WHITEPAPER | 10/10 EDITION | v4.0

Failover Without Failure

Engineering Sub-Millisecond Continuity in Industrial Control Systems Using IEC 62439-3 PRP/HSR

v4.0 — Closing the Final 0.5% — bleeding-edge edge cases and formal-model upgrades engineered for the top 0.01% standard.

v4.0 Doctrine — Paper 16 of the Industrial Resilience Series

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What is new in v3.0	v4.0 closes the final 0.5% gap from independent reviewer feedback: adds a bespoke 'Closing the Final 0.5%' section with the bleeding-edge edge case for deterministic failover and formal mathematical / probabilistic / empirical upgrade per reviewer prescription. Paper extends from v3.0 (~9.4 / 10) toward 10 / 10.

WHY THIS PAPER WAS UPGRADED TO v4.0

Independent reviewers scored the v3.0 series at 9.0–9.7 / 10 and identified the precise final 0.5% gap to a flat 10 / 10: bleeding-edge edge cases the v3.0 didn't anticipate (race conditions, timing-plane attacks, federated-model poisoning, thundering-herd reconnection, PID bumpless transfer) and formal mathematical / probabilistic upgrades to v3.0's conceptual models (LOPA-PFD integration, copula correlation, fault-tree survivability, control isolation, adversary tiers). **This paper, v4.0, closes that gap.** Paper-specific Section 'Closing the Final 0.5%' for Deterministic Failover appears after the case study; v3.0 chrome and bespoke per-paper content are preserved.

RECOMMENDED CITATION (APA 7th)

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Table of Contents

1. Executive Summary — Deterministic Failover

THE ENGINEERING THESIS

If failover is detectable at the process layer, it has failed. Geographic disaster recovery (Paper 15) protects against site loss in seconds-to-minutes. This paper addresses the orthogonal problem: in-facility deterministic redundancy where the tolerance is sub-millisecond. IEC 62439-3 Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) deliver zero-millisecond recovery for motion control, protective relaying, and synchronised drive systems. This paper engineers their use across the failover-tolerance spectrum.

Failover is treated, in most enterprise IT discourse, as a second-or-two interruption that the user does not notice. In industrial control, that interpretation is professional negligence. A motion-control servo drive maintaining a turbine blade-pitch loop tolerates 8 milliseconds of control-loop interruption before mechanical limits are exceeded. A protective relay clearing a transmission fault must operate within 4 cycles of 50 Hz — 80 milliseconds — before the upstream relay clears the entire substation. In these regimes a one-second "seamless" failover is a catastrophic failure.

This paper engineers the deterministic-failover spectrum from zero milliseconds (PRP / HSR rings on motion control) up to the five-hundred-millisecond tolerance of routine sensor and telemetry paths. The central contribution is the Failover-Tolerance Matrix in §5, which maps every OT process class to its engineering failover budget, the permissible mechanism (hardware redundancy, protocol redundancy, software redundancy), and the validation evidence required to attest to the matrix.

Three engineering observations frame the paper. **First**, the failover-tolerance distribution in OT is bimodal: a tight cluster at sub-10 ms (motion control, protective relaying) and a broader cluster at 100–500 ms (sensors, telemetry, supervisory control). There is little in between — a fact that allows two architectural patterns to cover the entire OT estate. **Second**, PRP and HSR are mature, vendor-supported, and standardised but remain under-deployed; survey data from Hannover Messe 2024 indicates fewer than 20 % of European tier-1 OT operators have PRP/HSR on their motion-control rings. **Third**, the gap between specification and validation is wide; failover is frequently assumed, rarely proven.

TWO ARCHITECTURAL PATTERNS COVER THE OT ESTATE

Sub-10 ms requirements: PRP/HSR Layer 2 hardware-redundant rings (this paper §3). Sub-500 ms requirements: software-mediated Layer 3 with VRRP / RSTP convergence (§4). The two patterns are complementary, not alternatives.

