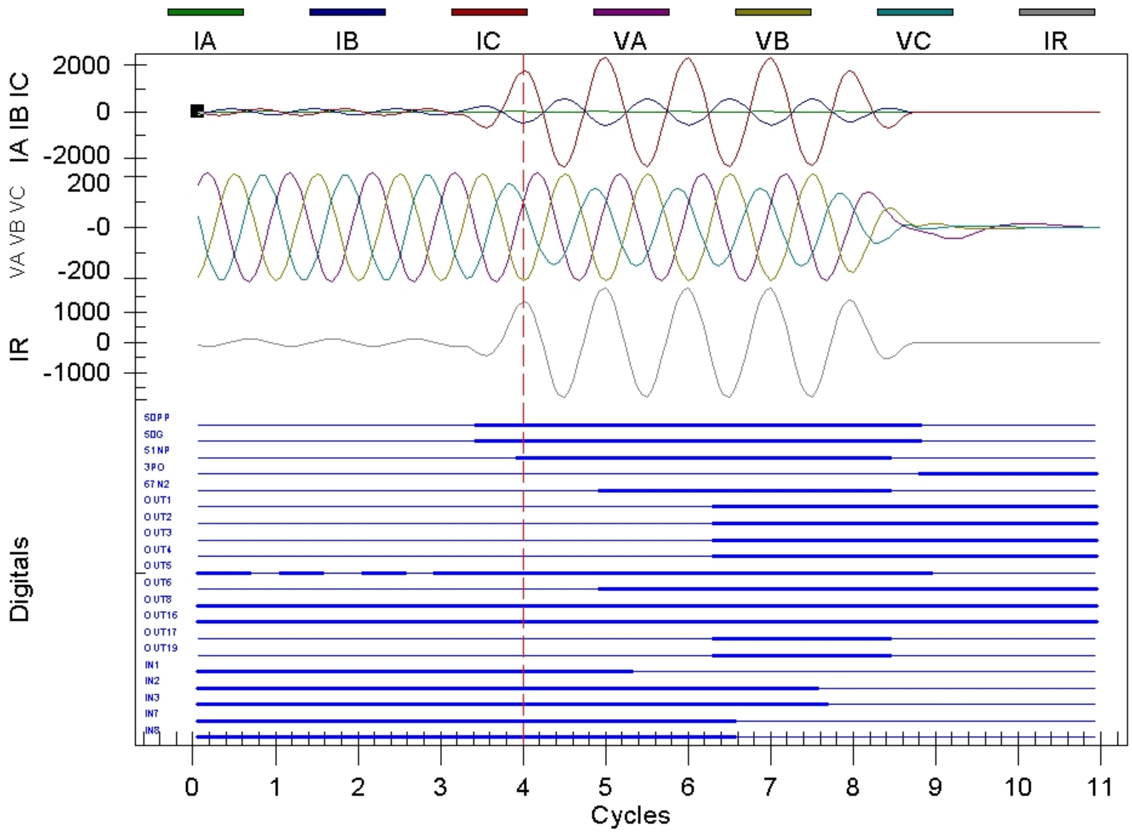


Figure 15: Long Mountain 352 Line Primary Relay Record

Fault simulations demonstrated that the presence of the auto played a significant role in this event by providing a sort of current divider network for Long Mountain current to flow into the fault on the Frost Bridge side of the open (see figure 16 below), a sort of “back door” to the fault. Involvement of B phase also had to have increased the ground current flowing from Long Mountain.

Figure 17 shows the Frost Bridge DFR record and pictures of the aftermath of the fault follow. Note that this time the wave trap for the line was taken out by the falling bus. Picture 10 is a shot of the fallen insulator. Relay operations were correct and desired.

The mechanism of failure in all of these bus events was determined to be cracking due to moisture accumulating within the insulator and freezing. Picture 11 shows ice that had formed on a healthy insulator. There are 24 sets of these insulators located at 10 stations across the NU system. Needless to say, all are currently scheduled for replacement.

