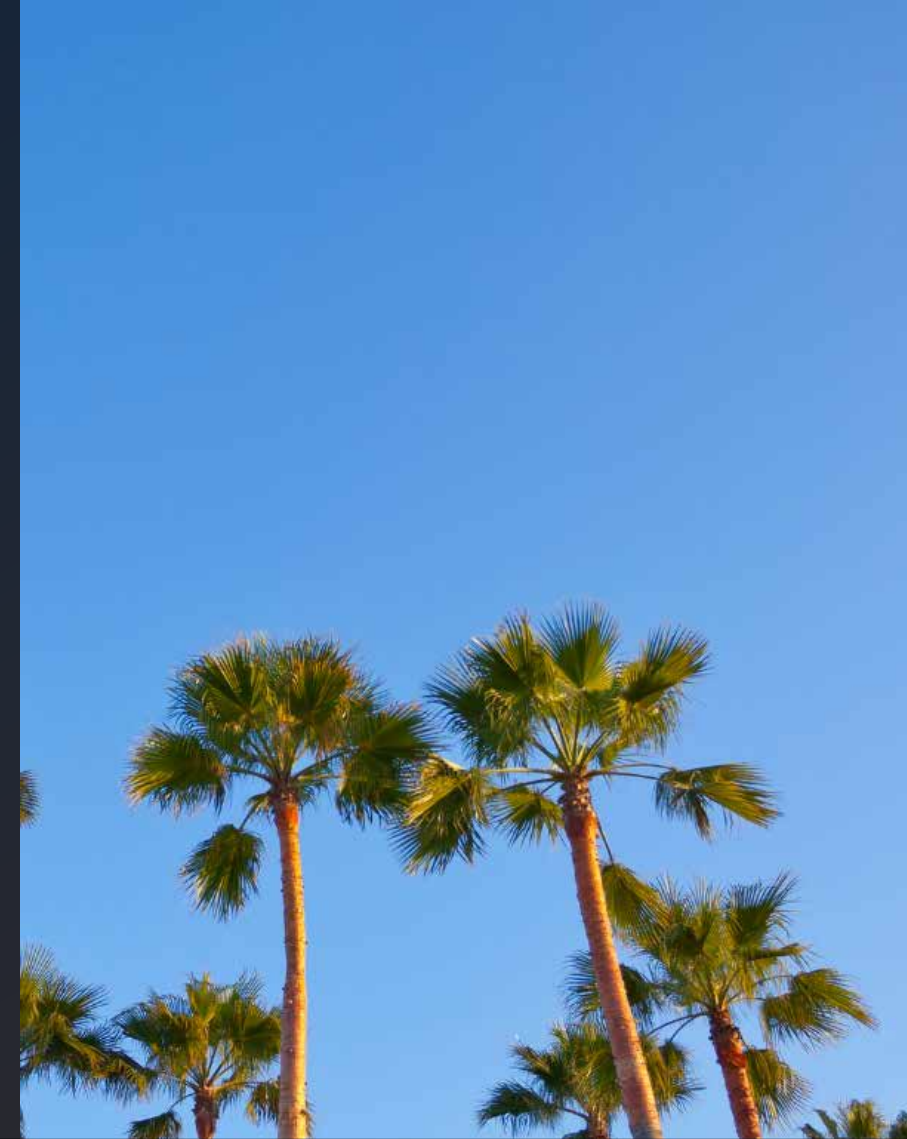


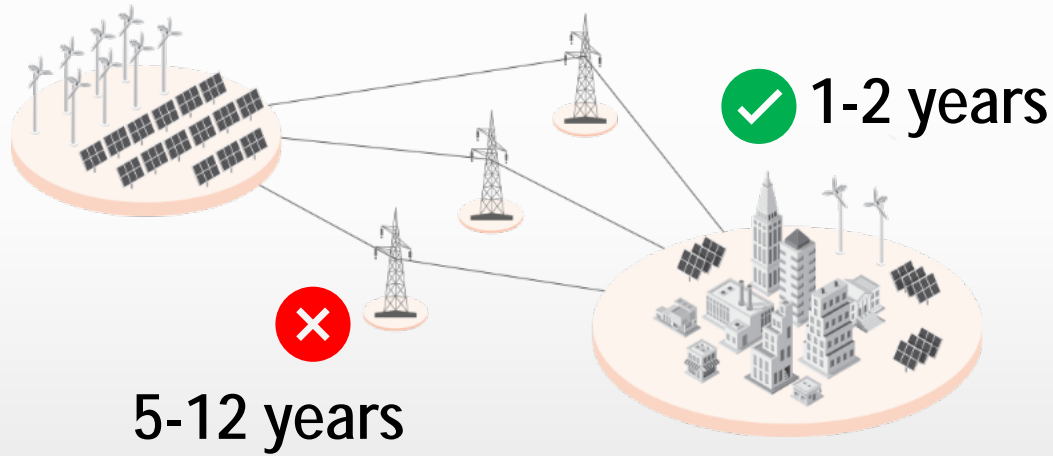
Automated CHIL/PHIL Simulations of Modular SSSC Using RTDS: Python-Driven Fault Sweeps, GTNET Integration, and Dynamic Relay Relocation

- u ROHIT JINSIWALE
- u Smart Wires, Inc.



The grid cannot keep up with the pace of change

✓ 2-3 years

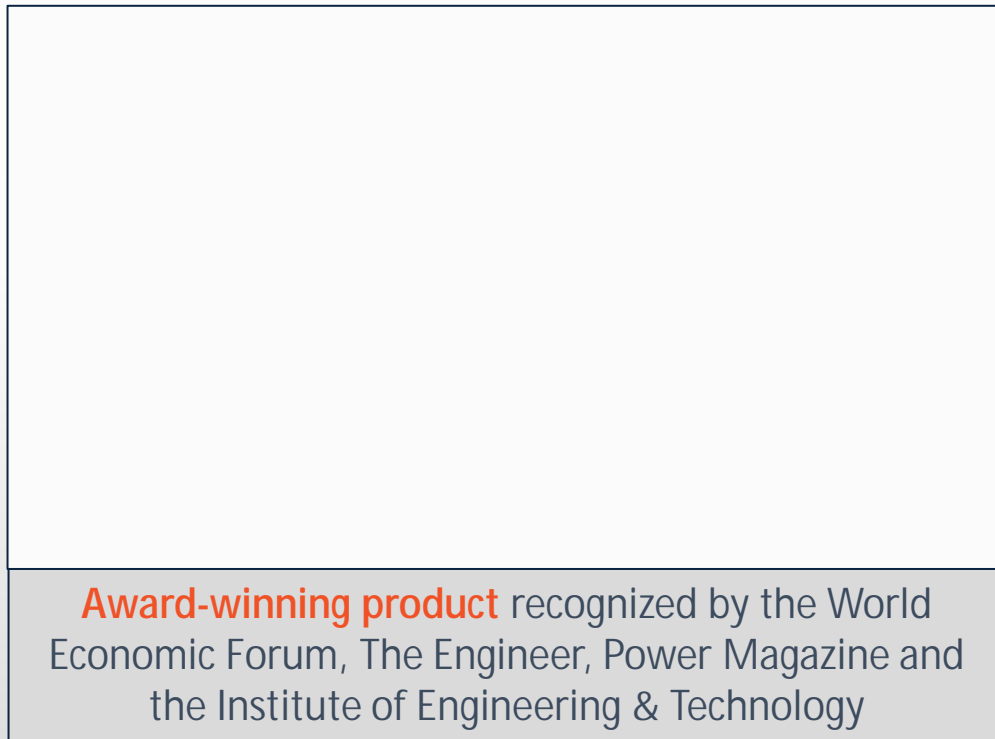


- Increased demand (data centers, electrification, AI)
- Growing access queue for generation connection
- Pressure for affordability without compromising on reliability

Need faster solutions that help unlock grid capacity to maintain reliability

SmartValve

SmartValve is an innovative, **digital power flow control technology** that quickly unlocks network capacity by pushing power off overloaded lines or pulling power onto underutilized lines. SmartValve revolutionizes the power flow control landscape with a transformerless device that offers flexible installation and control. Utilities use SmartValve to integrate renewables, resolve congestion, lower costs and improve reliability and resilience.