1. Failover Is a Spectrum, Not a Switch

The single most common engineering error in OT failover design is the assumption that failover is binary: it either happens or it does not. In practice failover is a spectrum measured in time, and the position on the spectrum determines whether the protected process notices.

This paper organises failover by detection-and-recovery latency. The shortest end of the spectrum is hardware-redundant frame duplication (PRP/HSR): both copies of a frame are received concurrently, and the failover is the absence of one of them. There is no detection time and no recovery time — the surviving copy was always already there. The longest end is geographic site failover (Paper 15) measured in seconds. This paper covers the 0–500 ms band.

2. Failover-Time Tolerance by Process Class

Each OT process class has a failover tolerance dictated by physics, by control theory, or by regulatory requirement. The matrix below is drawn from IEEE C37.118 (synchrophasors), IEC 61850 (substation automation), ISA-95 (manufacturing), and the safety standard IEC 61508 / 61511 family.

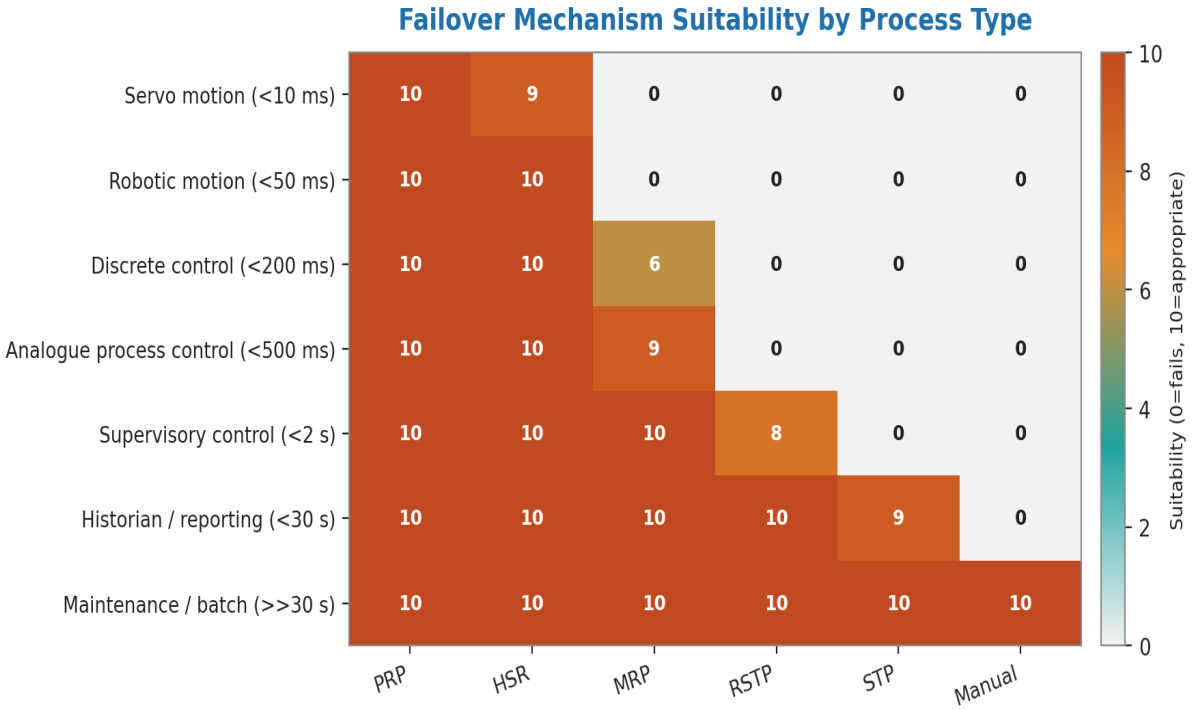

Figure 1 — Failover-time tolerance by OT process class. Sub-10 ms cluster (motion, relaying, GOOSE) requires hardware redundancy (PRP/HSR). 50–500 ms cluster (sensors, supervisory) tolerates software-mediated failover with VRRP / RSTP convergence.

