Practical Experience With Ultra-High-Speed Line Protective Relays

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***Abstract*—Breakthroughs in line protective relay design have brought about ultra-high-speed (UHS) protection elements that operate in a few milliseconds. In this paper, we present the real-world experience of implementing a UHS protective relay scheme on a 115 kV circuit at Baltimore Gas and Electric Company (BGE) and the driving factors to do so. We share the processes of placing a UHS protective relay into service, report on the commissioning process, and discuss factors to consider. An overview of BGE's standard line protection philosophy is given and compared to setting UHS directional, distance, and traveling-wave differential elements, along with fault location settings for the single-ended and double-ended traveling-wave fault location methods. We discuss the simplicity of creating relay settings for the UHS protective relay.**

We next focus on performance and lessons learned in implementing a UHS protective relay. We analyze the performance of UHS elements and the fault locator on real-world internal and external faults and compare with BGE's standard line protection and fault locating. The impact of the use of bushing potential devices with UHS protective relay elements is discussed. We present lessons learned from initial settings including experience with tapped transformer inrush and interfacing with communications and SCADA equipment. This paper will benchmark UHS relaying against phasor-based relaying from the utility viewpoint using actual field cases.

I. Introduction

Recent developments in the design of protective relays have brought about protection elements that can operate on traveling waves and incremental quantities [1]. One such ultra-high-speed (UHS) protective relay operates at speeds as fast as 1 ms using traveling-wave and incremental quantity methods [2]. This paper discusses a UHS relay that includes: a traveling-wave differential scheme (TW87), a permissive overreaching transfer tripping (POTT) scheme that uses traveling-wave directional (TW32) and incremental quantity-based time-domain directional (TD32) elements, and an underreaching incremental quantity-based time-domain distance element (TD21).

In addition to UHS protective functions, the relay performs accurate fault locating using double-ended traveling-wave fault locating (DETWFL) [3] and communications-independent single-ended traveling-wave fault locating (SETWFL) [4]. Reference [5] discusses measuring the performance of the UHS relay elements and [6] provides the testing methodology.

While this paper does not aim to derive all the theory of each protection function in the UHS relay, it does provide a working knowledge of the traveling-wave elements and the incremental quantity elements.

A. *Traveling Waves*

When a fault or disturbance occurs, the step change in voltage causes both a current and a voltage traveling wave (TW) to be launched in both directions from the point of origin.

1) TW Differential Scheme

For TW87, it is expected that the current transformer (CT) polarities face outward of the differential zone just like those of a phasor-based line current differential (87L). This results in an addition of current between the two relays that creates no net current when through current exists. The same relationship exists for TWs.

When a fault occurs external to the TW87 zone, the wave enters a terminal at one polarity and leaves the other terminal after the traveling-wave line propagation time (TWLPT) at the opposite polarity and relatively same magnitude. For an internal condition, the first wave magnitudes are of the same polarity and relatively same magnitude (these vary depending on the termination impedance, fault resistance, etc.).

The TW87 scheme [1] is designed to operate based on the timing and the magnitude and polarity information of the current traveling waves from both terminals.

2) TW Directional Element

The current TW for a forward event is launched toward the CT of a protective device and enters the non-polarity side of the CT. This inverts the current TW polarity on the relay secondary. A forward fault seen by the relay will have current and voltage traveling waves of opposite polarities. The UHS relay performs an integration of current and voltage traveling waves to produce a directional torque calculation as described in [7], such that a positive torque is achieved for a forward declaration (TW32F) and a negative torque is achieved for a reverse declaration (TW32R).

B. *Incremental Quantity Directional and Distance Elements*

The UHS relay also includes incremental quantity elements that operate using six loop incremental replica currents and incremental voltage quantities. These signals are filtered and processed as described in [2]. These quantities remove the steady-state conditions on the power system and react only to changes in current and voltage.

For a forward condition, it is expected that the incremental voltage and replica current quantities be of opposite polarities, while a reverse condition results in incremental voltage and replica current quantities that are of the same polarity.

While the relay uses an integrated torque to declare a direction, a general operating condition for these elements is a torque control equation that will be positive for a forward fault and negative for a reverse fault, as shown in (1) and (2):

$$\text{TD32F if } \Delta v \bullet -\Delta i_Z > \text{TD32ZF} \bullet \Delta i_Z{}^2 \quad (1)$$

$$\text{TD32R if } \Delta v \bullet -\Delta i_Z < \text{TD32ZR} \bullet \Delta i_Z{}^2 \quad (2)$$

where:

Δv is the incremental voltage change.

Δi_Z is the loop incremental replica current change.

TD32ZF and TD32ZR are the set points defined in [8].

For a forward Phase A-to-ground fault, the A-to-ground loop incremental replica current, DIZAG (DIZA–DIZ0), is opposite in polarity to that of the loop incremental Phase A voltage (DVA). This is shown in the UHS relay event reports in Section IV.

TD32 is then applied in a POTT scheme between the UHS relays. The POTT scheme uses TD32F to key the permissive trip, but tripping can be accelerated by also including the TW32F declaration to key the permissive. For a relay to trip via POTT scheme, it must declare a TD32F, receive a permissive, and POTT overcurrent supervision must be asserted.

The time-domain distance element (TD21) has both phase and ground distance elements that use the same incremental quantities to calculate a voltage at the reach point. If the calculated fault voltage (operating voltage) is greater than the restraint voltage, the element operates as described in [9].

C. Fault Locating

The UHS relay contains two TWFL algorithms: double-ended and single-ended. Each algorithm is illustrated in Fig. 1.

DETWFL uses the same direct fiber-optic communications channel for the TW87 scheme to perform the communications-based DETWFL.

The fault location is calculated using (3):

$$m = \frac{\ell}{2}\left[1 + \left(t_{L1} - t_R\right)/\text{TWLPT}\right] \quad (3)$$

where:

m is the fault location calculated.

ℓ is the line length.

TWLPT is the traveling-wave line propagation time.

t_{L1} and t_R are the initial wave arrival times for the left and right protective relays, respectively.

A communications-independent SETWFL can also be performed. The fault location is calculated with (4):

$$m = \frac{\ell}{2} \bullet \left(t_{L2} - t_{L1}\right)/\text{TWLPT} \quad (4)$$

Discriminating the reflected wave from the fault from other reflections (due to taps, remote buses, or other lines) can be difficult. Reference [4] provides the algorithm the UHS relay uses to identify the reflection from the fault to accurately locate the fault using the SETWFL method.

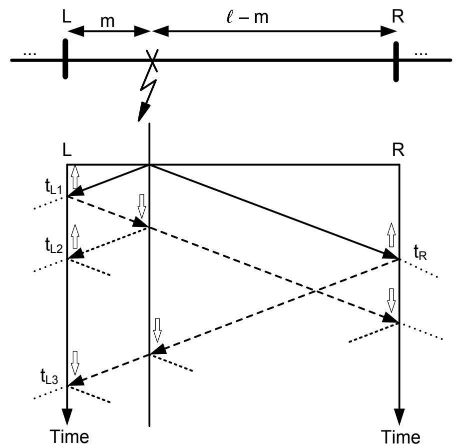

Fig. 1. TWFL on a two-terminal transmission line

Section II discusses the motivation of Baltimore Gas and Electric Company (BGE) to initiate the installation of a UHS relay and the creation of the BGE pilot. This section also discusses the selection of the transmission line.

Section III discusses BGE's present protection philosophy and practices for transmission line protection on the pilot line. This section also discusses the UHS relay settings, communications, commissioning, and the line energization test used by BGE to set the TW87 element.

Section IV provides the events captured by the pilot, including internal and external faults, and analyzes the overall performance of the UHS relay and compares it to existing protective relays in use at BGE.

Section V reviews the lessons learned from the pilot thus far, including settings considerations, corrections made throughout the pilot, and the effect that bushing potential devices (BPDs) had on the incremental quantity-based directional and distance elements.

Section VI discusses future applications of the relay functionality and tripping breakers using the UHS relay.

II. BGE Pilot

Before the implementation of new technology, a pilot installation on an active line is essential for analyzing performance, gaining experience, and discovering new applications. This section discusses why BGE chose to investigate UHS protection and how the pilot site was selected and its history.

A. Pilot Creation

A proposal was submitted to the 2017 BGE Innovation Program to pilot a new UHS line protective relay scheme. BGE approved the proposal with the UHS line relay because of the minimal number of settings that needed to be calculated and programmed. The limited number of settings was important because settings and/or logic design errors are the cause of a significant amount of BGE's misoperations.

