



PRC-028 Substation Compliance

*Disturbance Monitoring for Inverter-Based Resources — and How to
Achieve It With the SEL RTAC and Axion Platform*

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Preface

This book is written for the people who must actually make PRC-028 happen: the plant engineers, owner's engineers, compliance managers, and substation designers responsible for utility-scale solar, wind, storage, hybrid, and HVDC-connected facilities. It moves from the regulatory anatomy of NERC PRC-028-1 — applicability, the eight requirements, the phased clock — through the technical specifications that drive equipment selection, to a complete reference architecture built on the SEL Real-Time Automation Controller and SEL-2240 Axion platform, and finally to the operating discipline that keeps a compliant installation compliant and audit-ready.

Standards evolve and product capabilities advance. Requirement interpretations, dates, and specifications herein reflect the adopted PRC-028-1 and manufacturer documentation current as of this edition; readers must verify all obligations against the currently enforceable standard and the governing product manuals for their firmware. This book is educational; it is not a substitute for project-specific engineering by a licensed professional engineer.

— *Sandip R. Patel, P.E., Keentel Engineering, Tampa, Florida*

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Chapter 1 — Why PRC-028 Exists: The Inverter-Based Resource Visibility Gap

For a century, the machines that generated North America's electricity also explained themselves. A synchronous generator responds to a grid fault with physics — inertia, field dynamics, damper windings — and the protective relays around it capture oscillography as a matter of course. When something went wrong, investigators had data.

Inverter-based resources broke that assumption. A solar plant, wind facility, or battery energy storage system responds to a disturbance not with rotating mass but with control code, changing active and reactive power output in milliseconds according to firmware logic that varies by manufacturer, model, and settings file. When fleets of IBRs began tripping or reducing output during transmission faults — the Blue Cut Fire event in California, the Canyon 2 Fire event, and the Odessa disturbances in Texas — investigators repeatedly hit the same wall: the plants that misbehaved had little or no high-resolution recording. Facilities had been built with minimal oscillography, no unit-level visibility into inverter fault codes, and inconsistent time synchronization. Event investigations stalled, dynamic models could not be validated against measured behavior, and the same failure modes repeated across the fleet because nobody could prove exactly what had happened.

The regulatory response arrived through FERC Order No. 901, which directed NERC to close the IBR reliability gaps, and through a family of new Protection and Control standards developed under NERC's IBR work: PRC-028-1 for disturbance monitoring, PRC-029-1 for ride-through performance, and PRC-030-1 for post-disturbance analysis and mitigation. Of the three, PRC-028-1 is the foundation — the other two standards depend on the measured data it mandates. Ride-through performance cannot be demonstrated, and unexpected behavior cannot be analyzed, without records.

PRC-028-1, Disturbance Monitoring and Reporting Requirements for Inverter-Based Resources, became effective on April 1, 2025. For owners of utility-scale solar, wind, storage, and hybrid facilities, the practical question is no longer whether to install disturbance monitoring equipment, but how to do it economically — at existing sites that were never designed for it, and at new sites where the monitoring must be operational at commercial operation. This book lays out the standard's anatomy, the engineering specifications behind each requirement, and a reference architecture built on the SEL Real-Time Automation Controller (RTAC) and SEL-2240 Axion platform that Keentel Engineering deploys to achieve — and document — compliance.

Chapter 2 — Anatomy of PRC-028-1: Applicability and the Eight Requirements

2.1 Who and What Is Covered

PRC-028-1 applies to Generator Owners and, for certain interconnection-point obligations, Transmission Owners of inverter-based resources. The facility threshold captures both Bulk Electric System IBRs and a second category of non-BES IBRs: facilities with an aggregate nameplate rating of 20 MVA or greater

interconnected at 60 kV or above. In practice this sweeps in essentially every utility-scale solar PV plant, Type 3 and Type 4 wind facility, battery energy storage system, HVDC-connected resource, and hybrid facility of commercial significance. Facilities near the BES boundary should confirm applicability with their Regional Entity, and owners should note that resources below the bright-line thresholds can still be designated for compliance based on reliability need.

The word "aggregate" matters. A 12 MVA solar block co-located with a 10 MVA battery behind one interconnection is a 22 MVA facility for applicability purposes. Hybrid facilities should evaluate the combined nameplate at the point of interconnection, not the individual technology blocks.

2.2 The Requirement Structure

The standard is organized as eight requirements that follow a deliberate logic: three data types, each with a "where and what" requirement and a "how well" requirement, followed by data management and equipment maintenance obligations.