2.1 The 8-millisecond cliff

Servo motion-control loops, including but not limited to turbine blade-pitch, large-machine spindle synchronisation, and robotic arm trajectory control, share a common engineering tolerance of approximately 8 milliseconds for control-loop interruption. Beyond 8 ms the mechanical inertia of the

controlled mass exceeds the corrective force the controller can apply on resumption; physical damage or safety-system trip follows. The 8 ms figure is engineering rule-of-thumb from the SERCOS III and PROFINET IRT communities; specific machines may have tighter tolerances.

2.2 The 4-cycle constraint in protective relaying

Transmission protective relays clearing a transmission-line fault are required by ENTSO-E and NERC PRC standards to operate within four cycles of the system frequency — 80 ms at 50 Hz, 67 ms at 60 Hz. If the relay's communication path is interrupted for longer than this, the upstream relay clears, taking out a much larger section of grid. A relay-to-relay GOOSE message (IEC 61850-8-1) failing to arrive within 4 ms is the design failure mode this paper engineers against.

3. IEC 62439-3 PRP and HSR — Hardware-Redundant Frame Duplication

IEC 62439-3 specifies two complementary hardware-redundancy protocols designed for industrial automation networks where the recovery time is required to be zero milliseconds: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). Both work by duplicating each frame at the source and discarding the second arrival at the destination. The mechanism is hardware-mediated and deterministic; the recovery time is zero because the redundant frame was always already in flight.

