

# Testing and Commissioning Ultra-High-Speed Line Protection on a 345 kV Transmission Line

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**Abstract**—Public Service Company of New Mexico (PNM) selected ultra-high-speed (UHS) line protective relays for their 345 kV lines, in addition to their phasor-based protective relays. UHS line relays use principles based on incremental quantities and traveling waves (TWs) to provide speed and security. In this paper, we discuss the procedures followed during the commissioning, bench, and end-to-end testing of the PNM UHS line protection. In conclusion, we provide recommendations and best practices for testing a UHS line protective relay.

## I. INTRODUCTION

Public Service Company of New Mexico (PNM) is an investor-owned electric utility that serves customers and provides network integration transmission services to other utilities in the northern New Mexico portion of the Western Electricity Coordinating Council grid. PNM also operates 115 kV-and-lower voltage networks of the southwestern New Mexico system. PNM owns a total of approximately 14,338 miles of 46 kV, 69 kV, 115 kV, 230 kV, and 345 kV transmission lines.

The PNM bulk transmission system shown in Fig. 1 is designed to transmit power from northwestern New Mexico to load centers in the northern half of New Mexico. Most of the PNM load is in the Albuquerque metropolitan area. This project involved the line between San Juan and Rio Puerco, a critical interconnection between the East and West regions of the PNM service territory.

To service a new industrial load, the Cabezon substation was constructed and the original line between San Juan and Rio Puerco was split into two sections: San Juan to Cabezon (WW line) and Cabezon to Rio Puerco (CZ line). However, this split resulted in 170 percent compensation of the CZ line. To avoid misoperations on the overcompensated line, Zone 1 distance protection in the phasor-based relays at Cabezon was disabled [1]. Ultra-high-speed (UHS) relays were installed on the CZ line and WW line to provide fast, secure protection and accurate fault locating on these lines. Fig. 2 shows a one-line diagram of these lines in the PNM system.

Section II discusses the PNM line protection standard. Section III introduces UHS time-domain line protection and discusses the PNM motivation for protecting the WW line and CZ line with UHS relays. Section IV and Section V discuss methods to test time-domain line protection in the field.

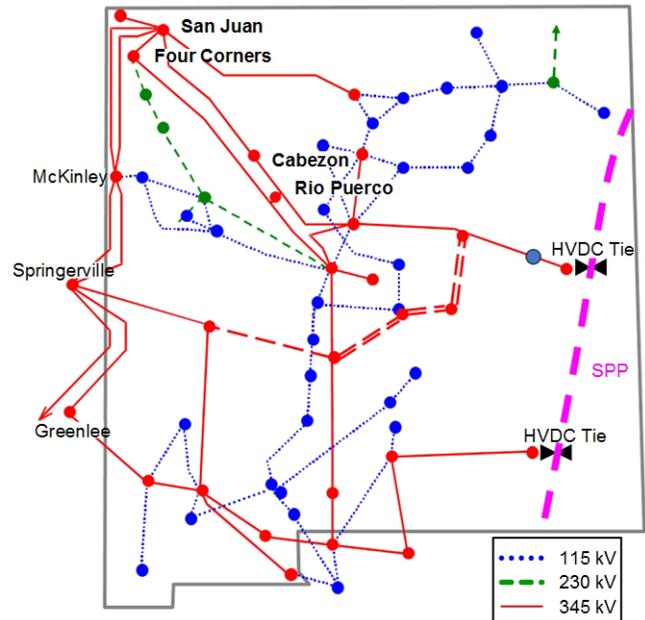


Fig. 1. PNM critical transmission lines.

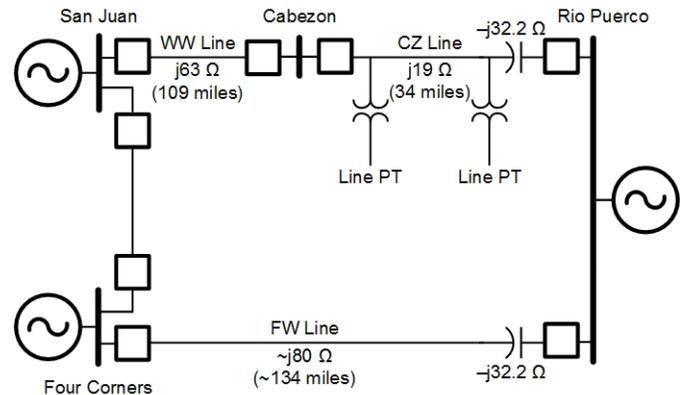


Fig. 2. One-line diagram of the PNM WW line and CZ line.

## II. PNM PROTECTION STANDARD AND PHILOSOPHY

The PNM line standard has traditionally required using three phasor-based relays for protection at the 345 kV voltage level. The standard requires using four zones of distance protection with quadrilateral characteristics for both phase and ground

elements. The standard requires permissive over-reaching transfer trip (POTT) schemes using directional-ground and negative-sequence overcurrent elements, and overreaching-distance elements (phase and ground). The reach of the Zone 1 phase-distance elements is set to 70–80 percent of the line impedance and the reach of the Zone 1 ground-distance elements is set to 50–80 percent. Zone 2 phase- and ground-distance elements are set to reach beyond the remote bus to provide enough reach for implementing a POTT scheme and step distance protection. The reach of the Zone 2 distance elements is set based on the system configuration but is typically 125–175 percent of the line impedance. Zone 3 phase- and ground-distance elements are set in the reverse direction with a reach set to coordinate with the remote bus Zone 2 reach. Zone 4 phase- and ground-distance elements are set in the forward direction and act as remote breaker failure backup. One directional ground time-overcurrent element is enabled to coordinate with the remote terminal relay. One level of directional instantaneous overcurrent (phase and ground) is also enabled to detect faults in 10–15 percent of the line. In addition to the distance protection, the standard requires line current differential protection. Refer to [1] for PNM protection system details.

### III. OVERVIEW OF UHS RELAY

UHS relay protection elements are based on incremental quantities and traveling waves (TWs). In general, the average operation time for the incremental quantity Zone 1 distance (TD21) element is 2–7 ms, depending on the fault location and source-to-line impedance ratio. The incremental quantity directional (TD32) element typically operates in 1–3 ms. The TW differential (TW87) scheme operates in 1–5 ms depending on the line length [2].

