Protecting EHV Transmission Lines Using Ultra-High-Speed Line Relays: A New Standard for PNM

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Abstract—**The Public Service Company of New Mexico's (PNM's) commitment to achieve zero emissions by the year 2040 has helped spur the growth of renewable energy resources in their electric grid, increasing the penetration of inverter-based resources (IBRs) into the system. IBRs provide additional load support and improve the renewable energy portfolio for PNM. However, IBRs also pose many challenges to PNM's existing extra-high-voltage (EHV) transmission line protection system. These challenges include lower fault current contributions, reduced system inertia, and nontraditional fault waveform signatures. As more IBRs are introduced into the electric grid, there becomes a greater need to modernize the protection system to overcome these challenges. This paper discusses the protection solution adopted by PNM for applications with high penetration of IBRs.**

With the goal of modernizing its line protection technology and the need for system-wide consistency, PNM standardized their EHV transmission line protection to include ultra-high-speed (UHS) line relays. The UHS line relay includes time-domain technology of traveling waves (TWs) and incremental quantities and phasor-based elements and schemes. The standardization allowed PNM to create a new line protection philosophy that allows single-pole tripping and reclosing, a new panel design, and an updated breaker failure scheme. The new protection standard employs best-known practices and innovative methods for designing, testing, and commissioning a protection system using UHS relays.

This paper discusses the PNM EHV transmission line protection standard and the application of the standard to more than six 345 kV transmission lines on which PNM has successfully installed this new line protection. The paper also discusses the validation testing of the protection scheme using hardware-in-the-loop simulation with a real-time digital simulator (RTDS). Onsite commissioning, end-to-end testing, and lessons learned are also discussed.

I. INTRODUCTION

Public Service Company of New Mexico (PNM) is the largest energy provider in the state of New Mexico, powering more than 500,000 residential and business customers across the state. PNM owns and operates 3,189 miles of transmission line network, carrying approximately three gigawatts (GWs) of electricity to their customers. More than 40 percent of the PNM transmission network is used by other utilities and independent power producers to move power to their customers in New Mexico, Arizona, and California. While PNM owns a diverse mix of generation resources that provide power to their customers, they plan to achieve zero emissions by the year 2040. The current renewable generation portfolio of PNM includes approximately 350 MW of wind energy sources and approximately 157 MW of solar energy sources. Partially via a customer-owned renewables program, PNM has been integrating solar and wind generation into the electric grid.

With the evolving electric grid, the uninterrupted transmission of power has become even more critical. This need calls for the line protection system to be extremely reliable.

Using prior experience with ultra-high-speed (UHS) relays, PNM revisited their protection philosophy and standardized their extra-high-voltage (EHV) transmission line protection system.

This paper discusses the PNM transmission line protection standard and its application to 345 kV lines, which are part of a power corridor that serves several wind energy interconnections totaling over 1 GW and growing.

II. BACKGROUND

PNM has a 345 kV transmission line corridor running east to west and multiple sites with a large amount of renewable generation. To maintain this corridor and its east-to-west flow, fast line protection and restoration is very important. The eastern interconnection is a direct current (dc) tie to Texas and is very limited in capacity. The energy is generated and sold to various third parties, including entities in the West. Fig. 1 shows the main lines and new generation upgrades on the east-to-west corridor.

Recently, PNM saw the addition of more than 1 GW of wind power on this corridor. To improve the availability of these lines during power system faults caused by single-line-to-ground faults, a reliable protection scheme that incorporates single-pole tripping and automatic reclosing is required. Previously, PNM commissioned a project that required the design and testing of a line protection scheme for an overcompensated line [1]. UHS relays with traveling-wave (TW)-based and incremental-quantity-based protection elements and schemes supplemented phasor-based relays that provided permissive overreaching transfer trip (POTT) and line current differential (87L) protection schemes. With the successful performance of the time-domain elements and schemes for several internal and external faults, PNM added UHS line relays to their new line protection standard, which was then implemented on six lines in the eastern PNM system. In subsequent sections of this paper, protection guidelines and actual site implementation of lines interconnected with a high penetration of renewable generation will be discussed.

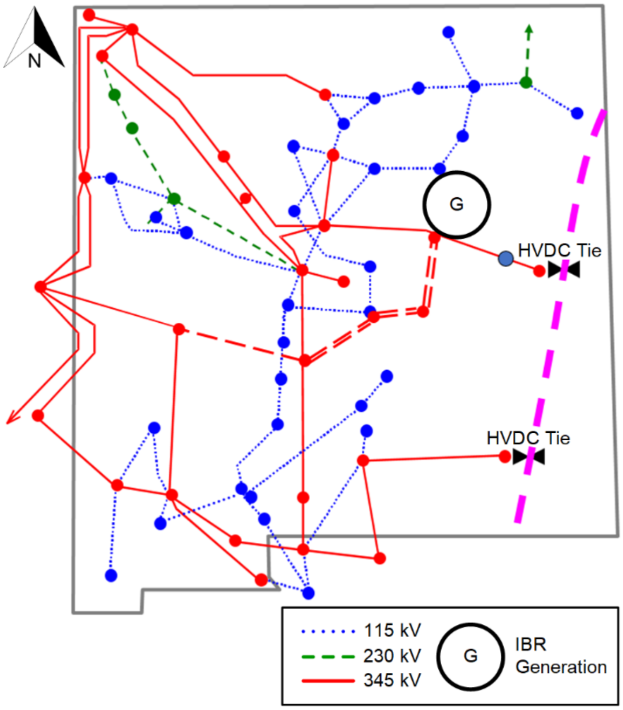


Fig. 1. PNM Transmission System Overview

III. THE PNM LINE PROTECTION PHILOSOPHY

The line protection philosophy for PNM includes three separate relay systems installed on each line terminal and are represented as the Main-1, Main-2, and Main-3 relays. Fig. 2 shows an example of a typical relay connection setup for the Main-1, Main-2, and Main-3 arrangement for a line with series capacitors and shunt reactors. The Main-1 and Main-2 relays are phasor-based relays that have identical functionalities and settings criteria. The Main-3 relay is a UHS relay that includes time-domain technology of TWs and incremental quantities, and phasor-based elements and schemes.

The phasor-based relays (Main-1 and Main-2) use the 87L and the POTT scheme for high-speed protection. These schemes require relay-to-relay communications, which are implemented through one of the following:

a. Multiplexed fiber-optic channel using synchronous optical network (SONET), which complies with IEEE C37.94 [2].
b. Direct fiber-optic channel (i.e., direct fiber optics).
c. Combination of a multiplexed channel and direct fiber optics. Fig. 3 shows a typical communications setup for this configuration.

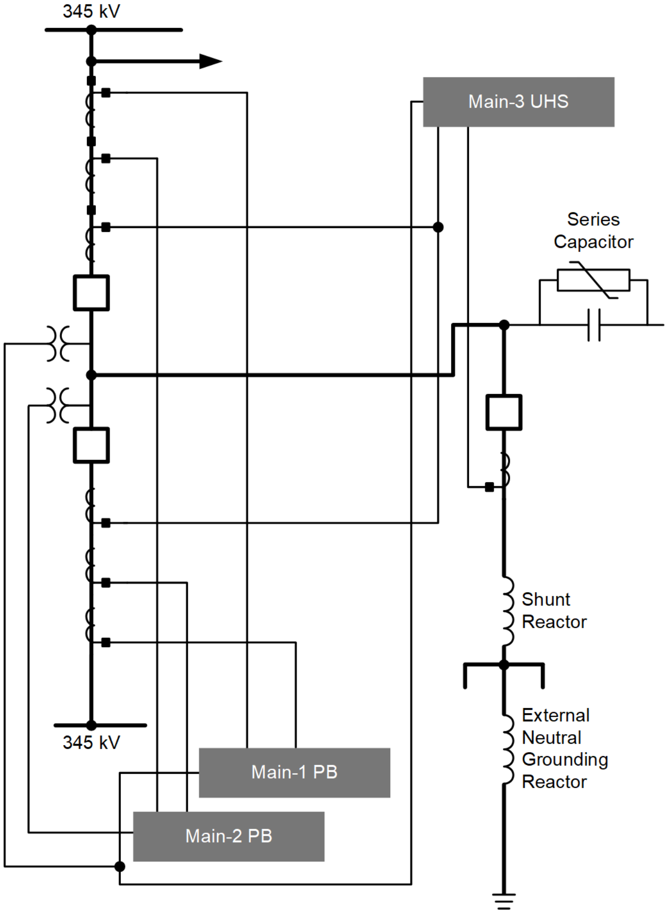


Fig. 2. Typical Relay Connection Diagram for Transmission Line Protection Scheme

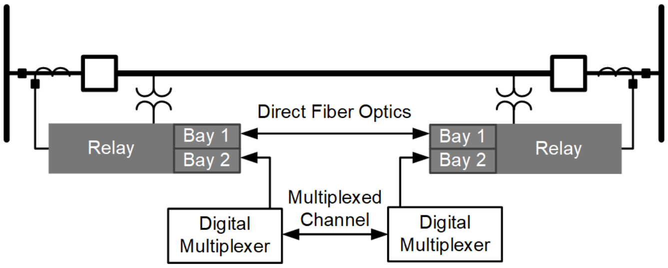


Fig. 3. Two Terminal Application With Multiplexed Channel and Direct Fiber Optics