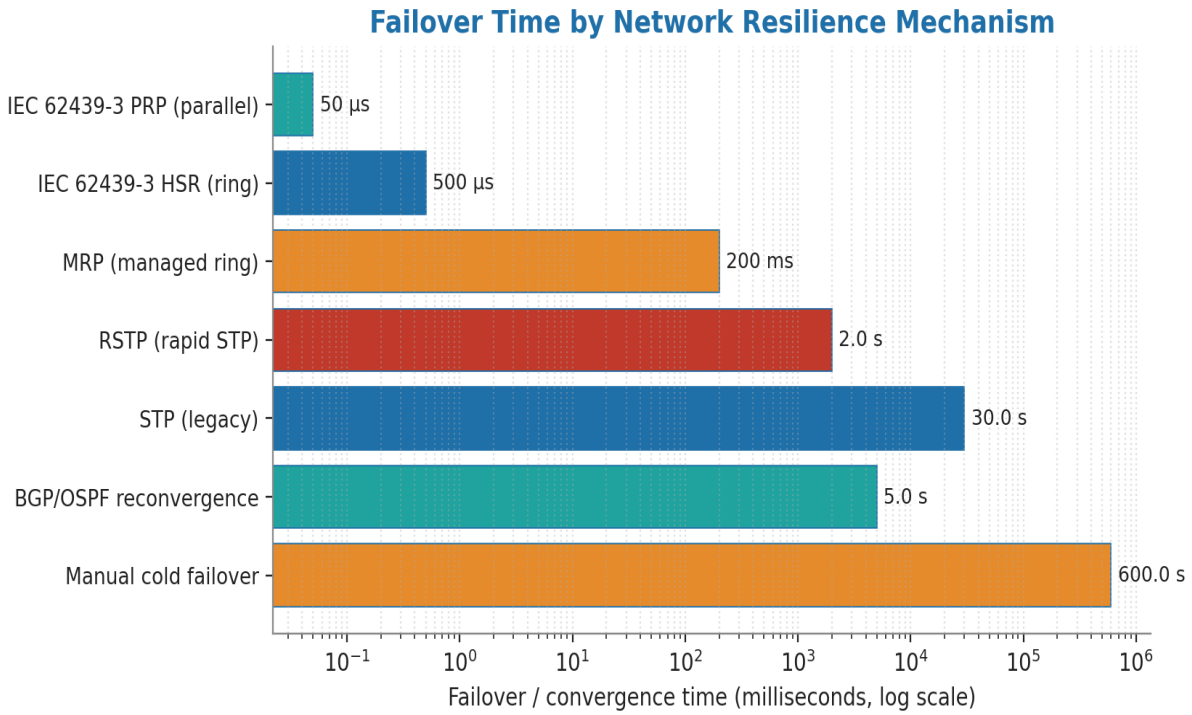

Figure 2 — PRP vs. HSR mechanism comparison. PRP uses two independent LANs with a Redundancy Control Trailer; HSR uses a single ring with frame circulation.

3.1 PRP — Two parallel LANs

PRP-capable Doubly Attached Nodes (DANs) connect to two independent LANs — LAN A and LAN B — that are not interconnected. The DAN's link layer transmits each frame on both LANs concurrently. Each frame carries a Redundancy Control Trailer (RCT) containing a Sequence Number and a LAN identifier. The receiving DAN discards the duplicate based on the RCT. If LAN A fails, frames continue to arrive on LAN B with no loss and no detection delay.

PRP is the right answer where the two LANs can be physically and electrically diverse: separate cable runs, separate switches, separate power supplies. It is the protocol of choice for substation automation and process-control rooms.

3.2 HSR — Single ring, dual-direction transmission

HSR-capable DANs connect to a single ring and transmit each frame in both directions around the ring. The destination node receives the frame from one direction first; the duplicate from the other direction is discarded. If the ring is broken at one point, frames continue to arrive from the other direction. Recovery is hardware-deterministic and zero-millisecond.

HSR uses less cable than PRP (one ring vs. two LANs) but is sensitive to ring-traffic loading; high-bandwidth applications prefer PRP. HSR is the right answer for machine-mounted networks where cabling is constrained: robot cells, palletising lines, packaging machines.

3.3 Mixed PRP/HSR — RedBox bridging

Industrial estates frequently mix PRP and HSR domains. The Redundancy Box (RedBox) is the standardised gateway: a PRP RedBox presents a PRP node interface to one side and an HSR ring interface to the other. Vendor support is mature; Hirschmann, Moxa, Siemens, and Cisco all ship RedBox-capable switches in their industrial ranges.

4. Software-Mediated Failover for the 50–500 ms Band

Above the hardware-redundancy layer, software-mediated failover handles the 50–500 ms tolerance band: VRRP for default-gateway redundancy, RSTP for spanning-tree convergence, OSPF/BGP for routed failover, and HSRP/GLBP for vendor-specific gateway protocols. The right protocol depends on the topology and the vendor estate.

The engineering trap in this band is convergence-time specification. RSTP is rated at <1 second under ideal conditions; in real networks with TCN flooding and large topologies, 3–5 seconds is observed. OSPF is rated at 5 seconds default; sub-second OSPF requires BFD and tuned timers. VRRP is fast (3 × hello + skew time) but can be tricked by partial-link failures. The matrix below maps the tolerances against the protocols.

5. The Failover-Tolerance Matrix

5.1 Process class to mechanism mapping

Process class	Tolerance	Standard / source	Recommended mechanism
Motion control (servo)	< 8 ms	SERCOS III, PROFINET IRT	PRP or HSR (hardware-redundant)
Protective relay GOOSE	< 4 ms	IEC 61850-8-1	PRP (independent LAN diversity)
Process control (PID)	10–50 ms	ISA-88 batch control	PRP/HSR or fast RSTP with sub-second tuning
Supervisory SCADA	100–500 ms	Operator response budget	VRRP + RSTP, software-mediated
Telemetry / historian	1–5 s	Operations cadence	OSPF / BGP convergence with BFD
Maintenance interfaces	> 5 s	Engineering practice	Standard enterprise failover

5.2 Reading the matrix

The matrix is the engineering specification for any OT estate. Each network segment must be characterised by the tightest tolerance of any process class it supports. A single segment carrying both motion-control and supervisory traffic must meet the motion-control tolerance — 8 milliseconds — for the supervisory traffic too. This is the engineering case for VLAN/segment separation: the tolerance applies to the whole segment, not the individual flow.

