Analysis of Mutual Coupling Effect on DCB Scheme Operation for an External Fault

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Introduction

An 115kV line fault event occurred that resulted in two unexpected operations of two 345kV paralleled bulk power system (BPS) lines. This paper presents an analysis of the event utilizing fault records, from digital fault recorders, and short circuit simulation to determine what happened and why one of the 345kV lines operated at both terminals and the other line operated at one terminal for the external fault on the 115kV parallel line. The fault records captured by disturbance monitoring equipment and the short circuit simulation provided valuable data which gave an insight into the nature of this disturbance. The fault records provided analog and digital data which allowed an efficient investigation and accurate diagnosis of the event.

Incident Summary

On March 15th, 2002, the National Grid Control Center reported that at 06:21:32 a C-phase to ground fault occurred on the 115kV C129N line. The fault was located 27% of the distance between Depot Street (DST) and West Medway substations. The Beaver Pond terminal of the C129N Line tripped instantaneously and the Millbury #2 terminal of the C129N Line tripped in 49.5 cycles. Simultaneously, the Millbury #3 and West Medway terminals of the 345kV 323 Line opened in 4.5 cycles. After the loss of the 323 Line and the Beaver Pond terminal on the C129N Line, the 345kV 357 Line tripped in 25 cycles at the West Medway terminal only. The time of operations is listed in Table 1 and the line configurations are shown in Figure1. The C129N, 323 and 357 lines share a common right-of-way with another 115kV D130 line, where the two parallel 345kV lines and the two parallel 115kV line are with zero sequence isolation, except for mutual coupling. The Control Center reported that the C129N line tripped and auto-closed correctly at both terminals, the 323 line tripped at both terminals simultaneously to the C129N Line fault and the 357 Line operated after the open of the 323 Line and the C129N Line at the Beaver Pond. Relay targets reported for this event are as follows:

- Millbury #2: C129N Time-Delayed Directional Distance Ground Zone 2 (DDGZ2, or 21N-Z2)
- Beaver Pond: C129N Directional Distance Ground Zone 1 (DDGZ1, or 21N-Z1)
- Millbury #3 323 Carrier Directional Ground Trip (CDG, or 67N) [1]
  323 Direct Transfer Tripping Send – Keyed by the CDG Trip

  357 Carrier Directional Ground Start (CDG, or 68)
- West Medway [2] 323 Carrier Directional Ground Trip (CDG, or 67N)

  357 Carrier Directional Ground Trip (CDG, or 67N)
  357 Carrier Blocking-Tripping Signal Receive

Note [1] *A part of the 323 line Carrier Comparison Blocking, DCB, scheme*
Note [2] *West Medway substation is NStar's property.*

Table 1 – Time of Operations for 2002-03-15 Event
(Set t = 0 while the fault occurred at 06:21:32:00 [3])

06:21:32:075	t = 4.5 cycles	Beaver Pond	129 CB	OPEN
06:21:32:075	t = 4.5 cycles	Millbury #3	314 & 343 CBs	OPEN
06:21:32:075	t = 4.5 cycles	West Medway	107 & 108 CBs	OPEN
06:21:32:487	t = 29.2 cycles	West Medway	104 & 105 CBs	OPEN
06:21:32:825	t = 49.5 cycles	Millbury #2	C129 & 29-41 CBs	OPEN
06:21:32:487	t = 29.2 cycles	West Medway [4]	104 CB	AUTO-CLOSE
06:21:47:075	t = 904.5 cycles	Beaver Pond	129 CB	AUTO-CLOSE
06:21:47:075	t = 904.5 cycles	Millbury #3	314 CB	AUTO-CLOSE
06:21:37:075	t = 304.5 cycles	Millbury #2	343 CB	AUTO-CLOSE
06:21:37:825	t = 349.5 cycles	Millbury #2	C129 CB	AUTO-CLOSE
06:22:42:825	t = 4249.5 cycles	Millbury #2	29-41 CB	AUTO-CLOSE

Note [3] *since the actual Sequence-of-Event is no longer available, the time listed at millisecond level may not be accurate. It is used for discussion purpose only in this paper.*
Note [4] *it was informed by NStar that the auto-closing of the 104 breaker was very fast, with no time-delay. It was checked and fixed by NStar but will not be further discussed in this paper. The time of auto-closing for the 105 breaker at the West Medway will not be discussed in this paper as well. There was no auto-close on the 107 and 108 breakers due to they being opened by the DTT.*

