Line Differential Protection at the Transmission Edge

TECHNICAL BRIEF

Applying Viper®-HV Recloser with SEL-411L Relays to Add Line Protection Terminals at Transmission Taps, Generator Interconnections, and Mid-Line Protection Points

Overview

The Viper-HV recloser gives utilities a practical way to add interruption, current measurement, and relay-based protection at transmission-edge tap locations without building a conventional substation terminal with line protection schemes at every site. When paired with the SEL-411L relay, the Viper-HV recloser can serve as the field platform for a line differential protection terminal, allowing utilities to improve protection dependability and fault-location capability while reducing the cost, footprint, and schedule burden associated with new switching stations.

These locations traditionally required a substation circuit breaker to serve as a protection zone terminal. However, when combined with the SEL-411L relay, the Viper-HV recloser can serve as the interrupting and current-measurement platform for a differential protection terminal at these locations, with the relay providing the differential logic.

The Protection Problem

Utilities connecting new generation, absorbing distributed energy resources, and adding taps to existing lines face a recurring constraint: extending protection to a new point on the transmission system has traditionally meant extending the substation to that point as well. Each terminal of a differential protection zone requires an interrupting device, current measurement, relay logic, communications, control power, and commissioning. Historically, that often meant building or expanding a substation terminal.

The problem is more consequential where inverter-based resources are involved. Solar photovoltaic, wind converter, and battery storage resources control their fault current electronically. Their short-circuit current contribution is often limited to a small multiple of rated current, in some cases near 1.0 to 1.2 per unit depending on inverter design, controls, and grid-code requirements, which can challenge distance protection and directional overcurrent elements designed around conventional rotating-machine fault behavior.

Line current differential protection addresses this by defining a specific electrical zone and evaluating differential current across all terminals simultaneously. The protection decision is based on current entering and leaving the zone, rather than impedance estimates or current signatures that inverter control behavior can distort.

The Viper-HV® recloser removes the constraint that kept differential protection confined to substations. As a pole-mounted, solid-dielectric recloser with ratings available up to 72.5kV, it puts an interrupting device on the transmission structure itself, which is what a differential tripping zone requires. The SEL-411L relay then runs the differential calculation using current measured at that Viper-HV recloser terminal.

How Line Differential Protection Works

How a Differential Zone Is Defined and Monitored

Line differential protection treats a defined section of line as a zone with measurable boundaries. A relay terminal is placed at each end, or at each terminal in a multi-terminal zone, and each relay continuously exchanges synchronized current measurements with the other terminals.

Under normal load flow and for faults outside the zone, current entering from one terminal exits through another terminal in a corresponding amount. The differential sum remains low and the relay remains restrained. For a fault inside the zone, current from one or more terminals flows into the fault and does not exit the differential zone. The differential sum rises above the operating threshold and a trip is initiated.

Bidirectional Current Flow

A four-terminal differential calculation evaluates the phasor sum of currents measured at all zone boundaries simultaneously. Under normal operating conditions with generation sources running and load flowing in multiple directions, the differential sum remains near zero because whatever current enters the zone from any terminal exits through the others. The relay is restrained regardless of whether current is flowing toward the source, toward the load taps, or in a combination of directions reflecting mixed generation and load conditions.

This is the fundamental advantage of the differential approach for tapped lines with generation. A distance relay at a source substation must estimate fault location from a single measurement point and must account for the effect of generation infeed when determining whether the apparent impedance falls within its operating zone. As the generations' source strength changes, the infeed effect changes, and the relay's effective reach changes with it. Infeed doesn't adversely impact differential relays applied at each source of infeed. A fault inside the zone produces a differential current that the relay detects regardless of what generation is online at the moment of the fault.

SEL-411L Differential Functions

The SEL-411L applies a generalized alpha plane line current differential algorithm to phase, negative-sequence, and zero-sequence current components. The relay exchanges instantaneous current samples between terminals and applies scaling for current transformer ratio differences and in-line transformer ratio differences where required.