Req.	Subject	What It Obligates
R1	SER data — locations and quantities	Sequence of Events Recording for the IBR facility: breaker/switching-device status changes, and inverter-level information such as fault codes, alarms, and ride-through status
R2	FR data — locations and quantities	Fault Recording of AC voltage and current quantities at defined facility locations, typically main power transformers, collector feeders, and reactive power devices
R3	FR data — performance and triggering	Trigger conditions the fault recording must respond to: neutral (residual) overcurrent, AC phase overvoltage and undervoltage, and overfrequency/underfrequency
R4	DDR data — electrical quantities	Continuous dynamic disturbance recording of voltage, current, real and reactive power, and frequency at specified locations, typically at or near the point of interconnection
R5	DDR data — performance	Input sampling rate of at least 960 samples per second and output recording rate of at least 60 times per second for the recorded electrical quantities
R6	Time synchronization	Recorded data time-stamped and synchronized to a common, traceable time reference so records from different devices and facilities align during event reconstruction
R7	Data management and reporting	Data retrievable for the required retention window and provided upon request in standard formats: COMTRADE (IEEE C37.111-1999 or later) with file naming per COMNAME (IEEE C37.232-2011 or later)
R8	Recording-capability failures	Upon discovery of a failure of SER, FR, or DDR recording capability: restore within 90 calendar days, or initiate a Corrective Action Plan

Each requirement carries a corresponding Measure defining acceptable evidence — actual data recordings or derivations, or documents describing device specifications, configurations, and settings. That evidentiary dual-path is significant for program design: a well-documented design standard, applied consistently and kept current, is itself compliance evidence. Chapter 11 returns to what an audit-ready evidence package looks like.

Engineering Note — Read the Final Standard, Not the Drafts

The unit-level recording obligations changed materially between the circulated drafts and the adopted PRC-028-1, particularly regarding inverter-level data and "if capable" relief for existing equipment. Programs scoped against draft language have, in Keentel's experience, carried unnecessary hardware cost. Re-baseline every requirement interpretation to the final enforceable text and its Implementation Plan before committing procurement.

Chapter 3 — The Data Triad: SER, FR, and DDR

PRC-028-1 is built on three distinct recording disciplines. They answer different questions, run at different speeds, and impose different equipment demands. Conflating them is the most common early design error.

3.1 Sequence of Events Recording (SER)

SER is the time-stamped log of discrete state changes: a breaker opened, a disconnect closed, an inverter posted a fault code, a ride-through mode asserted. Its value is causal ordering — establishing, to millisecond resolution, what happened first. For IBR facilities the standard's reach into inverter-level information is the novel element: fault codes, alarms, and ride-through status originate inside the OEM's control system, which means SER design is as much a vendor-coordination exercise as a wiring exercise. Existing units may have qualified relief where the equipment is not capable; new units should have unit-level SER capability specified in the procurement documents, because no such relief attaches to equipment an owner chooses to buy.

3.2 Fault Recording (FR)

FR is triggered, high-speed oscillography: point-on-wave voltage and current captured around a disturbance, the raw material of protection analysis. The standard defines both where FR must exist — the facility's main power transformers, collector feeders, and reactive devices — and what must wake it up: residual overcurrent, phase over- and undervoltage, and frequency excursions. FR answers what the electrical system actually did during the fault window: current magnitudes and asymmetry, voltage depression and recovery, breaker clearing.

3.3 Dynamic Disturbance Recording (DDR)

DDR is continuous, phasor-domain recording of the quantities that describe system dynamics — voltage, current, real and reactive power, frequency — captured without interruption so that slow phenomena invisible to a triggered recorder are preserved: power oscillations, frequency events, voltage excursions, and the IBR control-system behavior between and after faults. DDR is what makes ride-through performance demonstrable under PRC-029 and what feeds model validation. Because it never stops, DDR is fundamentally a storage-engineering problem, which Chapter 8 quantifies.

Attribute	SER	FR	DDR
Nature	Discrete event log	Triggered waveform capture	Continuous phasor recording
Typical resolution	1 ms time stamps	Kilohertz-class sampling	≥960 sps input, ≥60 fps output
Primary question	What happened, in what order?	What did the waveforms do during the fault?	How did the plant behave dynamically, before, during, and after?
Storage character	Small, cumulative	Bursty, event-driven	Large, continuous

Chapter 4 — Technical Specifications That Drive Equipment Selection

4.1 The DDR Performance Floor

Requirement R5 sets the two numbers that dominate recorder selection: input sampling of at least 960 samples per second and an output recording rate for electrical quantities of at least 60 times per second. The 960 sps floor — 16 samples per cycle at 60 Hz — exists because IBR control dynamics live at speeds conventional disturbance recorders were never specified to resolve. Any equipment evaluation should treat these as minimums to be exceeded with margin, not targets to be met exactly: recording headroom is cheap at design time and unobtainable during an event investigation.