The UHS relays (Main-3) also use the communications channel setup described for the Main-1 and Main-2 relays to provide high-speed protection using a POTT scheme. Additionally, if the direct fiber optics is available to use for relay-to-relay communications, the TW-based differential (TW87) protection scheme is enabled. Refer to Fig. 4 for the communications channel setup for the Main-3 relays using the direct fiber optics and the multiplexed channel over SONET.

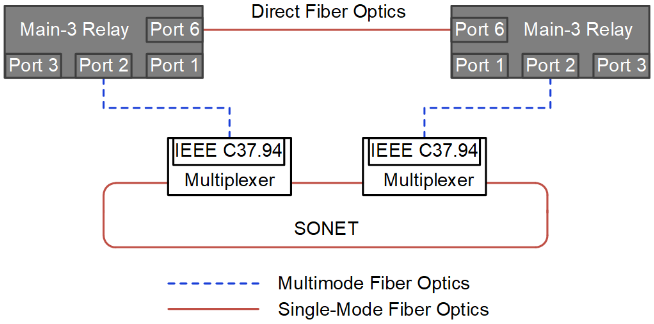


Fig. 4. Communications Channel Setup for Main-3 Relay

In case relay-to-relay communications are lost for any of the Main-1, Main-2, or Main-3 relays, line protection is also provided by phase and ground step distance and overcurrent elements.

Some of the aspects that influenced the protection and control philosophy include:

1. Incorporating single-pole trip and reclose (SPTR).
2. Protecting lines with series capacitors or shunt reactors.
3. Protecting lines in the vicinity of inverter-based resources (IBRs).

A. *Tripping Scheme and Power Transfer*

The Main-1, Main-2, and Main-3 relays, if selected for single-pole switching (SPS), trip single pole for single-phase-to-ground faults. Additionally, Main-1 and Main-2 relays provide high-speed single-pole reclose (SPR).

In power systems, such as the simplified one depicted in Fig. 5, tripping and reclosing all three phases for single-phase-to-ground faults can cause the system to lose synchronism under certain operating conditions.

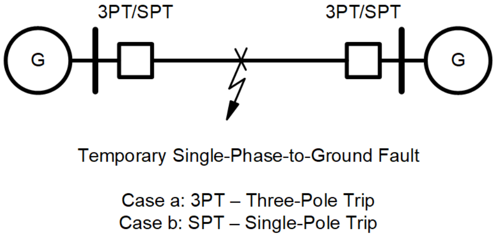


Fig. 5. Simplified Transmission One-Line Diagram

Fig. 6 depicts the power transfer capability for the simplified system shown in Fig. 5. It shows that for a three-pole trip (3PT), the power flow interrupts on all three phases of the faulted line, which significantly increases the accelerating area (A_1). In this example, the power system loses synchronism because $A_1 > A_2$, which is the decelerating area [3] [4].

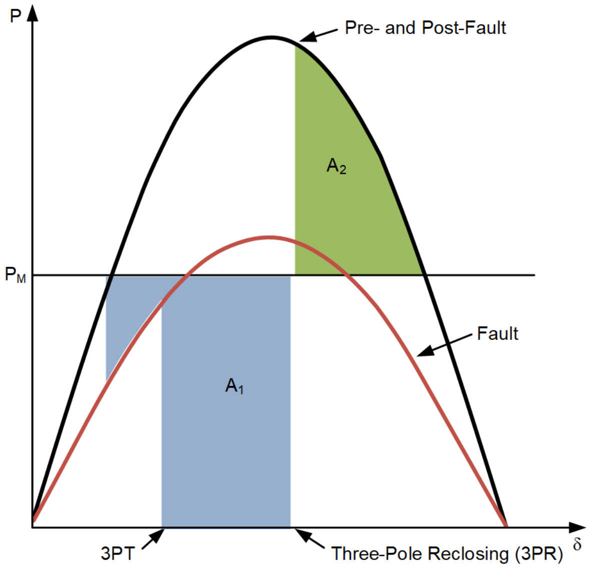


Fig. 6. Case a: Power Transfer Capability Curve During a Three-Pole Trip Event [3]

Fig. 7 shows the effect of an SPS scheme, which is a combination of a single-pole trip (SPT) and SPR, that trips only the faulted phase for the single-phase-to-ground-fault, as shown in Fig. 5. SPS does not allow the power to fall to zero; but instead, to maintain a value provided by the curved labeled SPO (a single-phase open condition). Area A_1 for SPT is smaller than that for 3PT (see Fig. 6); therefore, based on an equal area criterion, the system is stable [3] [4].

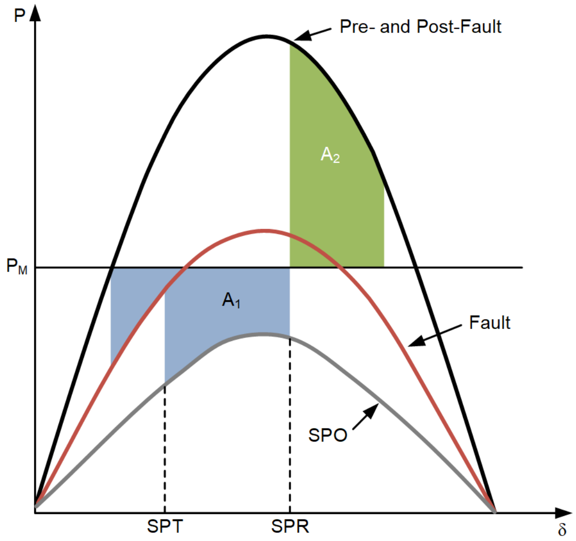


Fig. 7. Case b: Power Transfer Capability Curve During a Single-Pole Trip Event [3]

For single-phase-to-ground faults, the relays trip the corresponding breaker pole. The single-pole open (SPO) time allows the secondary arc to extinguish. After this time, the automatic reclosing scheme closes the open breaker pole. If the fault persists, the scheme trips all three phases and blocks reclosing. For all faults involving more than one phase, the scheme trips all three phases.

An SPS scheme imposes extra requirements on both circuit breakers and relays [5]. Circuit breakers need to have independent contact-operating mechanisms for single-pole tripping and reclosing. An SPT is achieved by mechanisms that are controlled individually by the tripping relays, whereas an SPR is achieved through a single close coil, which closes all phases that are open at the time. High-speed automatic reclosing is implemented without any intentional delay, beyond an allowance for arc deionization, and without having to perform a synchronism check. In a dual-line breaker scheme, PNM implements an SPTR on one breaker and a 3PT on the other, while still maintaining the power flow through the rest of the two phases.

To establish the standards, the SPS scheme was designed and validated using real-time digital simulator (RTDS) testing in the laboratory. Functional testing was conducted in the field for field validation. The successful implementation was also verified by an in-service line fault event, as discussed in Section VIII.