This section briefly describes the principles of the incremental quantity- and TW-based elements.

#### A. Elements Based on Incremental Quantities

By applying the superposition principle, a faulted network can be decomposed into a pre-fault network and a fault network [3]. The incremental quantity-based protection elements operate on signals generated from the fault network. In the fault network, the driving force is the pre-fault voltage at the fault point. Thus, for a forward fault, the incremental voltage is in front of the relay and the incremental current is measured by the relay as flowing in the reverse direction. For a reverse fault, the incremental voltage is behind the relay and the incremental current is measured by the relay as flowing in the forward direction.

Using these observations and applied signal processing, the TD32 element proposed in [3] and [4] declares a forward disturbance when the incremental voltage and the incremental replica loop current have opposite polarities.

The TD21 element described in [5] is designed to calculate a voltage at the reach point using its measured incremental voltage and current. If the calculated incremental voltage magnitude is greater than the pre-fault voltage at the reach

point, the element asserts and declares that the fault is within the zone of protection. The TD21 element is comprised of a phase and a ground element.

#### B. Elements, Schemes, and Fault Locators Based on Traveling Waves

The sudden change in voltage at the fault point launches current and voltage TWs that propagate toward line terminals. The ratio of the incident voltage TW to the current TW is the characteristic impedance of the line. Measurements of the relative arrival times and polarities of the TWs at each terminal allow for UHS line protection and allow fault locating with an accuracy within two tower spans.

For a forward fault, the initial voltage and current TWs are measured by the relay as having opposite polarities because of the polarity of the current transformers (CTs). For a reverse fault, the relay will measure voltage and current TWs with the same polarity. As described in [4], this is the general operating principle of TW32. When enabled, TW32 is used only in the POTT scheme transmit logic to speed up keying the permissive trip signal sent to the remote relay. TW32 is not used to directly trip the UHS relay. This element does not require any settings from the user.

The TW87 scheme operating principle described in [3] is based on the current TWs captured at the local and remote line terminals. For an internal fault, the first current TWs arrive at each terminal with the same polarity and a difference in arrival times that is less than the traveling-wave line propagation time (TWLPT). For an external fault, the TW enters one terminal and leaves the other after traversing the entire length of the line. Thus, the initial TW arrives at the line terminals with opposite polarity, and a difference in arrival times that is equal to the TWLPT. Typically, the TWLPT setting is measured through a line energization test [6].

In addition to these protection elements, the relative timing of the initial current TWs at each terminal is used in the double-ended traveling-wave-based fault locator (DETWFL) [7]. The single-ended traveling-wave-based fault locator (SETWFL) described in [8] and [9] uses the initial current TW and the first subsequent reflection from the fault to identify the fault location. Both TW-based fault locating methods can accurately locate faults within one tower span.

#### C. Introducing UHS Line Protection to PNM

As discussed in Section I, protection challenges on the CZ line and the critical nature of the east-to-west interconnection motivated PNM to investigate new technologies. UHS relays using incremental quantities and TWs respond to events prior to the voltage change across the capacitor bank, hence these relays are better suited to protect series-compensated lines. Fig. 3 shows the operating time comparison between UHS relays and phasor-based relays on the CZ line using a real-time digital simulator (RTDS). Numerous test cases were simulated to evaluate the performance of the UHS line protection. Based on the performance, from both speed and security aspects, PNM applied UHS relays on the WW line and CZ line in conjunction with their traditional phasor-based protection schemes.

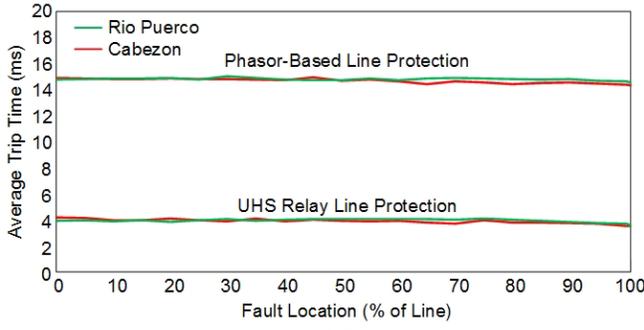


Fig. 3. Comparing the operation time of phasor-based line protection and UHS line protection on the CZ line.

#### IV. UHS RELAY TESTING

##### A. Testing Protection Elements That Use Incremental Quantities

Testing incremental quantity-based elements can be performed using traditional relay test equipment, but it requires considerations that are not typically applicable when testing phasor-based relays.

###### 1) Testing Using States

State simulation is commonly used, along with traditional test equipment, to test the operation of protection elements and schemes. It is common to use pre-fault and fault states that specify the magnitude and angle of the applied phase voltage and current signals. The signals produced by the test may exhibit a sharp change when the applied signals transition from the pre-fault state to the fault state. Fig. 4 shows a typical relay test equipment user interface.

	1			2		
Name	State 1			State 2		
V A-N	66.40 V	0.00 °	60.000 Hz	16.40 V	0.00 °	60.000 Hz
V B-N	66.40 V	-120.00 °	60.000 Hz	66.40 V	-120.00 °	60.000 Hz
V C-N	66.40 V	120.00 °	60.000 Hz	66.40 V	120.00 °	60.000 Hz
I A	5.000 A	0.00 °	60.000 Hz	20.00 A	-86.00 °	60.000 Hz
I B	5.000 A	-120.00 °	60.000 Hz	5.000 A	-120.00 °	60.000 Hz
I C	5.000 A	120.00 °	60.000 Hz	5.000 A	120.00 °	60.000 Hz
CMC Rel	0 output(s) active			0 output(s) active		
Trigger	1.000 s			200.0 ms		

Fig. 4. Pre-fault state (State 1) and fault state (State 2).

Fig. 5(a) shows the Phase A test current captured by the UHS relay for a single-phase-to-ground fault using state simulation. A sharp change in the signal occurs at the transition point from the pre-fault state (with an RMS magnitude 5 A and an angle of  $0.0^\circ$ ) to the fault state (with an RMS magnitude of 20 A and an angle of  $-86.0^\circ$ ). In this test, the pre-fault state was applied for exactly 1 s. Fig. 5(b) is the incremental replica current calculated by the UHS relay, which is used in the incremental quantity-based protection algorithms. The sharp change at the transition point caused an artificial incremental replica current.