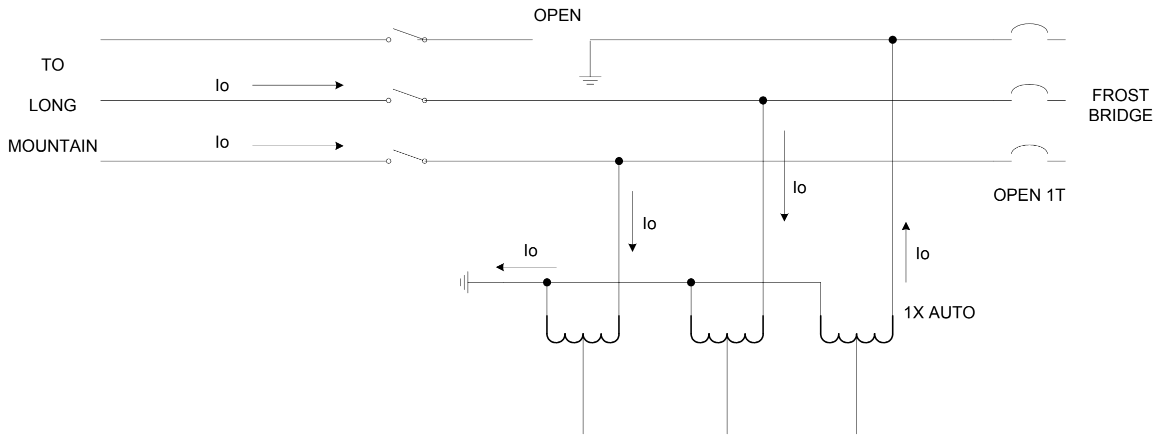


Figure 16: Ground Fault Current Flow at Frost Bridge