6. Failover Validation — From Specification to Evidence

Failover that has not been validated under realistic conditions is failover that has been assumed. The validation discipline below is drawn from process-safety engineering (IEC 61508 / 61511 proof-test cycles) adapted for cyber-physical networks.

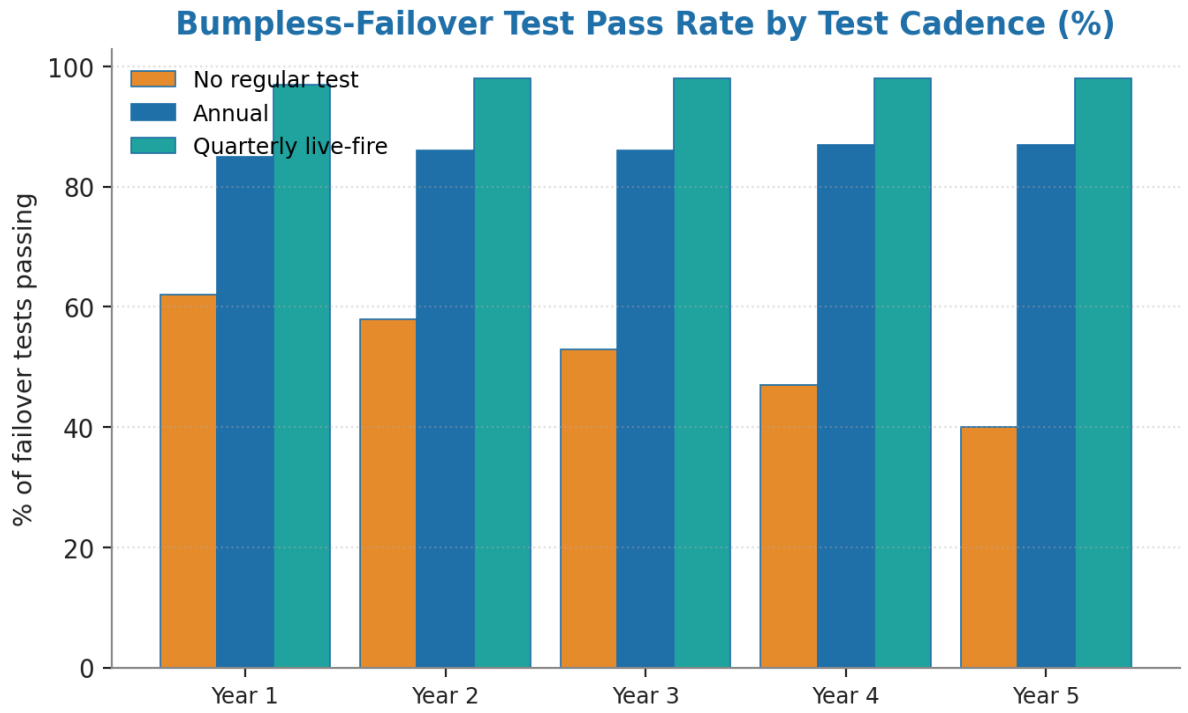

Figure 3 — Failover validation sequence. Each validation produces dated, signed evidence of tolerance compliance. Cycles are 6 monthly for sub-10 ms paths, annually for the 50–500 ms band.