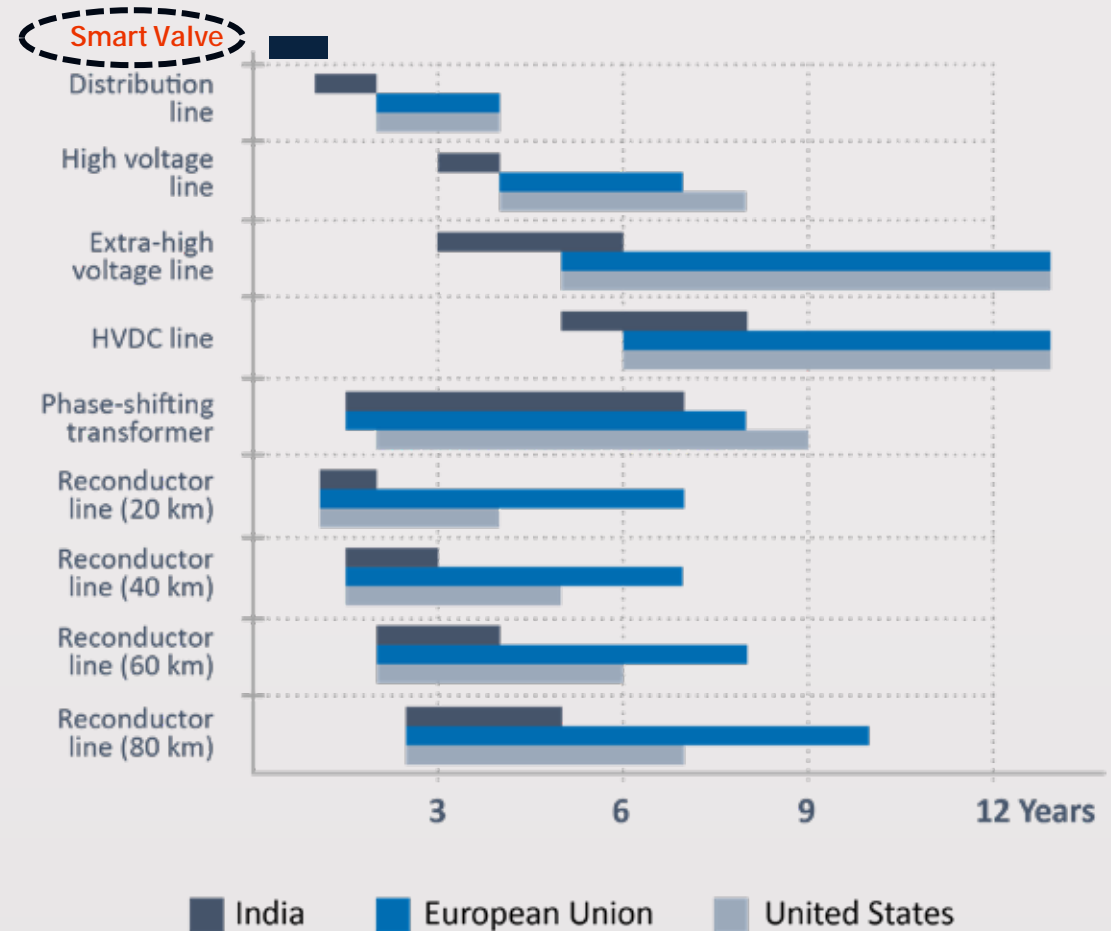
Key features:

- Transformerless, modular Static Synchronous Series Compensator (SSSC) that employs VSC technology
- Integrated fast-acting bypass
- High reliability and redundancy
- Voltage agnostic and redeployable
- Modular design enables flexible and scalable installations
- Various control modes available
- Quick to deliver and deploy
- Multiple network applications including power flow control and dynamic services