A dedicated external fault detection algorithm provides security against current transformer saturation on external faults. The algorithm monitors the relationship between instantaneous differential current and restraining current at fault inception and coordinates the security action across all terminals by sharing external fault detection bits.

Multi-Terminal Scheme Operation

For a four-terminal zone, relays are configured in master mode, meaning each relay receives current data from all remote terminals and performs the full differential calculation independently. This configuration is commonly used because each relay can trip its associated interrupting device directly. Depending on the selected SEL-411L communications architecture and settings, the scheme can be configured to maintain tripping capability using master-outstation and direct transfer trip logic when a channel is unavailable. The actual fallback behavior must be validated for the selected channel topology and utility protection philosophy.

Inverter-Based Resource Considerations

Differential protection can provide a more dependable protection basis than schemes that rely primarily on apparent impedance or current in inverter-dominated environments, but settings should still be reviewed against the expected fault current contribution from each connected terminal.

Reliable communications channel quality is essential. The differential calculation depends on synchronized, accurate current measurements from all terminals. For critical generation interconnections, redundant communications architecture should be considered.

Backup Protection on Communications Failure

The SEL-411L includes five zones of phase and ground distance protection, available with mho and quadrilateral characteristics, along with directional overcurrent elements. The Best Choice Ground Directional Element can be enabled at each terminal for backup directional ground protection. These elements can operate continuously or be configured to support backup protection when the line differential communications channel is unavailable, and reach settings should be reviewed based on the maximum and minimum infeed conditions. When channel quality and synchronization are restored, the relay can be configured to return to differential operation according to the utility's settings and commissioning practice.

Viper-HV® Recloser as the Field Terminal

Viper-HV is a pole-mounted, solid-dielectric recloser with ratings available up to 72.5kV. Magnetically actuated vacuum interrupters, internal multi-ratio current transformers, and line-side voltage sensors are built into the same device, so it functions as a self-contained field platform rather than a collection of separately mounted components.

The internal current transformers feed the current measurement the SEL-411L terminal needs at that location. When the relay issues a trip, reclose, or lockout, the Viper-HV recloser opens or closes as configured under the utility's protection philosophy, and it supports single-phase or three-phase operation with programmable reclosing and lockout behavior.

This architecture fits best where the electrical zone can be clearly defined, where selective fault clearing matters, and where a conventional substation terminal would be difficult to justify on cost, schedule, or site grounds. It is not a universal substitute for substation protection. It is a practical way to apply proven protection functions at transmission-edge tap locations where a full substation terminal may be impractical, too slow to permit, or difficult to justify economically. By placing interruption, measurement, control, communications, and field operability at the tap, the Viper-HV recloser helps utilities move protection closer to the fault and create protection boundaries that were previously difficult to implement.

The same field device also supports remote operability and system visibility. The Viper-HV recloser can integrate into SCADA through DNP3 or IEC 61850, giving operators status, fault data, and remote switching commands at the location. Its voltage sensors and current transformers provide real-time measurement at the recloser location, which adds visibility on transmission corridors that may previously have had no instrumentation between substations. When a permanent fault results in lockout, that status and fault data can support fault detection, isolation, and restoration logic, and the same platform can support planned reconfiguration and automatic transfer schemes where remote operation is required.

System-Level Validation

Conventional transmission protection is built from independently qualified components. Circuit breakers are tested as standalone devices under breaker standards such as IEEE C37.04, C37.06, and C37.09. Protection relays are tested independently under relay-specific standards such as the IEEE C37.90 series. Those standards verify how each component performs on its own, not how the interrupter, control, protection logic, and wiring behave once they are wired together. That combined behavior is usually confirmed late, during site acceptance testing or field commissioning, which is also the most schedule-constrained part of a project.

