

INESCTEC

success story

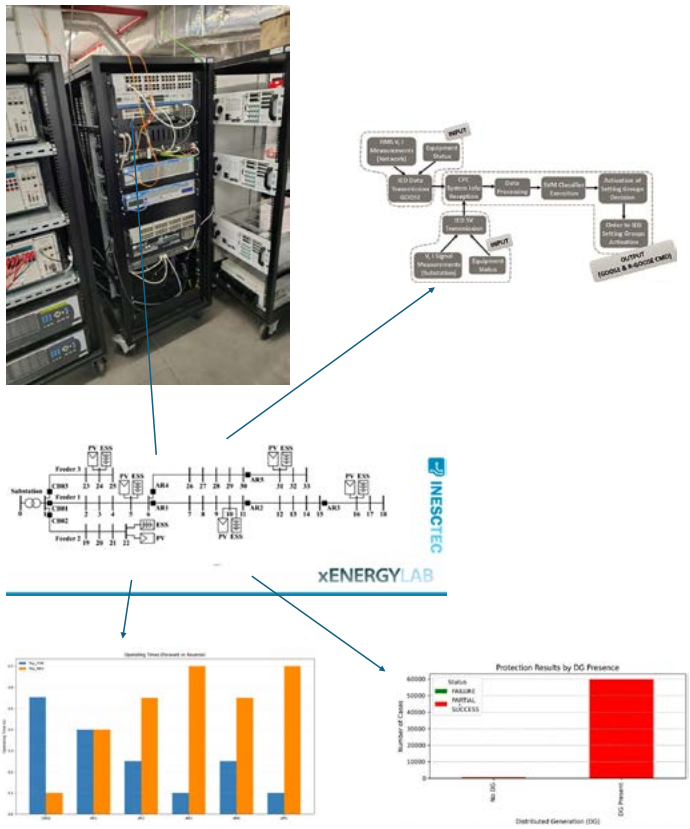
A Digital Substation in-the-Loop (DSiL) at INESCTEC

Accelerating advanced grid protection and automation with OPAL-RT

opal-rt.com

OPAL-RT TECHNOLOGIES

Setting the stage for innovation



The Institute for Systems and Computer Engineering, Technology and Science (INESC TEC) is a leading R&D institution in Portugal with international reach, focused on scientific research and technological development, technology transfer, advanced consulting and training, and pre-incubation of new technology-based companies.

The Centre for Power and Energy Systems (CPES), one of INESC TEC's 13 R&D centres, works in Power and Energy Systems and is a world reference in large-scale integration of Distributed Energy Resources.

Part of CPES activity takes place in the x-Energy Lab – Laboratory of Smart Grids and Electric Vehicles – which supports validation in real environments. It focuses on testing and validating innovative technologies for economy decarbonization, with emphasis on electric power grid integration. In this context, x-Energy Lab has maintained a decade-long strategic collaboration with OPAL-RT Technologies, a global reference in real-time simulators, continuously developing a PHIL/HIL test setup based on OPAL-RT systems that is now a core testing and validation platform.

The most recent development capitalizing on OPAL-RT's real-time simulation solutions is the Digital Substation in-the-Loop (DSiL) platform, a state-of-the-art testing and validation infrastructure that enables safe, repeatable, and comprehensive validation of advanced Protection, Automation and Control (PAC) applications. With DSiL, a wide spectrum of functionalities and interoperability scenarios can be evaluated in depth:

- Comprehensive IEC 61850 multi-protocol scenarios (GOOSE, Sampled Values, MMS),
- Validation of algorithmic performance for protection, automation, and control under realistic and stressed network conditions,
- Assessment of timing response across synchronized physical and virtual IEDs,
- Experimentation with innovative protection philosophies, grid automation strategies, and digital substations apps needed for the energy transition.

By supporting safe and scalable laboratory-based studies long before any field roll-out, DSiL allows INESC TEC and partners to test, evidence, and iterate innovative solutions in a controlled and fully instrumented environment, helping to bridge the gap between R&D and operational deployment in next-generation power systems.

