PNM’s Standardization on Ultra-High-Speed Line Relays to Protect Their EHV Transmission Network

Daniel Marquis
Public Service Company of New Mexico

Milind Malichkar, Ashish Parikh, Greg Smelich, and Kamal Garg
Schweitzer Engineering Laboratories, Inc.

Presented at the
16th International Conference on Developments in Power System Protection
Hybrid Format (virtual and in-person at Newcastle Gateshead, United Kingdom)
Presented Virtually
March 7–10, 2022

PNM'S STANDARDIZATION ON ULTRA-HIGH-SPEED LINE RELAYS TO PROTECT THEIR EHV TRANSMISSION NETWORK

Daniel Marquis[1], Milind Malichkar[2], Ashish Parikh[2], Greg Smelich[2], Kamal Garg[2]*

[1]Public Service Company of New Mexico, Albuquerque, New Mexico, USA
[2]Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA
**milind_malichkar@selinc.com*

Keywords: UHS RELAYS, IBR, STANDARDIZATION, SINGLE-POLE TRIPPING.

Abstract

Public Service Company of New Mexico (PNM) has committed to achieving zero emissions by 2040, which has prompted the growth of renewable energy resources in their electric grid, thus increasing the penetration of inverter-based resources (IBRs) into the system. IBRs provide additional load support and improve PNM's renewable energy portfolio; however, IBRs also pose many challenges to PNM's existing extra-high-voltage (EHV) transmission line protection system. With the goal of modernizing their line protection technology to overcome these challenges and obtain 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 and incremental quantities, as well as 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 PNM's EHV transmission line protection standard and its application to more than six 345 kV transmission lines on which PNM has successfully installed this new line protection.

1 Introduction

Public Service Company of New Mexico (PNM) is the largest energy provider in New Mexico, operating 3,189 miles of transmission line network with more than 40 percent being used by other utilities and independent producers to supply power in New Mexico, Arizona, and California. PNM plans to achieve zero emission by 2040 and owns a diverse mix of generation resources including approximately 350 MW of wind energy sources and 157 MW of solar energy sources which are being integrated into the electric grid in conjunction with customer-owned renewables programs. Uninterrupted transmission of power is critical and calls for a 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 (a shortened version of [1]) discusses PNM's transmission line protection standard and its application to an east-to-west 345 kV transmission line corridor with a limited capacity direct current (dc) tie interconnection in Texas. To maintain this rapidly growing corridor, fast line protection and restoration is crucial.

2 Background

Recently, more than 1 GW of wind power was added 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 [2]. 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.

3 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. 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. An overview of transmission line protection and fault locating using UHS relays is provided in [1].

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 implemented through either a multiplexed fiber-optic channel using synchronous optical network (SONET), which complies with IEEE C37.94

[3], a direct fiber-optic channel, or a combination of a 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-optic channel is available to use for relay-to-relay communications, the TW-based differential (TW87) protection scheme is enabled. Fig. 1 illustrates the communications channel setup for the Main-3 relays using the direct fiber optics and the multiplexed channel over SONET.

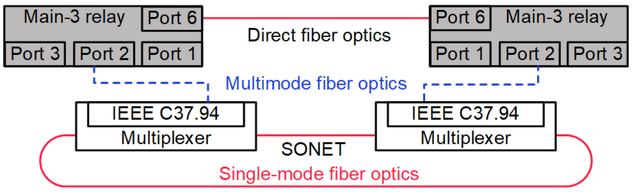

Fig. 1. Communications channel setup for Main-3 relay.

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 incorporating single-pole trip and reclose (SPTR), protecting lines with series capacitors or shunt reactors, and protecting lines in the vicinity of inverter-based resources (IBRs).

3.1 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, tripping and reclosing all three phases for single-phase-to-ground faults can cause the system to lose synchronism under certain operating conditions.

For a three-pole trip (3PT), the power flow is interrupted on all three phases of the faulted line. As explained in [1], this significantly increases the accelerating area used in the equal area criterion, and the power system will lose synchronism if the accelerating area is larger than the decelerating area [4] [5].

