Interruption of Island Generation and Load when Tie Line Load Limits are Missed

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Introduction

The incident location in question is a popular vacation island in the Northeast that is tied to the mainland transmission grid at two different locations by undersea cables each being about 30 miles in length. Each undersea cable terminates at a 40MVA transformer in a double-ended straight bus station on the island. Also on the island, there exists a 15MVA combustion turbine generator (CTG) serving as a backup supply for the loss of a single undersea cable and a 7.5MVA battery energy storage system (BESS) to facilitate bumpless load transfer to and from the CTG. *Figure 1* illustrates these details. The CTG is run and carries load monthly per operations and maintenance (O&M) testing requirements. In September 2023 operators were performing their monthly CTG testing when an unexpected trip occurred on one of the two undersea cables. Targets indicated that the cable tripped on directional (reverse) power, overvoltage and undervoltage. At the same time the CTG tripped with an underfrequency target.

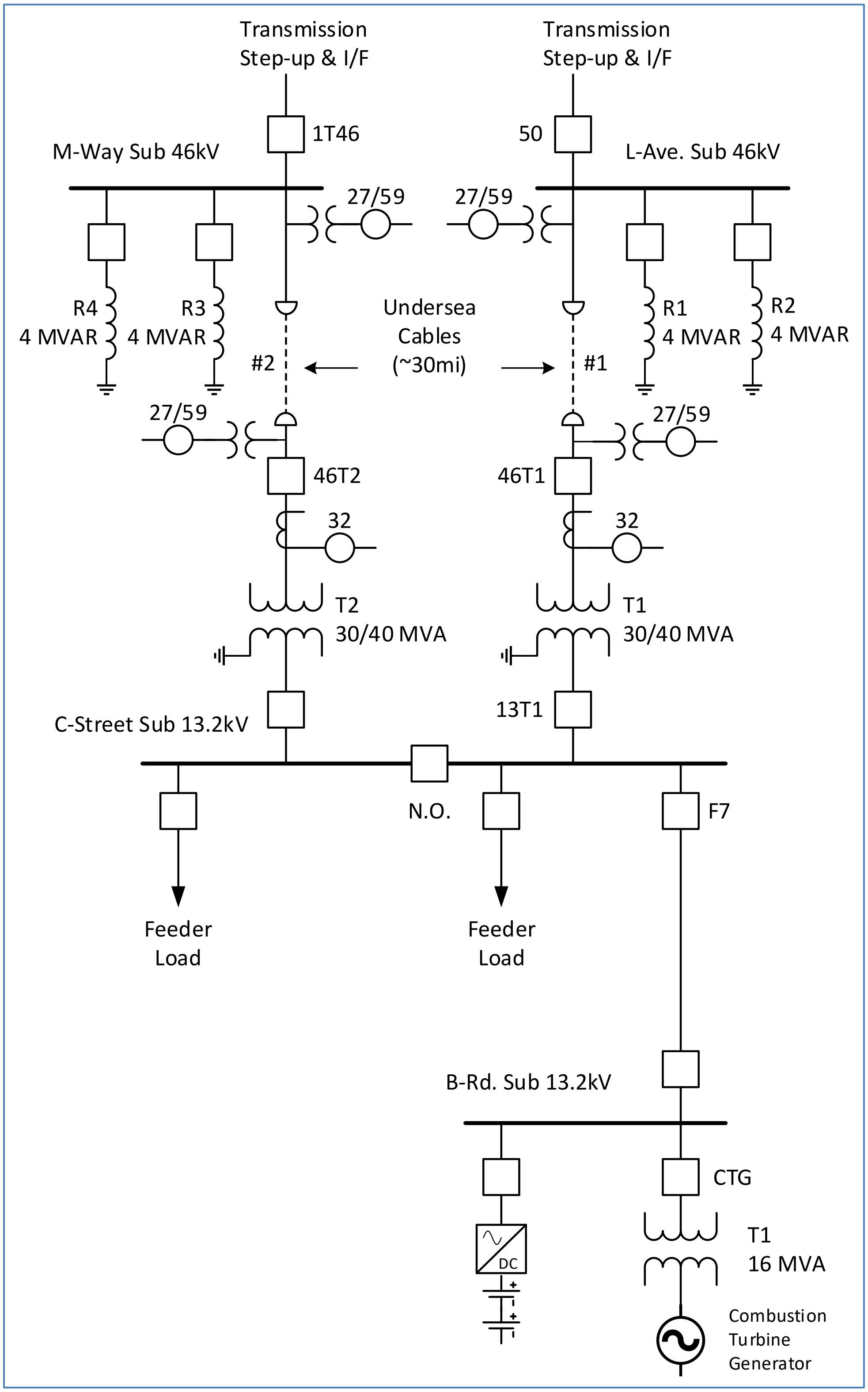
The investigation started as a search for answers to the question of what the O&M testers on the far side of the island did wrong to cause a CTG trip that also resulted in tripping the associated tie cable on the opposite side of the island. The focus shifted to errant operation of the undersea cable with the nuisance cable trip causing CTG tripping by anti-islanding protections. It ended with a recognition that a reverse power (32) relay application was long misunderstood.