4.2 Fault-Recording Triggers

Requirement R3 enumerates the trigger classes fault recording must implement — neutral (residual) overcurrent, AC phase overvoltage and undervoltage, and over/underfrequency. A compliant design implements these as configured trigger elements with documented thresholds and pickup times, and the configuration record itself becomes Measure evidence. Good practice layers additional triggers the standard does not require — sequence-component and rate-of-change-of-frequency elements — because the marginal cost is a settings entry and the marginal value during an oscillation or ride-through investigation is substantial.

4.3 Time Synchronization

Requirement R6 exists because untimed data is nearly worthless for event reconstruction: records from the plant, the transmission owner's recorders, and neighboring facilities must align on a common time base traceable to UTC. The engineering implication is a facility time architecture — a GNSS-disciplined clock, distribution via IRIG-B and/or Precision Time Protocol, and verification that every recording element is actually locked. Millisecond-class alignment satisfies event sequencing; the reference architecture in this book delivers microsecond-class synchronization, which additionally enables synchrophasor-grade measurement from the same hardware.

4.4 Data Formats and Retention

Requirement R7 standardizes the deliverable: records in COMTRADE per IEEE C37.111 (1999 revision or later) with file names conforming to IEEE C37.232 COMNAME (2011 revision or later), retained so they remain retrievable for the standard's retention window and produced upon request from the Reliability Coordinator, Regional Entity, or NERC within the required response period. Two operational consequences follow. First, retention is a rolling engineering property of the recorder — the continuous archive must be sized so the retention window survives worst-case recording load. Second, retrieval must be a documented, rehearsed procedure, not an improvisation: an owner who cannot produce a requested record inside the response window has a violation regardless of whether the data technically exists.

Verify the Enforceable Text

Retention windows, response periods, and phased dates in this book reflect the adopted PRC-028-1 and its Implementation Plan as published. NERC standards are living documents subject to revision and regional variance; every compliance program should tie its internal procedures to the currently enforceable version retrieved from the NERC Reliability Standards library, and re-verify at each program milestone.

Chapter 5 — The Compliance Clock: Phased Implementation

PRC-028-1 became effective April 1, 2025, with implementation phased by facility category. The structure rewards early movers and punishes owners who treat the far dates as the start date.

Facility Category	Obligation	Date
BES IBRs in operation before the effective date	50% of the owner's applicable assets compliant with R1–R7	April 1, 2028
BES IBRs in operation before the effective date	100% of applicable assets compliant with R1–R7	January 1, 2030

Facility Category	Obligation	Date
New BES IBRs entering service after the effective date	Compliant with R1–R7	Later of July 1, 2026 or commercial operation date
All applicable BES IBRs	R8 recording-failure obligation (90-day restore or CAP)	January 1, 2026
Category 2 non-BES IBRs (≥ 20 MVA, ≥ 60 kV)	R1–R7 on the later phased schedule per the Implementation Plan	Per Implementation Plan — verify current dates

Three planning realities deserve emphasis. First, the new-resource schedule is effectively "operational at COD": a facility reaching commercial operation after mid-2026 must energize with its disturbance monitoring working, which puts the DFR design on the critical path of the substation package rather than in a post-COD punch list. Second, the 50% milestone for existing fleets is a portfolio decision — owners with dozens of sites need a prioritization logic (interconnection voltage, plant size, regional scrutiny, outage windows) and a repeatable site design, because bespoke engineering at every plant will not scale to the 2030 date. Third, R8 is already live: any facility with recording capability today carries the 90-day restore-or-CAP obligation now, which means recorder health monitoring and failure-discovery documentation cannot wait for the R1–R7 dates.

Owners should also account for the market realities around these dates: qualified engineering resources, recorder hardware, and instrument-transformer lead times are all being consumed by an entire industry converging on the same deadlines. Extension mechanisms exist for circumstances genuinely beyond an owner's control, but an extension request supported by a documented, in-flight program is a very different conversation with the Regional Entity than one that begins after the milestone has passed.

Chapter 6 — PRC-028 in Context: Neighboring Standards and Regional Overlays

6.1 PRC-002-5: The Synchronous Sibling

PRC-002 remains the disturbance-monitoring standard for the conventional system, and its current revision, PRC-002-5, clarifies the boundary by excluding IBRs — which now live under PRC-028-1. The two standards are parallel in architecture (SER, FR, DDR; formats; retention) but differ where IBR physics demands it, most notably in unit-level SER reach into inverter controls and in the recording performance floor. Transmission Owners with recorders at IBR interconnection points, and owners of mixed portfolios, must track obligations under both standards; the reference architecture in this book is documented by its manufacturer as designed to exceed both PRC-002 and PRC-028 recording requirements, which is precisely why a single platform standard across a mixed fleet is attractive.