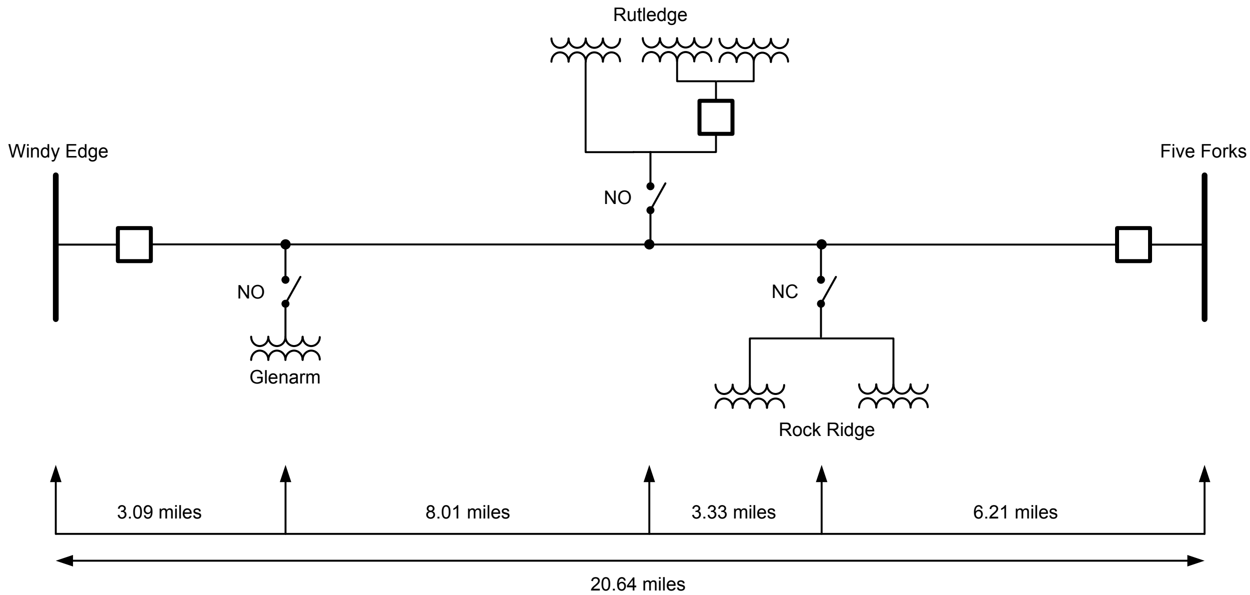

Fig. 2. 115 kV transmission line selected for the pilot

Another capability of this relay was the high-speed tripping using traveling-wave and incremental quantity functions. Though the BGE system does not have many voltage stability concerns, there are lines close to sources of generation that would benefit from the faster fault clearing of UHS tripping.

In addition to traveling-wave protection functions, the relay also has traveling-wave fault locating, which has been proven accurate to within a tower span on multiple internal faults and is discussed in Section IV.

In November of 2017, UHS relays were installed on a 20-mile, 115 kV transmission line. The relays were commissioned and put into service without live breaker tripping so that the performance of the relays could be evaluated. BGE's service territory is approximately 2,300 square miles with 1,337 circuit-miles of transmission lines between 39 transmission-only substations. Most of the transmission lines do not exceed 30 miles. During the selection of the pilot site, records from 2010–2017 that compared the number of trips on each transmission line were analyzed. The line was selected because it had a relatively high number of faults compared to other lines on the BGE system. The selected line had 8 trips since 2010 due primarily to contact from birds. Other considerations in selecting the line were the availability of direct fiber-optic communication between the two stations for the TW87 channel and the availability of panel space.

B. Line Construction

The pilot line (110511 circuit) consists of approximately 20 miles of overhead transmission line with 2 normally tapped distribution transformers that are both located at the Rock Ridge substation, as illustrated in Fig. 2. There are 4 other tapped distribution transformers: 3 at Rutledge and 1 at Glenarm. The loads from these transformers can be supplied by the 110511 circuit during abnormal system conditions, but normally these loads are supplied by another circuit. The existing 110511 line protection scheme is designed to protect up to the high side of each of the transformers at Rock Ridge or up to the tapped loads during abnormal system conditions. The protection system for the pilot was configured around only the normal operating condition of the line. Each transformer at Rock Ridge has a differential zone that wraps the high side of the transformer to the low side of the bus. For a transformer/bus zone fault, the respective high-side circuit switch opens along with the 115 kV terminals at Windy Edge and Five Forks (for a high-side fault), allowing the 110511 circuit to automatically reclose 2 seconds after the transformer has been isolated.

C. Line History

The line selected for the pilot is over a century old and it was one of BGE's first transmission lines built to bring generation from southeastern Pennsylvania. In the 1960s, the line was reconductored, but prior to that it was converted through tower modification from a double 66 kV, 25 Hz line to a 115 kV, 60 Hz line. During the modification, modern avian clearance standards were not considered, which has resulted in the high rate of line contact from birds and subsequent trips.

III. UHS Relay Settings and Commissioning

With the pilot line selected, it was necessary to determine how the pilot UHS relays were to operate and how best to apply them to the line. This section discusses the existing BGE line protection philosophy and the existing protection on the pilot line. It also discusses the relay settings and the available communications and details the commissioning process of the relay, including the line energization test to determine the TWLPT.

A. Protection Philosophy

BGE's 115 kV transmission line protection philosophy consists of at least one communications-assisted high-speed tripping scheme—usually a POTT scheme used in conjunction with a backup step distance 21/51G/67G scheme. Because of the relatively small service territory, there is a good communications network with access to direct fiber and multiplexed communications over a digital protection system integrated network ring.

1) Existing Protection

The existing primary protection for the 110511 circuit is a POTT scheme that uses 2 microprocessor phasor-based distance and directional relays that communicate the permissive trip signal over a direct single-mode fiber. The backup protection for this line consists of: standalone step distance relaying that trips instantaneously on phase and ground Zone 1 at an 80% reach and an overreaching time delay tripping phase and ground Zone 2 reaching to 120% with all lines in service. The existing primary and backup relays also have a ground time overcurrent and a directional ground instantaneous element programmed for tripping. The standard protection philosophy is to have high-speed clearing for all faults on 100% of the line. The protection philosophy in the event of a communications channel failure is to delay fault clearing for line-end faults while maintaining coordination with adjacent circuits. Adequate primary and/or backup protection for 100% of the line must be maintained.

2) UHS Relay Settings

The UHS relays required only a minimal number of settings be calculated because most of the required settings had been calculated for the existing relaying scheme. Previously determined settings included the AC input and phase rotation settings, as well as the positive-sequence line impedance magnitude and angle (Z1MAG and Z1ANG) and the zero-sequence line impedance magnitude and angle (Z0MAG and Z0ANG). The power system setting total line length was 20.64 miles. The line length is significant as it drives the accuracy of TWFL.

A TW87 blocking zone was created at the tap of Rock Ridge to secure TW87 for downstream faults that were not on the transmission line between Windy Edge and Five Forks. This was to be set at 0.3 per unit line length at Five Forks and 0.7 per unit at Windy Edge, both with a radius of 0.03 per unit (however, due to a settings error, the Windy Edge side was mistakenly set at 0.75 pu). The TD32 set points were set as suggested in [8] based on source and line impedance values. The TD21 phase and ground reaches were set at 0.75 and 0.7 per unit line length. The UHS relays were set to trip on phase and ground TD21, TW87, and the POTT scheme, which included TW32 keying.

During the initial stages of the pilot, all the overcurrent settings were left at low values. These settings were later adjusted to allow for proper relay performance, as discussed in Section V. The TWLPT was the only setting that needed to be measured during the commissioning process.

B. Communications

The UHS relays require a direct fiber-optic communications channel for the TW87 element, but the only direct fiber available in this application was a 12-strand optical ground wire (OPGW) that had no spare strands available. To free the necessary number of strands, the existing POTT communications channel, which used two of the strands, was converted to the digital multiplexed network. To do this, the serial communications port on the phasor-based POTT relays was converted to fiber using a single-mode fiber-optic transceiver. Communications were then routed to a serial interface digital signal card on a time-division multiplexing (TDM) shelf that tapped into the protection digital network to the remote terminal. With this conversion complete, there were two free fiber-optic strands available to use with the UHS relay.

To download the events and have remote access to the relay, a high-speed remote connection was made to the relay at each terminal. This was achieved by connecting the available 1 Gb small form-factor pluggable (SFP) engineering access fiber-optic port of the relay to a separate network going in and out of the substations that could be accessed from a central location. The challenge in doing this was that the relay only supported a 1 Gb SFP fiber-optic port. Therefore, the existing network ports had to be upgraded to a 1 Gb SFP fiber-optic port. Until this upgrade was made, events had to be downloaded locally from the relay for analysis.

C. Commissioning

The UHS relay at the Windy Edge terminal was wired into the existing 2000/5 A CT circuit tapped at 1200/5 A in a single-bus breaker configuration, as shown in Fig. 3. The potential connections were made to the existing BPDs on the line-side bushings of the oil circuit breaker (OCB).