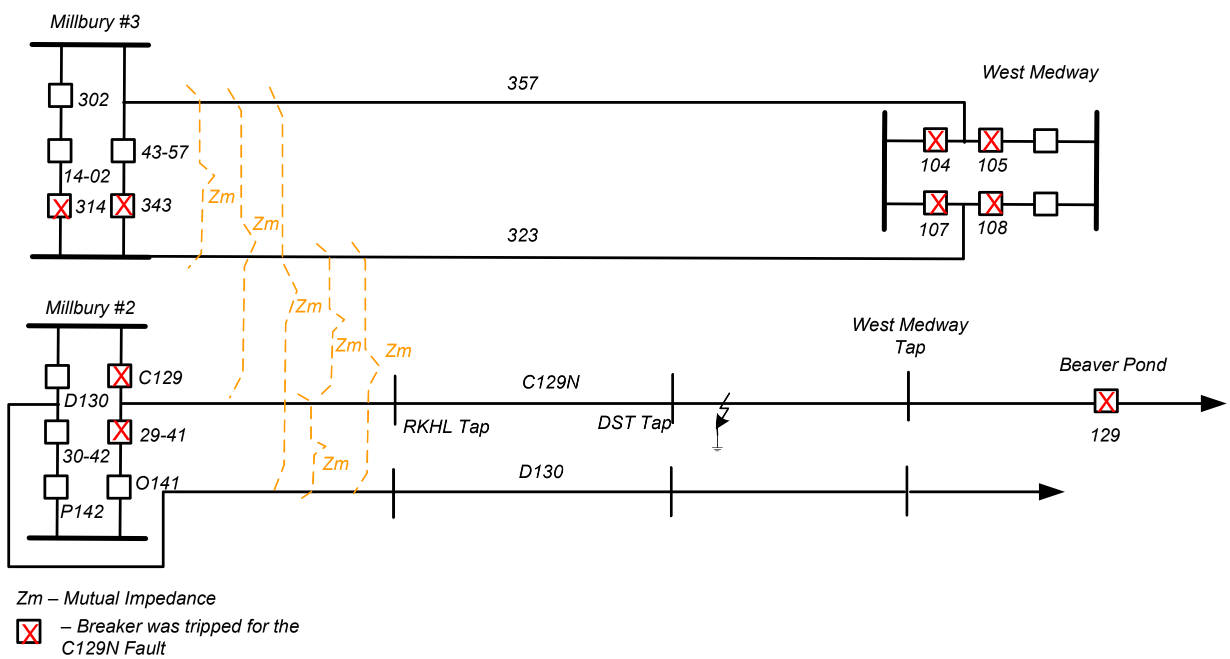

Figure 1. System One Line Diagram with the C129N Line Fault

Investigation and Finding

Was it a single-circuit or multi-circuit fault? Could it be a simultaneous fault? The first step of the investigation was to verify the system configuration. The four (4) lines share a common right-of-way, where the C129N and 323 lines are next to each other and inside the right-of-way. It was also noticed that the two parallel 345kV lines and the two parallel 115kV lines are with zero sequence isolation, except for mutual coupling (Figure 1). Next, the relay targets, the time-of-operations and the fault records captured by the Millbury DFRs (Figure 2) were collected, which indicated that a C-phase-to-ground fault occurred on the 115kV C129N Line, located 27% of the distance between Depot Street and West Medway substations. Further review of the same record concluded that no fault had occurred on the paralleled 323 and 357 Lines, however, there was significant neutral current (3I0) flowing on the 323 Line from West Medway to Millbury #3 during the C129N fault due to the effects of mutual coupling. Based on the relay targets and fault records, the detailed finding was summarized as follows:

1. The C129N Line directional distance ground Zone 1 (DDGZ1) relay at the Beaver Pond sensed the fault and tripped the terminal within Zone 1 time (4.5 cycles). The Millbury #2 terminal of the line cleared in 49.5 cycles by the time-delayed directional distance ground Zone 2 (DDGZ2) relay. It was further verified that all relay operations involving the C129N relay settings were correct.