6.2 PRC-029-1 and PRC-030-1: The Consumers of the Data

PRC-029-1 establishes voltage and frequency ride-through performance requirements for IBRs — remaining connected and continuing to deliver current through defined disturbance zones, with momentary cessation prohibited in the no-trip region — with design obligations effective October 1, 2026, and performance demonstration obligations that depend on disturbance monitoring data. PRC-030-1 obligates analysis and correction of unexpected IBR performance following disturbances. Both standards presume the existence of exactly the records PRC-028 mandates: an owner cannot prove ride-through, and cannot perform credible post-event analysis, without SER, FR, and DDR. Compliance programs should therefore treat the three standards as one data-driven lifecycle — record (PRC-028), perform and demonstrate (PRC-029), analyze and correct (PRC-030) — and design the monitoring architecture for all three consumers at once.

6.3 Regional Overlays

Regional frameworks can layer additional or accelerated obligations on the same equipment. In ERCOT, for example, dynamic disturbance and event-recording obligations under the region's own rule changes apply alongside PRC-028-1, with their own retention and provision duties — some already in force. A single, well-designed disturbance monitoring installation can satisfy multiple rulebooks simultaneously, but the compliance evidence must trace to each framework's citations separately. Owners operating across regions should maintain a requirements matrix per site, mapping every recording capability to every obligation it discharges.

Chapter 7 — Reference Architecture: SEL RTAC + Axion Digital Fault Recorder

The architecture Keentel deploys most often for PRC-028 compliance pairs an SEL Real-Time Automation Controller with SEL-2240 Axion I/O over a dedicated EtherCAT network. One platform then discharges all three data obligations: Axion protection-class modules provide the high-fidelity measurement front end, the RTAC's Digital Fault Recorder extension and continuous recording groups provide FR and DDR, the tag and SOE infrastructure provides SER, and the same controller carries the plant's SCADA, protocol conversion, and HMI duties it would host anyway. The DFR capability is documented by the manufacturer as designed to exceed the recording requirements of both PRC-002 and PRC-028.

7.1 Performance Envelope Versus the Standard

PRC-028-1 Demand	Platform Capability	Margin
DDR input sampling ≥ 960 sps (R5.1)	Continuous oscillography recorded at 3,000 samples per second per channel	3.1× the floor
DDR output rate ≥ 60 fps (R5.2)	Dynamic disturbance / synchrophasor data at up to 120 messages per second; PMU rate configurable (60 typical)	1–2× the floor
Triggered fault recording (R2/R3)	Event recording at 24 kHz with 24-bit resolution on Axion AC protection modules	400 samples per cycle
SER (R1)	1 ms Sequence of Events time-stamping across contact and communications points	Meets the SER convention
Time synchronization (R6)	Sub-microsecond measurement accuracy; PTP high-accuracy input and IRIG-B distribution	Orders of magnitude beyond ms-class
Formats and retrieval (R7)	COMTRADE generation for fault records and on-demand continuous-recording extracts; SOE and fault-location exports in CSV	Native to the workflow
Continuous retention	3 ksps continuous oscillography retainable 30+ days on SSD; drives to 8 TB	Exceeds retrievability windows

7.2 Platform Selection

DFR functionality requires the modern RTAC compute tier running R153-V0 or later firmware: the SEL-3555, SEL-3560, SEL-3350, or the SEL-2241-2 Axion CPU module. Legacy controllers — the SEL-3505 class and the original SEL-3530 generation — do not support the fault-recording and continuous-recording engines and must be replaced (with project conversion) as part of a compliance retrofit. On the SEL-3555 and SEL-3560E, an additional PCIe card — the SEL-3390E4 network adapter or

the SEL-3390T time-and-Ethernet adapter — supplies the dedicated EtherCAT interface to the Axion I/O; the 3390T additionally brings a high-accuracy PTP time input suitable for synchrophasor-class synchronization. Firmware licensing must include the FileIO, Dynamic Disturbance Recording, and Continuous Recorder options — a procurement line item that is easy to miss and painful to discover at commissioning.