Solve critical grid challenges

1. Utilize capacity on the existing grid earlier
2. Resolve urgent or uncertain needs
3. Support outage management and extend outage windows
4. Extend asset life of existing equipment
5. Use new infrastructure more efficiently

Decrease project timeline to under 2 years

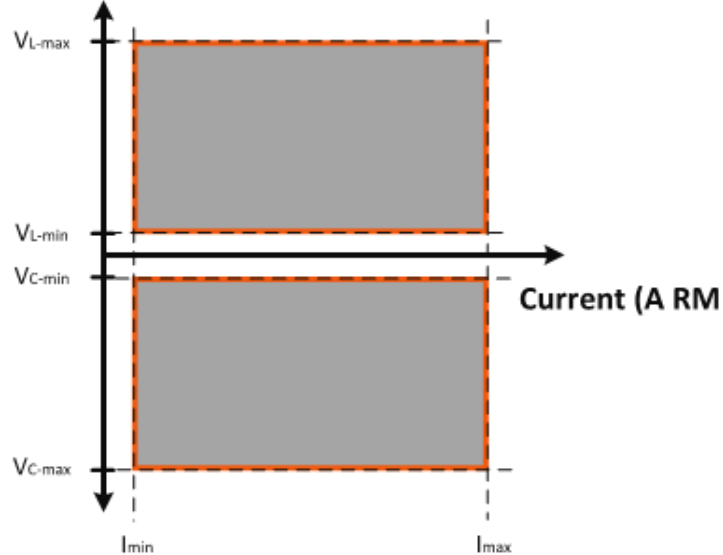


SmartValve Operation

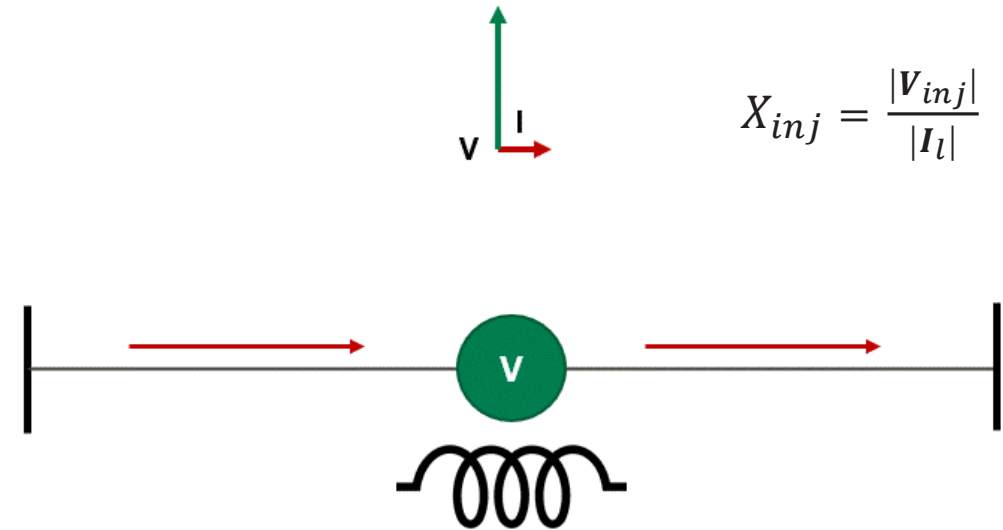
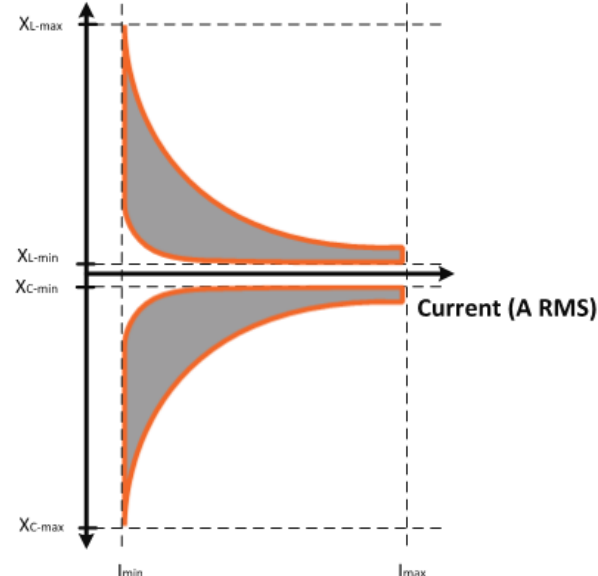
- ✓ **SmartValve** injects a voltage with a 90° phase shift with respect to the line current resulting in a capacitive ($- \Omega$ s) or inductive ($+ \Omega$ s) equivalent reactance.
- ✓ The curve shows the achievable reactance range with respect to line current that the device can inject.
- ✓ Operational limits of each deployment depend on the type and number of devices installed.