2. During the C129N fault, the 323 Line opened at both the Millbury #3 and West Medway (NStar) terminals. The line tripped at both terminals within 4.5 cycles. The current flow through 323 Line during the C129N fault for 3I0 was from the West Medway to Millbury #3. The 3I0 magnitude on the 323 Line at the Millbury #3 end was approximately 440 to 460 amperes, which is above the carrier directional ground trip (CDG) relay pickup of 360 ampere. (Note: The CDG function is a part of the 323 Carrier Comparison Blocking, DCB, scheme and the relay's directional control is zero-sequence voltage polarized.) As a fact, the 323 Line CDG relay at the Millbury #3 picked up and cleared the local terminal and sent a direct transfer tripping (DTT) signal to the West Medway resulting in the opening of the breakers 107 and 108 on the 323 Line. Since the breakers at the West Medway opened by the DTT, there was no auto-close on the 107 and 108 breakers at the time. It was most likely that the 323 CDG relay at the Millbury #3 misoperated due to the mutual coupling effects between the D130, C129N, 323 and 357 lines.

3. After the loss of the 323 Line and the Beaver Pond end of the C129N, the 357 Line became a main supply to the fault. It is important to keep in mind that the Millbury #2 end of the C129 Line had not yet cleared the fault. The 3I0 ground current, flowing from West Medway to Millbury, sensed by the 357 CDG start relay at the Millbury #3 was exceeded the pickup point of 200 amperes, therefore, the reverse-looking CDG start relay picked up and sent a carrier blocking signal to the West Medway. The 3I0 also exceeded the pickup setting of the 357 CDG trip relays at the West Medway. While, the 357 Line was correctly restrained from tripping due to the receipt of carrier blocking signal from the Millbury #3. As per further finding from NStar, for some unknown reason, approximately 29 cycles into the fault, there was a two (2) cycle interruption of the carrier blocking signal (i.e. a carrier hole) on the 357 Line at the West Medway terminal. This resulted in a single-end trip of the 357 Line at the West Medway only. It appeared that there were some problems on the 357 power line carrier system at this terminal.

Based on the findings described above, the investigation focus then moved to identify why did the 345kV 323 CDG trip function of the DCB scheme at Millbury #3 respond to the 115kV C129N fault in the non-trip direction , and why did the 357 blocking signal was interrupted to receive for a short period of time at the West Medway.