Platform	Fit for PRC-028 DFR Duty	Selection Notes
SEL-3555	Highest capacity — large multi-recorder or combined DFR/SCADA/synchrophasor duty	Xeon-class, 8–64 GB RAM, RAID-1 capable storage to 7.68 TB, redundant supplies; PCIe card required for EtherCAT
SEL-3560E / 3560S	Compact high-performance installations	Xeon-class in surface-mount form; 3560E takes one PCIe expansion card; verify the narrower –40° to +60°C rating against the enclosure design
SEL-3350 (3U)	The workhorse for single-substation DFR + RTU consolidation	Quad-core, storage to 7.68 TB, 48 serial ports in 3U, optional redundant supplies; native Ethernet ports EtherCAT-capable
SEL-2241-2 in Axion	Distributed or space-constrained plants; DFR embedded in the I/O chassis itself	Modern quad-core CPU module resident on the Axion backplane; DisplayPort local HMI; redundant supplies in chassis

7.3 The Measurement Front End

The Axion side of the architecture is a modular chassis system — SEL-2242 backplanes in 10-slot, 4-slot, and dual 4-slot formats — populated per the site's channel map: SEL-2243 power couplers (which also carry the node-to-node EtherCAT links), SEL-2245-42 AC protection modules terminating CT and PT secondaries for the FR/DDR quantities, SEL-2245-43 analog input modules for auxiliary quantities, and SEL-2244 digital input/output modules for breaker and disconnect status, alarms, and DFR status outputs. A digital input variant with battery-monitoring capability (0.5% DC accuracy) lets the same installation watch the station battery — one of the auxiliary quantities every disturbance investigation eventually asks about. The platform scales to 60 modules and beyond a thousand digital inputs, so channel-count growth is a configuration exercise rather than a replacement project.

7.4 EtherCAT Network Rules

The RTAC-to-Axion link is EtherCAT, and its rules are strict enough to deserve their own paragraph in every design package: exactly one Ethernet interface on the controller is dedicated to EtherCAT; the connection from that port to EtherCAT Port 1 on the first node's power coupler (Slot A) is direct — the protocol is non-routable and no switches are permitted; and subsequent Axion nodes daisy-chain coupler to coupler. Modern platform documentation additionally describes star, sequential, and combination topologies for multi-node layouts; the governing document for any given firmware is the SEL-5033 manual, and the topology should be fixed during design, not discovered during commissioning.

Chapter 8 — Sizing the System: Channels, Storage, and Instrument Transformers

8.1 Channel Math Before Hardware

The design sequence that controls cost runs: single-line diagram → monitored areas → measurement points → module count → chassis and platform. Working from the facility SLD, the engineer marks every location where R1, R2, and R4 quantities live — the point of interconnection, main power transformers (both sides where required), collector feeders, reactive devices, and the breakers and disconnects whose status feeds SER. Each three-phase V+I measurement point consumes an AC protection module input group; each block of status points consumes digital-input channels. Only after that map exists should anyone pick a platform, because the channel count — not habit — determines whether the site is a single 10-slot node or a multi-node network, and whether a 3350 suffices or a 3555's capacity is warranted.

8.2 Storage Engineering for Continuous Recording

Continuous recording is where storage design becomes compliance design. Each voltage or current channel configured for continuous recording at 3 kHz consumes roughly 600–700 MB per day. A modest plant recording, say, 24 analog channels continuously is producing on the order of 15–17 GB per day — about half a terabyte per month — before fault records, PMU streams, and SOE archives. Drives up to 8 TB are available on the SEL-3555, SEL-3560E, and SEL-3350, and the design deliverable is a simple table: channels × rate × retention target, with margin for event bursts and with the R7 retrievability window as the floor, not the goal. On the 3555, RAID-1 mirroring of the data drives adds loss protection for the archive that is the entire point of the installation.

8.3 Instrument Transformers: The Long-Lead Reality

The recorder is rarely the schedule risk; the copper is. Brownfield sites frequently lack spare CT cores or accessible PT secondaries at the required locations, and adding them means outages, and sometimes procurement with the longest lead time in the project. Two design rules follow. On existing facilities, exhaust the reuse options first — existing protection-class CTs and PTs and the event-capable relays already on collector feeders can discharge a substantial share of the FR obligation with reconfiguration rather than construction. On greenfield facilities, specify dedicated measurement cores before steel is ordered: a spare CT core costs almost nothing at procurement and a fortune after energization. Ratios are entered in the DFR configuration as X:1 (a 1200:5 CT is entered as 240), and the CT/PT data sheet for every source belongs in the compliance evidence file.

Chapter 9 — Configuration: From Single-Line Diagram to Running Recorder

The RTAC DFR extension reduces what was historically days of recorder engineering to a menu-driven configuration measured in hours, with no code written. The workflow below mirrors the sequence

Keentel executes on a typical IBR collector substation; every artifact it produces is simultaneously compliance evidence.