Mitigating the growing complexity of modern power grids

THE CHALLENGE

Modern power grids face unprecedented challenges: large-scale integration of inverter-based resources (IBRs), proliferation of distributed intelligent devices, and tighter resilience requirements against telecom and cyber disruptions. In this context, developing and validating advanced Protection, Automation & Control (PAC) becomes significantly more complex.

Traditional approaches are not enough. Purely software-based simulations are efficient for early design, but they lack protocol- and timing-level realism to validate multi-vendor interoperability and the behavior of physical hardware under sub-millisecond constraints. Conversely, field tests are costly, time-consuming and risky, and rarely allow safe replication of extreme or fault conditions.

This gap called for a platform that faithfully replicates a digital substation: including IEC 61850 Process/Station Bus (GOOSE, Sampled Values, MMS), precision time sync (IEEE 1588 PTP), gigabit ethernet network, while integrating physical and virtual IEDs under a common time base. For INESC TEC (as for the wider industry), it became imperative to enable safe, repeatable, and scalable laboratorial campaigns for:

1

Interoperability under realistic network timing and load

2

Deterministic performance assessment with hardware-timestamped evidences

3

Development of advanced protection and control logics

4

Thorough validation and pre-deployment de-risking of new applications

INESC TEC's Digital Substation in-the-Loop (DSiL) leveraging OPAL-RT

THE SOLUTION

In response to these challenges, INESC TEC is developing the Digital Substation in-the-Loop (DSiL) platform using OPAL-RT's solution as the technological provider. DSiL combines high-fidelity real-time EMT simulation with physical hardware-in-the-loop and a multi-vendor IEC 61850 communication environment, creating a rigorous and versatile ecosystem to design, test, and validate next-generation PAC functions in the lab with field-representative level of realism.

Key components

- **Real-time simulator:** OPAL-RT OP5707XG, running EMT models with 125 µs time step for the HV/MV substation and feeders.
- **Software stack:** RT-LAB and HYPERSIM for real-time execution and model management, plus Python scripting for automated campaigns.
- **Physical & virtual IEDs:** Commercial relays and controllers (hardware and software/container versions) synchronized to a common IEEE 1588 PTP time base.
- **IEC 61850 lab communications:** Process Bus with GOOSE and Sampled Values from the real-time model, and Station Bus with MMS reports/controls in a SCADA-like application driven by the OPAL-based simulation.
- **Analog front-end amplifiers:** Voltage and current amplifiers interfacing simulated quantities to physical IED I/O, enabling closed-loop behavior.
- **Evidence & repeatability:** Real-time events and scenario metadata stored in a structured database, enabling advanced application-level development and studies.

What this enables

Deterministic, repeatable campaigns at scale under a unified IEEE 1588 PTP timing domain, with auditable evidence for every test condition.

Multi-vendor IEC 61850 interoperability (GOOSE, SV, MMS) on a common EMT and time base, tailored for validating advanced protection and control schemes in a field-representative laboratory framework.

Driving faster, safer validation

BENEFITS AND RESULTS

The deployment of the DSiL platform at INESC TEC has yielded clear, practical, and measurable benefits for PAC development and pre-deployment assurance across the institute's R&D programs and collaborative projects.

A side-by-side comparison is provided in Table 1 to position DSiL against software-only and field testing.