The Viper®-HV recloser is engineered, assembled, and validated as one system before it leaves the factory. The interrupter, control, protection logic, and wiring are tested together rather than qualified separately and integrated later. One example of this is Simulated Surge Arrester Operation testing under IEEE C37.60, which applies a simulated lightning-induced surge to the assembled recloser and control and confirms the control does not misoperate and that the system retains full function afterward. This type of system-level validation helps reduce the installation risks that might otherwise be discovered later during site acceptance testing or field commissioning of separately sourced equipment.

This matters most at taps and mid-line locations, which are often remote, difficult to access, and constrained by limited outage windows. Validating the system before shipment moves integration risk out of the field, where a return visit is expensive and slow, and into the factory, where it is not.

Communications Architecture

The SEL-411L supports serial and Ethernet communications architectures for line differential protection. Serial applications can use channel-based synchronization when the channel is symmetrical, or external time synchronization where channel symmetry cannot be assured. Ethernet differential applications require external time synchronization using IRIG-B or IEEE 1588 Precision Time Protocol.

Two-terminal applications can use redundant serial channels. Ethernet applications support two- through four-terminal differential zones using dedicated Ethernet ports and a dedicated virtual local area network for 87L traffic. Two, three, and four terminal differential protection require Ethernet communications and external time synchronization.

In a four-terminal deployment, each relay typically uses two Ethernet ports in a primary and media-failover arrangement, with external time synchronization provided to all terminals from GPS clock infrastructure. The SEL ICON (MUX) supports terrestrial based time, which when incorporated in the design, will remove the GPS clock infrastructure at the Viper-HV recloser terminals. The ICON will provide the GPS signal.

Communications architecture is part of the differential protection scheme, not an add-on. For project planning, communications availability should be evaluated as early as device placement because telecom constraints can affect schedule, cost, and the feasible protection architecture. Channel quality, redundancy, time synchronization, and fallback to backup protection should be evaluated during protection design with the same rigor as Viper-HV recloser placement and relay settings.

FIELD EXAMPLE

A Four-Terminal Line with Two Generation Taps

A utility operates a 69kV sub-transmission line running approximately 35 miles from a source substation to a rural distribution substation. Two taps sit along the route. At mile 12, a paper mill draws 69kV service and runs its own 15MW co-generation unit, which exports power to the grid during normal production. At mile 22, a 20MW run-of-river hydro site connects through a step-up transformer.

Under normal conditions, current flows from the source substation toward both taps and the distribution substation at the end of the line. When the mill co-generation and the hydro site are both producing near full output, current reverses on sections of the line, and the transmission corridor becomes a path for the co-generation to export onto the transmission grid.

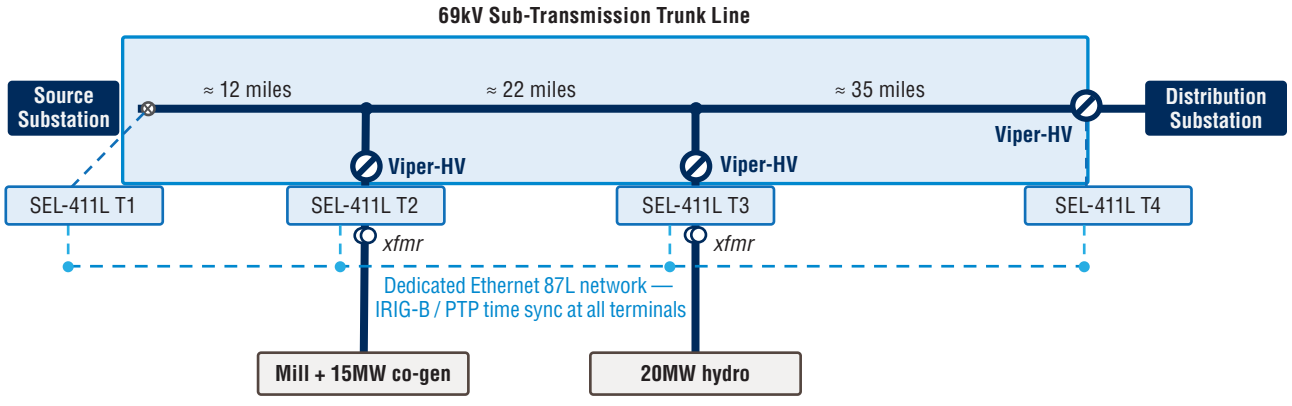
The utility had relied on overcurrent and distance protection at the source substation to cover the full line. As co-generation and hydro output grew, that approach became less reliable. The apparent impedance seen by the source relay shifted depending on how much generation was online, which meant a fault near the mill tap could cause the source breaker to operate and interrupt the hydro site and the distribution substation as well, even when those sections were unaffected by the fault.