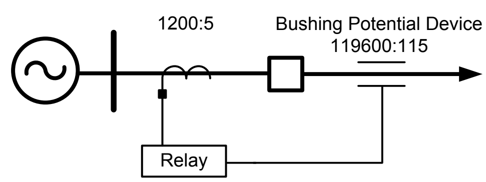

Fig. 3. Windy Edge UHS relay connection

At the Five Forks terminal, the UHS relay was wired into the existing 1200/5 A CT circuit tapped at 1000/5 A in a single-bus breaker configuration, as shown in Fig. 4. The potential connections were made to the existing potential transformers located on the source side of the OCB.

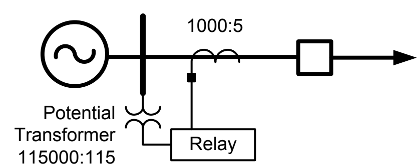

Fig. 4. Five Forks UHS relay connection

On each terminal, the trip output contact was wired into a one-bit indication SCADA point so that it generated a remote alarm when the relay issued a trip command. Parallel to the trip output contact, the relay alarm output contact was wired to generate an alarm should the relay or communications fail (e.g., TW87 channel failure). Control power to each relay was achieved using a 132 V dc local battery system.

D. Line Energization Test

To use the TW87 function of the UHS relay successfully, the propagation time of a traveling wave on the line must be set. The value for this setting can be determined using (5):

$$\text{TWLPT} = \frac{\ell}{\text{LPVEL} \cdot \text{c}} \quad (5)$$

where:

TWLPT is the traveling-wave line propagation time.

ℓ is the line length in miles (meters).

LPVEL is the line propagation velocity.

c is the speed of light of 186,000 miles/s ($3 \cdot 10^8$ m/s).

Applying (5) to the 20.64-mile pilot line, and if the waves propagate at the speed of light, TWLPT is 101 µs.

If (5) is only used as a marker to look for wave reflections from the open terminal, LPVEL can be left at 1. A typical value for LPVEL is 0.98 for overhead lines; for underground lines, a typical value is 0.48. If an LPVEL of 0.98 is assumed for the pilot line, the TWLPT is closer to 113 µs.

Best practice is to measure the TWLPT by performing a line energization test, where one breaker is closed and the breaker on the other side of the line is left open. This causes traveling waves to be launched from the breaker closing end (at time T_I), travel to the open breaker, and then be reflected toward the closing end relay with the wave now with opposite polarity at time T_R. TWLPT can be determined as shown in (6).

$$\text{TWLPT} = \frac{\text{T}_\text{R} - \text{T}_\text{I}}{2} \quad (6)$$

Fig. 5 shows the plots of three phase TW currents from the TWLPT test during line energization from Five Forks. The transient seen on IB at $t = 0$ ms was the initial closure. The transient induces a wave due to secondary cable coupling on Phases A and C as shown on IA and IC at the same instant. It is assumed that this initial wave is Pole B of the breaker closing first, with Pole A closing approximately 0.8 ms later. The Pole C closure could not be determined since it appears the pole closed at a voltage zero.

The first pole closure was used as the reference because the incident and reflected waves were clear. Typical practice is to use the final pole closure. Fig. 6 shows the alpha Clark component that removes zero-sequence coupling. A time difference of 226.016 µs was seen, resulting in a TWLPT setting of 113.50 µs.

IV. Pilot Event Analysis

During the pilot, several power system events were captured by the UHS relay. The events included three internal Phase A-to-ground faults and one external Phase C-to-ground fault. This section highlights the performance of the protection elements and the fault locating of the UHS relay during these events. UHS operation is compared to the existing phasor-based protection.

A. Internal Faults

The three internal faults are detailed in Table I. All the internal faults of the pilot were Phase A-to-ground faults that occurred on various portions of the line. Overall, it was observed that the TW87 element was issuing trips between 0.6 and 1.6 ms after TWDD asserted (the first indication of any disturbance). At the Five Forks terminal, the TW32 elements operated in 100 µs for the three internal faults and the TD32 element operated in less than 1.4 ms for the three internal faults. When the fault was within the reach of the TD21 element, the relay at Five Forks asserted TD21 at 3.66 ms and 5.9 ms. At the Windy Edge terminal, TD32, TW32, and TD21 did not operate for the three internal faults. This is investigated further in Section V.

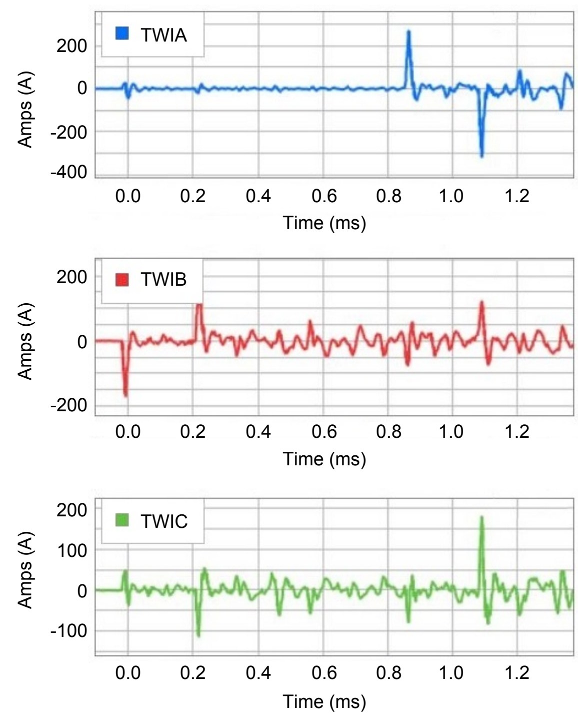

Fig. 5. Line energization test phase TW components

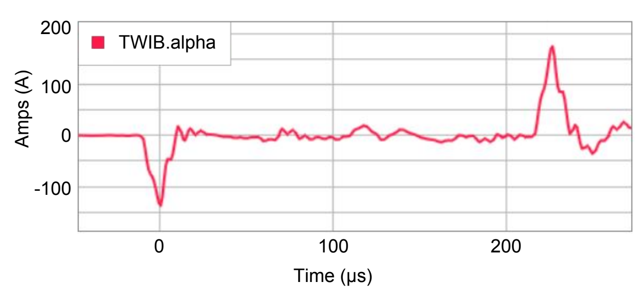

Fig. 6. Phase B TW alpha current during the line energization test

TABLE I
INTERNAL FAULT SUMMARY: PROTECTION

Event	Relay	Location (mi)	Operating Time (ms)				
			TW87	TD21	TD32	TW32	Existing
1	Five Forks	16.98	1.3	Beyond reach	1.4	0.1	19
	Windy Edge	3.66	0.6	—	—	—	9
2	Five Forks	9.13	1.06	3.66	1.36	0.06	17.5
	Windy Edge	11.52	0.9	—	—	—	11.9
3	Five Forks	4.5516	1.0	5.9	1.3	0.1	11.5
	Windy Edge	16.098	1.0*	Beyond reach	—	—	~20

* Scheme did not operate due to the TW87 blocking region setting. The operation time is from the event replay.

Fig. 7 and Fig. 8 show the asserted protection elements of Event 1 from Windy Edge and Five Forks, respectively, with the 1 MHz analogs. Relay Word bits from Windy Edge are shown in red and Relay Word bits from Five Forks are shown in blue.

In the following sections, the performance of the TW87, directional, distance, and fault locating elements are examined individually and the UHS relay protection is compared to the existing protection.