Complicating the analysis was the almost complete lack of oscillograph data and SOE data not being readily available. This lack of data was a consequence of most of the relays involved being either electromechanical or static type relays. Using apparently contradictory relay targets, the mystery could still be unraveled with some close attention to what each relay target meant and what each protection function did.

System Overview

It is worth noting the complexity of this local system to better appreciate tasks involved with operating the system on a normal day as well as some unique involved with CTG testing. Refer to *Figure 1* for details. There are two interconnection points that are 4 towns apart (M-Way and L-Ave subs) on the mainland 115kV transmission grid. That grid belongs to a neighboring transmission owner (TO). At both interconnection stations voltage steps down to a 46kV bus where each undersea cable terminates. Both cables are roughly 30 miles in length and each cable produces roughly 8 MVAR of capacitive charging power. Consequently, there exists at each mainland station two stages of 4 MVAR shunt reactors that both consume reactive power and control voltage at the mainland end of the cables.

Figure 1: Area 1-Line Diagram



Both undersea cables terminate on the North side of the island at C-Street sub, which is a double-ended straight-bus station with a normally open tie breaker. On the South side of the island the B-Rd sub is normally supplied by C-Street T1 transformer. There is an alternate feed from C-Street sub T2 which is omitted because it was not relevant to this study. At B-Rd station there is the CTG as well as the BESS.

It is worth mentioning that the interconnection agreement with the host TO does not allow the backfeed of real power into their 115kV system at either point of interconnection. This is monitored and enforced with directional overcurrent relays at the points of interconnection. At the same time directional power relaying is employed on both cables at C-Street as a backup cable protection against overvoltage by detecting a condition whereby the cable is energized by island generation while the remote end of the cable is open. Consequently, these are all the things the system operator must monitor during normal operation and particularly during CTG testing:

- Real power flow that the mainland 115kV points of interconnection.
- Real and reactive power flow at the 46kV points of island interconnection.
- Real and reactive power flow as well as voltage and frequency at the CTG terminals.
- Real and reactive power flow at the BESS terminals.

Incident Summary

On September 19, 2023, operators were performing monthly CTG testing at Bunker Rd. After Labor Day the tourists have all left the island, so island load is drastically reduced from what it is during the summer months. Consequently, operators set the BESS plant to charge at a constant rate of 6 MW to facilitate loading the CTG near its 15MVA rating. During CTG testing, the C-Street end of Cable #1 to L-Ave Sub (46T1) breaker tripped. The remote L-Ave breaker (50) was also tripped as was the B-Rd generator breaker (CTG).

Investigation and Analysis

As was previously mentioned, all the relays involved with these events were static type relays except for the multifunction generator protection relay on the CTG. Fortunately, a portable DFR was previously at the L-Ave station, and it captured events on the mainline side of the #1 cable with both high speed event and slow speed swing records. The CTG's multifunction relay provided an oscillograph record of the generator trip. However, the one place where an oscillograph record would have been most useful was on the C-Street end of the #1 cable. Another limitation was RTU event data as opposed to SOE data. SOE data would have been tagged with the exact time whereas RTU event data simply time tags the event when the RTU is scanned by the SCADA master station, so the event record shows only which points changed from scan to scan with about 2-3 seconds between scans. Still a skilled protection engineer can apply logic to the relay targets knowing the intended design of the protections and discern a credible sequence of events that would fit with the targets observed.

All the relay targets collected by field technicians are listed in *Figure 2* with all the relays except for the B-Rd CTG relay being static relays.

Figure 2: Reported Relay Targets

L-Ave:	
27/59	Cable #1 A/B Relay, Overvoltage time target
27/59	Cable #1 B/C Relay, Overvoltage time target
DTT CH3/4	Received from C-Street (annunciator point)
C-Street:	
32R	Directional power relay, Over target
27/59	Cable #1 A/B Relay, Overvoltage time target (3-sec)
27/59	Cable #1 B/C Relay, Overvoltage time target (3-sec)
27	Bus1 A/B Under voltage time target
27	Bus1 B/C Under voltage time target
27	TR1 A/B Under voltage time target
27	TR1 B/C Under voltage time target
B-Rd:	
13.2kV CTG UF Def-time	