The SPS scheme, a combination of a single-pole trip (SPT) and SPR, trips only the faulted phase for the single-phase-to-ground-fault. SPS does not allow the power transferred across the line to fall to zero; therefore, the acceleration area for SPT is smaller than that for 3PT, and based on an equal area criterion, the likelihood of the system remaining stable is increased [1] [4] [5].

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.

To establish the standards, the SPS scheme was designed and validated using real-time digital simulator (RTDS) testing in the laboratory. To implement the standard, commissioning testing was conducted in the field for field validation. Information about the testing and commissioning process is provided in [1], along with the analysis of a field event that verifies successful implementation.

3.2 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 that operate depending 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 of line protection when applied to series-compensated lines [6] [7].

In this section, we discuss how these challenges were addressed. First, 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 [7].

Next, 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 uncompensated lines, depending on the configuration. Validation using the RTDS is required to verify the reliability of the distance elements [2]. 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.

Finally, 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 [8].

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 [8]. 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. Fig. 2 shows 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.

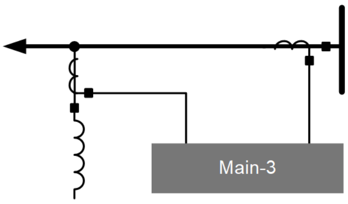

Fig. 2. Typical connections for the line-zone shunt reactor CT to the UHS relays.

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.

3.3 Protecting Lines in the Vicinity of IBRs

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.

The IBRs may or may not supply negative-sequence currents, depending on the control modes. The interconnection transformer provides the path for zero sequence. Three-phase fault currents during a sub-transient 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. 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 PNM standard calls for using the phasor-based and UHS relays to implement the following protection schemes.

3.3.1 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.

3.3.2 UHS Relay (Main-3)

Communications-assisted schemes, described in [2], 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; 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.

4 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 [2]. With this adoption, PNM standardized 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.

4.1 Standard Protection Panel Design

Consistent with the line protection philosophy, the standard consists of two phasor-based (Panel P1) relays and one UHS (Panel P2) protective relay. The two phasor-based protective relays provide dual-redundant line protection with SPT and automatic reclosing. All 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. 3.

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 block 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 make the test switches consistent with other panels, which minimizes operational errors.

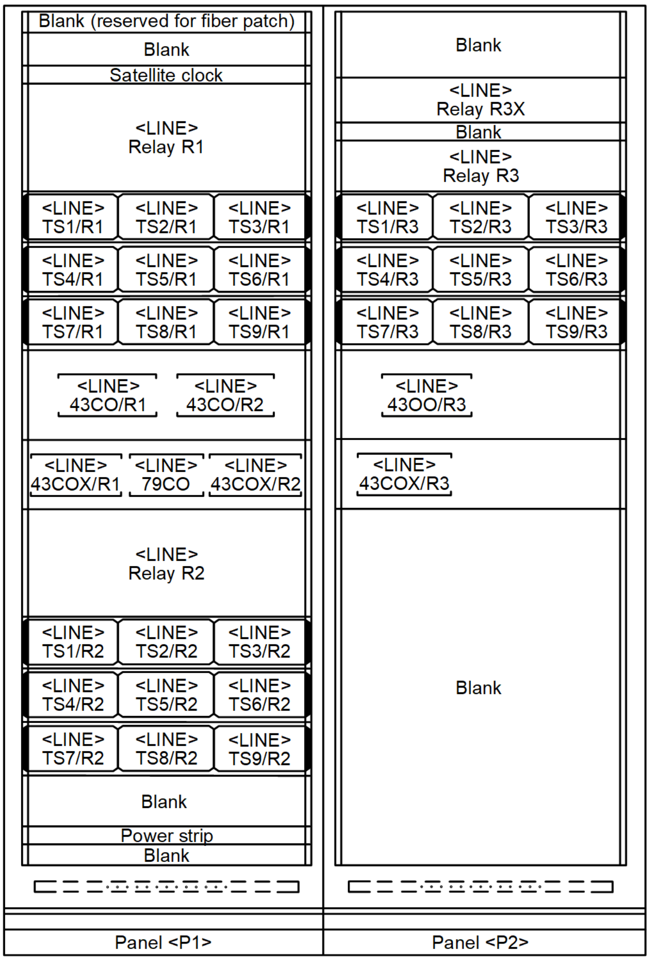

Fig. 3. Standard protection panel layout.