Neither tap had a circuit breaker, and a differential zone needs one at every terminal. Building switching stations at both taps would have solved the coordination problem, but not at a cost the tap loads could justify. The Viper-HV® recloser removes this constraint by putting the interrupting device on the pole at the tap itself, so the tap can become a real protection zone terminal without a new substation.

A Viper-HV recloser was installed at the mill tap and a second at the hydro tap. At each location, the recloser's internal current transformers supply

Four-Terminal Line Differential Protection — Viper®-HV Recloser + SEL-411L

87L Differential Zone — T1 to T2 to T3 to T4 (full line, Ethernet 87L)



Four-terminal zone: the trunk continues past the hydro tap to a distribution substation, so that far-end terminal (T4) is included in the zone and its through-current is measured rather than appearing as differential current. Four-terminal 87L requires Ethernet communications.

the current measurement the SEL-411L terminal use, and the recloser carries out that terminal's trip, reclose, and lockout commands. The source substation and the distribution substation each use their existing circuit breakers with SEL-411L terminals added. Four terminals now define the main-line differential zone along the transmission corridor: the source substation breaker, the mill Viper-HV® recloser, the hydro Viper-HV recloser, and the distribution substation breaker.

The single-line defines the main-line differential zone by the four interrupting terminals shown on the transmission corridor: the source substation breaker, the mill Viper-HV recloser, the hydro Viper-HV recloser, and the distribution substation breaker. At the hydro tap, the Viper-HV recloser is installed at the main-line tap boundary, with the hydro tap conductor and step-up transformer downstream of the recloser. For the main-line 87L function, the hydro Viper-HV recloser is the differential terminal at that tap; equipment beyond the Viper-HV recloser toward the hydro transformer is outside the main-line differential zone and is protected by local tap protection and the hydro facility's transformer, generator, and interconnection protection. The same boundary principle applies to any tap terminal used in this application: the Viper-HV recloser marks the main-line differential terminal, while equipment downstream of the recloser is protected by local tap, customer, or generation interconnection protection.

The Viper-HV recloser's embedded current transformers measure current flowing through the recloser while it is closed. That measurement is used by the line differential function as the tap terminal current, and it can also be used by separate directional overcurrent elements set to look downstream into the hydro tap. The two protection functions are independent: 87L protects the defined main-line zone, while directional overcurrent protects the hydro tap connection when the fault is beyond the Viper-HV recloser toward the hydro transformer.

Event 1: Internal Main-Line Fault with Bidirectional Generation

During a period of high hydro output and moderate mill co-generation, a tree contact fault occurred on the main transmission trunk about three miles from the mill tap, inside the four-terminal line differential zone. At that moment, current was flowing into the zone from the source substation, from the mill co-generation, and from the hydro site.

Operating in master mode, each SEL-411L terminal configured to evaluate the multi-terminal differential calculation and issued a local trip for an internal-zone fault. The source substation breaker opened, the Viper-HV recloser at the mill tap opened, the Viper-HV recloser at the hydro tap opened, and the distribution substation breaker opened. Because the fault was inside the defined differential zone, the protection action removed all terminals that could contribute current to that zone.