B. Protecting Lines With Series Capacitors or Shunt Reactors

Series capacitors improve the power transfer capability of the transmission line. They also influence the magnitude and direction of fault currents, which, in turn, influence the magnitude and phase angle of voltages measured at different points in the network. This has an impact on the performance of protection functions, whose operation depends on the magnitude and phase angle properties of the measured voltage and current. Other phenomena, such as voltage and current inversion at the relay location, subharmonic frequency oscillations, series capacitor metal-oxide varistor (MOV) protection, and series capacitor bypassing controls, can influence the performance of different protection functions. Numerous technical papers discuss the challenges to line protection when applied to series-compensated lines [6] [7]. In this section, we discuss how these challenges were addressed:

- Subharmonic frequency oscillations caused by transmission line series capacitors may delay phasor-based differential scheme operation for internal faults. To achieve a faster tripping, the line differential alpha plane characteristic blocking angle (87LANG) is decreased. Decreasing the blocking angle expands the operating region on the alpha plane characteristic, which allows the differential element to assert faster [8].
- Subharmonic frequency transients cause the impedance to oscillate, which may cause an overreach of Zone 1 distance elements. Therefore, the Zone 1 reach is set to a reduced reach of the total line impedance as compared to normal practice for noncompensated lines, depending on the configuration. Validation using the RTDS is required to verify the reliability of the distance elements [1]. Additionally, the Zone 1 distance element is inhibited when the protected channels are fully available and allow relay logic to engage distance elements only when the communications channels are not in service or reliable.
- Bypassing series capacitors, the load current creates a voltage drop across the capacitors that asserts the incremental-quantity-based directional (TD32) element, which sees these switching events in a forward direction that operates a POTT scheme. However, a POTT scheme should not trip because it is not a fault. To address the series capacitor bypass challenge, the UHS relay POTT scheme incorporates ultra-fast independently configurable phase and ground directional overcurrent supervision. To keep the POTT scheme secure during bypass of series capacitors, these thresholds are set above the maximum switching current [9].

PNM has installed several shunt reactors on the transmission lines. When the line-side shunt reactor is switched, it abruptly changes the voltage at the reactor location and generates incremental current and voltages at both line terminals, which asserts the TD32 element forward at both terminals [9]. This assertion is correct because the event is on the line, in a forward direction for both relays. However, the event is not a fault and the POTT scheme should not trip for it. To resolve this issue, UHS relays allow current transformers (CTs) from the reactor to be wired to separate inputs on the relay. Refer to Fig. 8 for the typical CT connections in this application. Main-1 and Main-2 relays receive the CTs from the line breakers; therefore, the reactor is included in the line zone of protection.

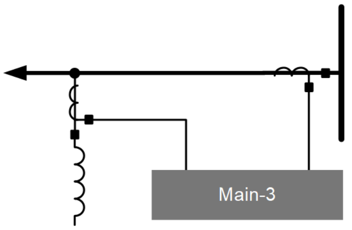


Fig. 8. Typical Connections for the Line-Zone Shunt Reactor CT to the UHS Relays

These currents are then phasor-summed internally. Because the reactor CT is wired with the opposite polarity relative to the line CT, it results in the subtraction of the reactor currents from the line currents when they are phasor-summed. This prevents the transient currents from reactor switching to be considered as line fault currents.

C. Protecting Lines in the Vicinity of Inverter-Based Resources

The term IBR most commonly refers to photovoltaic-powered sources or Type 3 and Type 4 wind-powered generators. The interconnection of the utility with the IBRs is generally a three-winding transformer, wye-grounded, with delta tertiary (refer to Fig. 9).

Many technical papers discuss the protection challenges with IBRs, such as [10] [11] [12].

As shown in Fig. 9, the IBRs may, or may not, supply negative-sequence currents, depending on the control modes. The interconnection transformer provides the path for zero sequence, if connected as shown in Fig. 9. Three-phase fault currents during a subtransient period are limited to 1.1 to 1.5 per unit, instead of approximately 6 per unit, as is the case for synchronous generators. Hence, the protection scheme and selection of set points require additional considerations and verification to ensure that the protection scheme can detect system faults in all scenarios. Many relays use the relationship of I_2 and I_0 to perform the faulted phase identification, which is critical for the success of an SPT scheme. The lack of conventional fault signatures can adversely affect the faulted loop selection logic, the directional supervision logic, and the reactance comparator polarization in quadrilateral distance elements, which makes backup protection using time-delayed distance elements challenging. The IBR responses during various system fault conditions are still under investigation because the IBRs from various manufacturers respond differently [11]; therefore, more field data are needed to determine the actual response of protective relays and protection schemes during these fault scenarios.

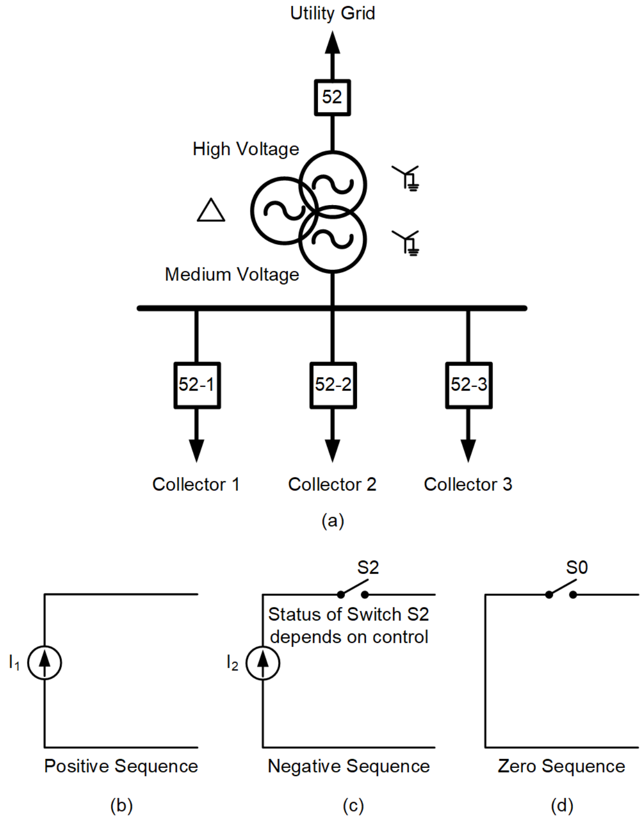


Fig. 9. IBR Interconnection and Fault Current: Positive-Sequence Equivalent of an IBR (b), Negative-Sequence Equivalent of an IBR (c), and Zero-Sequence Equivalent of an IBR (d) [13]

The PNM standard calls for using the phasor-based and UHS relays to implement the following protection schemes.

1) *Phasor-Based Relay (Main-1 and Main-2)*

An 87L scheme and a pilot protection using weak infeed logic takes advantage of the fault current contribution from the line terminal that is connected to the bulk power system.

The use of a negative-sequence differential scheme has been disabled and a ground (zero sequence) differential scheme is used, taking advantage of the ground current contribution from the wye-grounded winding of the transformer at the IBR interconnection point. Additionally, a POTT scheme using ground directional overcurrent element is enabled, depending on the application.

As previously mentioned, the instantaneous distance element (Zone 1) is inhibited when the 87L protection channel is fully available. Distance elements were configured similar to installations with lines connected to the bulk power system.

2) *Ultra-High-Speed Relay (Main-3)*

Communications-assisted schemes, described in [1], perform satisfactorily on the lines connected with IBRs. However, in scenarios in which the relay-to-relay communications channel is not available or reliable, a reliable backup element is needed at the terminal connected to the IBR. As explained in [10], unconventional sources, such as IBRs, create challenges for distance elements in line protection applications. However, the TD32 element works correctly if the circuit opposite the fault, relative to the relay location (i.e., in front of or behind the relay), is inductive for the first few milliseconds of the fault. Reference [10] also explains that IBR sources and the connecting circuit (lines and transformers) can be considered as inductive during the first few milliseconds of a fault and, therefore, the TD32 element operates correctly even near unconventional sources. Additionally, even though an unconventional source may supply an unusual current pattern during a fault, the voltages at the line terminals follow the apparent line impedance. Therefore, the principle of apparent impedance works in systems with IBRs [10].

PNM implemented a concept derived from [10] that uses a combination of apparent impedance distance characteristic, TD32, and undervoltage elements for backup protection on one of the lines, which has high penetration of IBR. An apparent impedance zone provides a plain impedance measurement that is independent from the memory voltage and negative-sequence current. The phase offset distance element is directionalized with the combination of TD32, apparent impedance, and undervoltage elements. The ground offset distance element is directionalized in a similar manner; however, with the addition of a zero-sequence directional element (32G). For tripping, directionalized ground and phase offset distance elements are supervised by the respective overcurrent element.

IV. TRANSMISSION LINE PROTECTION AND FAULT LOCATING USING ULTRA-HIGH-SPEED RELAYS

This section provides a brief overview of time-domain principles that use incremental quantities and TWs to provide UHS protection elements and schemes. These include the incremental-quantity-based directional (TD32) element, the incremental-quantity-based distance (TD21) element, the TW-based directional (TW32) element, and the TW-based differential (TW87) scheme. TW-based fault locating (TWFL) methods used by UHS relays to locate faults with a high level of accuracy are also discussed. Implementation details for all protection and fault locating functions described in this section are available in [14]. The phasor-based elements and schemes available in UHS relays, such as distance elements, directional elements, switch-onto-fault logic, definite- and inverse-time overcurrent elements, and definite-time over- and undervoltage elements, are not discussed in this section. Reference [14] provides details associated with these functions.