Phasor-based relays calculate the magnitude and angle of an applied voltage and current signal after applying band pass filtering to isolate the signals near the fundamental frequency. The relays are essentially unaffected by dc offset and high-frequency signals (i.e., short abrupt changes). Aside from filtering, many phasor-based relays also do not sample the

applied signals at a rate high enough to observe the sharp change; therefore, it often goes unnoticed.

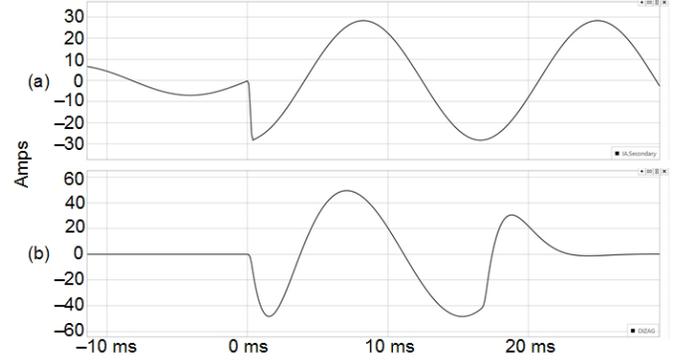


Fig. 5. Transition from pre-fault state to fault state that produces a sharp signal change in the incremental current: (a) phase current; and (b) incremental replica current.

Elements that operate on incremental quantities, such as the TD32 and TD21 elements described in Section III.A, are subject to unexpected operation if a sharp signal change occurs during the transition between states.

The abrupt change is a function of the time duration associated with the pre-fault state, and the specified phase angle of the signal applied during pre-fault state and during fault state. Transitioning from the pre-fault to the fault state at the exact time specified by (1) ensures that the incremental current develops as a sine wave [2].

$$t_0 = \frac{1}{\text{NFREQ}} \cdot \left( \text{NC} - \frac{\text{angle}(\Delta I)}{360^\circ} \right) \quad (1)$$

where:

NFREQ is the nominal frequency.

NC is the number of integer cycles of the pre-fault voltages and currents the user wants to apply.

$\Delta I$  is the incremental current for the faulted phase.

Fig. 6 shows the same pre-fault and fault signals from Fig. 5, except the pre-fault signal was applied for 1.0046 s. The pre-fault duration was calculated from (1) using NFREQ = 60, NC = 60, and  $\text{angle}(\Delta I) = -100.2^\circ$ . Applying this transition time to the pre-fault state removes the sharp signal change at the transition point and allows the incremental current to develop as a sine wave.

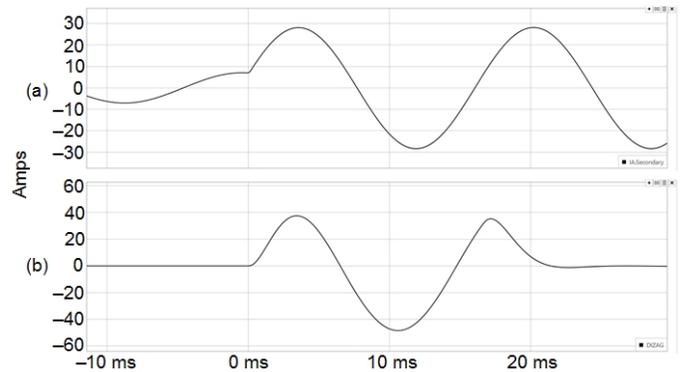


Fig. 6. Transition from pre-fault state to fault state that produces no sharp signal change in the incremental current: (a) phase current; and (b) incremental replica current.

This test approach can be used for bench testing the TD21 element and TD32 element.

## 2) Testing Using Realistic Fault Signals

Many test equipment manufacturers make software that allows the user to model a system and apply a specific fault type at a specific location [10] [11]. Depending on the software and test equipment, these signals can either be applied immediately through test equipment connected to the relay, or they can be saved as a COMTRADE file for playback to the relay later. Using a COMTRADE file:

- Ensures the voltage and current signals are based on the system parameters and provides a continuous signal transitioning from pre-fault to fault.
- Eliminates the abrupt change that might occur when using a state sequencer.
- Proves ideal for bench and end-to-end testing both phasor-based protective relays and UHS relays.

To test the UHS relays installed by PNM in the field, COMTRADE test files were generated using an RTDS. The PNM system was modeled in an RTDS and used to test the performance of the two protection systems as part of factory acceptance testing. The same environment was used to generate test files representing internal and external faults with different fault types and locations. During commissioning, these test files were played back to the UHS relays using traditional relay test equipment. This configuration allowed verifications of wiring, relay health, relay settings, and operation of elements that use incremental quantities.

Fig. 7 shows the test signals of a Phase C-to-ground (CG) fault simulation on the CZ line that was played back during commissioning testing.

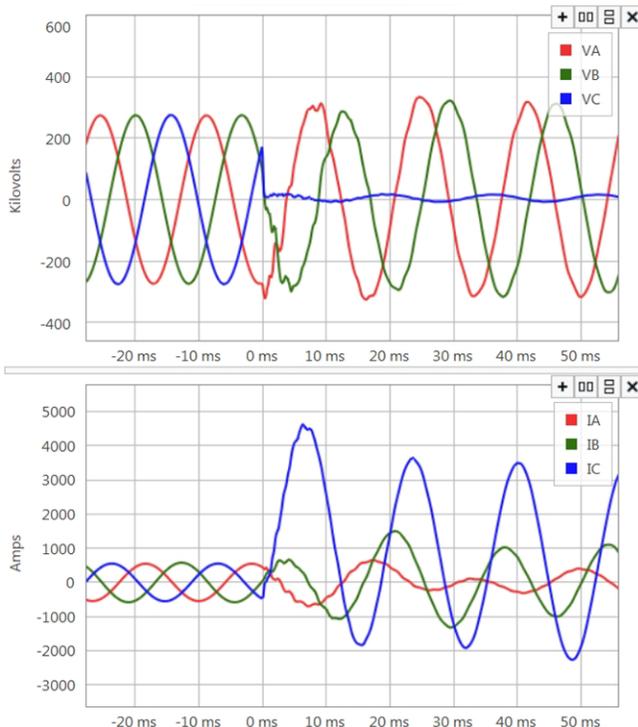


Fig. 7. Test signals recorded by the UHS relay for testing the incremental quantity element for a CG fault at 10 percent down the CZ line from Cabezon.