9.1 The Asset Model

The extension organizes the plant as assets of three types. Bus assets carry voltage-only measurement. Generic assets carry voltage and current — the right model for transformers, inverters, reactors, and capacitor banks. Transmission line assets carry voltage and current plus impedance-based fault location, with line impedance parameters and restraint factors. Feeders are modeled as line assets; where a layout permits current measurement on a bus, modeling it as a generic asset captures both quantities. Line assets accept current summation from two CT sources — the mechanism that handles ring-bus and breaker-and-a-half positions where a line's current is the sum of two breaker CTs. The asset names chosen here propagate into channel names, PMU names, and event records, so the naming convention is an audit artifact: name assets after the plant's real equipment designations.

9.2 The Configuration Sequence

The end-to-end sequence: insert the Digital Fault Recorder extension into an R153+ project; set the global parameters (station and company identity — which flow into COMTRADE headers — nominal frequency, phase rotation, PMU data rate, continuous-recording retention days, fault-recording rate and record lengths with pre-trigger time); define the Axion nodes with chassis size and module layout, entering module variants and CT/PT ratios; define the substation assets and bind each to its measurement modules; configure trigger conditions per asset; map digital inputs (breakers on falling-edge triggers so a 52A dropout produces a fault record, disconnects monitored without triggering, unused points disabled); assign local monitoring outputs; and finally toggle Build DFR to true. The build step auto-generates every device object, all required settings, the IEC 61131-3 logic, a continuous recording group referencing the EtherCAT modules, and a PMU per asset — the objects that would once have been weeks of manual engineering, created consistently in minutes.

9.3 Triggers Mapped to R3 — and Beyond

Trigger Family	R3 Status	Typical IBR-Site Settings Practice
Phase over/undervoltage	Required	Per-phase and neutral elements; thresholds around 105% / 95% of nominal with ~1-cycle (16 ms) pickup as a defensible starting point, tuned to the plant's ride-through envelope
Neutral (residual) overcurrent	Required	Set above maximum standing unbalance on the collector system; coordinates with feeder ground protection
Over/underfrequency	Required	Tight brackets around nominal (e.g., 60.1 / 59.9 Hz) with deliberate pickup delay
Rate of change of frequency	Beyond the floor	±0.1 Hz/s class elements with ~1 s pickup capture frequency events and inertia-response questions

Trigger Family	R3 Status	Typical IBR-Site Settings Practice
Sequence components (V1/V2/V0, I1/I2/I0)	Beyond the floor	Enable on transformer and POI assets; negative- and zero-sequence triggers catch unbalanced events phase elements miss
Power triggers	Beyond the floor	Useful on the POI asset for output-reduction events — the exact behavior PRC-030 will ask about

9.4 Verification and In-Service

Commissioning follows the same three-layer philosophy Keentel applies to all substation communications: transport (the EtherCAT network and every module nominal), data (live-data inspection of every channel against primary injection or known system values, forced values where appropriate), and application (staged trigger tests producing real COMTRADE records that are pulled through the actual retrieval workflow and opened in the event-analysis tool). The project compiles to zero errors and zero warnings before download; after Go Online and download, the configuration runs in service independent of the engineering connection. The commissioning records — injection sheets, trigger test records, retrieved sample COMTRADE files, time-sync verification — are retained as the foundation of the R-series evidence package.

Chapter 10 — Time Architecture: Satisfying R6 With Margin

A defensible R6 design has three layers. The reference is a GNSS-disciplined substation clock. Distribution reaches the recorder as demodulated IRIG-B and/or Precision Time Protocol — on the modern RTAC platforms, PTP is supported on standard Ethernet ports, and the SEL-3390T card accepts a high-accuracy PTP input with sub-microsecond performance, then redistributes time downstream over IRIG-B and time protocols so every connected IED shares the reference. Verification is continuous: the DFR's local monitoring includes a Synchronized status derived from the presence of high-quality IRIG-B or PTP sync on the controller and on every attached AC protection module, and that status belongs on SCADA and in the alarm philosophy — because unsynchronized records discovered after an event are a loss that cannot be repaired retroactively.

Designing to microsecond-class accuracy rather than the millisecond class that event sequencing strictly requires buys two things: the plant's DDR channels are simultaneously synchrophasor-grade (each DFR asset already instantiates a PMU), and the facility is future-proofed against oscillation-analysis and wide-area monitoring use cases that arrive with the PRC-029/PRC-030 lifecycle. The time architecture drawing, clock data sheet, and sync-verification records are all Measure evidence.