A. Line Protection Using Incremental Quantities

Incremental quantities of voltage and current represent the pure fault network (i.e., they exclude load) and are calculated as the difference between the present instantaneous sample and the one-cycle-old sample. These signals are low-pass filtered and then applied to directional and distance elements (TD32 and TD21, respectively). For each element, the UHS relay calculates incremental voltage and incremental replica currents for six measurement loops: each phase-to-ground and phase-to-phase loop.

The TD32 element compares polarities of the incremental loop voltage and the incremental replica loop current. These signals have opposite polarity for faults in the forward direction and the same polarity for faults in the reverse direction. To implement this concept, the relay calculates an operating torque as the product of the sign-inverted incremental loop voltage and incremental replica loop current. A positive torque indicates a forward direction and a negative torque indicates a reverse direction. The relay also calculates forward and reverse restraining torques using the incremental loop replica current and relay settings for the forward and reverse impedance thresholds, respectively. The operating and restraining torques are integrated and the integrated operating torque is compared against the integrated forward and reverse restraining torques. The TD32 element declares a forward direction when the integrated operating torque is positive and exceeds the integrated forward restraining torque. On average, the TD32 responds to faults in approximately 1.5 ms. The TD32 element is suitable for series-compensated lines and single-pole tripping applications. It may be used to accelerate the permissive signal used in a POTT scheme or the blocking signal used in a directional comparison blocking (DCB) scheme. It is also used to supervise the TW87 scheme when applied to series-compensated lines and the TD21 element. It is not intended for direct tripping of circuit breakers [14].

The TD21 element is an underreaching Zone 1 distance element that typically operates between 2 and 5 ms without relying on a protection channel. It uses the currents and voltages measured at the relay location to calculate the incremental voltage at the reach point and compares it to the pre-fault voltage at the reach point. The calculated incremental voltage will be larger than the pre-fault voltage for an in-zone fault and it will be less than the pre-fault voltage for an out-of-zone fault. The TD21 element is suitable for series-compensated lines and can be set using the line impedance alone, neglecting the inline and adjacent series capacitors. The TD21 element is phase-selective and suitable for single-pole tripping applications [14].

B. Line Protection and Fault Locating Using Traveling Waves

When a fault occurs on a line, the step change in voltage at the fault point launches TWs, both current and voltage, which move toward each line terminal. The TWs move at approximately 98 percent of the speed of light on overhead lines and at approximately 45 to 85 percent of the speed of light on underground cables. These current and voltage TWs have the same polarity and are related in magnitude by the characteristic impedance of the line. When these TWs arrive at each line terminal, the current TW becomes inverted due to the orientation of the CTs. The installed UHS relays then detect and record the transient signals by using a data acquisition system with 1 MHz sampling rate and 18 bits of resolution.

The TW32 element uses the relationship between the current and voltage TWs at the local terminal to make a directional decision. That is, if the current and voltage TWs have opposite polarity, the fault originated in front of the relay (forward direction); if the current and voltage TWs have the same polarity, the fault originated behind the relay (reverse direction). The TW32 element makes a directional decision in approximately 0.1 ms and may be used to accelerate the permissive signal used in a POTT scheme or the blocking signal used in a DCB scheme; it is not intended for direct tripping of circuit breakers.

The TW87 scheme uses the relative arrival time, polarity, and magnitude of current TWs at the local and remote terminals to determine whether or not the fault occurred on the protected line. Because of CT orientation, the current TWs observed at the local and remote terminals have the same polarity for a fault that originated on the protected line. Additionally, the arrival times of these TWs are separated by less than the TW line propagation time (TWLPT). TWLPT is the one-way travel time for a TW to traverse the entire line length (LL). TWLPT and LL are configuration settings required by the UHS relays. If the fault originated external to the protected line (e.g., on an adjacent line), the initial TWs observed at the local and remote terminals will have opposite polarity and the arrival times will be separated by TWLPT. Furthermore, operate and restraint signals are calculated using the magnitudes of the TWs and are based on the expected relationships described here for internal and external faults. The TW87 scheme requires a direct fiber-optic channel between the local and remote relays and it operates for faults on the line in 1 to 5 ms. Accuracy of the TWLPT setting is critical for the security of the TW87 scheme.

The double-ended TWFL (DETWFL) method uses the relative arrival time of the initial local and remote current TWs, in addition to the TWLPT and LL relay settings, to accurately locate faults. This method requires that the local and remote relays exchange time stamps of the initial TW that arrived at each end and that the relays are synchronized to a common time reference. This is accomplished by using either a direct fiber-optic channel for relay-to-relay communications or by using an

IEEE C37.94 encoded channel, along with external IEEE C37.118 [15] compliant clocks with submicrosecond accuracy connected to the Inter-Range Instrumentation Group time code format B (IRIG-B) input on each UHS relay. Fault location results using the DETWFL method may be obtained when relay-to-relay communications are unavailable by using the offline methodology described in [16]. The UHS relay incorporates the result from the DETWFL method in a line monitor function. The line monitor detects, tabulates, and alarms on low-energy disturbances and recurring faults on the line to improve line maintenance and reduce the number of line faults [17].

When the initial TW arrives at the local terminal, a reflected TW is generated that travels back to the fault location. When it arrives at the fault, another reflected TW is generated that comes back to the local terminal. The single-ended TWFL (SETWFL) method provides accurate fault locating by using the difference in arrival times of the initial TW and first reflected TW from the fault, in addition to the TWLPT and LL relay settings. This method is independent of relay-to-relay communications and synchronization to a common time reference.

The SETWFL and DETWFL methods have a field-proven track record with reported errors that are within one tower span (300 meters or 1,000 feet). Accuracy of the TWLPT and LL settings are critical for the accuracy of the TWFL methods.

V. PNM PROTECTION STANDARDS DEVELOPMENT

With rigorous testing performed using the digital simulators on one of the series-compensated lines, PNM had already decided to use the UHS relays in the tripping mode [1]. With this adoption, PNM standardized on the phasor-based relays (Main-1 and Main-2) and UHS relays (Main-3) to protect their EHV transmission system. This section discusses the protection standards employed by PNM for EHV lines.

A. Standard Protection Panel Design

Consistent with the line protection philosophy, the standard consists of two phasor-based (Panel P1) and one UHS (Panel P2) protective relays. The two phasor-based protective relays provide dual-redundant line protection with SPT and automatic reclosing. The three protective relays, in addition to the associated test switches and control switches, are housed in two free-standing open rack panels, as shown in Fig. 10.

Each of the relays has a dedicated relay cutout switch (43CO) to put the relays out of service and a common reclosing cutout switch (79CO) to disable the SPT and automatic reclosing. The panel design is an open rack, free-standing panel, 32 inches wide, with Panels P1 and P2 mounted side by side. The status of the 43CO switch is transmitted to the remote relays, which blocks the differential protection on the remote relays when the local relay is taken out of service by rolling a 43CO switch.

Panel design also includes the standardization of the panel wiring, relay input/output (I/O) list, and test switch designations. Each of the output contacts on the relays are wired via two separate test switch blades to facilitate the testing. Enough spare contacts are wired in the panel for future modifications for specific applications. The 43CO contacts are also wired in series with the output contact to provide an additional isolation point for trip contacts. This standardization helps the PNM field crews to locate and correctly identify wiring connections and the test switches consistent with other panels, which minimizes operational errors.