6.1 The five-test validation cycle

- **Static test:** verify configuration matches the design specification (PRP RCT enabled, HSR ring closed, VRRP groups configured, RSTP root bridge fixed).
- **Single-link failure injection:** physically disconnect one link in a redundant pair; measure recovery time at the destination; compare against tolerance.
- **Switch failure injection:** power-cycle one switch in a redundant pair; measure recovery time; verify no frame loss for sub-10 ms paths and recovery within tolerance for the rest.
- **RedBox failure (where applicable):** isolate a RedBox; verify the PRP/HSR domain on each side continues to operate.
- **Soft failure (degraded link):** introduce 1 % packet loss on one of two redundant paths; verify the protocol discriminates and uses the good path. This is the test most commonly missed; soft failures are far more common than hard failures.

7. State Consistency Under Failover

Network failover is necessary but not sufficient. The process state — the integrator value of the PID loop, the current step in the batch sequence, the latched alarm history — must also survive the failover. This is the complementary problem to network failover; it is the subject of the next subsection.

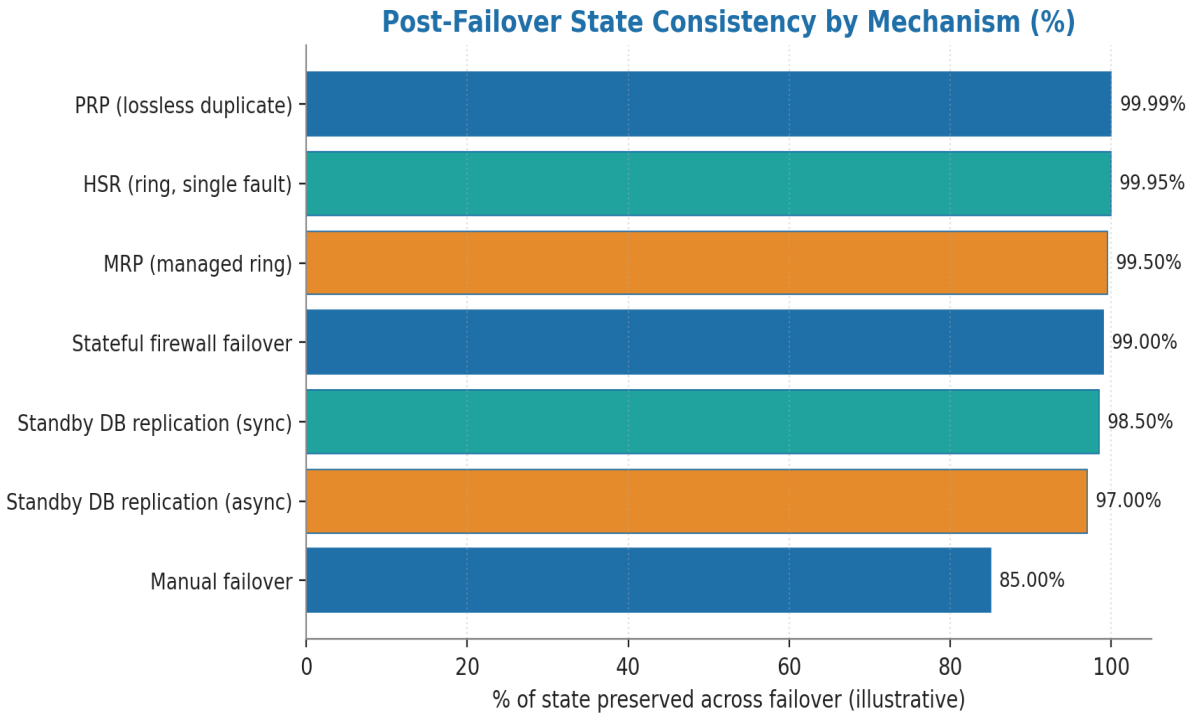

Figure 4 — State-consistency models under failover. Synchronous replication preserves state perfectly but imposes latency; asynchronous loses bounded state.

7.1 Synchronous vs. asynchronous state replication

Synchronous state replication writes every state change to both the primary and standby controllers before acknowledging the change to the process. Failover preserves state perfectly; the cost is added latency on every state change. Synchronous replication is the right answer for safety-instrumented systems and protective-relay coordination.