## B. Testing TW-Based Fault Locators and Protection Elements and Schemes

TW-based features available in UHS line protection operate using measured signals in the range of hundreds of kilohertz. To measure these signals, the UHS line protection samples the applied voltage and current signals at 1 MHz and applies additional filtering to isolate the high-frequency TW signals. Most traditional test equipment cannot produce the high-frequency signals required to simulate the TWs that occur on a line when a fault occurs [11] [12]. Therefore, commissioning testing of TW-based line protection and fault locators requires test equipment capable of emulating the TWs. Reference [12] describes the compact test equipment used in the field for commissioning testing of TW-based features in the UHS line protection installed on the PNM 345 kV transmission line. The TW test equipment can generate current TWs by producing signals with a 4 A/ $\mu$ s step change. These signals have a nominal current rating of 5 A, a rated rise time of  $< 1 \mu$ s, a halfway decay time of nearly 400  $\mu$ s, and injection timing accuracy of less than 16 ns [13]. Precise TW injections with this degree of accuracy are necessary for testing the TW87 scheme, DETWFL, and SETWFL.

Traditional relay test equipment in conjunction with the TW test equipment verified the operation of TW-based functions. Both devices were wired to the UHS line protection and the test equipment was time synchronized, as shown in Fig. 8.

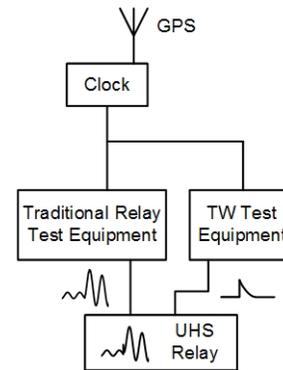


Fig. 8. Configuration for superimposing time-aligned TWs on signals at the fundamental frequency.

With this configuration, the traditional test equipment provides the signals necessary to satisfy the lower frequency supervisory conditions [2] and the TW test equipment applies the precisely controlled high-frequency TW-like signals.

## V. END-TO-END COMMISSIONING TESTING

### A. Test Setup

To verify the correct UHS relay settings and protection scheme operation, traditional test equipment and TW test equipment are combined as an integrated set for testing all incremental quantity- and TW-based elements simultaneously. Fig. 9 shows the configuration of a practical system to test UHS relays with incremental quantity- and TW-based elements. This system uses traditional relay test equipment that applies voltage and current signals with a bandwidth of several kilohertz, and TW test equipment that applies step signals. The UHS relay has

two three-phase current input channels to accommodate applications such as breaker-and-a-half and dual-breaker bus configurations. This also allows the UHS relay to interface with the current outputs of the traditional relay test equipment and the TW test equipment using individual channels; the applied current signals from each are then combined inside the relay.

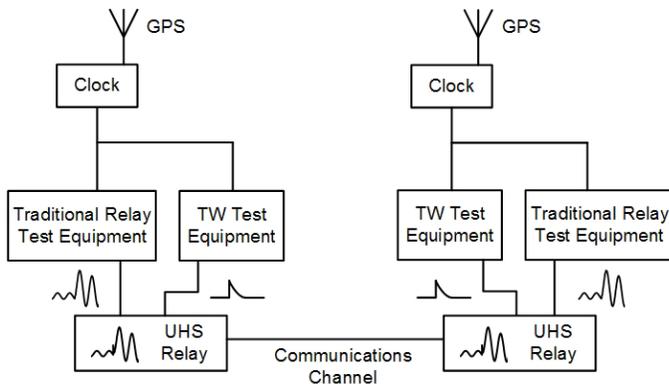


Fig. 9. Test setup configuration for end-to-end testing of incremental and TW elements and schemes.

Aligning the nominal- and high-frequency signals requires time synchronization between the test equipment. For end-to-end testing, time synchronization is also required between the two terminals. When using this configuration, it is important that the TW signals be applied precisely when the signals at the nominal frequency transition from the pre-fault to the fault condition. That is, the UHS relay must detect a disturbance in the incremental quantities that is simultaneous with a TW disturbance. To satisfy this condition, the traditional test equipment was configured to apply exactly 1 s of the pre-fault condition at a desired time using time-based triggering. This configuration was used because most test equipment can be time triggered on the top of second. Similarly, time-based triggering was used in the TW test equipment to inject exactly 1 s after the traditional test equipment initiates the pre-fault condition to align the applied TWs with the transition to the fault condition. This can only be accomplished using test equipment that is time synchronized using GPS satellite clocks.

As mentioned previously, the test files were generated using an RTDS and were played back using the traditional relay test equipment. The test procedure described here is used exclusively to verify correct operation of the protection system, including the protection communications channel and settings. Additional tests were performed to verify phasing, electrical wiring, communication interfaces, and other aspects that are part of typical commissioning tests.

Commissioning testing included the TD21 element and the POTT and TW87 schemes. The TW32 element was disabled on the WW line and CZ line, therefore it was excluded from the test. The DETWFL results were observed but were not part of the official commissioning procedure and, therefore, not recorded.

The COMTRADE test files are sampled at 8 kHz and include the nominal frequency voltage and current signals for both internal and external faults at various locations in the

system. Voltage and current signals in these test files are injected using traditional relay test equipment to verify the incremental quantity-based functions. The current output of the traditional relay test equipment is connected to one set of three-phase current inputs (i.e., W current channel) of the relay, and the current TW signals generated from the TW test equipment are connected to the other set of three-phase current inputs (i.e., X current channel) of the relay. The two sets of current inputs are then superimposed by configuring the UHS relay to sum the two three-phase current inputs internally. Each test case is documented regarding fault type, location, and expected operation of protection functions to facilitate result validation. The TW87 scheme and TW fault locator only operate on the current TWs. However, the TW87 scheme uses the polarity of the pre-fault voltage at the fault location for security [2]. For example, when testing a forward fault, if the TW test equipment is configured to inject a positive current step in the faulted phase, the fault should be simulated at the positive voltage point on the wave.