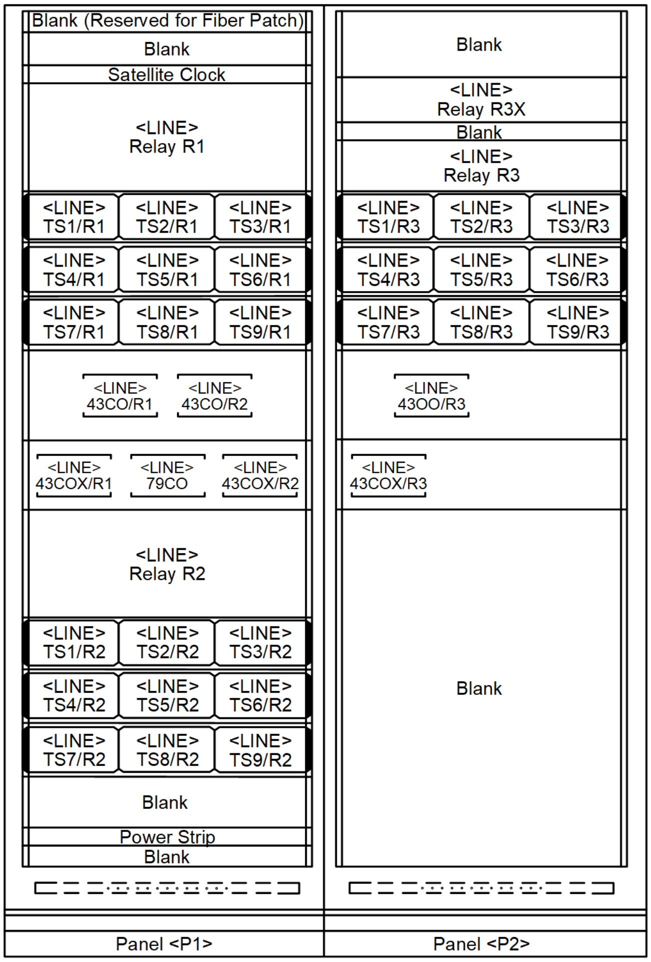


Fig. 10. Standard Protection Panel Layout

B. *Single-Pole Trip and Automatic Reclose*

PNM applies SPTR on some of their transmission lines with voltage levels of 230 kV and above, depending on the transmission line and the interconnections. The eastern corridor is effectively radial, necessitating the use of SPTR to avoid significant disruption to power flow, transmission services, and equipment. Fig. 11 shows a typical bus configuration for a 345 kV station with a breaker and a half. Lines L1 and L2 share breaker BKR 12. For Line L1, the SPTR is applied to BKR 1 (outer breaker) only, while BKR 12 (middle breaker) is set to trip three pole with no reclose. The same applies to Line L2. The SPO time interval is set to 23 cycles (383 ms) to achieve a total dead time of approximately 30 cycles. The 79CO cutout disables the reclosing and trips both BKR 1 and BKR 12 breakers, three poles with no reclose.

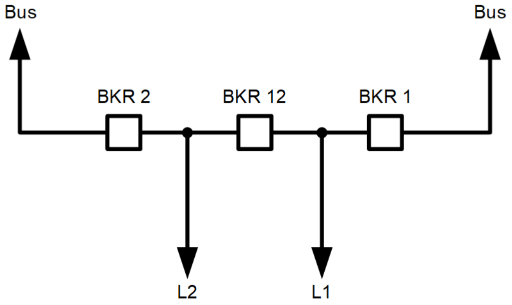


Fig. 11. Typical 345 kV Single-Line Diagram

PNM also applies pole discrepancy logic inside the protective relays to detect a stuck single pole after an SPT. This logic monitors the pole status for 60 cycles after the trip. After the 60-cycle window, if all three poles are not open or all three poles are not closed, then the logic issues a three-pole trip. Fig. 12 shows the logic implemented in the relays. This logic is set faster than the mechanical pole discrepancy timer in the breakers.

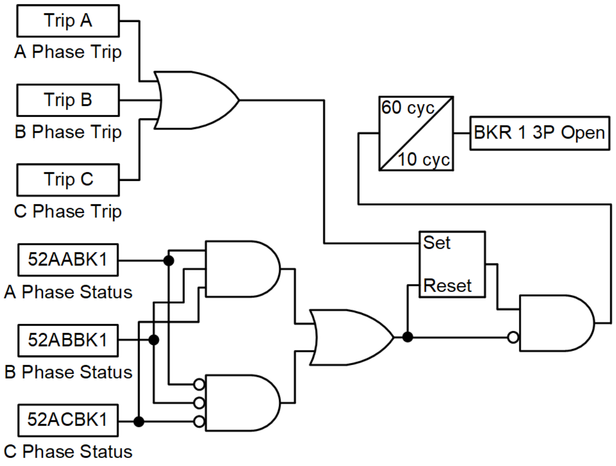


Fig. 12. Pole Discrepancy Logic for BKR 1

Fig. 13 shows the additional breaker pole discrepancy logic in Main-1 and Main-2 to detect if the two poles are open during the reclosing cycle. The breaker opens three pole (3PO), two cycles after this condition is detected.

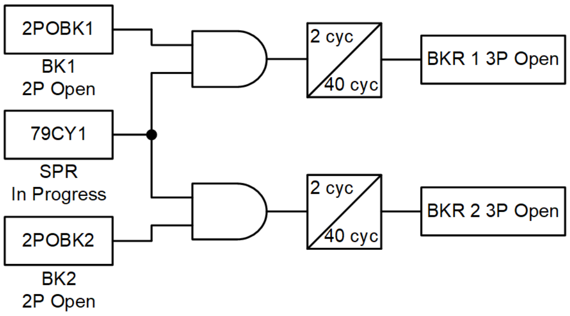


Fig. 13. Trip on Two Poles Open (2PO) During Reclosing

C. *Breaker Failure Protection*

The breaker failure (BF) logic resides in the protection relays (Main-1 and Main-2) with 12 cycles of breaker failure timer to coordinate with remote backup distance elements. The relays trip the breaker failure lockout (86BF) for the failed breaker. PNM only uses 86BF lockouts to block the closing of breakers in the vicinity of the failed breaker, and the relays provide the breaker failure transfer trips (BFTT) to adjacent relays. The adjacent relays trip their zone breakers directly. For the line relays, a BF direct transfer trip (DTT) is sent to the remote end via a differential communications channel.

From Fig. 14, if BKR 12 fails to open for a fault on Line L1, Relay/L1 trips the 86BF/BKR 12 and issues a BFTT to Relay/L2. With receipt of the BFTT, Relay/L2 trips BKR 2 and sends a BF DTT to the remote end of L2. The 86BF/BKR 12 blocks the closing of BKR 1, BKR 12, and BKR 2 until manually reset locally or remotely. Single-pole breaker failure logic is enabled for SPT applications.

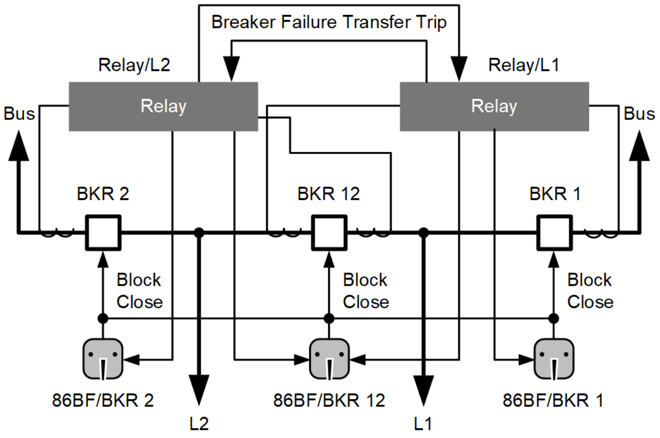


Fig. 14. Breaker Failure Scheme

D. *Phasor-Based Distance Protection*

Instantaneous phasor-based distance elements are blocked when the differential communications channel is healthy and enabled. Logic in Fig. 15 asserts an 87 alarm to arm the distance elements. The time-delayed overreaching elements are not supervised by this logic because they provide critical backup functionality, both local and remote.

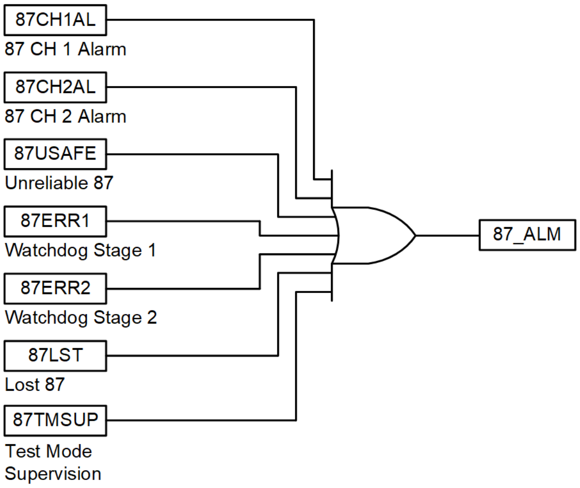


Fig. 15. Channel Health Alarm

VI. PROTECTION AND CONTROL SCHEME VALIDATION

PNM applied the developed line protection standard on more than six EHV lines in their system. The protection and control scheme for one of the lines was tested using the RTDS to validate the relay performance, as well as the overall control scheme.