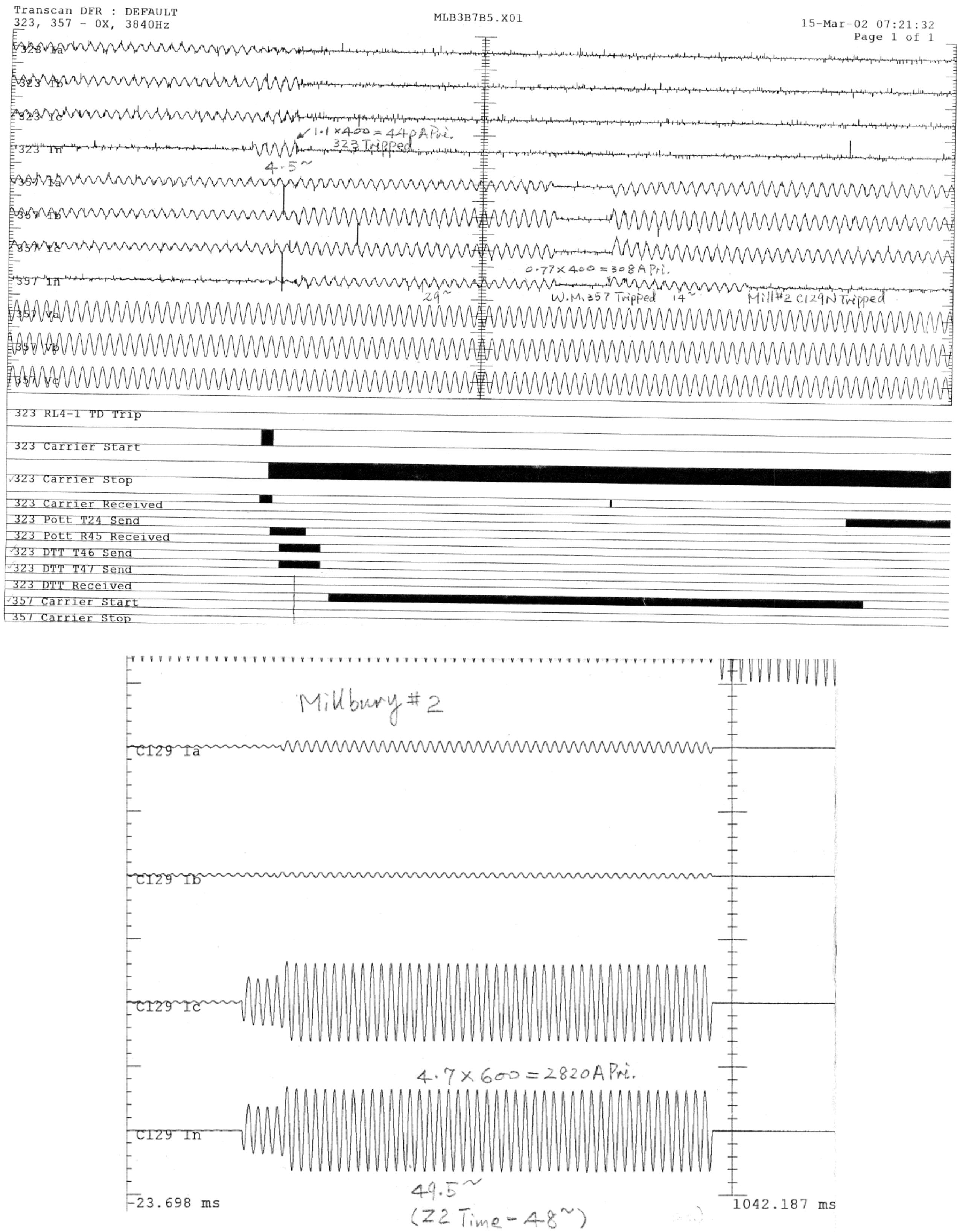

Figure 2. C129N, 323 and 357 Line DFR Records at Millbury Substation at 06:21:32:00

Explanation and Analysis

Transmission line parallel along the same right-of-way present problems to the associated line relays since the lines are mutually coupled. For a positive and negative sequence, mutual impedances are usually less than 10% of the self-impedances and so can be neglected. However, for zero sequence, mutual impedance can be up to 70% of the zero sequence self-impedance and so is significant. Furthermore, when transmission lines with different voltage are on the same right-of-way, the zero sequence mutual impedance is more significant for the line with the higher voltage than it is for the lower voltage line. Therefore, mutual impedance affects the magnitude of ground fault currents. It can also result in incorrect directional sensing on the unfaulted lines for some fault locations on the parallel lines if the mutual coupled lines are with zero sequence isolation, except mutual coupling, in other words, they are not connected on the same bus.

Refer to the system one-line configuration (Figure 1), it is noted that the 115kV C129N and D130 lines are mutual coupled and tied together on the same bus at the Millbury #2 substation, and the 345kV 323 and 357 lines are mutual coupled and tied together on the same bus at both Millbury #3 and West Medway substations. However, the two pairs of the lines are not connected together through transformers, i.e. with zero sequence isolation, except mutual coupling. This fact implies that, during this fault, the directional ground relays on the 323 and 357 lines might challenger to sense direction correctly. Besides the possible directional sensing issue, it is believed that the increasing magnitude of ground fault current, i.e. 3I0, on the two 345kV lines contribute to the CDG false operations.

In order to quantitatively analyze the false operations on the 323 and 357 CDG relays, several fault simulations were conducted by using the short circuit program. The simulation results showed that:

1. Due to the physical arrangement between the lines and the different voltage level of the lines (Figure 1), the mutual coupling effect was more significant on the 323 lines than on the 357 and D130 lines during the original C129N fault. In other words, the magnitude of the ground fault current 3I0 on the 323 Line increased more significantly than on the other two lines. In addition, the level of magnitude increase of 3I0 also depended on the fault locations. For the C129 faults located between the Rocky Hill (RKHL) tap and West Medway tap, the ground current 3I0 on the 323 Line might exceed the pickup setting of 360 amperes on the 323 CDG relays at the Millbury #3 and West Medway. See Table 2 in detail.

2. Since the faulted C129N line is with zero sequence isolation, except mutual coupling, with the 323 and 357 lines, mutual inductance might cause incorrect directional sensing on the 323 line CDG relays for faults on the C129N Line between the Rocky Hill tap and West Medway tap. Therefore, the CDG relays at both terminals might see the C129N faults as internal faults. See Table 2 and Figure 3 in detail.