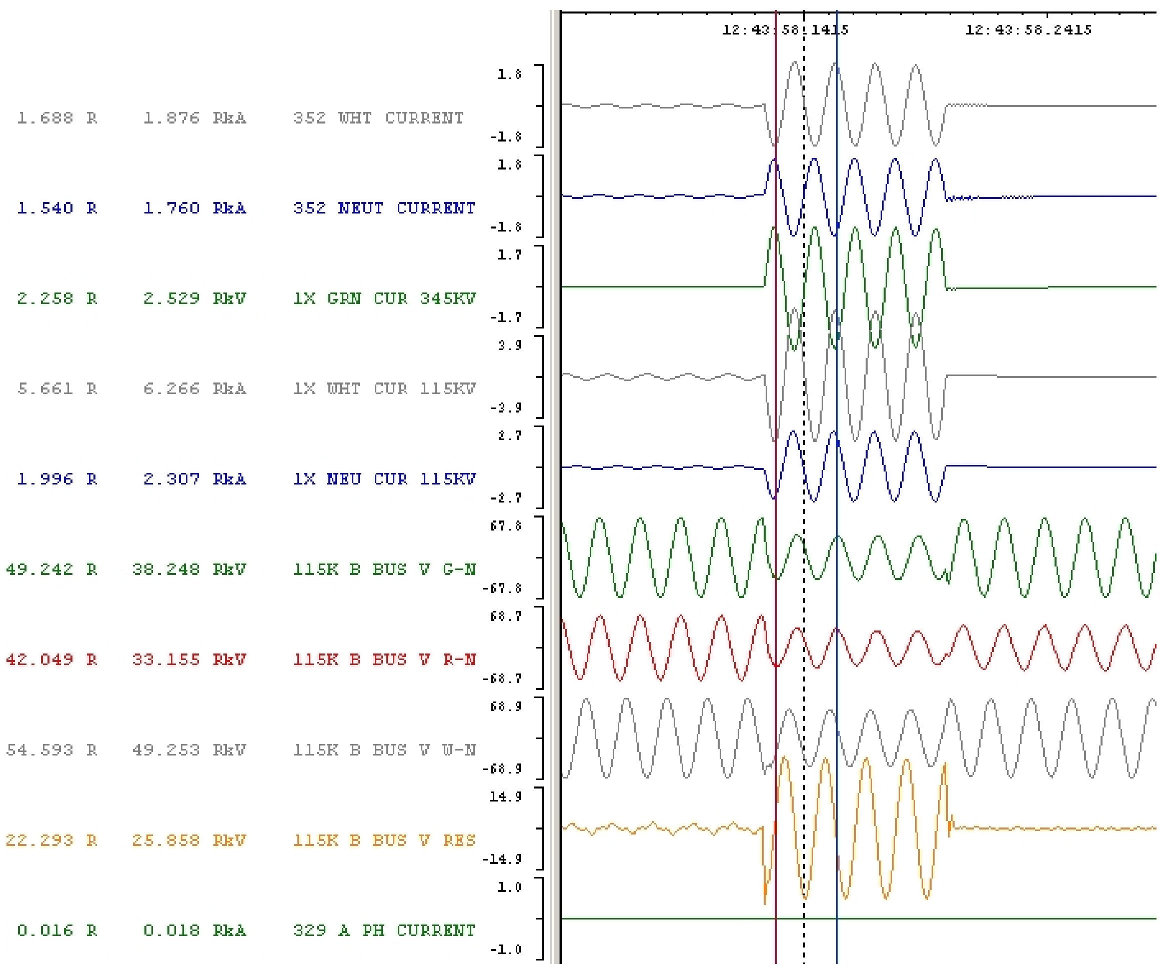
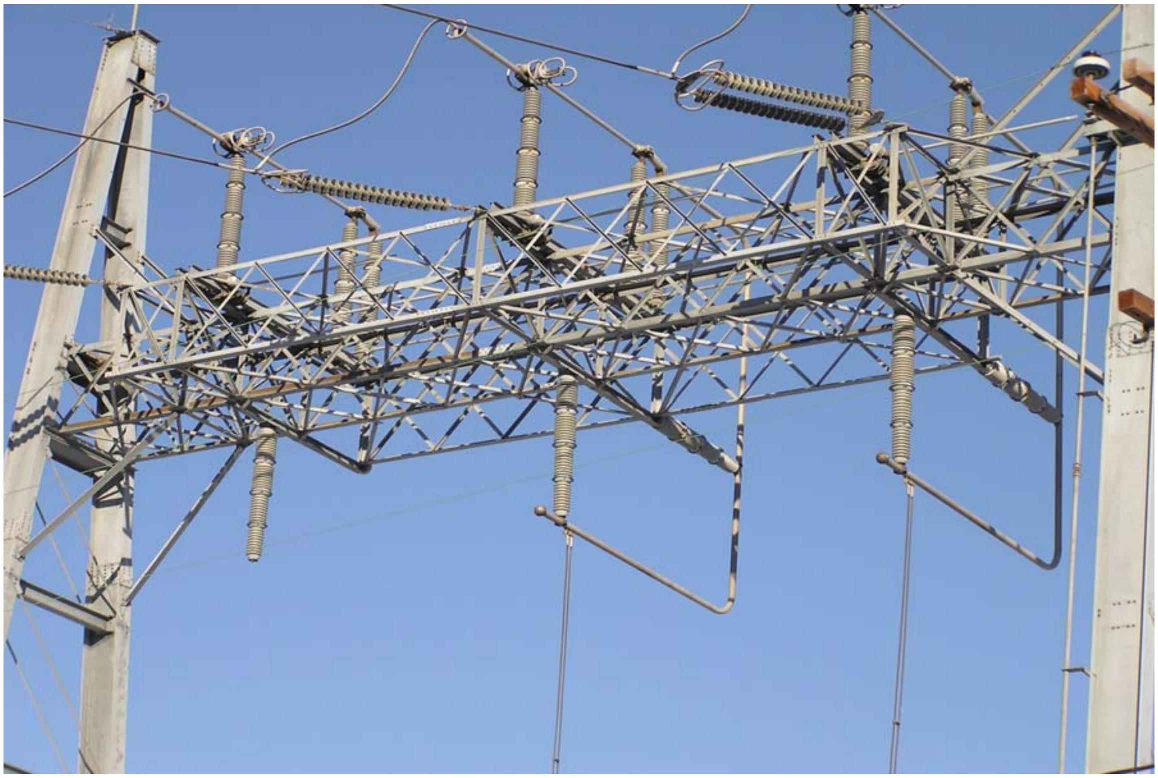