4.2 SPT 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. 4 shows a typical bus configuration for a 345 kV station with a breaker-and-a-half scheme. 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).

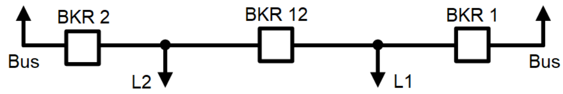

Fig. 4. Typical 345 kV single-line diagram.

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. 5 shows the logic implemented in the relays. This logic is set faster than the mechanical pole discrepancy timer in the breakers.

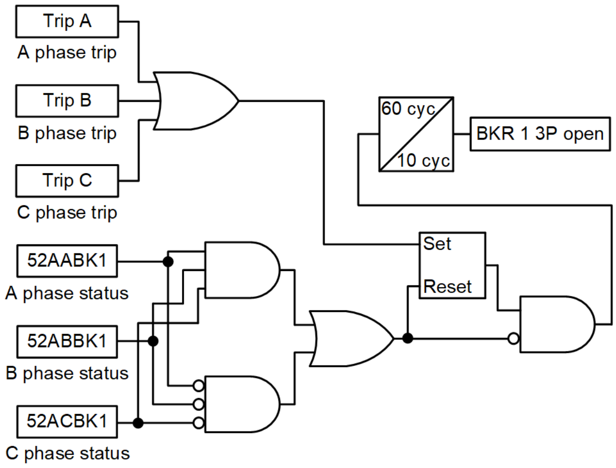

Fig. 5. Pole discrepancy logic for BKR 1.

Fig. 6 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 the three pole (3PO), two cycles after this condition is detected.

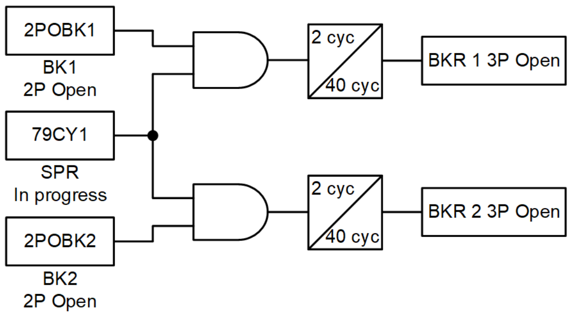

Fig. 6. Trip on two poles open (2PO) during reclosing.

4.3 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 BF 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. 7, 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 BF logic is enabled for SPT applications.

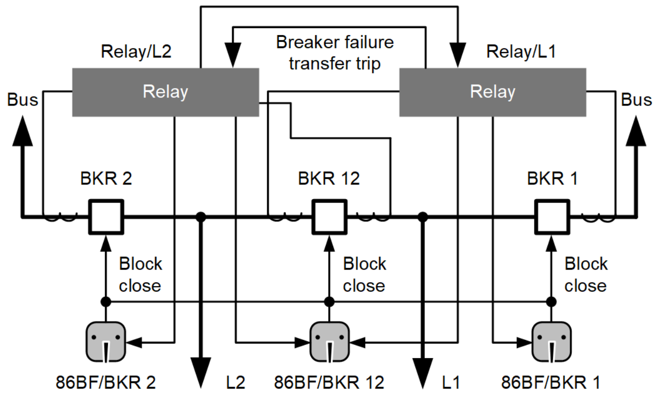

Fig. 7. BF scheme.

4.4 Phasor-Based Distance Protection

Instantaneous phasor-based distance elements are blocked when the differential communications channel is healthy and enabled. Logic in Fig. 8 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.

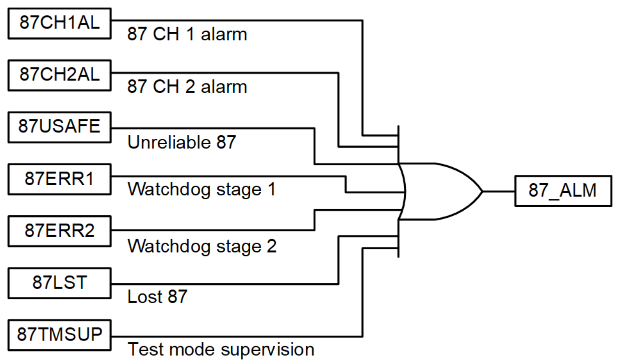

Fig. 8. Channel health alarm.