3. Due to the physical arrangement between the lines (Figure 1), the mutual coupling effect was much less significant on the 323 and 357 lines for the D130 line faults than for the C129N faults. The fault simulation concluded that the 323 and 357 line CDG relays at both ends will not misoperate on the D130 ground faults because the 3I0 on the two lines is lower than the CDG pickup level. See Table 4 in detail.

4. Based on bolted fault simulation results, magnitude of the ground current 3I0 on the 323 Line at the Millbury #3 end could be as high as 526 amperes during this C129N fault (See Table 2), which is a little above the actual 3I0 of 460 amperes captured from the fault records. This indicated that the fault was a non-bolted fault with a small C-phase-to-ground impedance or resistance involved.

   In additional, the fault simulation results quantitatively proved how the mutual coupling affected the directional sensing of the 323 CDG relays for this particular fault. The following sequence phasing diagrams (Figure 3) illustrate that the 323 CDG relays at both terminals were fooled into responding to this external C129N fault as an internal fault. However, the directional sensing would work as expected if the fault were located close to the Millbury #2 (Figure 4), which demonstrates how fault location is sensitive to directional sensing on ground relays with zero sequence polarized directional control for mutual coupled lines.

5. The simulation results also showed that magnitude of the ground current 3I0 on the 357 Line at the Millbury #3 end could increase from 81 amperes to 429 amperes after the loss of the 323 Line and the Beaver Pond end of the C129N (Table 3). This result is a little above the actual 3I0 captured from the fault records since the fault was a non-bolted fault.

To investigate why the blocking signal was interrupted briefly on the 357 Line at the West Medway, NStar tested the carrier system and informed that the interruption of the carrier signal could have resulted from a degraded coax cable between the tuner and the carrier transmitter/receiver.

Base on the above discovery, it was concluded that the root cause of the misoperation on the 323 and 357 CDG trip relay at the Millbury #3 and West Medway was due to mutual coupling effect between the four parallel lines.

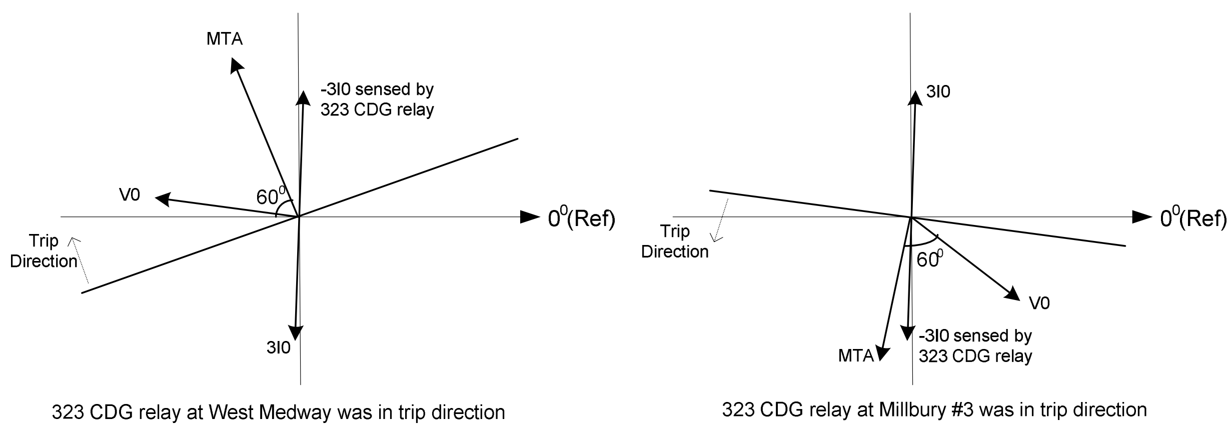

Figure 3. Characteristic of Directional Sensing on the 323 CDG Relays with the C129N Line Fault