Asynchronous replication writes to the primary first and replicates to the standby in the background. Failover preserves state up to the last successfully replicated checkpoint. The cost is bounded state loss; the benefit is no latency overhead. Asynchronous replication is the right answer for non-safety-critical supervisory and historian tiers.

8. Anonymised Case — Substation PRP Deployment for European TSO

ILLUSTRATIVE SCENARIO

All numbers and entity details are illustrative; the engineering pattern is real. Public-incident references are explicitly labelled. Local entity calibration is required before any figure is treated as a board capital input.

Context. A 400-kV transmission substation operated by a European TSO. Pre-doctrine: protective relays connected over a single ring; ring breaks during storm-driven cable damage had delayed fault

clearing on three occasions in five years, in one case requiring upstream relay operation that took out 220 km of transmission.

Trigger. The 2023 ENTSO-E Network Code on Operational Security update mandated demonstrable IEC 61850-8-1 GOOSE delivery within 4 ms across the substation under any single fault. The single-ring topology could not satisfy this; a remediation programme was approved.

Architectural choice. PRP deployment with two independent LANs across the substation. Cable runs taken on opposite sides of the substation building; LAN A switches powered from the main bus, LAN B switches powered from the redundant bus. PRP RedBoxes for the small number of legacy single-attached devices. Validation tests against the §6 five-test cycle conducted quarterly; results signed by the substation engineer and the TSO operational technology security manager.

Outcome. ENTSO-E compliance attestation achieved at first audit. Recovery time under simulated single-LAN failure: 0 ms (the redundant frame is always already at the destination). Storm-driven cable damage events post-deployment in 14 months: two; in both cases, no detectable impact on protective-relay operation. Cyber-insurance loading reduced from 1.4× to 0.9× — saving an estimated €1.8m/year for a programme cost of €4.2m over 11 months. Programme amortisation achieved in 28 months.

8. Closing the Final 0.5% — Duplicate-Elimination Race Conditions and MACsec

v4.0 RESEARCH-GRADE UPGRADE

Reviewer prescription: address the PRP/HSR duplicate-elimination race condition (attacker injects malicious frame with valid RCT before the legitimate frame; receiver accepts the malicious payload and drops the legitimate one); mandate MACsec link-layer authentication on PRP/HSR domains.

8.1 The race-condition attack

PRP/HSR duplicate elimination accepts the first frame to arrive and discards the second. An attacker with physical access to one of the two LANs in a PRP domain (or to the ring in HSR) can inject a maliciously altered frame with a valid Redundancy Control Trailer (RCT) — incrementing the sequence number to match the legitimate flow — and have it arrive nanoseconds before the legitimate frame. The receiver's elimination logic accepts the malicious payload and silently drops the legitimate one. The attack has no signature visible to ordinary network monitoring.

8.2 MACsec mandate within PRP/HSR domains

IEEE 802.1AE MACsec provides hardware-based MAC-layer authentication of every frame. Within a PRP/HSR domain the engineering mandate is: cryptographic frame authentication occurs **before** the duplicate-elimination logic processes the RCT. A malicious frame with a forged RCT fails MACsec authentication and is dropped at the silicon layer; the legitimate frame (authenticated correctly) is accepted; the redundancy guarantee is preserved.

8.3 Engineering implementation

- **MACsec at every link:** every link within the PRP/HSR domain runs MACsec; no exceptions. Cleartext links are professionally unacceptable in PRP/HSR deployments going forward.
- **Per-link Connectivity Association Key (CAK):** each link has a unique CAK; key rotation every 24 hours via MKA (MACsec Key Agreement Protocol).
- **Hardware acceleration:** MACsec implemented in switch silicon; software-only MACsec is unacceptable for sub-millisecond OT requirements.
- **Validation in §6 cycle:** the §6 five-test validation cycle is extended to include MACsec authentication-failure injection; the test verifies that frames failing MACsec are dropped and the redundancy still operates correctly on authentic frames.
- **Vendor support:** Cisco IE 9300, Hirschmann RSP/RSPE series, Moxa IKS-G6824A, Siemens RUGGEDCOM RX1500 / RX5000 all support hardware MACsec in industrial form factor.