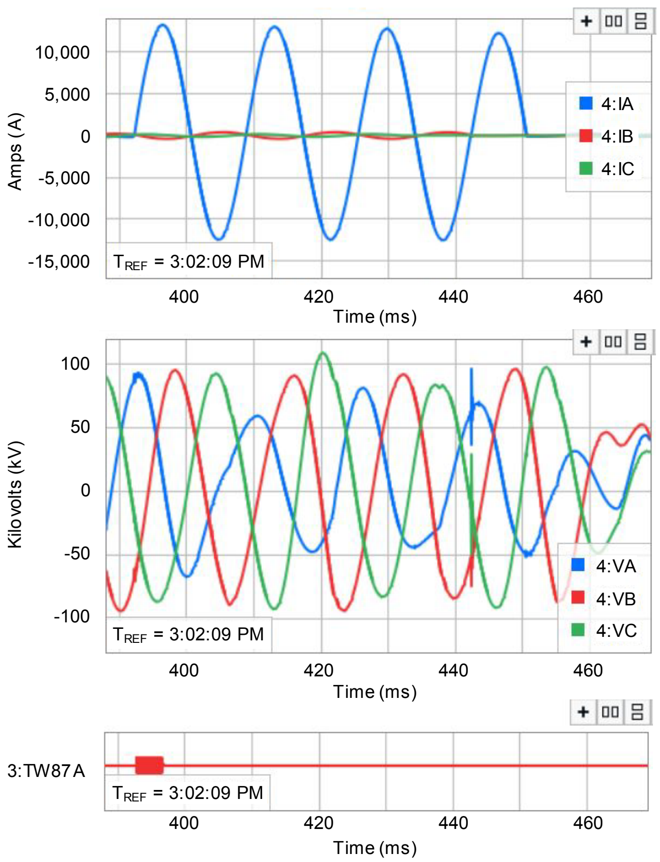

Fig. 7. Windy Edge Event 1 trip

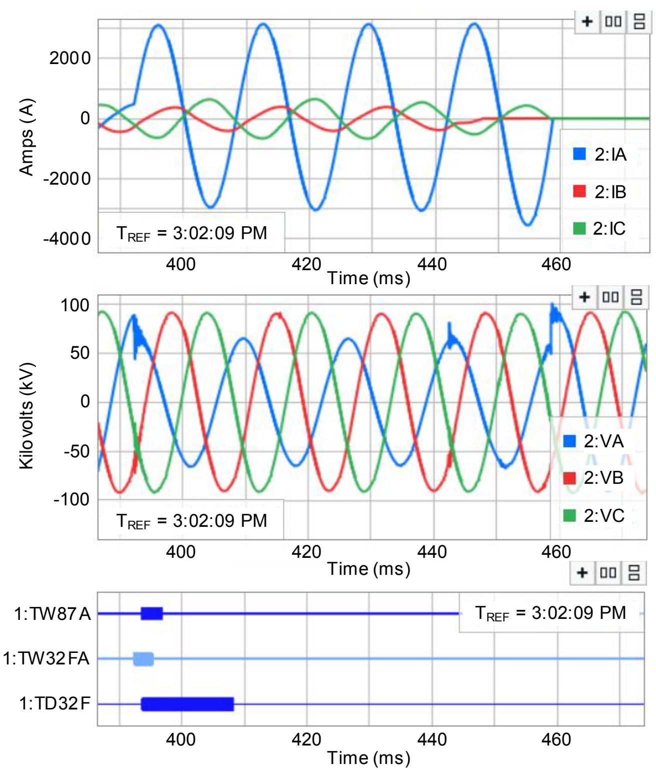

Fig. 8. Five Forks Event 1 trip

1) *TW Differential Scheme*

Recall from Section I that for an internal fault the local and remote TWs should have the same polarity and should arrive within the TWLPT, or 113.5 µs. Fig. 9 shows the detection time of a disturbance and the TW87A output asserted for a Phase A trip due to the TW87 scheme. Fig. 9 and Fig. 10 present the alpha Clarke components of Phase A local and received remote TW current (TWIA.alpha and TWIAR.alpha, respectively), as seen from Five Forks.

Fig. 10 shows the first waves at both terminals. The two waves are of the same polarity and the time difference between them is 72.072 µs, which is well within the TWLPT.

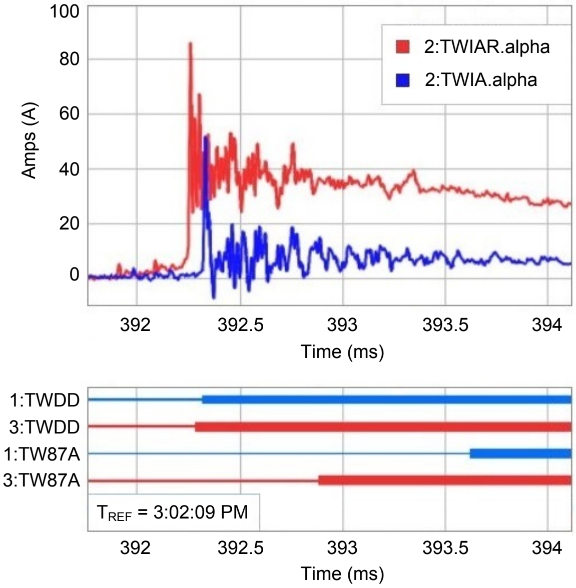

Fig. 9. TW87 scheme operation for Event 1

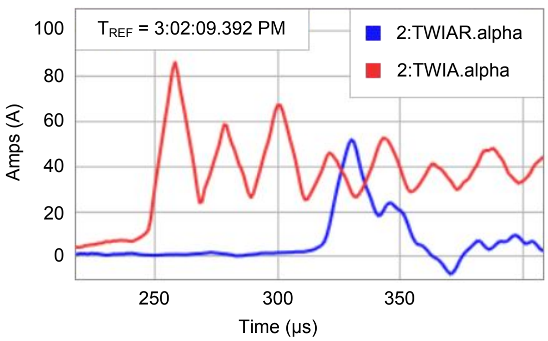

Fig. 10. TWs of the same polarity and within TWLPT for the internal fault for Event 1

2) Directional Elements

Fig. 11 displays the delta quantities of the Phase A-to-ground incremental loop replica current (DIZAG) in secondary amps and the Phase A incremental voltage (DVA) in secondary volts. As expected for a forward fault, the incremental replica current and voltage are of opposite polarity, leading to a TD32F assertion in 1.4 ms.

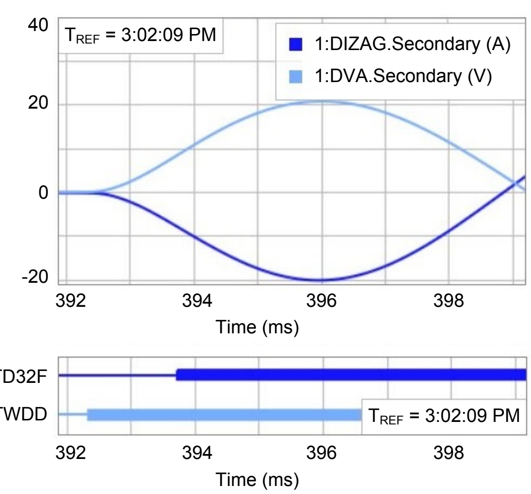

Fig. 11. TD32 asserted forward at Five Forks for Event 1

Fig. 12 shows the alpha Clarke components of the TW current (TWIA.alpha) in primary amps and TW voltage (TWVA.alpha) in kV for the TW32 element operation. The opposite polarity of the incident current and voltage TWs results in a TW32F declaration in less than 100 µs.

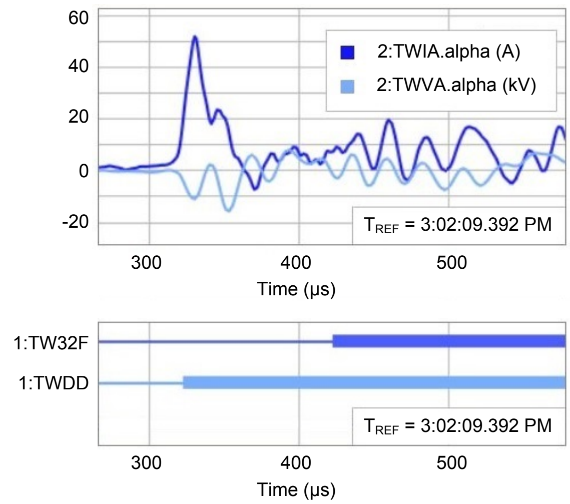

Fig. 12. TW32 operation within 100 µs at Five Forks for Event 1

3) Distance

All the faults seen during the pilot were ground faults, thus the analysis of the distance elements focuses specifically on TD21G. Regarding the UHS relay at Five Forks, the TD21 operated as expected for all three internal events. Event 1 was beyond the reach point and the element restrained. Event 2 and Event 3 resulted in TD21 assertions of 3.66 and 5.9 ms, respectively. The Windy Edge relay element TD21G did not operate for Event 1 or Event 2, both of which were within the reach setting of the relay. Why the element did not trip for these events is analyzed in Section V.

An example of TD21 operation is shown in Fig. 13. Fig. 14 zooms in on the event to provide better visibility of when the elements operated. Note that to get a TD21G assertion, the UHS relay must also declare a forward direction (TD32F) and meet the incremental replica overcurrent supervision (OC21AG).