Figure 17: Frost Bridge 352 Line DFR Record



Picture 8: Frost Bridge 352 Line Terminal

Picture 9: Fallen Trap at Frost Bridge

Picture 10: Failed Insulator at Frost Bridge

Picture 11: Ice Formation on Healthy Standoff Insulator

Ludlow "Pliers" Event: September 20, 2006

System Operations:

We can often get a feel for how successful an installation project is going to be by observing how well the first day goes. This one didn't go so well.

Primary and backup line as well as breaker failure relays were scheduled for replacement on the Ludlow to Northfield 354 line last September. Right at the start of installation we convinced ourselves why we needed to replace the breaker failure relays on this line when we inadvertently dropped a pair of pliers onto the Ludlow 5T relay (see figure 18 for one line).

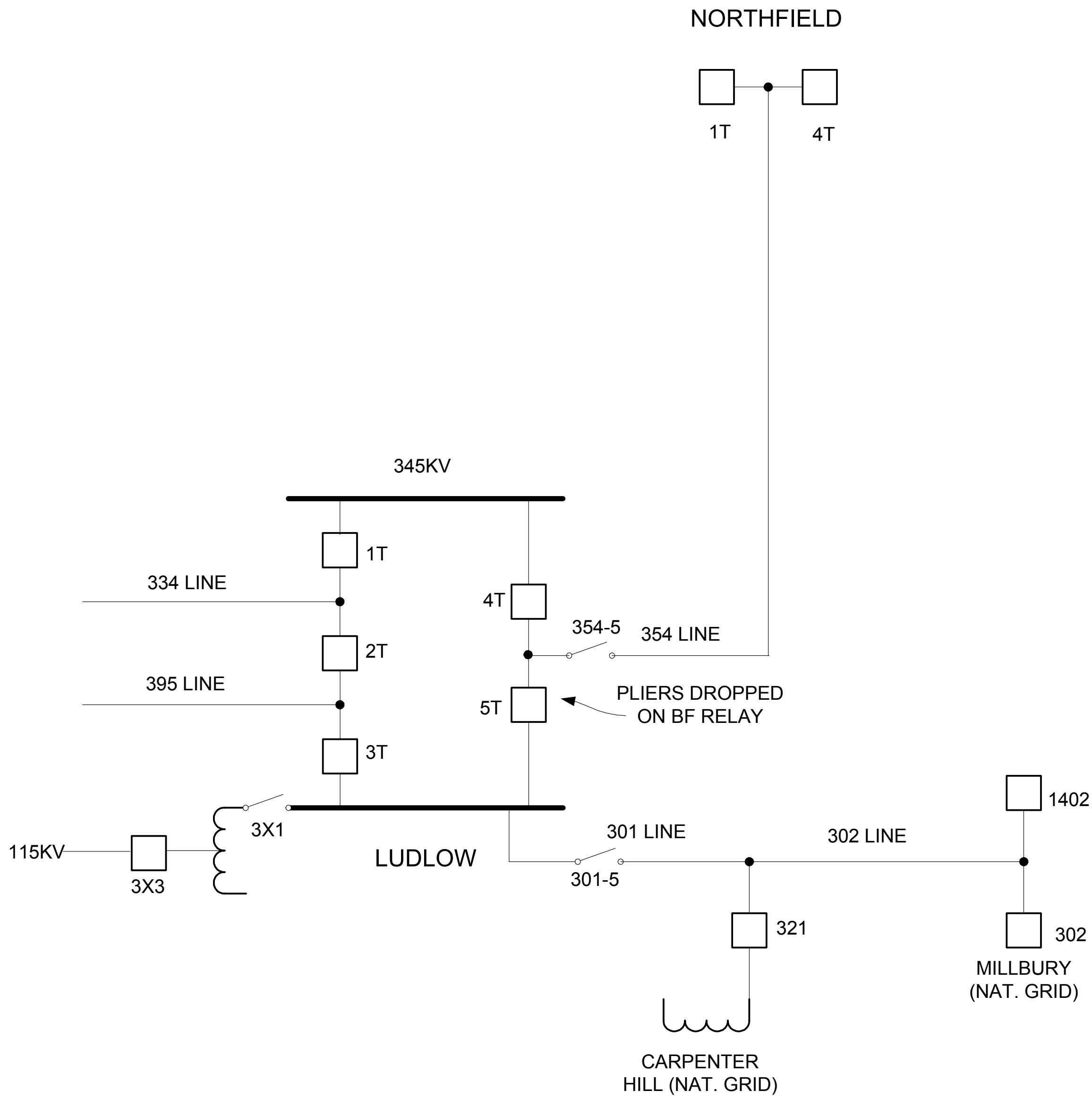


Figure 18: One Line for "Pliers" Event

Immediately, the 5T breaker went into breaker failure even though it had not failed to open for a true fault event. Consistent with NU practice, breakers 3X3, 3T and 4T were tripped, the remote ends of the 301 and 354 lines were transfer tripped (or so we thought), and the line MOD's for both the 301 and 354 lines at Ludlow were opened (see Table 4 for SOE). National Grid terminal operations were not recorded by NU SCADA and hence are not shown here.

DATE/TIME	STATION	ID	DEVICE	OP