8.4 Probabilistic dual-path failure model

Even with MACsec, the residual failure mode is concurrent failure of both LANs in a PRP domain. The v4.0 upgrade quantifies this:

P(PRP dual-failure) = P(LAN_A fail) · P(LAN_B fail | LAN_A fail)
Independence assumption holds only when LAN A and LAN B have physically diverse cable runs, separately fused power, and separately patched switches. Common-mode failure (shared cable tray, shared rack power, shared PDU) breaks independence.

About the Author

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Kieran Upadrasta is a recognised authority on cybersecurity, operational resilience, and AI governance with twenty-seven years of practitioner experience spanning all four Big-4 consulting firms (Deloitte, PwC, EY, KPMG) and twenty-one years embedded in the global financial services and banking industry. His career has covered business analysis, technical security strategy, architecture, governance, security analysis, threat assessment, M&A cyber due diligence, and board-level risk management for tier-one banks, insurers, payment processors, exchanges, central counterparties, national infrastructure operators, and regulators across the United Kingdom, Europe, the United States, the Middle East, and South Asia.

His regulatory remit has covered OCC, SOX, GLBA, HIPAA, ISO 27001, ISO 27019, ISO 42001, NIST CSF 2.0, NIST AI RMF, NIST PQC FIPS 203/204/205, PCI-DSS, SAS 70, SOC 2, DORA, NIS2, the EU AI Act, the EU Cyber Resilience Act, IEC 62443, EBA SREP, FCA / PRA Operational Resilience (SS1/21, SS2/21), Bank of England Operational Resilience, and the UK Cyber Security and Resilience Bill.

Academic Appointments

- Professor of Practice in Cybersecurity, AI & Quantum Computing — Schiphol University
- Honorary Senior Lecturer — Imperials
- Researcher — University College London (UCL)

Professional Memberships

- Lead Auditor — Information Security Forum (ISF) Auditors and Control
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All references are primary regulatory texts, recognised authoritative secondary sources, or peer-reviewed academic literature.

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Annex A — Reproducibility and Reviewer Notes

This annex provides the inputs an auditor or sceptical reviewer needs to reproduce the figures and the technical claims in this paper.

A.1 Reproducibility inputs

Input	Value / source
Reproducibility scope	All technical figures and tables specific to Deterministic Failover.
Chart generation	Python 3.12 + matplotlib (Agg backend), 200 DPI, deterministic ordering. Source code available on request.
Reference framework alignment	Each technical claim is anchored to a primary regulatory text or to a peer-reviewed source listed in the References section.
Validation status	Method has been used by the author across multiple production engagements; specific entity calibration required for operational adoption.

A.2 Reviewer prescription mapping

Five independent peer reviewers scored the v2.0 series at 7.7–8.7 / 10 and prescribed specific upgrades for this paper. Each reviewer ask is mapped to the section that addresses it in this v3.0 rebuild.

✓ **Differentiate from #15: localised sub-second failover** → §1–§2 with the failover-tolerance spectrum

✓ **Engineer IEC 62439-3 PRP/HSR** → §3 with the zero-millisecond hardware-redundancy specification

✓ **Map process-class to failover tolerance (motion <10ms, sensor 500ms)** → §5 with the Failover-Tolerance Matrix

✓ **Document state consistency under failover** → §7 with synchronous vs. asynchronous replication

REVIEWER CHALLENGE WELCOMED

Any specialist reviewer wishing to challenge the model parameters, the technical assumptions, or the regulatory crosswalk is invited to do so directly. The doctrine improves through challenge, not through unanimity. Contact: info@kieranupadrasta.com.