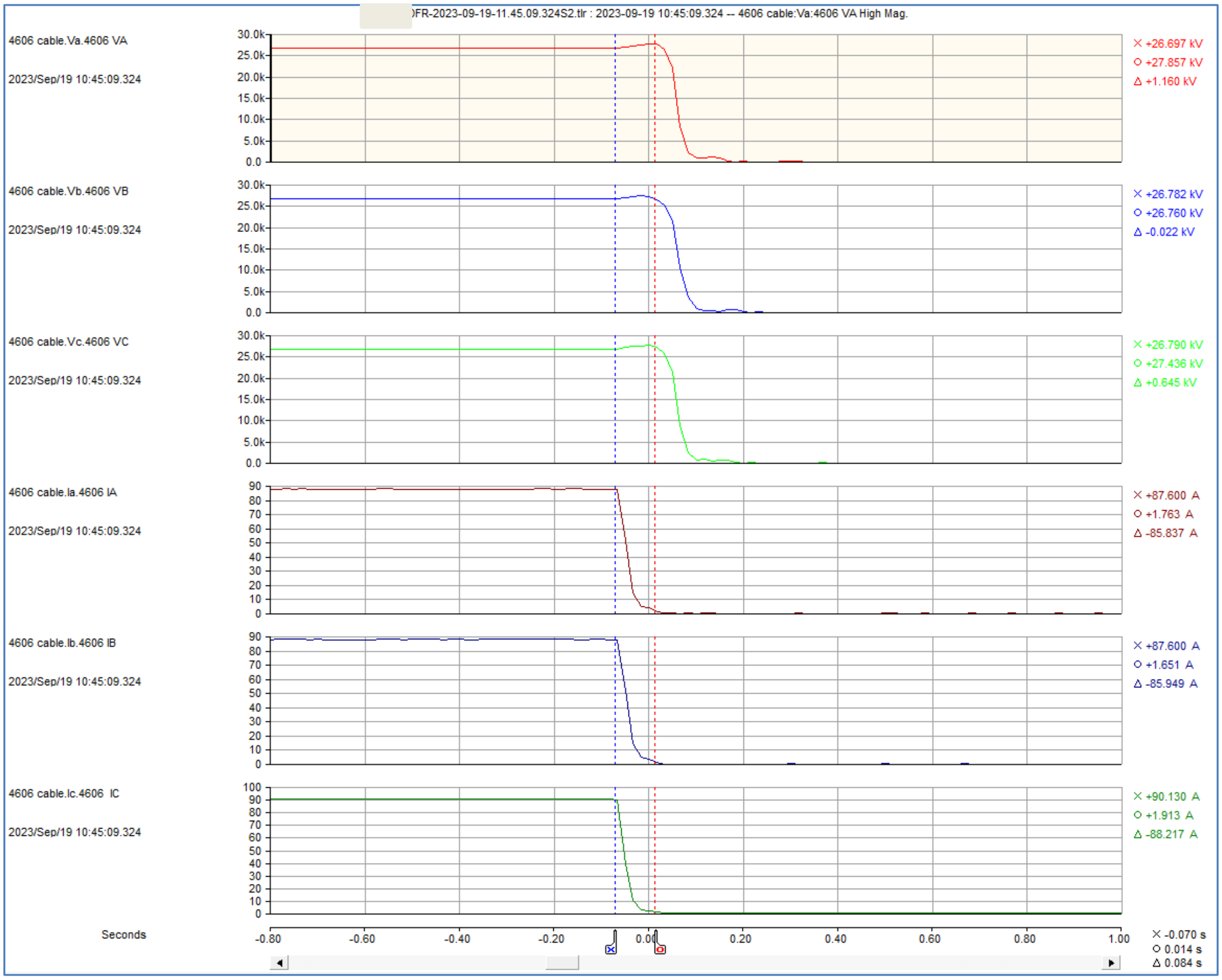
Analysis of SCADA RTU event data and an intimate knowledge of the protections lead to a presumption that the directional power (32R) relay on the C-Street end of the #1 cable (refer to *Figure 1* for location) was the first tripping action to occur. The 32R relay tripped the C-Street 46kV cable breaker. The action of C-Street's 46T1 breaker opening would normally transfer-trip the L-Ave #1 cable (50) breaker. L-Ave cable overvoltage (27) tripping via phase AB and BC relays would be a normal response to the cable being open ended at C-Street.

Recall the C-Street 32R relay normally serves as a backup cable protection detecting a remote end open condition so why would it trip when the remote end wasn't open? That is explainable by an excess of imported VARs at the C-Street end of the #1 cable. A conversation with the system operator revealed that the operator was focused on not exporting watts from C-Street into the #1 cable because that was his understanding of the 32R relay behaved. That would later prove to be a misunderstanding of how the 32 relay actually behaved.

After the C-Street to L-Ave #1 cable tripped, the CTG would be islanded with all the island load attached to the C-Street #1 bus including the load presented by the BESS's set 6MW charging rate. Naturally the generator would fall behind and its frequency decline causing the definite-time underfrequency (81) trip.

So how does this theory of events compare with the oscillograph records that were collected from the L-Ave DFR and the B-Rd CTG relay?