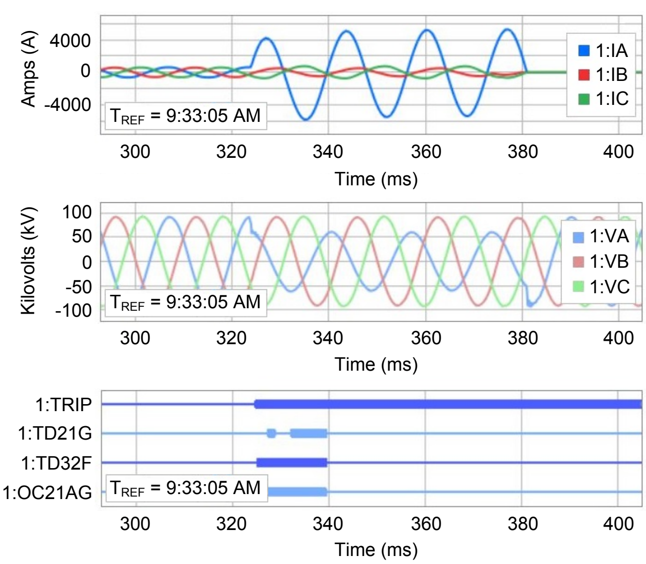

Fig. 13. TD21G asserted at Five Forks for Event 2

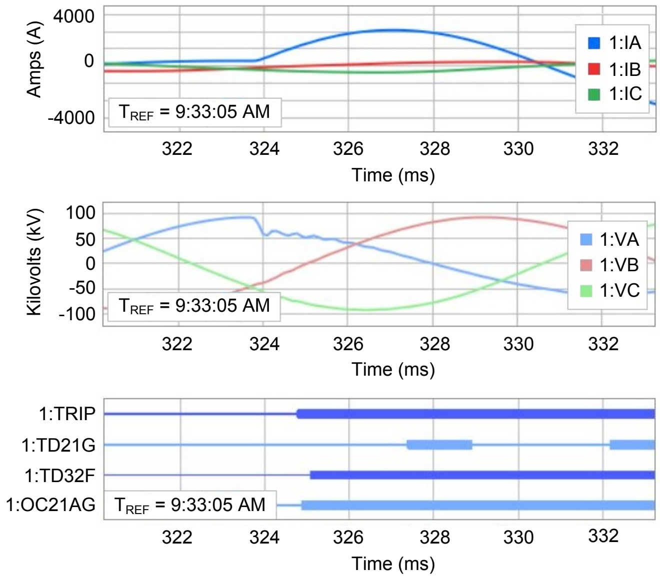

Fig. 14. Incremental quantity elements operation at Five Forks for Event 2

Fig. 15 provides the operating and restraint quantities in the event report that caused the TD21AG assertion.

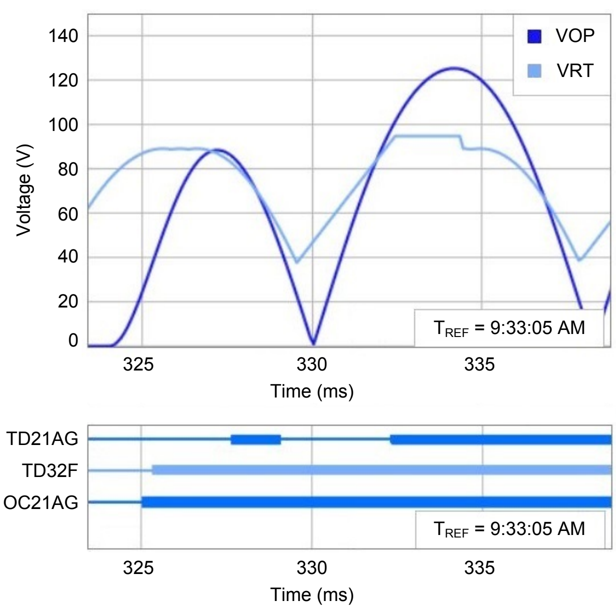

Fig. 15. TD21 operating quantities at Five Forks for Event 2

4) *Fault Location*

The UHS relay provided excellent fault locating during the pilot, as shown in Table II. The largest error associated with DETWFL was less than 0.12 miles. The largest error the relay calculated using SETWFL was less than 0.21 miles. In 3 cases the relay did not calculate the single-ended traveling-wave fault location and this is attributable to the reflected waves not exceeding the minimum sensitivity requirement of the relay. The location was manually calculated using event analysis software and the results are documented in Table II.

The existing fault location in Table II was not calculated through the existing relaying, but by an impedance-based line model. This model was less consistent and was only accurate to a half mile at best and over 3.5 miles at worst.

Fig. 16 shows successful DETWFL and SETWFL operations for Event 2. Fig. 16 shows the first waves seen at both terminals that allowed both relays to calculate the double-ended traveling-wave fault location, as well as the clear reflection at Windy Edge that allowed the single-ended traveling-wave fault location.

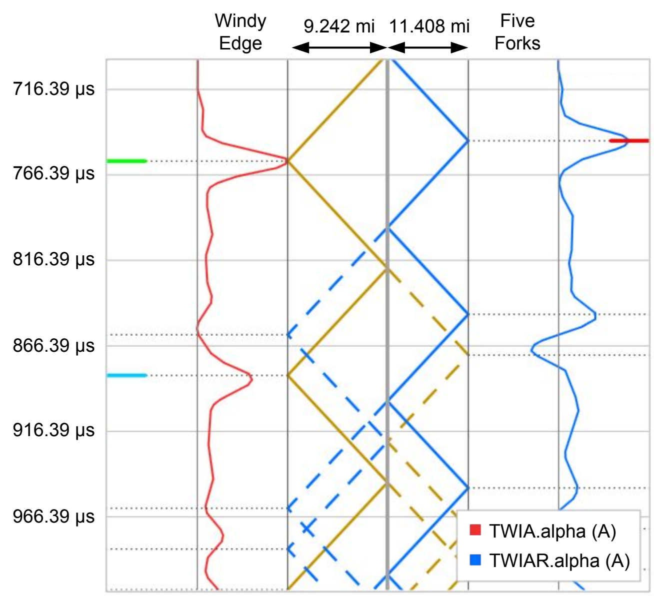

Fig. 16. Bewley diagram of TW currents recorded at Windy Edge for Event 2

5) *Comparison to Existing Protection*

Presently, the line is protected primarily by a phasor-based POTT scheme with directional ground overcurrent and a secondary step distance scheme. The UHS and phasor-based relays at Five Forks all have the same IRIG time synchronization, so the UHS relay performance could be compared easily to the existing protection. The UHS relay outperformed the phasor-based relay Zone 1 and POTT Zone 2 protection by an average of 13 ms. Table I shows a comparison for each relay and each event. Fig. 17 illustrates the difference in performance between the phasor-based relays (5:TRIP and 6:3PT) and the UHS relays for Event 1 at Five Forks.

While time synchronization was not available at Windy Edge, a conservatively estimated alignment of the data showed that the UHS relay still performed at least 8 ms faster than the phasor-based relay.

TABLE II
INTERNAL FAULT SUMMARY: FAULT LOCATION

Event	Relay	Fault Location (mi)			
		Actual	DETWFL	SETWFL	Existing[*]
1	Five Forks	16.98	16.881[†]	16.943[‡]	13.70
	Windy Edge	3.66	3.769	3.868	4.21
2	Five Forks	9.13	9.242	9.416[‡]	8.50
	Windy Edge	11.52	11.408	11.579	9.81
3	Five Forks	4.5516	4.552	4.586	3.974
	Windy Edge	16.098	16.098[†]	16.053[‡]	19.63

[*] Existing fault location methods are based on BGE's fault information and system model.

[†] Results from event replay with correct settings.

[‡] Taken using only local TWIA and using event report software to calculate values.

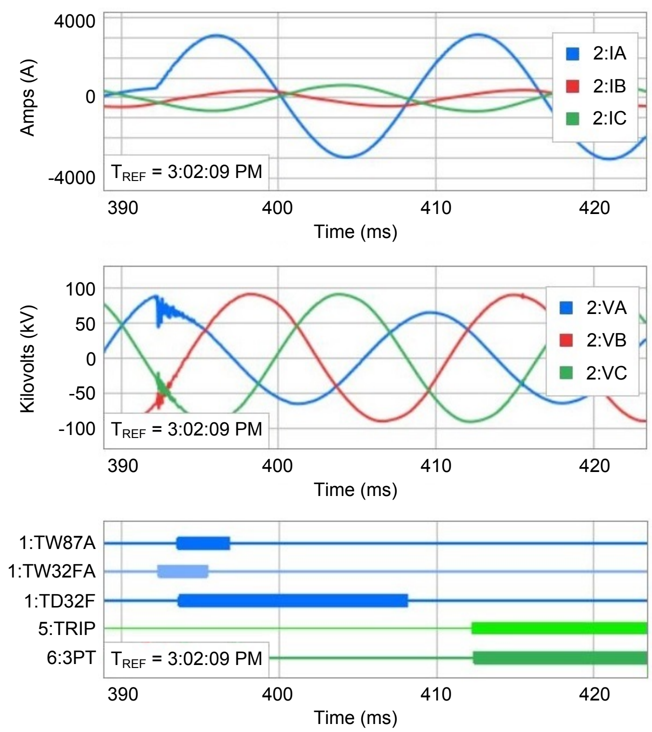

Fig. 17. Performance of the UHS relay compared to the existing protection scheme at Five Forks for Event 1

B. External Fault

During the pilot, a Phase C-to-ground fault occurred close to the remote substation on the line section behind Five Forks. The UHS relays successfully restrained all the protection schemes. The complete event, from fault inception to remote breaker clearing, is shown in Fig. 18. When Five Forks declared a reverse on TW32R followed by TD32R, the Windy Edge relay declared a forward, as expected.