Comparison of testing approaches with DSiL

CHARACTERISTIC	SOFTWARE ONLY	DSIL (INESC TEC)	FIELD TESTING
Hardware Realism	★★ Low	★★★★ Very high	★★★★★ Highest
Cost	★ Very low	★★★ Medium	★★★★ Very high
Safety	★★★★ Very high	★★★ High	★★ Low
Reproducibility	★★★ High	★★★★ Very high	★ Very low
Extreme scenarios evaluation level	★★★ Medium	★★★★★ Excellent	★ Difficult
Communication testing	★ Limited	★★★★★ Excellent	★★★★ Good
Multi-vendor testing	★★★★ Good	★★★★★ Excellent	★ Limited
Development speed	★★★★ Very fast	★★★ Fast	★ Very slow
Scalability	★★★★★ Excellent	★★★★★ Excellent	★ Difficult

To make these benefits concrete and translate comparative features into engineering value, we highlight the evidence-based validation of INESC TEC's Adaptive Protection Scheme (APS) carried out using the DSiL platform. This case study demonstrates, in tangible terms, how DSiL enables the important, repeatable, and protocol-authentic testing required to advance state-of-the-art PAC solutions before they reach operational deployment.

Performance & robustness of an adaptive protection scheme

INTEGRATED VALIDATION

The DSiL platform was crucial for rigorously testing and validating the developed Adaptive Protection Scheme (APS), a core advanced application running a substation centralized control unit. The APS uses a unified framework combining Artificial Intelligence (AI) and optimization techniques to dynamically adjust directional overcurrent protection settings (ANSI 67/50) based on real-time network conditions.

Realistic Digital Substation Testing Environment - APS

The APS was validated in a field-representative setup:

- OP5707XG real-time simulator running detailed EMT models
- Full IEC 61850 process/station bus integration (GOOSE/SV/MMS)
- IEEE 1588 PTP time alignment
- Physical and virtual IEDs operating in the same domain

This mirrors the physical and communication architecture of a modern substation, ensuring results translate directly to operational contexts.

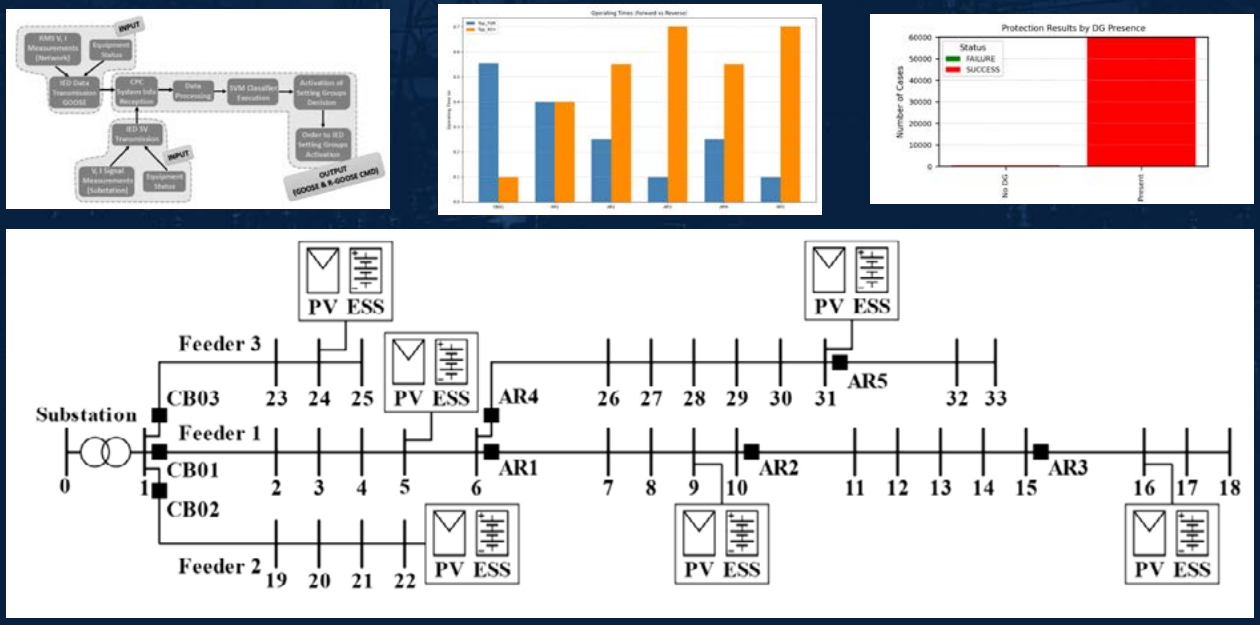


Figure 2 : (Left) APS functional architecture showing GOOSE input processing, ML-based state classification, and setting group activation logic. (Center) Operating time analysis under forward and reverse scenarios. (Right) Protection coordination results demonstrating substantial improvement in fault clearance success under varying DG presence. (Bottom) IEEE 33-bus complete distribution system model implemented in DSiL Setup.