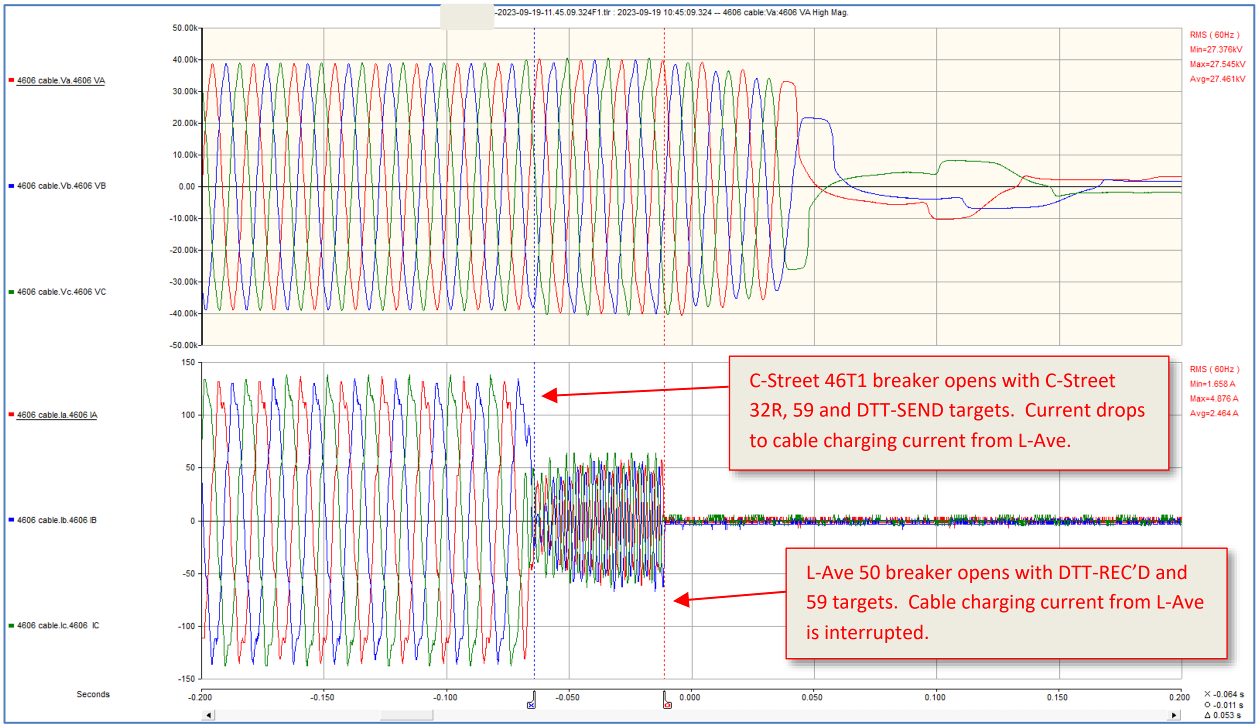
Figure 3: L-Ave Portable DFR Slow Speed Swing Record



Comments:

- *The voltage rise shown in the top 3 traces about the red O marker is consistent with an expected voltage rise at L-Ave following the opening of the C-Street end of the #1 cable (4606) regardless of whether the shunt reactors are switched in or out.*
- *The current drop shown in the bottom 3 traces is consistent with the C-Street end of the cable opening and the L-Ave current dropping from load levels to charging current.*
- *The C-Street overvoltage relays measure voltage on the line side 46T1 breaker so the 27/59 relays would still see voltage until the L-Ave breaker opened. That is consistent with the reported C-Street overvoltage (5) targets.*

Figure 4: L-Ave Portable DFR High Speed Fault Record

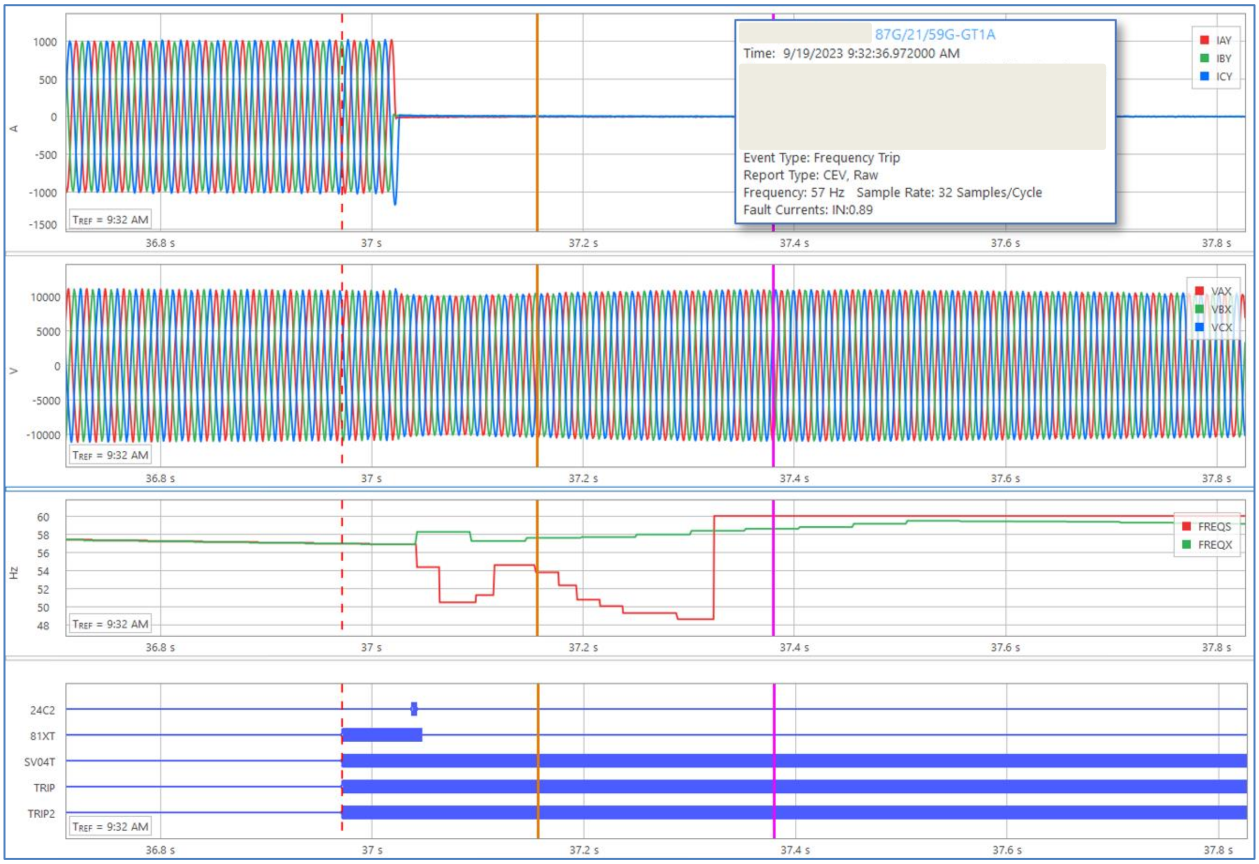


Comments:

- *The L-Ave #1 cable (4606) load current reduces to charging current supplied from L-Ave after the C-Street 46T1 breaker opens. The blue X marker indicates the C-Street breaker opening while the red O marker indicates L-Ave 46kV 50 breaker opening.*
- *The stated purpose of the C-Street #1 cable (4606) directional power (32R) relay is to trip for cable charging current on the occurrence of a cable being energized by C-Street generation while the L-Ave end is open. Relay setting records indicate a tripping setpoint of 2.88 MW (primary). While this setting doesn't directly translate to a particular MW or MVAR value, it is meant to operate for about half of the charging VARs the cable provides to C-Street when the L-Ave side is open.*

The DFR records of *Figure 3* and *Figure 4* are consistent with the assertion that C-Street opened first and then transfer tripped L-Ave.

Figure 5: B-Rd CTG Relay Record



Comments:

- *81XT represents the underfrequency function (81X6TP = 57.00 Hz, 81X6TD = 0.03s) for this event.*
- *FREQS represents the busbar frequency while FREQX represents the generator frequency. TRIP asserts both are below 57Hz.*

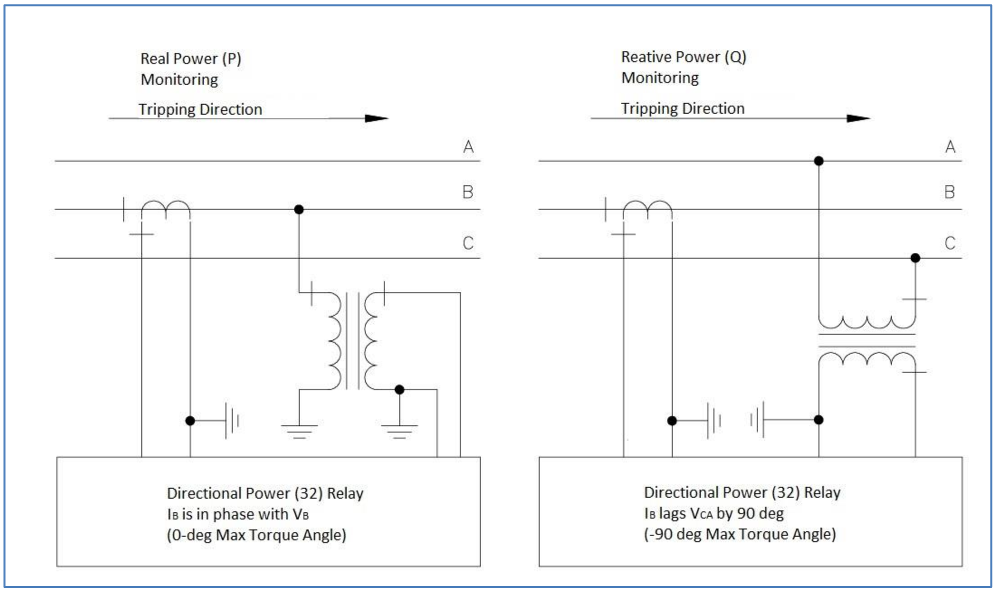
The B-Rd CTG relay record of *Figure 5* is consistent with the assertion that the C-Street was islanded with excess load resulting in a frequency decline.

So far, the available DFR and relay event data fits the asserted theory enumerating the order of events and the likely causes. However, it remains to be explained how the system operator apparently lost control of the C-Street #1 cable power flow conditions as measured by the #1 cable 32R relay, which then lead to the unexpected 46T1 breaker trip and subsequent trips. It turns out that the application of this directional power relay on the C-Street end of the #1 cable is quite unusual and it is also quite clever but none of this cleverness was accurately conveyed to engineers and operators. Instead, the written description of this scheme is quite misleading. The following text describing this relay scheme is what was made available to engineers, operators, technicians, and other maintenance personnel.

> *When there is island generation, a definite time directional power relay (32-C), adjusted to detect a flow of charging current toward the cable, prevents back-feeding the cable for loss of the 115kV source or for back-up protection for 115kV source ground-faults.*

While none this description is technically incorrect, it fails to convey any of the useful aspects of how this scheme works. As it turns out this directional power (32) scheme is a rather unusual application and referring to it as a reverse power (32R) scheme is misleading. To better understand this specific directional power (32) relay application first let's review common applications of directional power relays. *Figure 6* illustrates the common connections for a directional power relay applied for sensing either real or reactive power.