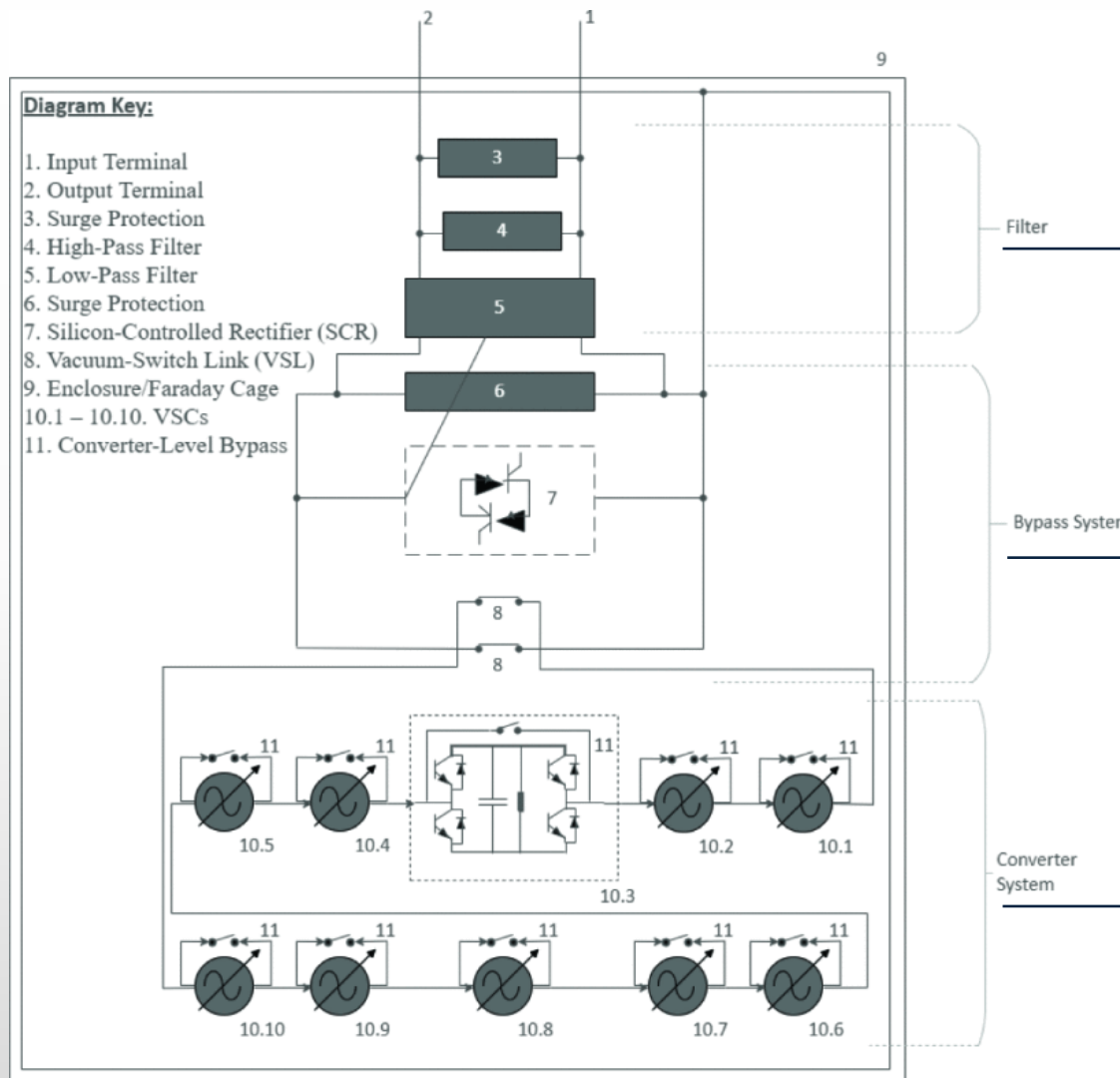
Injected Voltage (V RMS)