The COMTRADE test files are constructed with a 1 s pre-fault condition as shown in Fig. 10. Fig. 10 shows the three-phase voltage and current signals for an internal Phase B-to-ground (BG) fault simulation on the CZ line. Fig. 11 provides a closer look at the Phase B voltage when the fault occurs. Fig. 11 shows that the pre-fault voltage is positive when the fault occurs. In this forward fault, the relay at Rio Puerco should measure a positive initial current TW and a negative initial voltage TW for Phase B.

If the traditional relay test equipment is triggered at hh:mm:00 to start the file, the TW test equipment will inject the pulses at hh:mm:01 so the TWs are aligned with the fault occurrence.

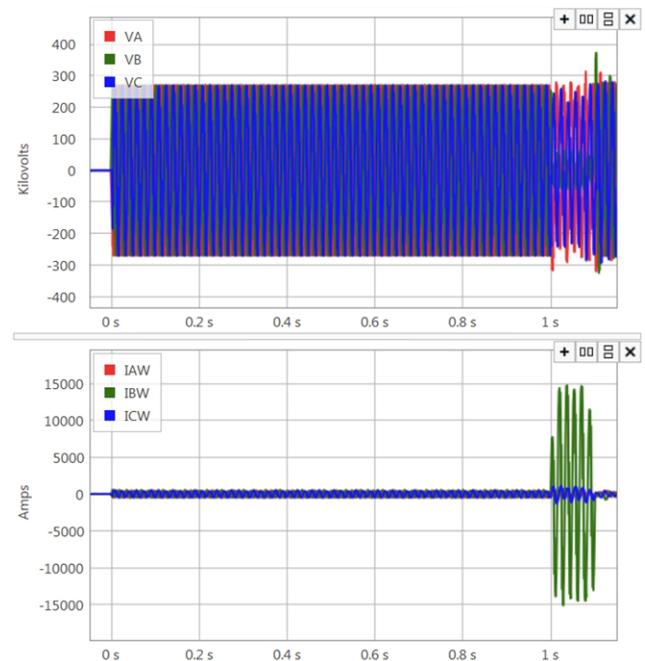


Fig. 10. COMTRADE test files sampled at 8 kHz for a BG fault at 10 percent of the CZ line from Rio Puerco.

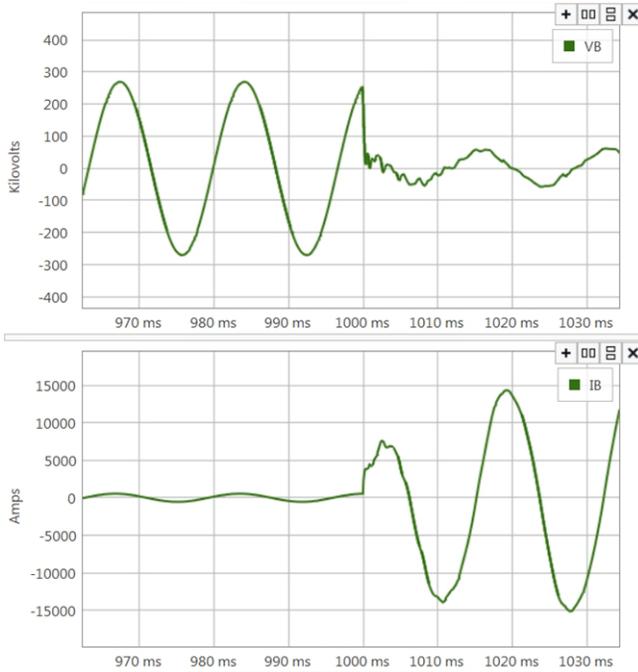


Fig. 11. Test signals recorded by the UHS relay for a BG fault at 10 percent of the CZ line from Rio Puerco.

Fig. 12 shows the superimposed current signal from traditional relay test equipment and TW test equipment for the faulted phase, i.e., Phase B.

The Sequential Events Recorder (SER) was configured to include all concerned Relay Word bits. The SER was cleared prior to each test and captured following each test. All associated COMTRADE records from the UHS were saved following each test. The trip operation was verified by connecting the relay output contacts to the relay test equipment inputs. In addition, direct transfer trip (DTT) and POTT scheme signaling was verified using a remote I/O module to convert fiber outputs to copper and wiring the I/O module outputs to the inputs of the relay test equipment.

For each line at 0, 10, 50, 90, and 100 percent, two internal faults (one single-phase-to-ground and one phase-to-phase or phase-to-phase-to-ground) are tested. Similarly, behind each terminal, two different types of external faults (one single-phase-to-ground and one phase-to-phase or phase-to-phase-to-ground) are tested. Samples of different phases are selected to emulate and verify all phase indications. The TW87 scheme operation is verified only for single-phase-to-ground faults.

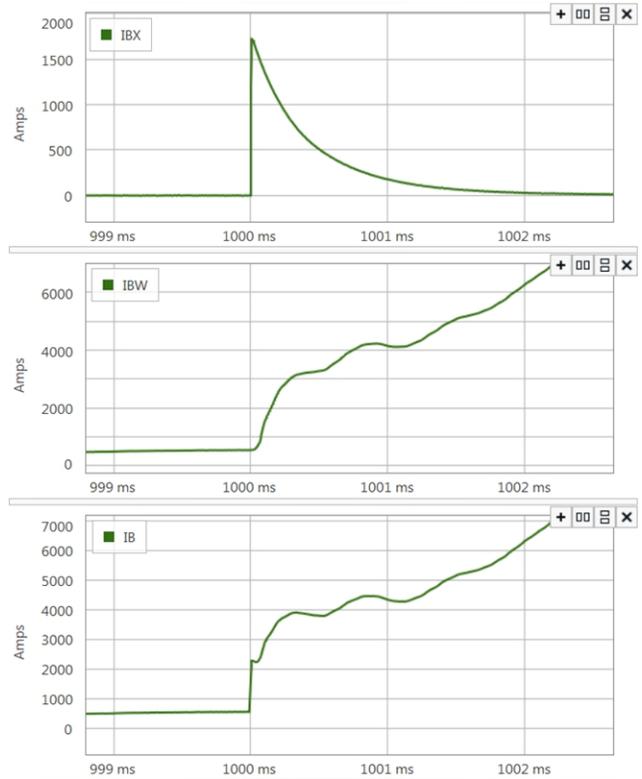


Fig. 12. TW device-generated pulse-IBX; traditional relay test equipment-generated current signal-IBW; and combined-current test signal measured by the UHS relay-IB (8 kHz superimposed with TW pulses).