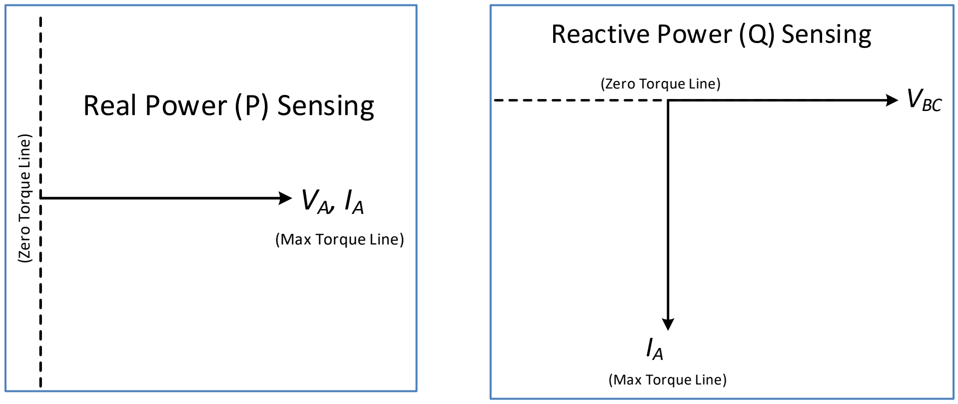
Figure 6: Directional Power (32) Relay Connected for Real (P) and Reactive (Q) Power Sensing



Comment: *This graphic was adapted from one provided in Reference #1.*

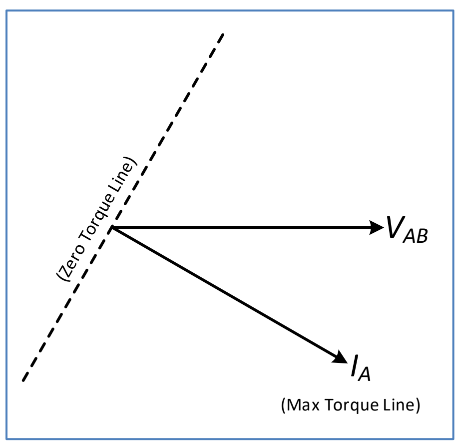
The real power sensing arrangement has the voltage and current inputs being in phase to derive a 0deg maximum torque angle. The reactive power sensing arrangement shifts the voltage reference by +90deg so the current lags the voltage by 90 deg resulting in a -90deg maximum torque angle. The vector diagrams in *Figure 7* that illustrate these two arrangements can be found in most textbooks on power system protection or any relay instruction book for directional power relays.

Figure 7: Resulting 32 Relay Characteristics From Figure 6



The directional power relay arrangement found on the C-Street #1 cable differs from both these common arrangements. At C-Street, the reference voltage is advanced 30 deg using V_{AB} as a reference for I_A. This produces a -30deg maximum torque angle and a +60deg zero torque angle. While such an arrangement is common for directional (67) relays, there is little if any coverage of such a directional power (32) relay arrangement in textbooks, technical papers, relay instruction manualsPutting or application guides. Using this arrangement, the C-Street directional power relay is measuring neither P nor Q alone but is instead measuring some combination of both.

Figure 8: C-Street 32 Relay Characteristic Derived from V_{AB} and I_A



Thinking the scheme was a reverse power (32R) scheme as advertised in operations and maintenance records, a first analysis attempt applied basic equations from the relay manufacturer's instruction manual but with as-found VT connections (refer to *Figure 9*).

Figure 9: 32 Relay Power Calculations from Relay Instruction Manual

$$E_{AN} := \frac{46\ kV}{\sqrt{3}} \angle 0\ deg = 26.558\ kV \qquad I_A := 250\ A \angle (0)\ deg$$

$$S := 3 \cdot E_{AN} \cdot \overline{I_A} = (19.919 \angle 0.000°)\ MVA$$

$$P := \mathrm{Re}(S) = 19.919\ MW$$

$$Q := \mathrm{Im}(S) = 0.000\ MVAR$$

32R Relay Sensing (Shift E_{AN} +30deg): $$P_{Meas} := 3 \cdot |E_{AN}| \cdot |I_A| \cdot \cos\left(\arg(E_{AN}) + 30\ deg - \arg(I_A)\right) = 17.250\ MW$$

The result seems confusing because with an 20MW all real power (P) import condition, the relay apparently measures a smaller real power quantity (17.25 MW) than the applied test condition. This provided no clarity. It is known that the relay was intended to trip for charging power (VARs) related to the cable being energized by island generation while the remote cable breaker was open. It is known that the cable produces roughly 7.5-8 MVAR of charging VARs. So far, this calculation doesn't explain the relay's 1.656 MW relay trip setting.

This lack of clarity prompted an interest in plotting the relay characteristic as a graphic expression of the load limits the relay imposes on the cable – something akin to a generator capability curve. Rather than pursue an analytical approach to producing data for plotting, an iterative plotting calculation method was chosen using the equations for test conditions and relay function in *Figure 9*. The method of deriving P and Q data points starts by selecting P and Q conditions corresponding to the relay's trip setting, $P_{Meas} = 1.656\ MW$. The applied test voltage was fixed at 1.0pu of the 46kV bus voltage. The test current angle would be incremented while the test current magnitude would be chosen such that the relay's measured power would equal its trip setting, $P_{Meas} = 1.656\ MW$. These iterations are illustrated in *Figure 10*. The resulting calculations produced the data table of PQ pairs in *Figure 11*. When plotted (see *Figure 12*), these data points represent a load limit curve the relay imposes on cable operation. The resulting curve is like a directional relay characteristic except with P and Q being scaled in primary MW and MVAR based on the 1.656MW as-found relay setting.