Integrated, field-representative validation

SCALE, SELECTIVITY, SPEED, AND ROBUSTNESS

- Scenario scale: APS was tested on an adapted IEEE 33-bus system, with 1,210 operating scenarios and 60,000+ fault scenarios studied offline, and brought online into deterministic HIL campaigns (an evidence base not practical in field tests).
- This massive scenario set provides a statistically robust basis for coordination and settings evaluation, with deterministic repeatability.
- The APS was exercised on an adapted HIL model of the IEEE 33-bus system, with 1,210 operating scenarios and over 60,000 short-circuit/fault scenarios. This significant scope, brought to real-time HIL validation, allows a level of robust, repeatable, and statistically significant evidence hardly attainable in field trials.
- Protection selectivity and coordination were quantified by comparing with utility baselines: traditional approaches resulted in >35% miscoordination under DER variability, while the APS achieved an overall “broad” clearance (strict primary+backup criterion for protection) of 99.9%, for all 60,000+ scenarios.

Why it matters

These results offer immediate, standard-validated evidence of an APS application performance under realistic power system scenarios, what is demanded by today’s grid modernization and utility requirements. The setup implementation and tests realized captured not just static benchmarks, but truly dynamic behaviors, sub-cycle protection response, and seamless operation in a multi-vendor IEC 61850 digital substation environment. This reliability and realism achievable thanks to the implementation of a high-fidelity setup combining real-time HIL simulation based on OPAL-RT, full digital substation architecture integration, and repeatable laboratory campaigns at scale.

The results obtained through the HIL validation campaigns leveraging OPAL-RT’s real-time environment demonstrate significant, measurable improvements over traditional protection methods, in summary:

METRIC	RESULT	DESCRIPTION & SOURCE
Failure Rate Reduction (vs. Traditional Schemes)	Reduced from >35% to 0.67%	Traditional schemes showed coordination problems in over 35% of simulated base scenarios. The proposed APS reduced the failure rate (blinding/miscoordination) to only 0.67%.
Fault Clearance Effectiveness (Broad)	99.9% Cleared	Across extensive short-circuit events analysis (spanning varied DG levels and fault-resistance regimes), the scheme achieved 99.9% clearance.
ML Classification Accuracy (Offline Training)	99.8% Accuracy	The trained ML classifier, used to map grid states to protection setting groups, was trained and tested achieving 99.8% accuracy across 1,210 operational scenarios.
Real-Time Decision Speed (Online Phase)	Average 0.6 ms	HIL validation demonstrated that the SVM-based classification process (which determines the appropriate setting group) achieved an average decision time of approximately 0.6 ms.
HIL Latency Verified Performance	Under 1 ms	HIL tests confirmed that the overall classification and setting activation process was completed in under 1 ms.



Ready to innovate?

For over two decades, OPAL-RT TECHNOLOGIES has been a global leader in real-time simulation and hardware-in-the-loop (HIL) testing. Since 1997, OPAL-RT has empowered engineers and researchers with accessible, innovative, and customized simulation technology—bridging the gap between modeling and real-world applications. By leveraging high-performance computing, OPAL-RT accelerates the development of advanced solutions in energy, automotive, aerospace, and beyond. With our ISO 9001:2015 certification and a strong commitment to sustainable development, we're not just developing technology—we're building a better future, together.

Explore our other success stories

Discover how industry leaders achieve engineering excellence with OPAL-RT's solutions.

OPAL-RT TECHNOLOGIES

opal-rt.com