09/20/2006 8:43:48.821	Ludlow	19S	19S-3T-2	Open
09/20/2006 8:43:48.828	Ludlow	19S	19S-4T-2	Open
09/20/2006 8:43:48.837	Ludlow	19S	19S-3X3-2	Open
09/20/2006 8:43:48.856	Northfield Mountain	16R	16R-4T-2	Open
09/20/2006 8:43:48.857	Northfield Mountain	16R	16R-1T-2	Open
09/20/2006 8:43:49.569	Ludlow	19S	301-19S-5	Open
09/20/2006 8:43:50.541	Ludlow	19S	354-19S-5	Open
09/20/2006 8:43:56.671	Northfield Mountain	16R	16R-1T-2	Closed
09/20/2006 8:43:56.683	Northfield Mountain	16R	16R-1T-2	Open
09/20/2006 8:43:58.969	Ludlow	19S	19S-5T-2	Open

Table 4: SOE for "Pliers" Event

Now the odd operations transpired. First off, the Northfield terminal (breaker 1T) of the 354 line reclosed, even though it can only do this live bus-live line. It immediately tripped open, followed by the Ludlow 5T also tripping open (the 5T at Ludlow should have been locked out from operation by the opening of its DC control circuit breakers). The breakers at Millbury also tripped along with the Ludlow 5T.

Analysis:

Discussions with National Grid revealed that only one of their 2 terminals transfer tripped when the quasi breaker failure operation occurred at Ludlow. Carpenter Hill successfully tripped, but the Millbury terminal of the 302 line did not. This explained why the 1T breaker at Northfield reclosed live-live, as the 354 line was kept live though the still closed 5T breaker at Ludlow.