## B. Commissioning Test Results

### 1) Internal Fault on WW Line

Fig. 13 shows the Phase A-to-ground (AG) fault simulation on the WW line. The fault was 46 percent away from the San Juan terminal. Fig. 14 shows the test signals captured by the relay at San Juan. The reach of the TD21 phase and ground elements was set to 0.75 and 0.7 (in per unit [pu] of the line impedance), respectively. For this event, the expectation was that the TD21 ground element should operate on both terminals, the TD32 element should detect forward events on both terminals (therefore the POTT scheme should operate for this fault), and the TW87 scheme should operate. As shown in Fig. 14, the pre-fault voltage of Phase A is positive, as is the polarity of the injected current TWs when the fault occurs. This relationship is expected for an internal fault.

The relay response at Cabezon is shown in Fig. 15. Fig. 16 shows the TW pulses captured by the relay at the San Juan terminal and the Cabezon terminal; it demonstrates that the TWs arrived at San Juan ahead of Cabezon by less than TWLPT, and the TW87 scheme operated as expected.

As shown in Fig. 14 and Fig. 15, the TW87 scheme operated within 1 ms, the TD32 element operated within 2 ms, and the TD21 element operated within 4 ms.

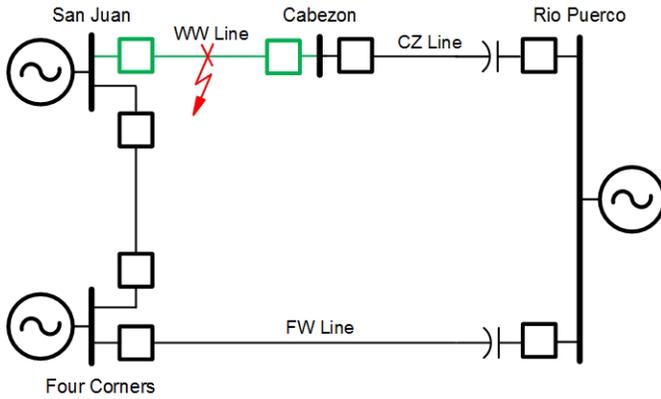


Fig. 13. Test scenario of an internal fault on the WW line, where an AG fault is simulated at 46 percent from San Juan.

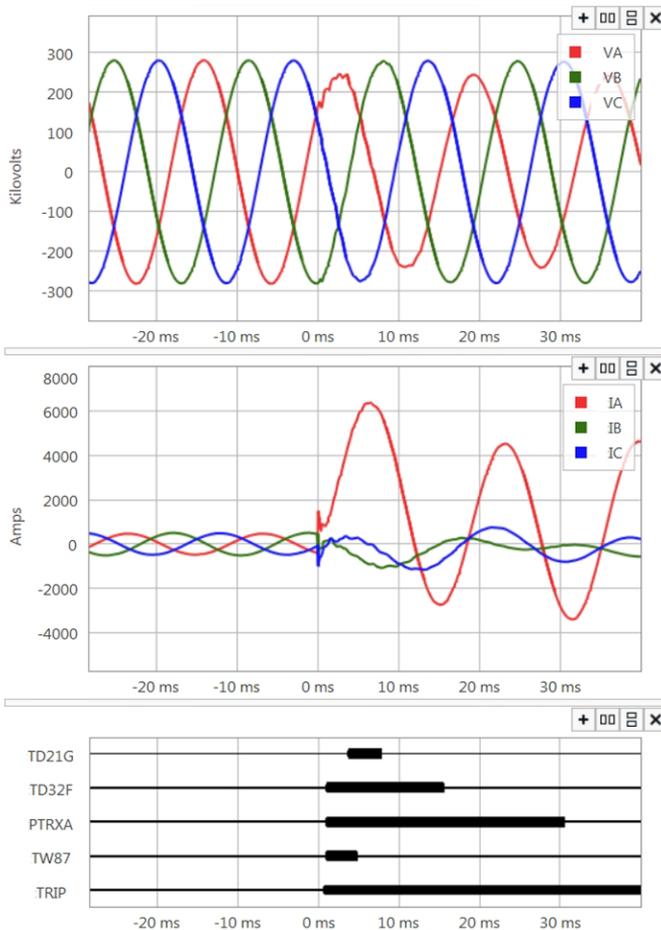


Fig. 14. Test signals recorded by the UHS relay at 1 MHz sampling rate and the protection element response at San Juan for an AG fault on the WW line.

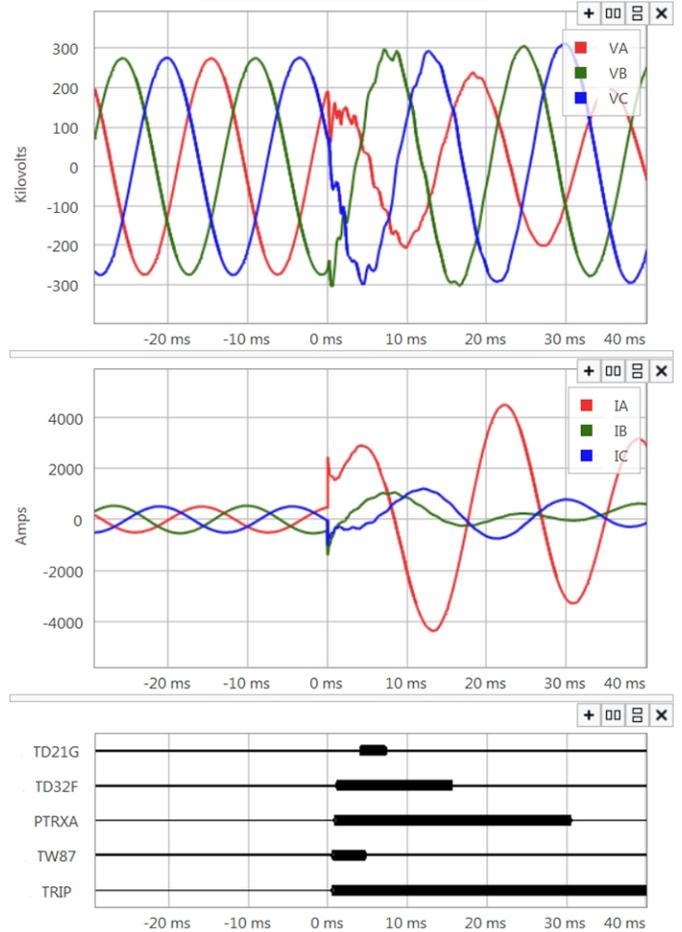


Fig. 15. Test signals recorded by the UHS relay at 1 MHz sampling rate and the protection element response at Cabezon for an AG fault on the WW line.