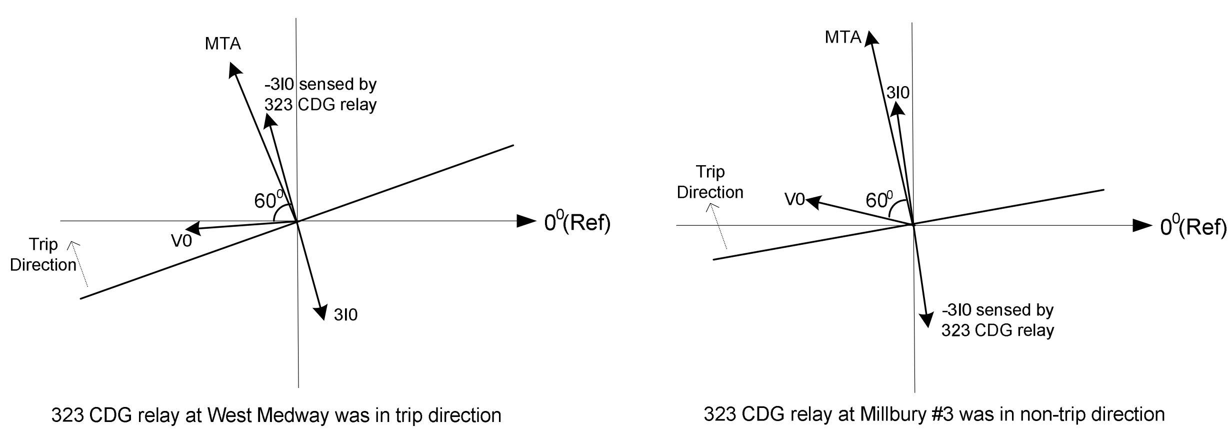

Figure 4. Characteristic of Directional Sensing on the 323 CDG Relays with a C129N Fault at 40% of Millbury #2 - RKHL

Table 2. 3V0/3I0 Sensed by the 323 CDG Relays for C129N Ground Faults

C129N Ground Fault Location	3V0 (Pol Volt) Sensed by 323 CDG @ W Medway (volt)	3V0 (Pol Volt) Sensed by 323 CDG @ Millbury #3 (volt)	3I0 Sensed by 323 CDG @ West Medway (Amp)	3I0 Sensed by 323 CDG @ Millbury #3 (Amp)
20% of Mill #2 - RKHL	1.7 @ -174 deg	7.2 @ 163 deg	59 @ -71 deg	59 @ 109 deg
40% of Mill #2 - RKHL	1.9 @ -178 deg	4.0 @ 167 deg	137 @ -83 deg	137 @ 97 deg
60% of Mill #2 - RKHL	2.2 @ 179 deg	2.1 @ 173 deg	210 @ -86 deg	210 @ 94 deg
80% of Mill #2 - RKHL	2.7 @ 176 deg	0.7 @ -152 deg	305 @ -88 deg	305 @ 92 deg
90% of Mill #2 - RKHL	3.1 @ 175 deg	0.7 @ -82 deg	370 @ -89 deg	370 @ 91 deg
RKHL Tap	3.7 @ 173 deg	1.5 @ -51 deg	460 @ -91 deg	460 @ 89 deg
50% of RKHL – DST	3.9 @ 173 deg	1.7 @ -49 deg	479 @ -91 deg	479 @ 89 deg
DST Tap	4.0 @ 173 deg	1.9 @ -47 deg	500 @ -91 deg	500 @ 89 deg
27% of DST – W Medway Fault Location	**4.1 @ 171 deg**	**2.3 @ -43 deg**	**526 @ -92 deg**	**526 @ 88 deg**
W Medway Tap	4.5 @ 168 deg	3.4 @ -38 deg	596 @ -93 deg	596 @ 87 deg

323 CDG May Misoperate on C129N Ground faults (rows from 90% of Mill #2 - RKHL to W Medway Tap)

Angle of 3V0 (Vpol) Changing

Magnitude of 3I0 Increasing

Table 3. 3I0 Sensed by the 357 CDG Relays for C129N Ground Faults

C129N Ground Fault Location	3I0 Sensed by 357 CDG @ West Medway (Amp)		3I0 Sensed by 357 CDG @ Millbury #3 (Amp)	
	Before 323 & C129 @ BeaverPd or Millbury#2 Opened	**After** 323 & C129 @ BeaverPd Opened	**Before** 323 & C129 @ BeaverPd or Millbury#2 Opened	**After** 323 & C129 @ BeaverPd Opened
20% of Mill #2 - RKHL	161 @ -85 deg	254 @ -84 deg	161 @ 105 deg	254 @ 96 deg
40% of Mill #2 - RKHL	89 @ -92 deg	250 @ -89 deg	89 @ 88 deg	250 @ 91 deg
60% of Mill #2 - RKHL	51 @ -111 deg	272 @ -94 deg	51 @ 79 deg	272 @ 86 deg
80% of Mill #2 - RKHL	36 @ -159 deg	319 @ -97 deg	36 @ 21 deg	319 @ 83 deg
RKHL Tap	63 @ 153 deg	402 @ -101 deg	63 @ -27 deg	402 @ 79 deg
50% of RKHL – DST	72 @ 149 deg	423 @ -102 deg	72 @ -31 deg	423 @ 78 deg
27% of DST – W Medway Fault Location	**81 @ 145 deg**	**429 @ -103 deg**	**81 @ -35 deg**	**429 @ 77 deg**
W Medway Tap	104 @ 140 deg	442 @ -105 deg	104 @ -40 deg	442 @ 75 deg