NU's standard design for transfer trip maintains the transmit signal until the line MOD opens (an MOD contact which opens only when the MOD is fully open is used to maintain the transmit signal – see figure 19). But when the 354 line MOD opened, we believe it flashed over, now creating a fault before it fully opened and interrupted the transfer trip signal to Northfield. The SOE shown in table 4 above is somewhat misleading in that it shows the 2 line MOD's opening well before the Northfield 1T reclosed. But MOD indication to CONVEX is taken from MOD contacts that change state immediately after the MOD begins to open or close. These change state a lot sooner than the contact that is used to maintain the transfer trip signal. The point here is that the MOD's were most probably still in motion when the 1T at Northfield reclosed. We theorized that the transfer trip signal was lost when the 354 line flashed over (due to induced noise), but voltage on the line was high enough to allow the Northfield terminal to reclose. The breaker immediately retripped once the transfer trip signal was re-established.

It's also significant to note that IRIG-B clock signals had not yet been tied into the relays at Ludlow, so these times are off and it is difficult to determine exactly what happened when.

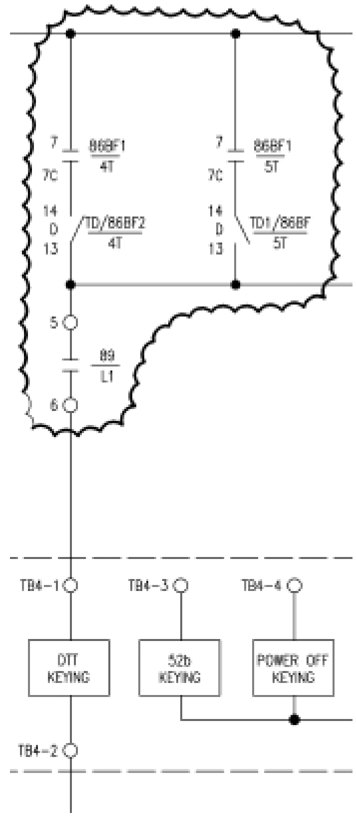


Figure 19: Typical TT Keying Circuit

Figure 20 is a relay record from the backup relay on the 301 line. This is the relay that issued the trip to the Ludlow 5T breaker. We can see from the record that a phase B to C fault ensued when the 354 line MOD opened. We know from this record that the fault was behind the terminal because a zone 3 non-tripping reverse element is picked up. The terminal was tripped by the relay's non-directional switch onto fault element (line pickup element). This element is typically active only 30 cycles after a breaker is closed. Even though the breaker was already closed prior to the fault, there was very little load current flowing and the onset of high fault current when the MOD opened caused this element to pick up. The record also shows that permission was received from the remote Millbury station (POTT RCVD ON), signifying that the remote overreaching zone 2 element saw the fault as well.

One other mystery remained to be solved: why did the Ludlow 5T breaker open to clear the fault if it's shunt trip breakers had been opened by the initial breaker failure operation?