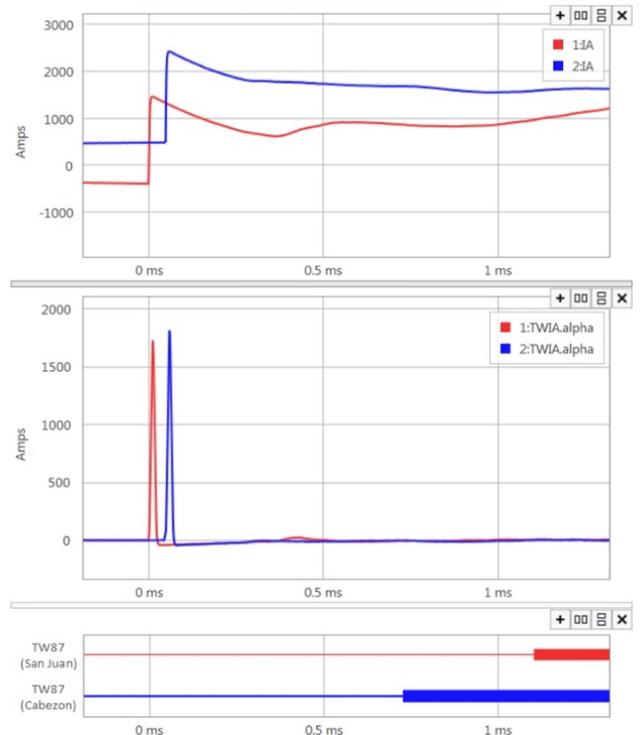


Fig. 16. Phase A currents and TWs captured at San Juan (Event 1) and Cabezon (Event 2) with the TW87 scheme operation at San Juan and Cabezon.

2) External Fault on WW Line

Fig. 17 shows a BG fault simulation on the FW line between Rio Puerco and Four Corners. The relay at the San Juan terminal and the relay at the Cabezon terminal restrained from operating. The expectation for this external fault was that the TD32 element at the San Juan terminal should declare a forward fault while the Cabezon terminal should declare a reverse fault (the POTT scheme should then restrain), the TD21 element should not operate, and the TW87 scheme should also restrain. When the BG fault occurred, the polarity of the Phase B current TW applied at the Cabezon terminal was opposite to the polarity of the Phase B pre-fault voltage; the polarities were the same at the San Juan terminal. This relationship is expected for an external fault.

Fig. 18 and Fig. 19 show the test signals with relay reactions at the San Juan terminal and the Cabezon terminal, respectively. Fig. 20 shows the current TWs captured by these two relays and demonstrates that the time difference between them equals the TWLPT. The TD21 element, POTT scheme, and TW87 scheme did not operate as expected.

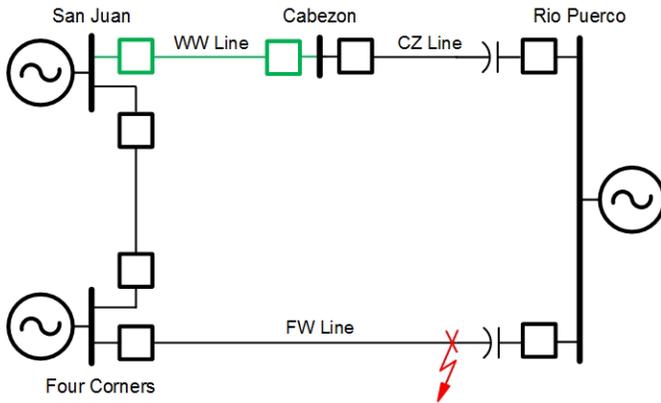


Fig. 17. Test scenario of an external fault for the WW line, where a BG fault is simulated behind Rio Puerco on the FW line.

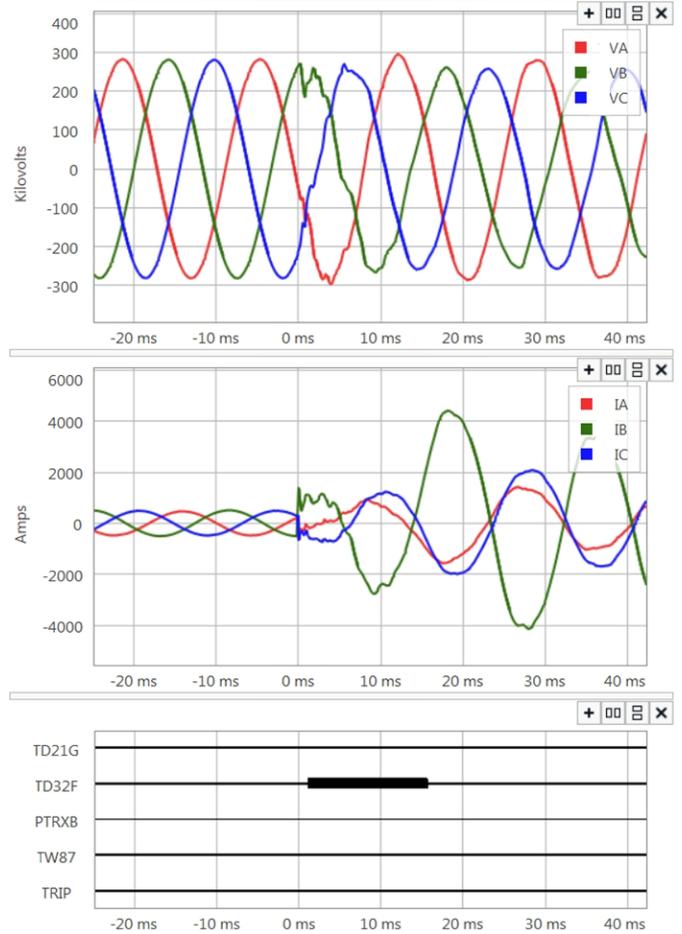


Fig. 18. Test signals recorded by the UHS relay at 1 MHz sampling rate and the protection element response at San Juan for a BG fault on the FW line.