Chapter 11 — Operating the Program: Retention, Retrieval, R8, and the Audit File

11.1 Retrieval as a Rehearsed Procedure

On the reference platform, every retrieval path is browser-based. Triggered fault records accumulate as COMTRADE files under the controller's event collection; continuous-recording extracts are generated on demand — operator selects start time, duration, and channels (3 kHz oscillography, PMU, digital) and the system produces a COMTRADE record for download; SOE logs and impedance fault-location results export as CSV from the file manager. The compliance procedure wraps these mechanics: who retrieves, within what internal deadline (set comfortably inside the standard's response window), in what naming discipline (COMNAME conformance is a requirement, not a style choice), delivered to whom, with what transmittal record. Run the procedure end-to-end at commissioning and annually thereafter; the rehearsal records are themselves evidence.

11.2 R8: Failure Management Is a Live Obligation

R8 starts a 90-day clock at the discovery of a recording-capability failure: restore, or initiate a Corrective Action Plan. Two program elements make R8 survivable. First, automated failure discovery: the DFR's alarm logic asserts on EtherCAT network abnormality, controller CPU burden above 75% for a sustained minute, storage below thresholds (10% or 4 GB), or memory exhaustion — and its Enabled/Ready/Recording/Synchronized/Alarm indications should be mapped to SCADA so a recording failure is a same-day alarm, not an audit-day surprise. Second, a documented discovery-to-disposition workflow: date-stamped discovery record, restoration work order or CAP initiation, and closure evidence. The watchdog behavior of the platform deserves a line in the operating procedure as well: a runtime-exception watchdog that reverts the controller to a default project is exactly the class of event that constitutes a recording-capability failure, and operations staff should know the recovery-and-report path in advance.

11.3 Security and Change Control Around the Recorder

The DFR is a cyber asset in a compliance-critical role, and the platform's native controls should be engaged rather than admired: allowlist-based execution control so only authorized applications run, role-based accounts with the factory-default credentials retired before energization, X.509 certificate management for encrypted access, syslog and network-audit reporting into the owner's monitoring, and the controller's ability to serve as an encrypted engineering-access gateway to downstream devices. Configuration changes to the recorder follow the same change-control rigor as protection settings — versioned projects, comparison between revisions, and an approval record — because an undocumented settings change that silently disabled a trigger is both a reliability failure and an evidentiary one.

11.4 The Audit-Ready Evidence Package

Assembled once and maintained, the package that makes a PRC-028 audit uneventful contains: the applicability determination; the site single-line with monitored areas and measurement points; the CT/PT schedule with ratios and data sheets; the design standard mapping each requirement to the implementing equipment and settings; the recorder configuration exports (asset definitions, trigger settings, recording rates, retention settings); time-architecture documentation and sync-verification

records; commissioning and trigger-test records with sample COMTRADE/COMNAME-conformant files; the retention and retrieval procedure with rehearsal records; the R8 discovery-and-disposition log; and dated transmittals for any data actually provided on request. Each item traces to a specific Measure. The discipline is not glamorous; it is the difference between an audit finding and an audit compliment.

Chapter 12 — Program Roadmap: Brownfield, Greenfield, and How Keentel Helps

12.1 Brownfield Strategy

For an existing fleet, the economical program runs: portfolio applicability screen → per-site gap assessment against R1–R8 (existing relays, RTUs, CT/PT inventory, time sources, communications) → interim-compliance configuration of existing capability (event-capable relays and existing controllers configured and retained now, protecting the owner under already-live retention and R8 obligations during the construction window) → standardized retrofit design (a repeatable RTAC + Axion pattern with a site-specific channel map) → prioritized rollout sequenced to the 50% and 100% milestones and to outage availability. Legacy controllers below the modern compute tier are replaced with project conversion; existing feeder relays keep their protection role and contribute FR coverage where their recording meets the specifications.

12.2 Greenfield Strategy

On a new facility, the cheapest disturbance monitoring program is the one specified before procurement closes: dedicated measurement CT cores in the substation package; unit-level SER capability written into the inverter OEM scope during factory coordination — new units get no capability relief; the DFR channel math sizing controller and storage; monitoring operational and commissioned at COD because the new-resource schedule effectively requires energizing compliant; and the evidence package assembled as construction documentation rather than reconstructed afterward. A facility designed this way satisfies PRC-028 as a byproduct of good substation engineering — and arrives pre-instrumented for the PRC-029 ride-through demonstrations and PRC-030 analyses that follow.

12.3 The One-Platform Dividend

The architecture in this book is deliberately not a single-purpose recorder. The same controller that discharges PRC-028 carries the plant RTU and SCADA concentration, protocol conversion across DNP3, IEC 61850, Modbus, and IEC 60870; the HTML5 HMI; secure engineering access to every IED; PMUs for wide-area visibility; and the IEC 61131 logic engine for plant automation. Owners who treat the compliance project as the modernization project — one platform, one software environment across every RTAC model, one evidence discipline — recover much of the compliance cost in operating-and-maintenance simplification.

