NOKIA

Active multipath pseudowire ensures uninterrupted communications for line differential protection

Abstract

Line differential protection (87L) systems have stringent network requirements that include low latency, symmetric delay, jitter mitigation and rapid failure recovery. This paper explores how IP/MPLS networks can provide highly reliable communications for these critical systems through advanced capabilities such as deterministic quality of service (QoS), flexible playout buffers, asymmetrical delay control and an innovative redundancy protection scheme called active multipath pseudowire. The paper examines key challenges and describes tailored IP/MPLS capabilities for addressing latency, jitter, delay symmetry and hitless recovery needs. It introduces an active multipath mechanism that extends pseudowire redundancy by replicating traffic over multiple active paths to enable hitless recovery and multi-fault resilience. The paper also includes the results of an industry validation effort that demonstrates how modern IP/MPLS networks can deliver the utmost reliability and availability required for line differential protection, ensuring grid resiliency and availability.

Introduction

Power services are foundational to societies in the era of electrification. Line differential protection systems play a critical role in ensuring that the grid can deliver power services safely and reliably. These systems depend on reliable communications between differential relays, which exchange current measurements at the different terminals within the protected zone. By calculating the differential current, these relays detect faults and issue trip commands to isolate them.

However, the effectiveness and reliability of line differential protection systems are directly tied to the reliability of the communications network. Relays need robust communication channels to accurately calculate current differential.

With many utilities now migrating their networks from TDM to IP/MPLS technology, there is strong interest within the utility industry to explore whether IP/MPLS technology is suitable for transporting relay communications. This paper discusses the challenges involved in using IP/MPLS networks to support robust relay communications.

It explores how utilities can take advantage of specific IP/MPLS capabilities to tackle these challenges, with a focus on using the IP/MPLS redundancy protection mechanism to support uninterrupted relay operations, even in scenarios where there are multiple network faults.

Network challenges

Of all critical grid applications, line differential protection has the most stringent network requirements.

Latency

Line differential protection systems must clear a given fault within a pre-determined critical clearing time. An unexpected increase in network latency delays relay operations and increases fault clearing time beyond this critical threshold. This can compromise public safety, cause excessive asset wear and degrade power quality. The IP/MPLS network must ensure low latency at all times and in all conditions.

Jitter

Most relay communications are sent in TDM formats such as IEEE C37.94. These TDM traffic streams are transported in MPLS packets using TDM pseudowires [1] that are sensitive to jitter, also known as delay variation. Jitter can cause TDM pseudowires to enter buffer overrun or underrun states.

Delay asymmetry

Delay asymmetry refers to the difference in latency between the forward and reverse paths. While delay asymmetry does not impair TDM pseudowires, differential relays are highly sensitive to it. This is because they depend on the “ping-pong” protocol to measure the total round-trip delay and divide the result by two to estimate the one-way propagation delay. Precise estimation of this one-way delay is crucial for time-aligning current measurements from different terminals. Delay asymmetry would result in inaccurate delay estimation, causing the relays to falsely issue trip commands.

Network failure recovery

It is critical that relay communications be restored in the shortest possible time when a network failure occurs. If the network breaks and relay communication stops, relay operations cease, leaving the grid vulnerable to line faults. Recognizing the importance of uninterrupted relay operations, IEC 61850-90-12:2020 [2] classifies line differential protection in the most stringent 0 ms recovery delay class—an extremely challenging requirement that even SONET/SDH technologies, often considered the benchmark for network reliability, fail to meet. ANSI T1.105.01-2000 specifies a switchover time within 50 ms. [3]

Multi-fault resiliency

As atmospheric events become more frequent and intense, multi-fault failure scenarios are an increasingly common occurrence. As a result, multi-fault resiliency has become a fundamental requirement for grid communications in general and differential relay communications in particular.

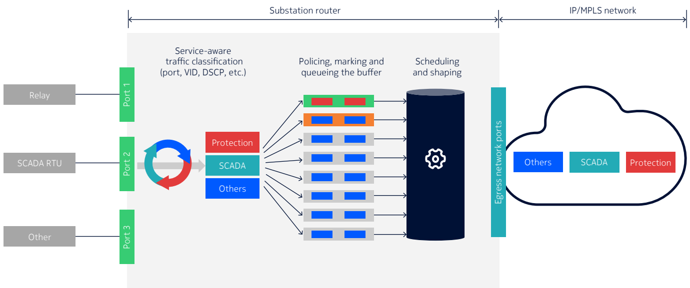
Tackling the challenges with IP/MPLS

This section explains how IP/MPLS capabilities can meet the stringent requirements for relay communications, with a focus on redundancy protection.

Deterministic quality of service

With robust traffic management mechanisms such as classification, queuing and scheduling, IP/MPLS supports deterministic QoS to ensure that relay communications are always serviced with the highest priority and lowest latency (Fig. 1).