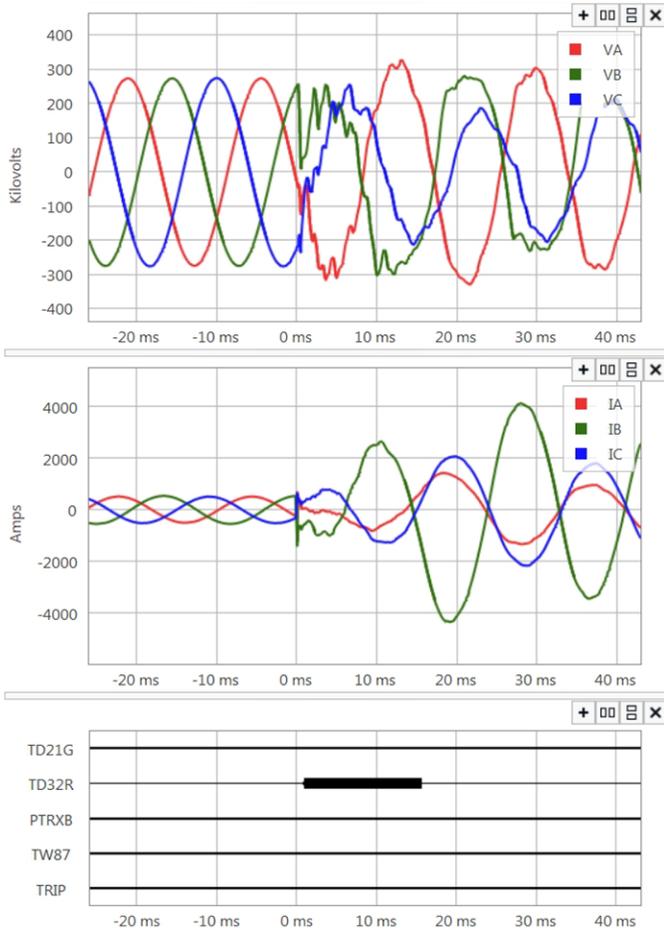


Fig. 19. Test signals recorded by the UHS relay at 1 MHz sampling rate and the protection element response at Cabezon for a BG fault on the FW line.

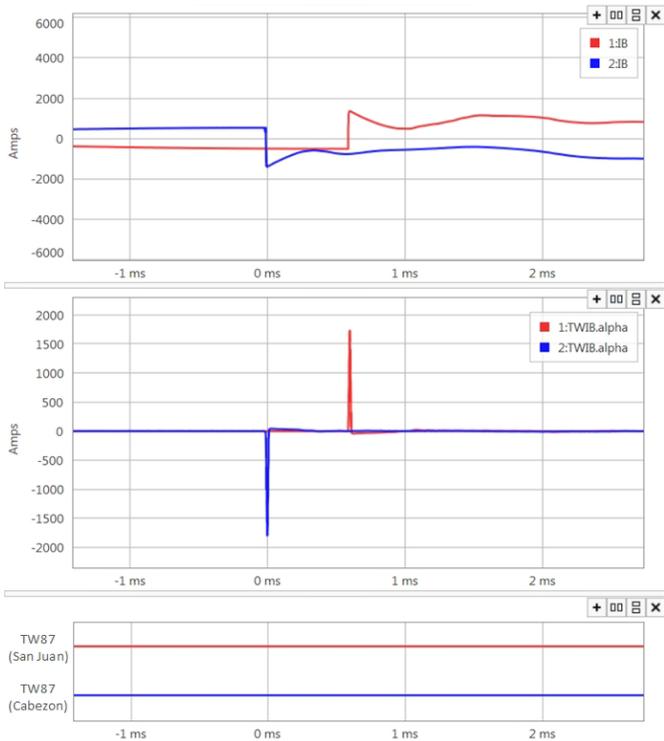


Fig. 20. Phase B currents and TWs captured at San Juan (Event 1) and Cabezon (Event 2) with the TW87 scheme restrained at San Juan and Cabezon.

## VI. CONCLUSIONS

The CZ line and WW line are critical to the PNM system operation. Because of CZ line overcompensation, the PNM team was challenged to investigate new technologies. UHS relays operating on incremental quantities and TWs are better suited for protecting series-compensated lines. Based on the UHS line protection performance during factory acceptance testing, PNM pursued the first application of UHS line protection on two of their 345 kV lines.

Methods to test the performance of UHS relays were presented during field commissioning. Traditional relay test equipment can be used to test incremental quantity-based elements. To test elements that operate using incremental quantities, use realistic signals that are representative of the power system. These realistic signals can be applied using the playback capabilities of traditional test equipment. To test TW functions, TW test equipment that can inject current with fast rise time, adequately slow decay, and precise timing is required.

This paper discussed the approach for commissioning UHS relays on the CZ line and WW line. For end-to-end testing, time-synchronized testing was used to verify the performance of the TD21 element, POTT scheme, and TW87 scheme.

## VII. REFERENCES

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## VIII. BIOGRAPHIES

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**Greg Smelich** earned a B.S. in mathematical science (2008) and an M.S. in electrical engineering (2011) from Montana Tech of the University of Montana. Greg began his career at Schweitzer Engineering Laboratories, Inc. (SEL) as a protection application engineer, where he helped customers apply SEL products through training and technical support, presented product demonstrations, worked on application guides and technical papers, and participated in industry conferences and seminars. In 2016, Greg made the transition to the SEL Research and Development (R&D) group as a product engineer, where he now helps guide product development, training, and technical support related to time-domain technology. He has been a certified SEL University instructor since 2011 and an IEEE member since 2010.

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