The transmission lines and power system involved in the testing were modeled in the RTDS test environment. The line that was tested radially serves as an interconnect for the wind farms in the vicinity. These IBRs were modeled in the RTDS to simulate their approximate behavior for the testing. Additionally, the modeled line has a static VAR compensator (SVC) at the strong-source end of the line and a synchronous condenser past the remote end of the line. Once the transmission line system was built in the RTDS, it was validated using the ASPEN OneLiner™ software model. The validation was performed using the fault current comparison for accuracy. Fig. 16 shows the simplified one-line diagram of the test system.

To verify the proper relay operation and the test setup, internal and external faults were performed. In the RTDS, batch testing can be performed, in which a multitude of faults can be applied at various locations and with various load flow scenarios. The batch test script records the event data for all faults, which can then be tabulated to study the relay performance and to identify any issues, such as misoperations [1]. Before the batch testing, miscellaneous tests were performed. The tests included protection and control elements such as:

- Switch onto fault
- High-impedance faults
- Internal-to-internal evolving faults
- Cross-country faults
- Distance element zone coverage verification
- Recloser test

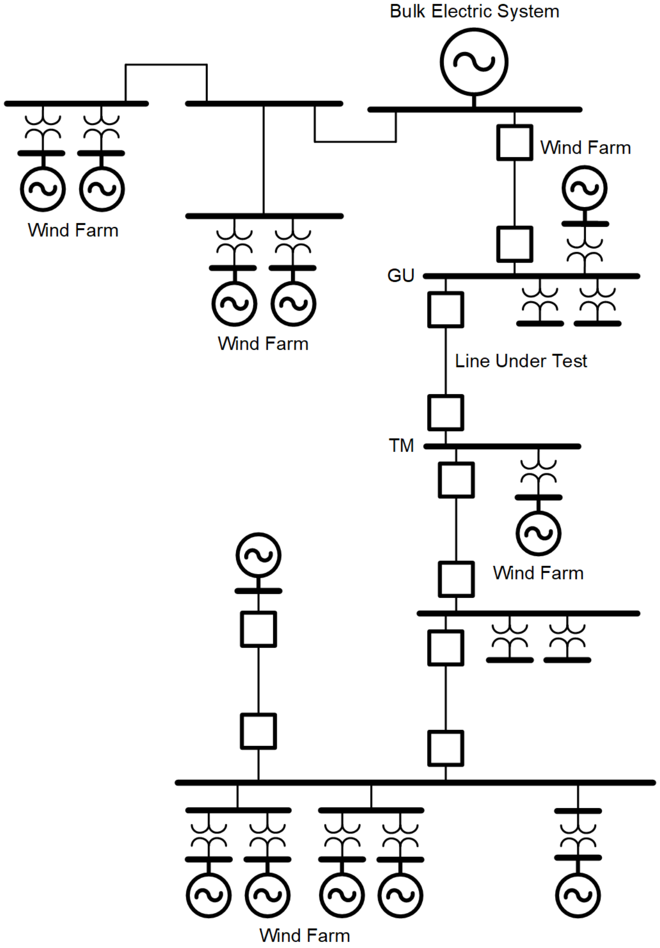


Fig. 16. 345 kV Line Tested With an RTDS

This section presents some of the batch test results from the RTDS testing of the UHS relays. Fig. 17 and Fig. 18 show the coverage of phasor-based and incremental-quantity-based distance elements along the line. Fig. 19 shows the average operating times for the UHS relay with TD21, phasor-based Zone 1, and POTT scheme enabled.

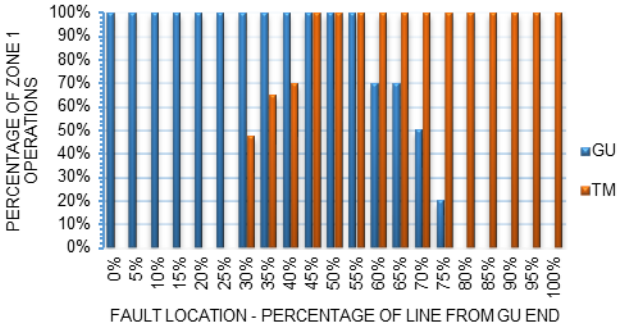


Fig. 17. Coverage of Phasor-Based Zone 1 From Local and Remote End

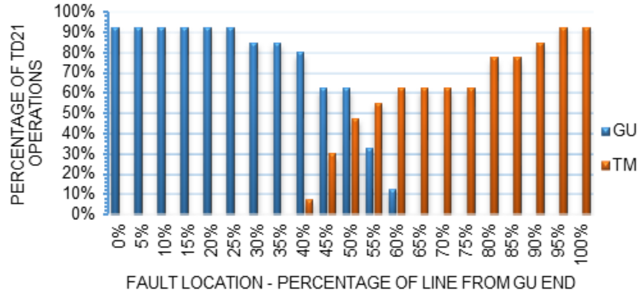


Fig. 18. Coverage of Incremental-Quantity-Based Distance Element From Local and Remote End

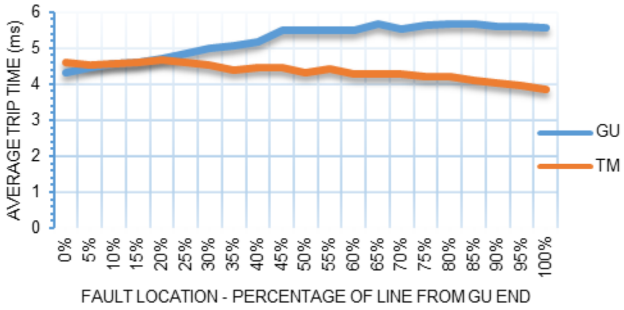


Fig. 19. Average UHS Relay Operating Time

Adjustments were made to the philosophy and standard based on the observations during the testing; some of which were previously described in this paper.

VII. TESTING AND COMMISSIONING – FIELD IMPLEMENTATIONS OF STANDARDS

At the time of writing, the EHV line protection standard described in this paper is applied on more than six lines in the PNM network. RTDS testing was conducted for one of the 345 kV lines to validate the protection standard. Once validation testing was completed, installation and commissioning testing of the new line protection was carried out, as needed, when existing relays throughout the PNM system were scheduled to be replaced. As is typical for a protective relay upgrade project, the removal of existing relaying was performed using proper relay isolation procedures during the line outage and the fabricated panels containing the new line protection relays were installed on the site.

This section discusses the procedures used for commissioning the PNM EHV lines that are protected by UHS relays. Complete commissioning procedures are written and approved prior to the commencement of any activities on site. This procedure is called an isolation, commissioning, testing, and restoration (ICTR) plan. Commissioning testing of the line relays includes alternating current (ac) functional testing, dc functional testing, protection element testing, breaker failure testing, end-to-end testing, and in-service readings and verifications.

A. AC Functional Testing

Once the field wiring was completed, ac functional testing was performed on the CT and potential transformer (PT) circuits to ensure the correct phasing. A test set was used to perform current injection into the CT circuit from the field (breaker cabinet) and the measurement was recorded in the relays. Similarly, voltage was applied to the PT circuits to verify correct phasing. Before injection, a single-point grounding was confirmed on the CT circuits to detect the existence of multiple grounds and to maintain a single grounding point. Precaution was taken to ensure that the PTs were isolated (fuses removed) before applying voltages on the circuit.

B. DC Functional Testing

DC functional testing was performed on every dc circuit that was wired to the relays. This included, but was not limited to, the circuits used for breaker trip and close signals, breaker status, breaker failure trips, and relay alarms. In an SPT application, it is very important to thoroughly test the SPT and pole statuses of each of the poles. This ensures opening of the correct pole for a corresponding phase SPT. The testing of any custom logic is conducted to validate its functionality. For example, the pole discrepancy logic in the relays was validated by tripping a single pole and making sure all three poles opened after a set time delay. This also included testing the SPTR logic on the breakers. During these tests on the line previously mentioned, the following scenarios were tested in the field:

1. SPT and successful reclose.
2. SPT on a permanent fault resulting in a 3PT after an attempt to reclose.
3. SPT with pole-open failure, resulting in a 3PT and breaker failure initiation.
4. SPT followed by a fault on another phase during an SPO condition, resulting in a 3PT and failed reclose.
5. SPT followed by a fault on another phase during reclaim, resulting in a 3PT.