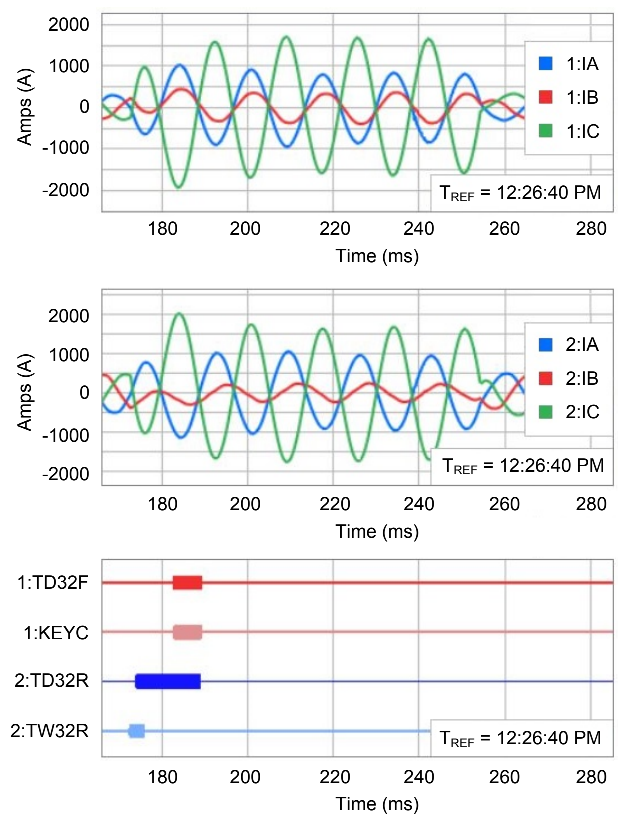

Fig. 18. Recorded phase currents from both terminals for the external Phase C-to-ground fault

In Fig. 19, a TD32R assertion occurs soon after the incremental voltage, DVC, and the Phase C-to-ground incremental loop replica current, DIZCG (DIZC–DIZ0), develop and are in phase with each other. There is a delayed response from Windy Edge, but ultimately the UHS relay asserts TD32F as the incremental quantities develop opposite polarities. TD32F then keys the permissive trip signal.

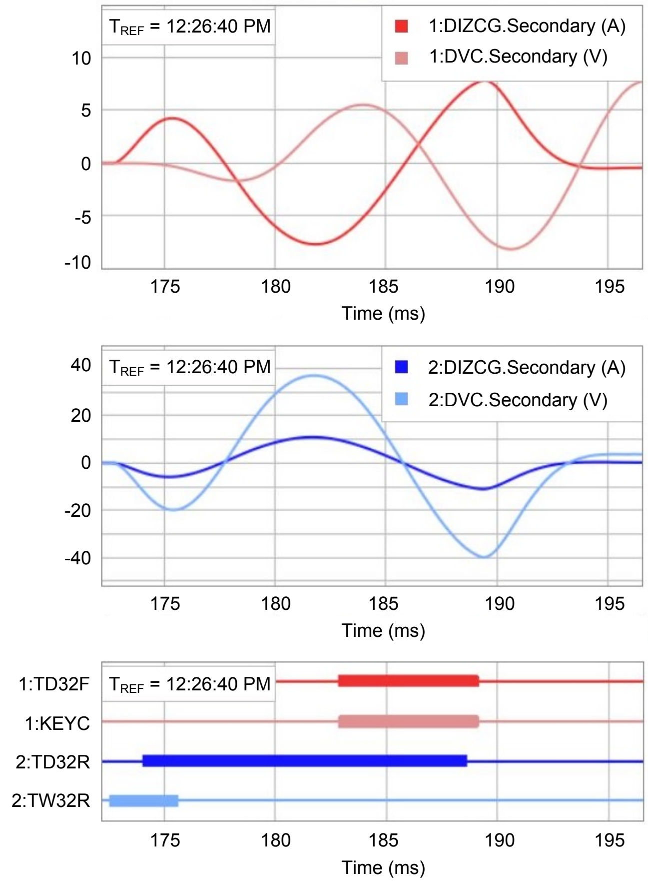

Fig. 19. Incremental quantities from both terminals for the external Phase C-to-ground fault

Fig. 20 shows the high-speed assertion of TW32 as soon as the disturbance detector identifies the fault with current and voltage TWs of the same polarity.

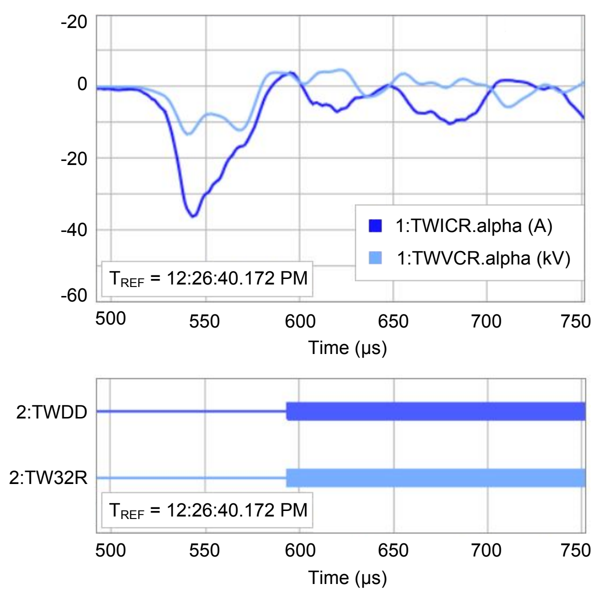

Fig. 20. TW32 declared reverse at the Five Forks terminal for the external Phase C-to-ground fault

Fig. 21 shows the Five Forks and Windy Edge Phase C alpha current TWs that are the TWLPT apart and of opposite polarities, which restrained the TW87 element for the external fault.

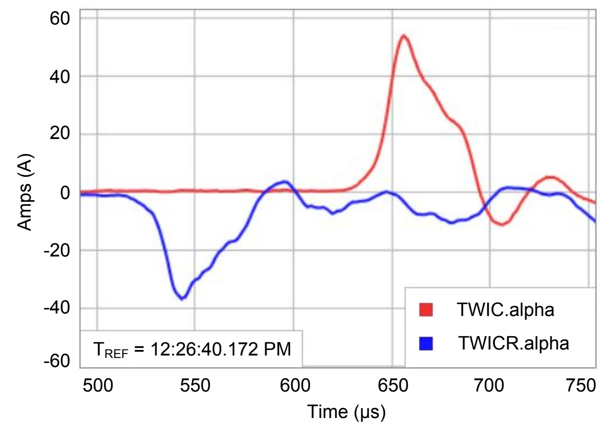

Fig. 21. TWs of opposite polarity and spaced the TWLPT apart for the external fault

V. Lessons Learned

This section discusses the settings errors made over the course of the pilot, including tripping on the TW disturbance detector. The trip on the POTT scheme due to the overly sensitive incremental overcurrent settings during tapped transformer inrush tripping is investigated and the new settings are reviewed. A failure to trip on TW87 due to incorrect TWFL blocking region settings is discussed and correct operation is verified after new settings are implemented. Finally, dependability concerns regarding BPDs and voltage-based UHS relay elements are investigated.

A. TWDD Trip

Initially the UHS relay was configured to trip based on sensitive TW-based disturbance detection, TWDD. The plan was to connect the TRIP output contact to SCADA equipment to notify of any disturbance, but it was found that this was causing nuisance alarms and event recording. Then the TWDD caused a premature trip before TW87 asserted. Using TWDD in the trip equation of the relay also resulted in the fault location value not being reported. Following the trip, it was determined that this was not a proper application, and the disturbance detector was removed from the trip equation. It is recommended by the manufacturer to use protection elements in the TRIP equation, and in the fault location trigger equation. Event report trigger can be configured to sensitive elements for capturing events for transients and external faults.

B. Transformer Inrush Tripping

As described in Section I, the UHS relay includes a POTT scheme that uses traveling-wave directional (TW32) and incremental quantity-based time-domain directional (TD32) elements to key permissive trip signals to the remote terminal. These directional elements may assert for internal disturbances caused by switching or for downstream tapped load distribution faults; therefore, the UHS relay applies overcurrent supervision to the received permissive signal before the relay issues a trip.

The UHS relay keys the permissive trip on the assertion of the time-domain directional element (TD32) and/or the traveling-wave directional element (TW32). For the pilot application, the relay was set to key on both directional elements. The relay will trip on POTT once it declares a TD32F and receives a permissive trip from the remote relay and POTT overcurrent supervision is met.