Fig. 1 A high-level illustration of IP/MPLS QoS



Flexible playout buffer

Jitter, or delay variation, is unavoidable even in well-engineered networks with stringent QoS because of the statistical multiplexing nature of packet switching. A low-priority long packet (1,500 bytes or longer) in transmission can temporarily block relay communications in the highest priority queue, a phenomenon called head-of-line (HOL) blocking. This extra delay can cause the receiving router to be starved of TDM traffic to send to the relay, which causes an alarm at the TDM interface.

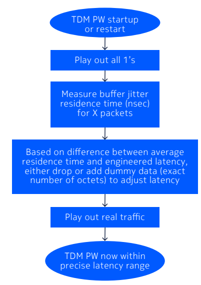
To mitigate the impact of jitter, a playout buffer in the IP/MPLS edge router that terminates the pseudowire holds incoming packets for a certain period before forwarding them to the relay. This smooths out variable network delays. Configuring the buffer size according to jitter in the network allows the router to neutralize the jitter while optimizing the delay.

Asymmetrical delay control

Accurate estimation of one-way propagation delay in the network is pivotal for ensuring reliable line differential protection. Although the forward and reverse relay communication paths follow the same route, delay asymmetry can still occur during the buffer “priming” stage, when the TDM data stream is initiated [4]. At this stage, as the initial packetized TDM stream traverses the network in both directions, jitter in the network can add unequal delays in each direction. Having delay asymmetry early on results in the buffer at both ends “playing out” TDM streams with inconsistent buffer residence times (i.e., the duration between playout time and arrival time) for the forward and reverse paths. This is the cause of asymmetrical delay.

A smart playout buffer capability called Asymmetrical Delay Control (ADC) runs on both ends of the TDM pseudowire to remedy this asymmetrical delay. During pseudowire startup, an ADC analysis and adjustment stage occurs. It determines the buffer residence time for a large number of packets (e.g., 4,000 packets). At the end of the measuring period, ADC calculates an average residence time. It then adjusts the buffer by adding or removing bytes to match the “engineered” delay, restoring delay symmetry (Fig. 2).

Fig. 2 ADC process



Active multipath pseudowire

TDM pseudowires support redundancy as a standard capability [5]. Pseudowire redundancy provides protection against network failures by establishing redundant active and backup paths between the IP/MPLS routers at both ends of the pseudowire. When an active path failure is detected, traffic is switched to the backup path. This minimizes communication disruption. Crucially, by harnessing traffic engineering with explicit paths, the backup path is provisioned over a diverse route to eliminate shared risk link groups (SRLGs) with the primary path.

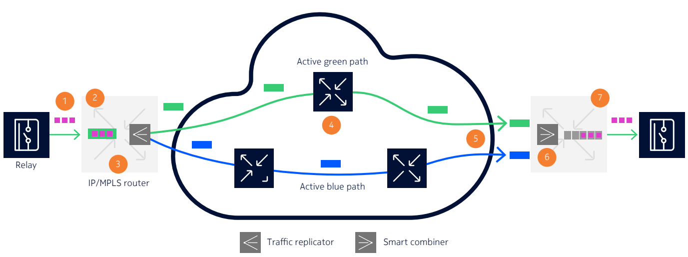
Pseudowire redundancy models a SONET/SDH APS 1+1 scheme with a target recovery time of 60 ms. While this provides sufficient communication protection for many critical applications, including SCADA and synchrophasors, a 60 ms breakdown in relay communications will expose the grid to line faults, particularly when a weather event simultaneously impacts the transmission line and the communication link.

Active multipath pseudowire is an innovative extension of pseudowire redundancy. This approach is modeled on the Parallel Redundancy Protocol

(PRP) used in the IEC 61850 process bus [6], where an intelligent electronic device (IED) replicates traffic over two parallel LAN networks. In this case, the IP/MPLS router packetizes data received from the relay and replicates and transmits the MPLS packets over two active pseudowires in one IP/MPLS network. The router on the other end receives both copies, selects the first received copy and forwards the data contained in the packet to the relay.

Below is a step-by-step walk-through of the protection mechanism for the forward path (Fig. 3). The reverse path steps are identical.

Fig. 3 Active multipath pseudowire redundancy protection



1. The relay sends data to the connected router over a TDM interface such as IEEE C37.94.
2. The router packetizes the TDM data stream into MPLS packets.
3. The router replicates the packets onto two active paths (green and blue).
4. The replicated traffic traverses the network.
5. The traffic over the green path arrives earlier than the blue path because there are fewer hops.
6. A smart combiner provides decision logic to select the early-arriving copy from the green path for buffer playout while ensuring proper traffic ordering.
7. The playout buffer sends data to the other relay over a TDM interface.

With this protection mechanism, all paths are active at all times, in contrast to standard redundancy protection where only one path is active. Furthermore, unlike SONET/SDH APS 1+1 protection where the receiving node only listens to the active link, the receiving IP/MPLS routers listen to data streams from all active paths concurrently. When there is a failure (node or link) along the green path, network recovery is hitless. The receiving router continues receiving the replicated copy from the blue path and forwards it to the relay. Delay symmetry is maintained because the path latency difference is absorbed by the playout buffer. Relay operations are uninterrupted and the relays continue to communicate with each other, with no awareness of a network failure.