C. Protection Element Testing

As mentioned in Section VI, relay settings for one of the lines were tested using the RTDS for complete protection and control scheme validation. During the onsite testing, protection element testing was performed to verify the operation of the elements and schemes. This testing included verification of set points for the line current differential, distance elements, and instantaneous and inverse-time overcurrent elements. This testing was performed using a secondary injection test set and the test script. The tests were performed independently at each end of the line and did not use the relay-to-relay communications channel. At the end of the testing, a report was generated to document the pass or fail results for the record.

D. Breaker Failure Scheme Testing

Breaker failure scheme testing was performed to validate the correct implementation of the scheme. During this testing, the adjacent relays were taken out of service, one at a time (maintaining the redundancy of protection). The secondary injection test set was used to create a fault condition and simulate a breaker failure on the line breakers (trip test switches were isolated to prevent the local relay tripping to simulate the breaker failure condition and relay-to-relay communications were disabled). While setting up for the breaker failure testing, care was taken to properly isolate the relays being tested using the approved procedure (i.e., ICTR plan) to prevent any undesired operation. The fault current was injected until the breaker failure timer expired, after which the line relay sent the trip to the breaker failure lockout and the BFTT to the relay on the adjacent line that shares the breaker. Relay event data were analyzed on the line and the adjacent relays to validate the correct operation of the breaker failure scheme.

E. End-to-End Testing

After successfully testing the protection elements and breaker failure scheme for all relays at each end of the line, complete end-to-end testing was performed. The purpose of end-to-end testing is to verify the operation of the protection scheme, and it includes functions that rely on the relay-to-relay communications channel, such as the POTT, 87L, and TW87 schemes. Traditional test equipment was used to test the phasor-based functions in the Main-1, Main-2, and Main-3 relays and incremental-quantity-based functions in the Main-3 relay. TW test equipment was used when testing the TW-based elements and schemes in the Main-3 relay.

End-to-end testing of UHS relays was performed using the setup in Fig. 20 [18]. This included the use of traditional relay test equipment capable of applying current and voltage signals at the fundamental frequency and TW test equipment that injects a current pulse (step change with rise time in the order of microseconds) to simulate TWs. The UHS relays provide two sets of three-phase current inputs for application to breaker-and-a-half and dual-breaker configurations. These inputs allowed for the current outputs of the traditional test equipment and TW test equipment to be connected to individual channels on the UHS relay. The two current channels were then combined inside the relay. To ensure testing was initiated simultaneously at both ends of the line and that the fault state of the fundamental frequency current and voltage were applied simultaneously with the TW signals, all test equipment was connected to a high-accuracy Global Positioning System (GPS) clock for time synchronization.

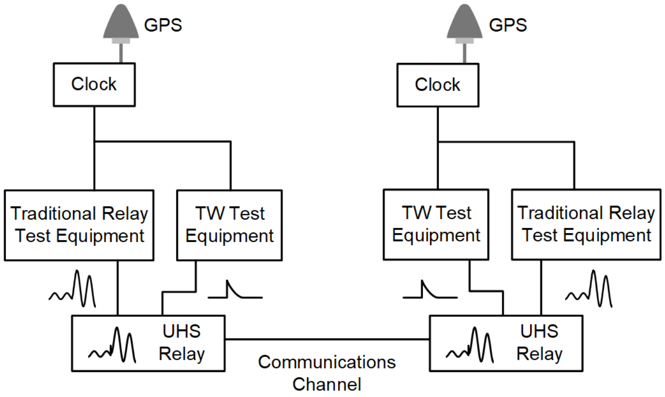


Fig. 20. Test Setup Configuration for End-to-End Testing of Incremental and TW Elements and Schemes

The traditional test equipment, shown in Fig. 20, provided signals with a bandwidth of several kilohertz. This was sufficient for end-to-end testing of phasor-based and incremental-quantity-based protection elements and schemes. The TW test equipment applied a step change in current with a rise time of 1 µs, a halfway decay time of several hundred microseconds, and an injection timing accuracy of less than 16 ns [2]. This was sufficient for end-to-end testing of TW-based protection and fault locating. Additional details regarding end-to-end testing of UHS relays by using this configuration are described in [18].

The setup in Fig. 20 was also used for end-to-end commissioning testing of phasor-based relays that were installed alongside UHS relays, with the exception that only the traditional test equipment was needed (i.e., the TW test equipment was not used).

During the end-to-end testing, several fault scenarios were run to verify the operation of the communications-based protection elements, which were previously mentioned. These scenarios included application of single- and multiphase faults, both internal and external to the protected line. Fault signals from the traditional test sets were applied to the relays. Communications channel health was also monitored and recorded to verify the specified latency and asymmetry of the communications path.

F. In-Service Reading and Verification

Once the complete testing was performed according to the ICTR plan, field drawings were marked for completion of functional checks. The relay system was then prepared for restoration and for placing the relays in service. This involved closing the test switches for currents, voltages, and the trip contacts and putting the 43CO switch in service. Clearance given for the relay work was released, allowing the switching crew to perform the primary switching, so they were able to close the line breakers and energize the line. Several checks were performed once the line was energized and the relays started receiving line currents and voltages. Metering and phasing verifications were performed to ensure expected values were displayed at the relays. The Relay Word bits were also checked to make sure no elements chatter was occurring. Relays were set to generate an event record when the line was energized, which allowed for validating and refining the TWLPT setting used in the UHS relays. Accuracy of the TWLPT value was necessary to ensure the accuracy of fault locating and the security of TW-based protection elements.

VIII. FIELD EVENT ANALYSIS: SINGLE-POLE TRIP AND AUTOMATIC RECLOSE

On June 9, 2021, the line protection relays on one of PNM's 40 mile, 345 kV overhead transmission lines successfully operated for a single-line-to-ground fault. The observations presented in this section are based on the original event analysis performed by Dr. Bogdan Kasztenny. The UHS relays issued an SPT signal in less than 1 ms, resulting in the fault being cleared in less than 24 ms. A few hundred milliseconds after the temporary fault was interrupted, the phasor-based relays automatically reclosed the circuit breakers, allowing the line to remain in service and minimize disruption. Fig. 21 shows the voltage and current signals captured by the UHS relay at the local terminal during the SPT and automatic reclose sequence. Fig. 22 provides a zoomed-in view of the fault signals and shows the performance of protection elements and schemes in the UHS relay and phasor-based relay.

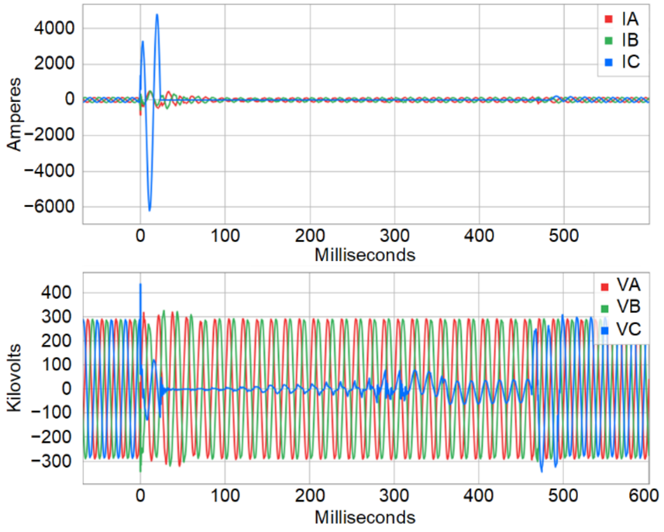


Fig. 21. Voltage and Current Signals Captured by the UHS Relay at the Local Terminal During Single-Pole Trip and Automatic Reclose for a Single-Line-to-Ground Fault