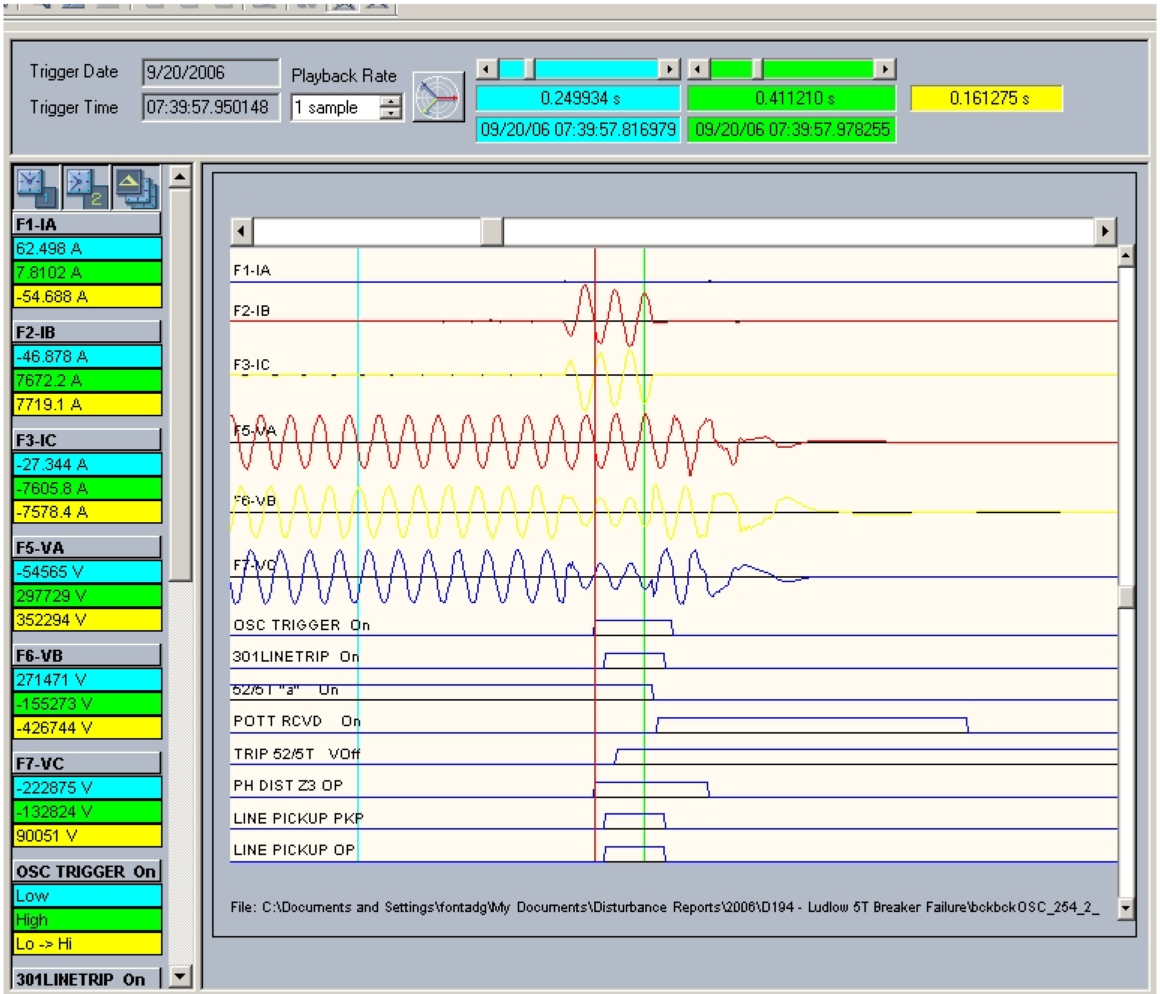


Figure 20: 301 Line Backup Relay Record

A review of figure 21 below, which is a cross-section of an identical breaker failure scheme as is used on the 5T breaker, shows separate relay contacts tripping the 86's and the shunt trip breakers. We can only draw the conclusion that the contacts tripping the 86 lockout relays were the ones actuated by the pair of pliers hitting the relay, and the shunt trip contacts did not actuate.

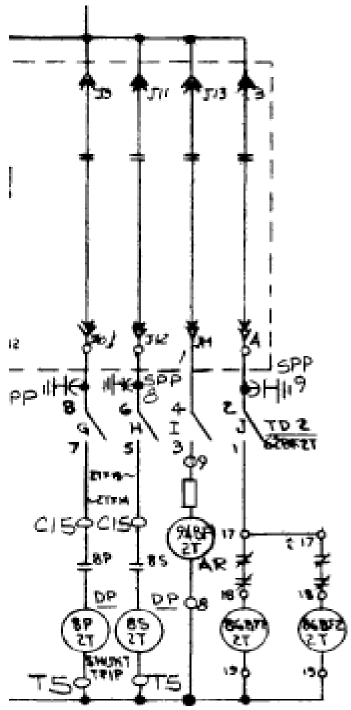


Figure 21: Breaker Failure Relay Trip Circuit

Relay operations for this event were anything but correct and desired, but they were precipitated by an unusual external non-system stimulus.

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