The POTT directional overcurrent supervision element is typically set by subtracting the load current from the expected minimum fault current (typically for a fault at the remote bus, assuming a weak source and fault resistance). For this pilot, these values initially were set at the minimum to observe all the internal disturbances. During normal switching of the Rock Ridge transformer, the UHS relay POTT scheme operated due to transformer inrush. Fig. 22 shows the absolute value in secondary amps of the Phase C ground loop replica current at Five Forks during the transformer inrush that exceeded the overcurrent supervision setting. This resulted in a trip once the PT signal was received from the remote Windy Edge terminal. The POTT logic of the relay extends assertion of the supervising fault detector for 15 ms to assure sufficient time for the remote terminal to send the permissive trip to the local terminal. This extension compensates for the channel delay.

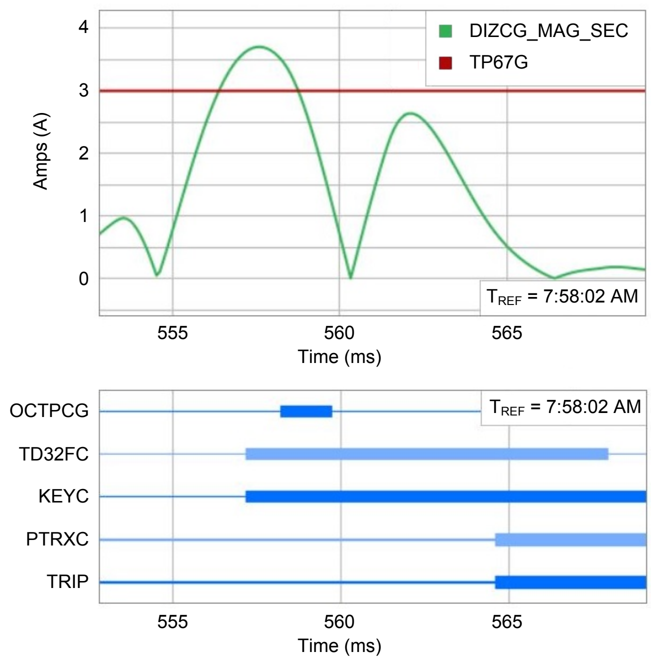

Fig. 22. Rock Ridge transformer inrush seen from Five Forks

Fig. 23 shows the Phase C loop replica current exceeding the overcurrent supervision setting at Windy Edge, allowing the received permissive signal (PTRXC) from Five Forks to trigger a trip.

The UHS relay is designed to capture and play back event records in COMTRADE format that are properly time-aligned (time-synchronized playback mode). The POTT overcurrent supervision threshold was increased to override the inrush condition. The event was replayed through both the relays and the POTT scheme restrained.

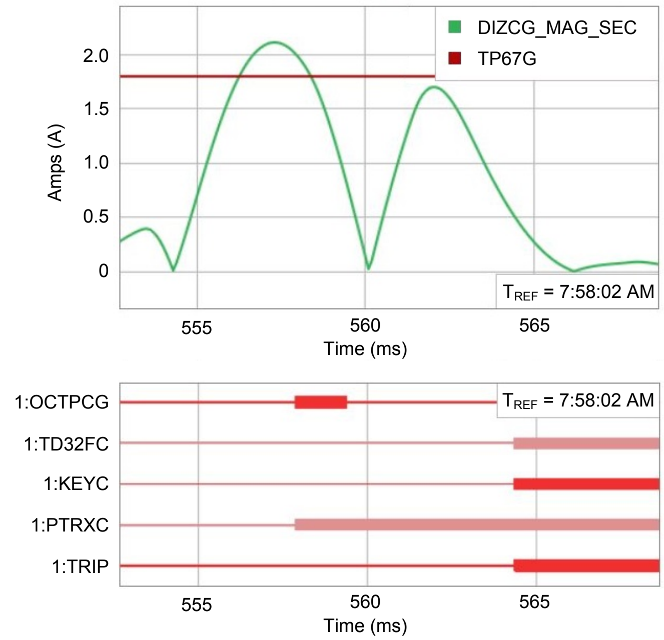

Fig. 23. Rock Ridge transformer inrush seen from Windy Edge

C. *TW87 Blocking Region Settings*

As alluded to in Section IV, Event 3 showed a trip for the relay at Five Forks, but not at Windy Edge. From the initial analysis, it was clear that the current traveling waves were of the same polarity and the time difference associated with the first traveling waves was within TWLPT (63.459 µs) of each other, as shown in Fig. 24. Further inspection of the TW87 settings revealed that blocking regions had been set with the intention of blocking operation at the Rock Ridge tap located 0.7 per unit of line length from the Windy Edge side (0.3 pu from Five Forks). While the Five Forks side was set correctly with a blocking location of 0.3 pu and a blocking radius of 0.03 pu, the Windy Edge side was set to 0.75 pu with a blocking radius of 0.03 pu. The traveling-wave fault locator reported this fault 0.22 pu (4.552 mi) from Five Forks, which would have been 0.78 pu from Windy Edge, falling just within the blocking region of the relay, and consequently blocking the TW87 trip only at that relay.

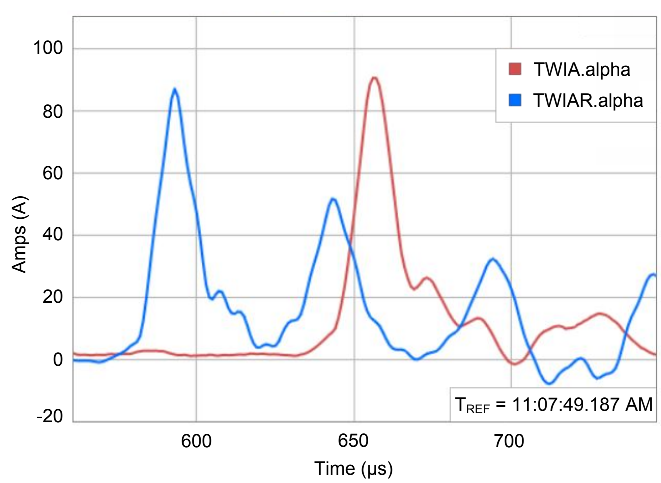

Fig. 24. TWs of the same polarity and within the TWLPT for the internal fault at Windy Edge for Event 3

Adjusting these settings and replaying the COMTRADE event resulted in a correct trip on TW87 in 1.0 ms and an accurate traveling-wave fault location at both relays.

D. BPD Response at the Windy Edge Terminal

For all three internal faults, the voltage-based elements (TW32, TD32, TD21) did not operate at the Windy Edge terminal. Windy Edge has BPDs for voltage, while Five Forks has conventional PTs. The response of the BPD relative to the conventional PT is apparent in Fig. 25 in which, for Event 1, very little voltage disturbance is seen at Windy Edge, but a significant disturbance is seen right at fault inception at Five Forks. There is a 2.5 ms delay in the DVA (Phase A incremental voltage) reaction to the fault as compared to DIZAG (Phase A-to-ground loop incremental current).

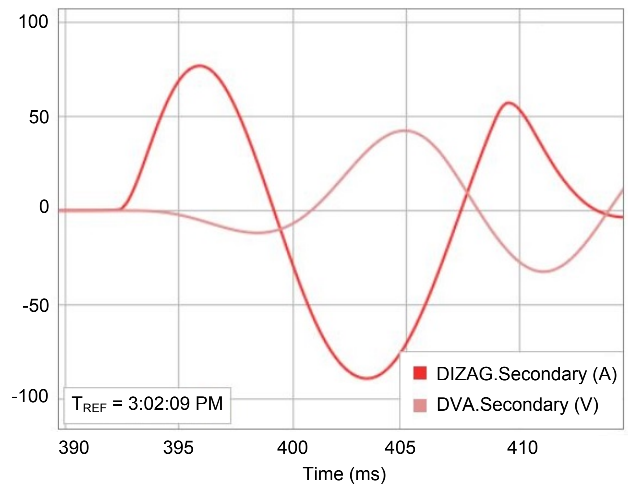

Fig. 25. Incremental voltage and replica current at the Windy Edge terminal for Event 1

For TW32 at Windy Edge, there was a very small peak voltage change on the order of 100 V primary, as shown in Fig. 26. At Five Forks, there was a 10 kV peak voltage TW, as shown in Fig. 12. For this reason, TW32F was not asserted at Windy Edge.

Fig. 27 shows how the Windy Edge BPD voltage appears unaffected by the fault at inception, with very little change until approximately 15 ms after Five Forks sees the fault. A clear voltage drop is seen at Five Forks, giving rise to the successful operations.

Fig. 28 shows a complete view of the voltages during the fault. The PT at Five Forks quickly reaches a new fault steady state while the BPD at Windy Edge did not settle within the measured timeframe.