5 Protection and Control Scheme Validation

The protection and control scheme for one of the lines—between the terminals referred to as GU and TM—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 volt-ampere reactive (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 fault simulation software. The validation was performed using the fault current comparison for accuracy.

To verify the proper relay operation and the test setup, internal and external faults were simulated. In the RTDS, batch testing was performed, in which a multitude of faults were applied at various locations and with various load flow scenarios. The batch test script recorded the event data for all faults, which was then tabulated to study the relay performance and to identify any issues, such as misoperations [2]. Before the batch testing, miscellaneous tests were performed. The tests included protection and control elements such as:

- Switches on fault.
- High-impedance faults.
- Internal-to-internal evolving faults.
- Cross-country faults.
- Distance element zone coverage verification.
- Recloser tests.

This section presents several batch test results from the RTDS testing of the UHS relays. Fig. 9 and Fig. 10 show the coverage of phasor-based and incremental-quantity-based distance elements along the line. Fig. 11 shows the average operating times for the UHS relay using the TD21, phasor-based Zone 1, and POTT scheme.

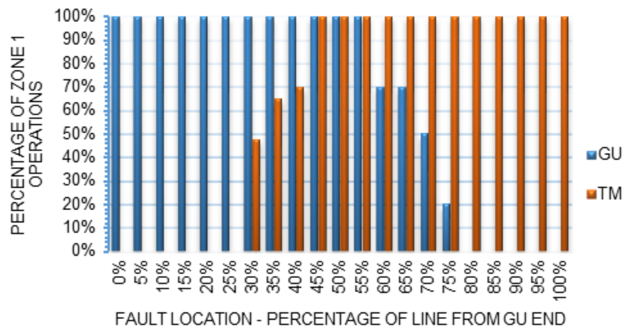

Fig. 9. Coverage of phasor-based Zone 1 from local and remote end.

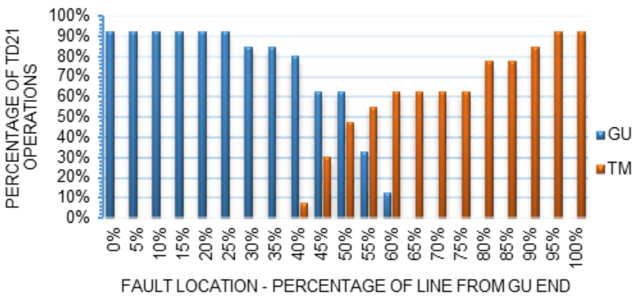

Fig. 10. Coverage of incremental-quality-based distance element from local and remote end.

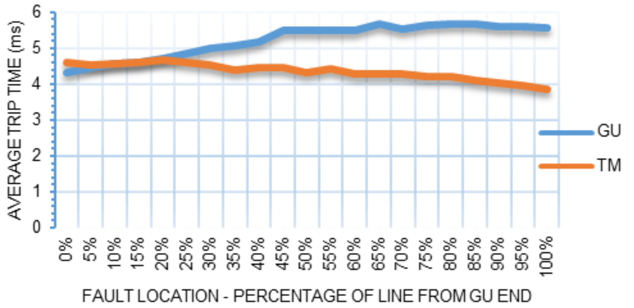

Fig. 11. Average UHS relay operating time.

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

6 Conclusion

PNM's evolving power system has led to an improved energy portfolio and a guaranteed future of sustainable energy but comes with the challenges of protecting the power system against abnormal conditions while increasing the availability of reliable power to customers. PNM realized the need to upgrade their transmission line protection system to maintain these critical lines. Acceptance of UHS relay technology was one of the first steps, with the next step being the standardization and implementation 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 PNM's standards, which were established based on present challenges, such as series compensation to improve 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 crucial. The RTDS simulation testing helped design the standards for various line applications. Standardization also led to consistency in the protection system across the EHV transmission network.

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20211111 • TP7042