A close inspection of this characteristic plot (see *Figure 12*) lends clarity to this application and exactly what the original protection engineer had intended for it. The data point representing the intended trip condition for an open ended cable energized by island generation at *Q = 0 MVAR* corresponds with the test power flow condition *S = 0 MW - 3.311 MVAR*. This imported reactive power (-3.11 MVAR) represents about half of the charging reactive power of the cable, so the 1.656 MW relay setting appears to be a potentially good setting. However, let's consider that this cable supplies a 40MVA transformer so let's also consider that a 40MVA load served with a 0.85 power factor requires about 21 MVAR of reactive power. That's well above the relay's tripping set point.

Suddenly the reason for the tilted characteristic becomes clear. The conundrum to be resolved is that the tripping setpoint for open cable's imported charging VARs is less than the reactive power requirements for serving the intended load. Tilting the characteristic this way biases the relay, so it requires more reactive power to trip as more real power is imported. This turned out to be a very clever solution that was never adequately documented or communicated.

Figure 10: Iterated 32 Relay Load Limit Calculations for Plotting

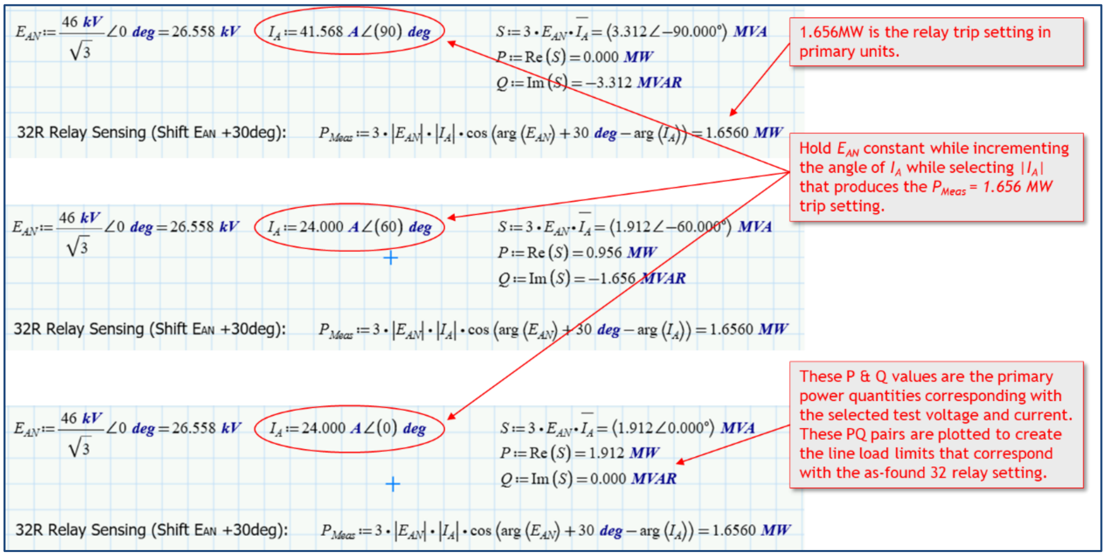
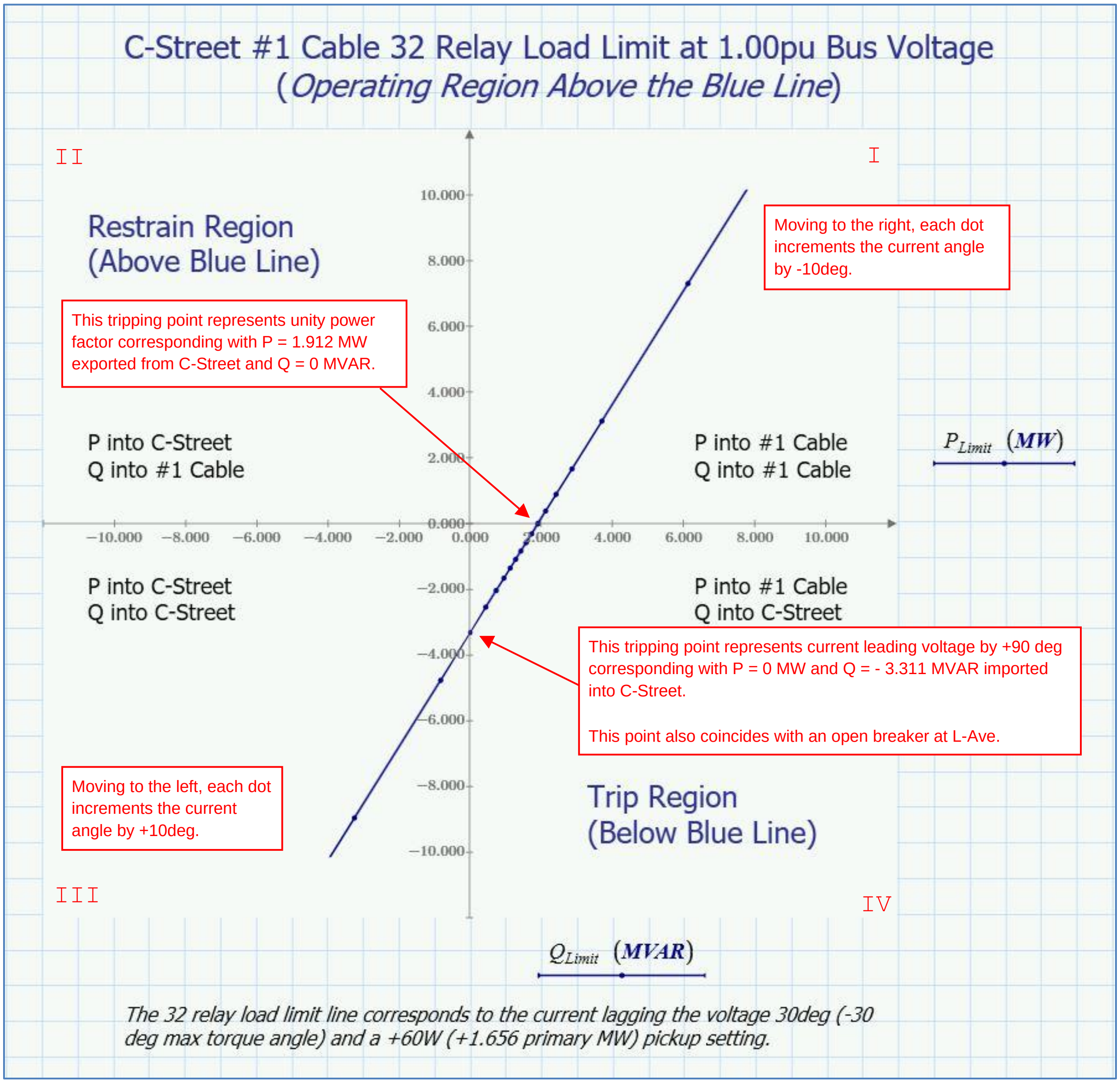