In summary, the poor voltage replication of primary to secondary voltage measured by the relay and the slow voltage response to faults by the BPDs restrained the operation of incremental quantity-based directional and distance elements.

BPD performance during the BGE pilot has raised concerns about the dependability of BPD operation when BPDs are paired with voltage-based elements, but there was no evidence that this dependability issue affected the security of the UHS relays. Previous studies of BPDs have raised similar concerns over the use of BPDs in protective relaying [10].

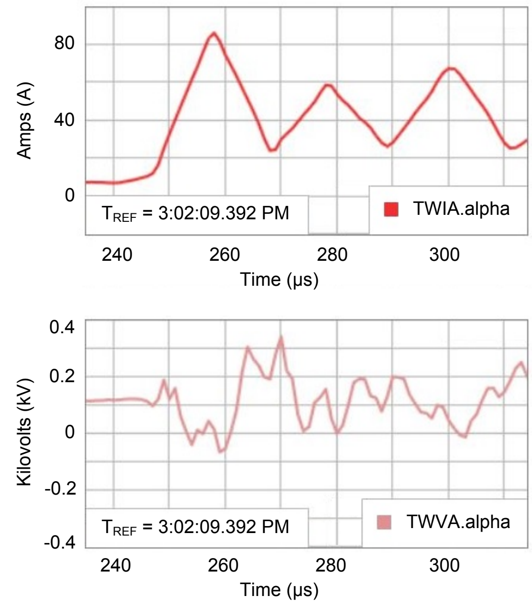

Fig. 26. TW voltage and current recorded at Windy Edge for Event 1

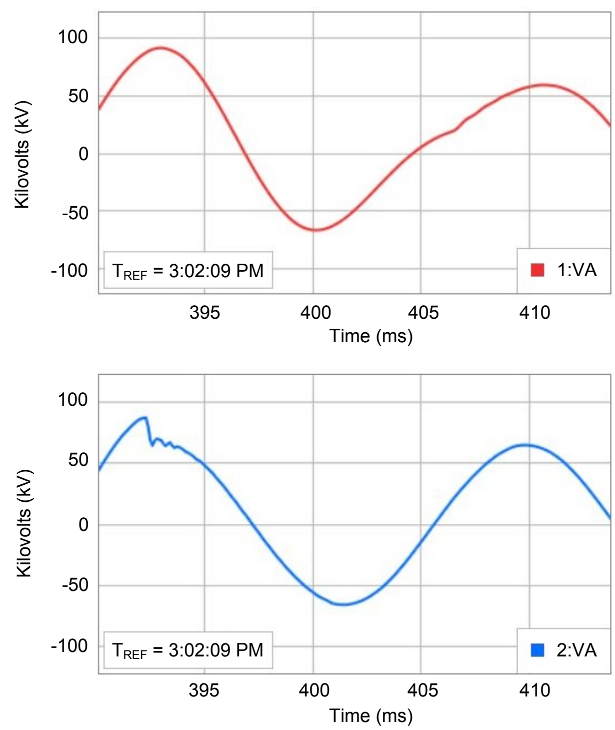

Fig. 27. Faulted phase voltage recorded at Windy Edge (top) and Five Forks (bottom) for Event 1

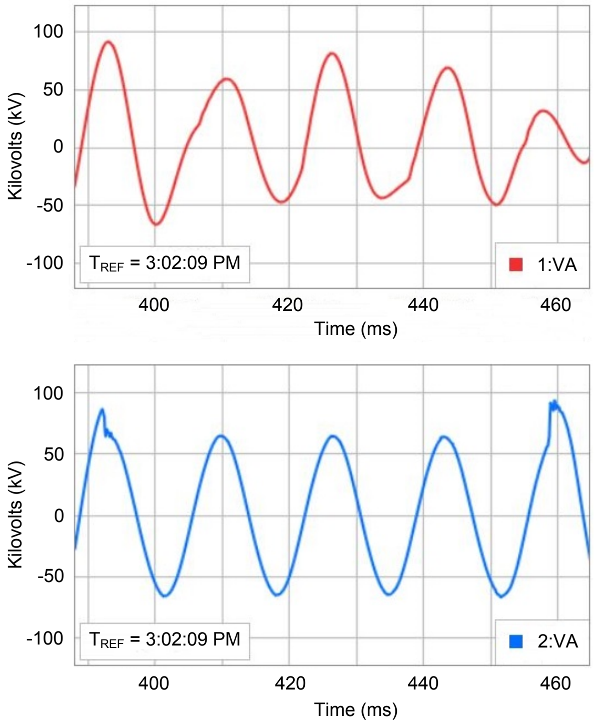

Fig. 28. Faulted phase voltage recovers early at Five Forks (bottom) compared to Windy Edge (top) for Event 1

VI. Next Steps

This section discusses the next steps of the UHS relay pilot. Circuit breaker tripping is discussed as a potential possibility for BGE, and the section concludes with a discussion on the use of BPD with UHS relays.

A. Path to Tripping

The pilot project was designed to test the new technology included in UHS relaying; therefore, breaker tripping was not implemented. The rating of the breakers at each terminal is one facet that must be considered before live breaker tripping is installed on this circuit. The asymmetrical short-circuit interrupting current may be exceeded depending on the X/R ratio and relaying operating time [11]. Careful calculation should be done to determine if UHS relaying can be applied for tripping and not exceed the breaker rating.

The BGE system generally does not have transient stability issues, so, for BGE, the advantage of speed with UHS protection is secondary to the advantages of accurate TWFL and the setting simplicity of the UHS relay. Impedance-based calculations are accurate for locating faults, but they are only as effective as the system is well designed. As seen in Table I, this circuit had some modeling issues that affected impedance-based fault locating. Ultimately, reliable, accurate fault locating results in more time to focus on specific locations, even when no obvious cause of a fault is found.

The UHS relay is advantageous in that it reduces the likelihood of a settings and/or logic design error because the relay has few calculated settings, most of which are also calculated for phasor-based relaying. Nevertheless, the present version of the UHS relay does have some disadvantages specific to BGE’s protection standards, i.e., no protection for line end faults during a communications failure and no ability to incorporate overreaching 21 or 51 elements.

The present protection philosophy at BGE does not solely rely on a communications channel for all its protection: both the primary and the backup relay must be able to protect 100% of the line without communication even if instantaneous fault clearing must be sacrificed. The UHS relay does not include overreaching elements that can be coordinated with adjacent circuits in the event of a communications channel failure. As such, at BGE a UHS relay would be applied as a third level of protection.

The addition of programmable logic and limited-capacity phasor-based functions will make the UHS relay more versatile in supporting other protection needs on this line, such as remote protection of the tapped sections.

B. Investigation of BPDs at Windy Edge

The results from the BGE pilot suggest that BPDs should not be relied on to provide reliable voltage quantities for voltage-based elements due to the performance variations. Further testing will determine whether the BPDs require retuning or if this is a physical limitation of the equipment.

There are few BPDs in use on the BGE system, and rarely are they tuned unless there is a significant voltage magnitude issue, which usually is associated with secondary burden changes when electromechanical relaying is replaced with microprocessor relaying. Given the small number of BPDs left on the system, and their poor response when used with time-domain functions, BGE would be well served in avoiding BPD voltage sources for UHS relay installations.

VII. Conclusion

UHS relays with ultra-high-speed protection elements, such as traveling-wave differential and directional along with incremental quantity-based distance and directional, allow protective relay tripping speeds as low as 1 ms. The traveling-wave fault locator routinely showed accuracy of approximately 0.1 miles in our pilot for both single-ended and double-ended methods. Over the course of the pilot, no security concerns were found when proper settings were applied.

BPDs pose a dependability concern when using UHS protection elements that use voltage. Further study is needed to see if proper tuning would alleviate these concerns and to evaluate performance with UHS elements.

The relay settings in this particular UHS relay are straightforward and minimal. Many of these settings are similar to the settings used to configure microprocessor-based line relays. A pilot can be established using existing settings with the addition of a line energization test upon commissioning. A direct fiber-optic communications link between two relays is required to evaluate the full functionality of the UHS relay; however, the POTT scheme can be accomplished using other communications methods. Single-ended protection and fault locating can be evaluated in standalone or radial applications. The UHS relay features event playback so applications without communication can be replayed in a lab environment where communication would be available to evaluate performance of the TW87 and POTT schemes offline. This also allows for the easy evaluation of settings changes.

This BGE pilot shows how implementing new technology can be an important and exciting opportunity for both the manufacturer and the customer. Such pilots provide a chance for the two entities to collaborate and learn from one another to advance technology and application. As the discussion of the Event 1 TWDD trip in Section V shows, communication and support between the manufacturer and technology experts is key to the success of any pilot.

VIII. Acknowledgments

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X. Biographies

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