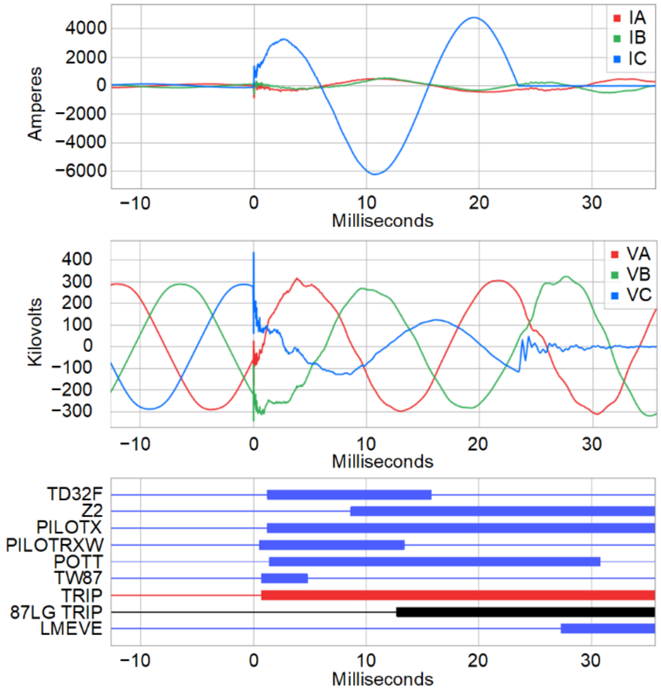


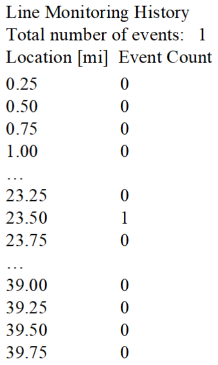
Fig. 22. Transient Record Showing Voltages and Currents Captured by the UHS Relay at the Local Terminal, as well as Performance of the UHS Relay and Phasor-Based Relay During the Fault

Fig. 22 shows that the UHS relay issued the trip signal due to operation of the TW87 scheme in less than 1 ms. This fast operating time was made possible by processing TW calculations in the relay every 1 µs, having low channel latency on the direct fiber-optic channel used for relay-to-relay communications (approximately 0.5 ms for this line), and the relays exchanging data packets over this channel every 25 µs. Within the time it took to make a trip decision, the UHS relay also selected the correct phase to isolate for this single-pole tripping application. After determining the faulted phase and declaring the trip condition, the UHS relay energized the trip coil of the circuit breakers using trip-rated output contacts that closed in 10 µs. An SF6 circuit breaker then interrupted the fault current in a cycle and a half, removing the fault from the PNM system in less than 24 ms. The two unfaulted phases experienced no interruption to service throughout the disturbance.

Fig. 22 also shows the performance of the POTT scheme in the UHS relay, which was configured to send a permissive trip signal based on the TW32 element, TD32 element, and phasor-based Zone 2 overreaching distance (Z2) elements. The local relay received the trip permissive signal from the remote UHS relay (PILOTRXW, keyed by the TW32 element) in less than 1 ms. With the assertion of TD32 in the forward direction, in addition to the received trip permissive signal, the local relay operated the output of the POTT scheme in less than 2 ms. The local relay also transmitted the trip permissive signal to the remote relay based on TD32 in less than 2 ms.

Additionally, Z2, which is also used for step distance backup protection as part of a fully dependable protection scheme, asserted and began timing in less than 9 ms. The negative- and zero-sequence directional elements (32Q and 32G, respectively) operated in less than 7 ms. The zero-sequence line current differential (87LG) scheme in the phasor-based relay, working over an IEEE C37.94 multiplexed channel, tripped in 13 ms. Without the high-speed operation of the UHS relay, it can be estimated that the fault current would likely have lasted one additional power system cycle (16.7 ms at 60 Hz). Similar performance was observed for the protection scheme at the remote end of the line.

Using the double-ended TW-based method, the UHS relay calculated the fault location to be 23.520 miles from the local terminal. Using this result, the line monitor in the UHS relay detected the fault (LMEVE asserted in Fig. 22) and incremented the event count for the bin at 23.50 miles. The line monitor detects, tabulates, and alarms on low-energy disturbances and recurring faults on the line. This helps provide targeted line maintenance and reduces the number of line faults with preventive maintenance. This is particularly useful for faults where automatic reclosing is used to restore service to the line following a temporary fault because the cause of the fault may not be investigated without data that suggests a recurring problem. Fig. 23 shows the line monitor data from the UHS relay at the local terminal, which contains all the line monitor bin counters.



```
Line Monitoring History
Total number of events:  1
Location [mi]  Event Count
0.25           0
0.50           0
0.75           0
1.00           0
…
23.25          0
23.50          1
23.75          0
…
39.00          0
39.25          0
39.50          0
39.75          0
```

Fig. 23. Line Monitor Data Showing Event Counts

IX. CONCLUSION

The PNM evolving power system has paved the way for an improved energy portfolio and a guaranteed future of sustainable energy. This, however, comes with a challenge of protecting the power system against the abnormal conditions and, in turn, increasing the availability of power to their customers. PNM realized the need to upgrade their transmission line protection system to maintain these critical lines. Acceptance of the UHS relay technology was one of the first steps in that direction. The next step was the standardization of the protection system. A high-speed protection system for faster fault clearing and reclosing to minimize the disruption of power flow was the natural choice.

This paper discussed in detail the PNM standards, which were established based on the present challenges, such as series compensation to improve the power flow on lines, coupled with the increased penetration of IBRs in the network. This paper also discussed the SPTR philosophy to take advantage of faster fault interruption, while maintaining the power flow and improving system stability. To solve these challenges, protection system validation is extremely important. The RTDS simulation testing that was performed helped design the standards for various line applications. Standardization also led to the consistency in the protection system across the EHV transmission network. A detailed testing and commissioning process, as described in the paper, helped the field crew apply the standards and provided a guide for testing and commissioning the UHS relays. This paper also presented an analysis of a field event, which provides the validation of successful design and implementation of the standards.

X. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Pavithra Gopinath and Jordan Bell for their involvement in the validation testing of the protection and control scheme. The authors are also thankful for the efforts of Jeffin Thomas, Francisco Noriega, Aaron Rawlings, and Tarik Wahidi on the field implementation, testing, and commissioning of the standards on the PNM EHV transmission lines and Jonathan Sykes, Vamsi Raghupatula, and Christopher Chesnut for their support and guidance. Last, but not least, the authors would like to thank Dr. Bogdan Kasztenny for his contribution on performing the field event analysis, from which we based the section "Field Event Analysis: Single-Pole Trip and Automatic Reclose."

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XII. BIOGRAPHIES

Daniel Marquis is a protection engineer at Public Service Company of New Mexico (PNM). Prior to working at PNM, he worked for the consulting firm TRC and attended graduate school at New Mexico State University (MSEE, 2009). He completed his undergraduate degree at Iowa State University (BSEE and French, 2004). His research interests include alternative energy in remote areas and microgrids.

Milind Malichkar received his MSEE from Michigan Technological University in 2012 and his BSEE from Sardar Patel College of Engineering, Mumbai University, India, in 2005. Milind worked for Voltas limited (IOBG), India, and Electromechanical Technical Associates (ETA), Abu Dhabi, UAE, as a project engineer for five years before joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2012. Presently, he is working as a project engineer supervisor at SEL Engineering Services, Inc. (SEL ES). Milind has experience in power system protection design and commissioning, short-circuit and coordination studies, and power system modeling and testing using control and power hardware-in-the-loop testing with a real-time digital simulator. He is a licensed professional engineer in the states of Washington, California, Alaska, and Arizona.

Ashish Parikh received his BEEE from Nirma Institute of Technology, Gujarat University, Ahmedabad, Gujarat, India. Ashish began his career at Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer in the India branch office. He rose to the rank of senior application engineer before transferring to SEL Engineering Services, Inc. (SEL ES) in Pullman, Washington, where he is currently an engineer in the protection group. Ashish maintains a high level of technical expertise in electric power system protection, system fault analysis, commissioning, and technical training. He also possesses a working level of technical expertise in electric power system automation. He routinely performs power system modeling for short-circuit, load flow, and arc-flash studies, as well as protective device coordination. In addition, he is involved with event report analysis, protection scheme design, relay settings and coordination, and relay selection.

Greg Smelich earned a BS in Mathematical Science and an MS in Electrical Engineering in 2008 and 2011, respectively, from Montana Tech of the University of Montana. Greg then 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 division 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. Greg is a registered professional engineer in the state of Washington.

Kamal Garg received his MSEE from Florida International University and India Institute of Technology, Roorkee, India, and his BSEE from Kamla Nehru Institute of Technology, Avadh University, India. Kamal worked for POWERGRID India and Black & Veatch for several years at various positions before joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2006. Presently, he is a principal engineer at SEL Engineering Services, Inc. (SEL ES). Kamal has experience in protection system design, system planning, substation design, operation, remedial action schemes, synchrophasors, testing, and maintenance. Kamal is a licensed professional engineer in the U.S. and Canada, senior member of IEEE, and member of many working groups in IEEE Power System Relaying and Control (PSRC) Committee. He holds two patents.

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