Figure 11: Corresponding PQ Load Limit Data for Plotting

$\Phi_{Current}$ (deg)	PF	$PF\_LeadLag$	S_{Limit} (MVA)	P_{Limit} (MW)	Q_{Limit} ($MVAR$)
115	−0.423	"Lead"	19.00	−8.028	−17.22
110	−0.342	"Lead"	9.534	−3.261	−8.959
100	−0.174	"Lead"	4.841	−0.841	−4.767
90	0.000	"Lead"	3.311	0	−3.311
80	0.174	"Lead"	2.576	0.447	−2.537
70	0.342	"Lead"	2.162	0.739	−2.031
60	0.500	"Lead"	1.912	0.956	−1.656
50	0.643	"Lead"	1.762	1.133	−1.350
40	0.776	"Lead"	1.681	1.288	−1.081
30	0.866	"Lead"	1.656	1.434	−0.828
20	0.940	"Lead"	1.681	1.580	−0.575
10	0.985	"Lead"	1.762	1.736	−0.306
0	1.000	"Unity"	1.912	1.912	0.000
−10	0.985	"Lag"	2.162	2.129	0.375
−20	0.940	"Lag"	2.576	2.421	0.881
−30	0.866	"Lag"	3.311	2.868	1.656
−40	0.776	"Lag"	4.841	3.708	3.112
−50	0.643	"Lag"	9.534	6.128	7.303
−55	0.574	"Lag"	19.00	10.90	15.56

Figure 12: C-Street #1 Cable 32 Relay Characteristic Using the As-found Trip Setting



Conclusions and Lessons Learned

- With the increased availability of oscillograph recordings and SER data provided by DFRs and numerical relays, there is still a need for being able to analyze simple target data in the context of how a protection scheme is intended to operate. This is not only an important skill to have for oneself, but it is also an important skill to convey onto incoming engineers. It is sometimes necessary for the protection engineer to transcend the instrumentation available.

- It was understood that protections performed exactly as intended. While it would be tempting to blame the nuisance tripping of the C-Street #1 cable during B-Rd CTG testing on system operator error, the directional power scheme was never properly understood by engineers, operators, technicians, and maintenance personnel alike. The reason for this universal misunderstanding was the descriptive literature left behind for them depicted a reverse power function. This underscores the need for good and accurate documentation but also a need to review unusual designs with supporting personnel so that unique features are clearly understood by all.

- The text describing C-Street's #1 cable directional power relay operation is deeply flawed. Describing the relay as a reverse power relay that is, "responding to the flow of charging current toward the cable," is misleading at best. Instead, the relay is a directional power wired in such a manner as to cause the relay to respond to imported VARs in a manner that it allows for increasing VAR import as Watt import increases. It is likely that a published diagram like *Figure 12* is needed to further clarify any verbiage that would be produced.

References

1. *Instruction Manual for Directional Power Relays BE1-32R and BE1-32O/U*, Basler Electric Publication 9171100990 Revision N, August 2005.
2. *Connection and Characteristics of BE1-32 Power Relays*, Basler Electric Application Note #PC-3201, February 1998.
3. *SEL-351-5, -6, -7 Protection System Instruction Manual*, Schweitzer Engineering Laboratories Date Code 20230831.
4. Blackburn, J. Lewis and Domin, Thomas J., *Protective Relaying Principles and Practices*, 4^{th} ed., CRC Press, Boca Raton, 2014, pp 61-63, 184.

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