323 CDG May Misoperate on C129N Ground faults (rows from RKHL Tap to W Medway Tap)

Magnitude of 3I0 Increasing

Table 4. 3V0/3I0 Sensed by the 323 CDG Relays for D130 Ground Faults

D130 Ground Fault Location	3V0 (Pol Volt) Sensed by 323 CDG @ W Medway (volt)	3V0 (Pol Volt) Sensed by 323 CDG @ Millbury #3 (volt)	3I0 Sensed by 323 CDG @ West Medway (Amp)	3I0 Sensed by 323 CDG @ Millbury #3 (Amp)
20% of Mill #2 – DST Tap	1.6 @ -160 deg	7.7 @ 164 deg	23 @ 67 deg	23 @ -113 deg
40% of Mill #2 – DST Tap	1.8 @ -172 deg	4.9 @ 167 deg	16 @ -98 deg	16 @ 82 deg
60% of Mill #2 – DST Tap	2.0 @ -173 deg	3.4 @ 174 deg	49 @ -103 deg	49 @ 77 deg
80% of Mill #2 – DST Tap	2.7 @ -175 deg	2.4 @ 177 deg	93 @ -105 deg	93 @ 75 deg
DST Tap	4.6 @ -177 deg	1.8 @ -139 deg	192 @ -107 deg	192 @ 73 deg
W Medway Tap	7.2 @ -179 deg	2.9 @ -98 deg	311 @ -120 deg	311 @ 60 deg

Note: 1. The 323 CDG relays will not misoperate on the D130 ground faults since the 3I0 sensed by the 323 relays is lower than the CDG trip pickup setting. 2. The 3I0 sensed by the 357 CDG relays is even lower.

Lessons Learned and Conclusions

The 115kV C129N and D130, and the 345kV 323 and 357 lines share a common right-of-way with zero sequence isolation, except mutual coupling, between the 115kV and 345kV lines, therefore, there is a very significant mutual coupling effect between these lines. From this fault investigation, it was realized that the mutual coupling effect was not fully taken consideration when the 323 and 357 CDG relays were originally set in 1980's due to a lack of analytic tools. As a result, they were set too sensitive and caused this misoperation on March 15th, 2002.

In order to improve the security of the 323 and 357 DCB scheme, and, to prevent any parallel line fault from causing an unexpected operation on this scheme for external faults, the setting pickups for the 323 and 357 CDG trip and start relays at both Millbury #3 and West Medway were increased immediately after this fault occurred.

As a result of the investigation, two recommendations were made:

- Replace the existing 323 and 357 zero sequence polarized CDG trip and start relays with negative sequence polarized directional ground relays.
- Review pickup settings for those zero sequence polarized directional ground relays used on mutual coupled lines across the system. The determination was that the increase in ground current 3I0, due to mutual coupling effect, must be considered when setting zero sequence directional ground relays.

Yujie Irene Lu has been employed in Protection Engineering at National Grid since 1990. She is a principal engineer in the Department of Protection Standards and Support, where she analyzes system disturbances on transmission and supply networks, performs system analysis for short circuit conditions, develops transmission protection and control system standards and guidelines, designs protection systems on a conceptual basis, specifies equipment and determines protection settings and logics. She has 20 year's experiences as a lead protection engineer on projects and completed installation of two major 345/115kV GIS transmission substations in National Grid recently. Previously, Irene worked for the Department of Energy of China for 5 years and for the Beijing Power Company for 2 years. Irene received a BSEE degree in Power Systems Engineering from Huazhong University of Science & Technology in China, and a MSEE in Electrical Engineering from Virginia Polytechnic Institute in Blacksburg, VA. She is a member of IEEE and a registered professional engineer in MA. She received the 2010 Outstanding Engineer Award from the Boston Chapter of the IEEE Power and Energy Society in November 2010.

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