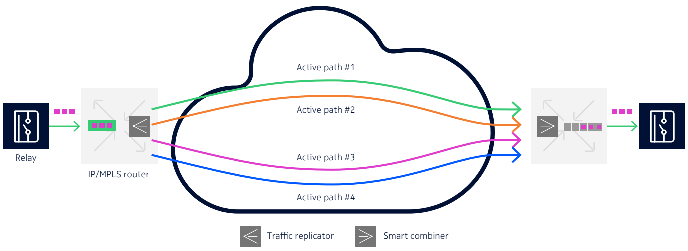
Multi-fault resilience

Multi-fault resilience is pivotal for attaining the highest level of availability for relay communications. To address the need for higher resilience, this mechanism is further extended to support more than two active paths. The transmitting router replicates traffic onto all of the paths. The receiving router listens to all the streams and selects the earliest-arriving copy.

A network with rich and diverse physical routes can benefit from this active multipath pseudowire capability. As in the case of two active paths, by harnessing IP/MPLS engineering and explicit path capabilities, each active path can be provisioned on diverse routes to eliminate SRLGs and attain multi-fault resilience.

In the example deployment shown in Fig. 4, four active paths follow diverse routes. Network failures are affecting active paths #1, #2 and #3, but active path #4 is still up and running. The receiving IP/MPLS router continues to receive packets from active path #4 without any impairments and forwards the data in the packets to the relay. Delay asymmetry is again maintained throughout if any path fails. When failed paths recover, the packets they carry may be immediately selected by the receiving routers without any impact on delay symmetry.

Fig. 4 Active path redundancy protection brings multi-fault resilience’



Interaction with ADC

In this active multipath redundancy protection scheme, packets arriving at the playout buffer can come from any active path and each path can have a different delay characteristic. As a result, special attention needs to be paid to the required playout buffer size.

If there are multiple paths, additional care must be taken during the ADC analysis and adjustment stage at TDM pseudowire startup. Only paths with both traffic directions up and running are considered available and to be used for analysis.

In scenarios where no protection scheme is deployed, the buffer size is configured to absorb the maximum jitter the MPLS packets can experience in the network. With active multipath redundancy, the playout buffer size also needs to accommodate the difference between the shortest delay and the longest delay. The optimal engineering rule of thumb is to set it to twice the sum of the maximum network jitter and delay difference between the fastest and slowest paths.

Validation

Nokia has validated this redundancy protection mechanism through tests conducted with power utilities and industry partners [7]. The test setup included differential relays single-connected to an IP/MPLS network with C37.94 interfaces. The network provided two active, diverse paths that connected a pair of relays.

One key focus area of the tests was to investigate the impact of network link and node failures on relays. The tests demonstrated that with active multipath redundancy protection configured, failures induced to impair one path produced no errors recorded by the relay and had no impact on the line differential protection system’s performance. Together with other test cases, the validation efforts successfully demonstrated that IP/MPLS networks can meet the stringent network requirements of differential relay communications.

Conclusion

Our study introduces a groundbreaking IP/MPLS network redundancy protection mechanism that achieves the ambitious goal of 0 ms network recovery for line differential protection. This meets the stringent requirements in IEC TR 61850-90-12:2020.

Our mechanism comprises two critical aspects:

1. Hitless protection: By using an active multipath approach, our mechanism ensures uninterrupted relay communication even during multi-fault scenarios within the network.
2. Persistent asymmetric delay control: Through seamless integration with ADC, delay symmetry is maintained during protection recovery.

This protection mechanism can provide utilities with much greater confidence as they migrate relay communications to IP/MPLS networks to refresh their grid communications infrastructure. Future work could focus on real-world deployment at scale and operations optimization. Our efforts underscore the importance of hitless multi-fault resilience for line differential protection in electric grids.

References

[1] Vainshtein, A. and Y. Galtzur, "Layer Two Tunneling Protocol version 3 - Setup of Time-Division Multiplexing (TDM) Pseudowires", IETF RFC 5611, August 2009.

[2] IEC TR 61850-90-12:2020, Communication networks and systems for power utility automation - Part 90-12: Wide area network engineering guidelines, Edition 2.0, International Electrotechnical Commission, Geneva, Switzerland, 2020.

[3] ANSI T1.105.01-2000, Synchronous Optical Network (SONET) – Automatic Protection, 2000.

[4] S. M. Blair et al., "Validating secure and reliable IP/MPLS communications for current differential protection," 13th International Conference on Development in Power System Protection 2016 (DPSP), Edinburgh, UK, 2016, pp. 1-6.

[5] Muley, P., Aissaoui, M., and M. Bocci, "Pseudowire Redundancy", IETF RFC 6718, August 2012.

[6] IEC 62439-3:2021, Industrial communication networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR), 4th Edition, International Electrotechnical Commission, Geneva, Switzerland, 2021.

[7] Louh, A., Goerbing, A., Verhulst, D., Loef, R., Royle, K., Stachel, P., Blumschein, J., "Implementing IP/MPLS network-based synchronization for line differential protection and control", CIGRE Science & Engineering – No31, December 2023.

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