All four terminals locked out according to the utility's protection philosophy. In this event, the value of the differential scheme was not selective isolation of only one span. The value was dependable detection of an internal fault under changing generation dispatch conditions, secure tripping of every configured terminal feeding the protected zone, and improved multi-ended fault location. The fault-location output narrowed the patrol area to the known tree-exposure section near the mill tap, reducing restoration time compared with patrolling the full line.

Event 2: Hydro Tap Fault Cleared by Directional Overcurrent

Several months later, a phase-to-ground fault occurred on the hydro tap conductor between the Viper-HV® recloser and the hydro step-up transformer. Electrically, this was not a trunk-line fault. Current from the main line flowed through the hydro Viper-HV recloser toward the faulted tap, while the hydro facility also contributed fault current from the transformer and generation side.

The hydro Viper-HV recloser's directional overcurrent element was programmed to protect the hydro tap and set to look downstream toward the hydro transformer. When it measured excessive current flowing from the main line through the recloser toward the hydro transformer, the relay issued a trip to the Viper-HV recloser. The recloser opened and interrupted the main-line contribution to the tap fault. This selective operation used the local current measurement and directional protection function at the hydro terminal. It was independent from the four-terminal line differential function, which was responsible for protecting the defined main-line zone shown on the single-line.

The hydro facility's transformer, generator, and interconnection protection cleared the generation-side contribution to the same fault. With both sources removed from the faulted tap, the main transmission line remained energized and service to the mill tap and the distribution substation was preserved. Because the downstream hydro tap conductor was outside the main-line differential zone, the desired operation was for the hydro tap directional overcurrent element to trip the Viper-HV recloser while the main-line 87L element remained secure. Once the hydro Viper-HV recloser opened, no current flowed through its embedded current transformers, so its measured terminal current was zero. The remaining energized terminals continued to exchange current measurements and supervise the defined main-line zone, subject to terminal status, communications, and scheme logic settings. The 87L remains available for any subsequent fault that occur on the transmission corridor, even with the hydro Viper-HV open.

Automatic reclosing for this tap application should be blocked or supervised unless the utility has verified that the hydro-side contribution has been removed and that reclosing into the tap is acceptable under the interconnection protection philosophy.

Reliability and Deployment Value

Together, these events show why the Viper-HV® recloser installation matters. The utility gained new protection capability at transmission-edge tap locations without building full switching stations at each site. For main-line faults, the Viper-HV recloser terminals allowed the taps to participate directly in the line differential zone, improving protection dependability under bidirectional generation flow and providing fault-location data that reduced patrol time. That reduction in patrol and restoration time can support System Average Interruption Duration Index improvement by shortening sustained outage duration after permanent main-line faults.

For downstream tap faults, the same field-installed device provided a selective interrupting point. Directional overcurrent protection at the hydro Viper-HV recloser isolated the tap while the rest of the main line remained in service, supporting System Average Interruption Frequency Index improvement by reducing the number of customers interrupted and supporting System Average Interruption Duration Index improvement by limiting restoration work to the affected tap. This is the core value of the application: moving protection, measurement, and interruption closer to the fault; enabling faster deployment of practical protection points; improving use of existing transmission assets; and creating targeted sectionalizing capability without the cost, footprint, and schedule burden of a new substation at every tap.

For more information

please visit our website: www.gwelectric.com

G&W Electric

G&W Electric is a leading provider of innovative power grid solutions that help utilities and grid operators protect, automate, and strengthen the electric grid. Our portfolio spans load and fault interrupting switches; reclosers; sensors; system protection equipment; power grid automation; cable accessories; and solutions for intelligent fault location, prediction, prevention and analytics. G&W Electric is headquartered in Bolingbrook, Illinois, with production facilities in the United States, Canada, Italy, Finland, China, and Mexico — delivering on our purpose to keep the lights on and the data flowing since 1905.

©G&W Electric, 2026
GW159
2026.11/RT