How Keentel Helps

Keentel Engineering delivers PRC-028 compliance as turnkey engineering: portfolio applicability screening and per-site gap assessments against R1–R8; disturbance monitoring equipment specification and procurement support; detailed design of the RTAC + Axion DFR architecture including channel maps, storage sizing, time synchronization, and network design; interim-compliance configuration of existing relays and controllers; DFR extension configuration, commissioning, and three-layer verification; and audit-ready documentation packages mapping every requirement to its evidence.

Because the same standards lifecycle continues into PRC-029 ride-through demonstration and PRC-030 disturbance analysis — and because Keentel's practice spans grid interconnection, EMT modeling, protection, and NERC compliance — the disturbance monitoring program we build is designed for everything the data will be asked to prove. Contact us at 813-389-7871 or contact@keentelengineering.com.

Appendix A — Requirement-to-Capability Mapping

Req.	Implementing Capability in the Reference Architecture	Primary Evidence
R1 (SER)	RTAC SOE infrastructure with 1 ms stamping; Axion digital-input modules for breaker/disconnect status; inverter fault codes, alarms, and ride-through status integrated over plant protocols	SER point list; SOE log samples; OEM data-interface records
R2 (FR locations/ quantities)	SEL-2245-42 AC protection modules on main transformers, collector feeders, reactive devices; two-source current summation for ring/breaker-and-a-half positions	SLD with measurement points; module/channel map; CT/PT schedule
R3 (FR triggers)	Per-asset voltage, residual overcurrent, and frequency trigger elements; sequence-component, ROCOF, and power triggers beyond the floor	Trigger settings export; staged trigger-test records
R4 (DDR quantities)	Continuous recording of V, I, P, Q, frequency per asset; auto-generated PMU per asset	CRG configuration; channel lists
R5 (DDR performance)	3,000 sps continuous input ($\geq 3\times$ the 960 sps floor); ≥ 60 fps output; 24 kHz / 24-bit triggered recording	Recording-rate settings; manufacturer specifications
R6 (time sync)	GNSS clock; IRIG-B and PTP distribution; sub-microsecond high-accuracy PTP option; continuous Synchronized status supervision	Time-architecture drawing; sync-verification records

Req.	Implementing Capability in the Reference Architecture	Primary Evidence
R7 (formats/retention)	COMTRADE fault records and on-demand CRG extracts; COMNAME-conformant naming; SSD retention sized 30+ days at full rate; browser retrieval workflow	Retention calculation; retrieval procedure and rehearsal records; sample files
R8 (failure management)	DFR alarm logic (EtherCAT abnormal, CPU, storage, memory thresholds) mapped to SCADA; discovery-to-disposition procedure	Alarm configuration; discovery log; restore/CAP records

Appendix B — Glossary

CRG — Continuous Recording Group — the RTAC's continuous-recording construct enabling on-demand COMTRADE extraction from a rolling high-rate archive.

DDR — Dynamic Disturbance Recording — continuous recording of phasor-domain quantities (V, I, P, Q, f) describing system dynamic behavior.

DFR — Digital Fault Recorder — the integrated recording function; on this platform, an ACCELERATOR RTAC extension that builds the complete recorder configuration.

EtherCAT — The deterministic industrial Ethernet fieldbus connecting the RTAC to Axion I/O modules; dedicated port, non-routable, direct connections only.

FR — Fault Recording — triggered, high-speed point-on-wave capture of voltages and currents around a disturbance.

IBR — Inverter-Based Resource — solar PV, Type 3/4 wind, battery storage, HVDC-connected and hybrid facilities interfacing through power electronics.

PMU — Phasor Measurement Unit — synchrophasor source; the DFR extension auto-generates one per configured asset.

POI — Point of Interconnection — the boundary at which the facility connects to the transmission system; primary DDR location.

PRCTPT — The Axion AC protection module class (SEL-2245-42) terminating CT/PT secondaries for recording and measurement.

SER / SOE — Sequence of Events Recording — time-stamped discrete event logging; SER is the standard's term, SOE the platform's.

About Keentel Engineering

Keentel Engineering is a power systems and grid interconnection consulting firm headquartered in Tampa, Florida, with offices in Austin, Sacramento, and Baltimore. Service lines include point-of-interconnection and grid interconnection engineering, power system studies, substation and transmission design, EMT modeling and power quality, renewables and battery energy storage engineering, NERC compliance, and owner's engineer services. Florida Engineering Firm Registry No. 36853.

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