Effective Reactance (Ω)



SmartValve Schematic



The SmartValve harvests all power from the line to operate the control and communication circuits and senses line current for control and fault-protection purposes.

Filter Capabilities

- The high-pass filter allows the passage of high frequency transients.
- The low-pass filters allow the power line frequency to enter the SmartValve.

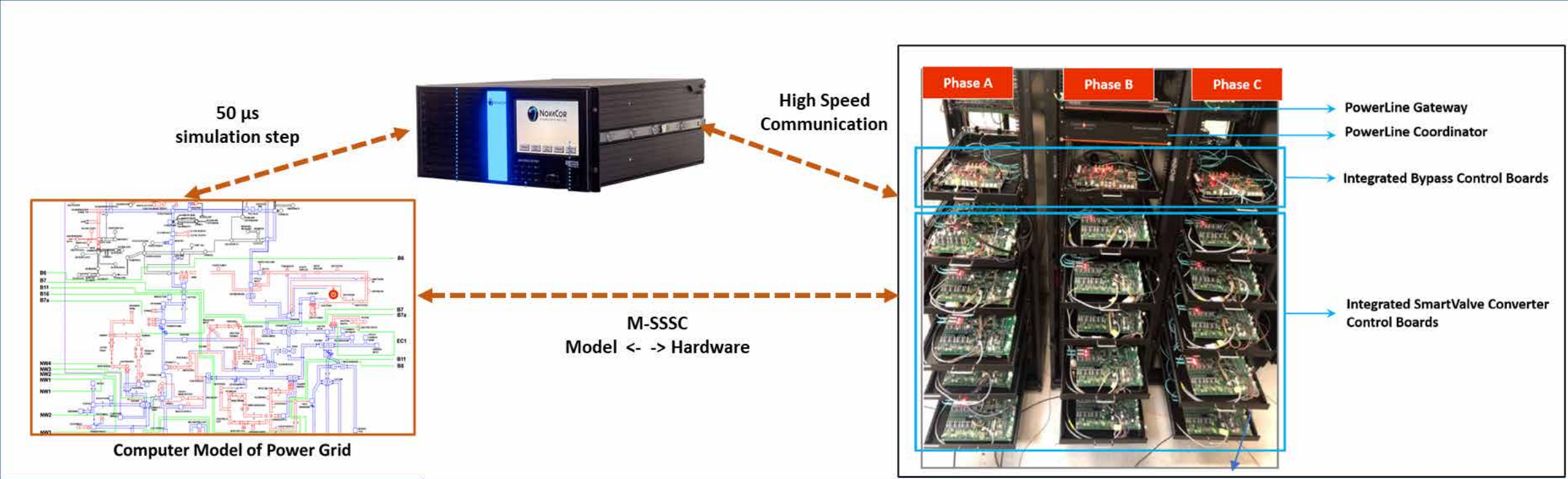
Bypass Capabilities

- The vacuum switch links (VSLs) primarily conduct current during steady-state conditions.
- The silicon-controlled rectifiers (SCRs) primarily conduct current during grid faults (e.g. a fault on the line connected to the SmartValve).

Injection Capabilities

- The core components of each Voltage-Sourced Converter (VSC) are four semiconductor switches and the DC Link capacitor for achieving series voltage injection

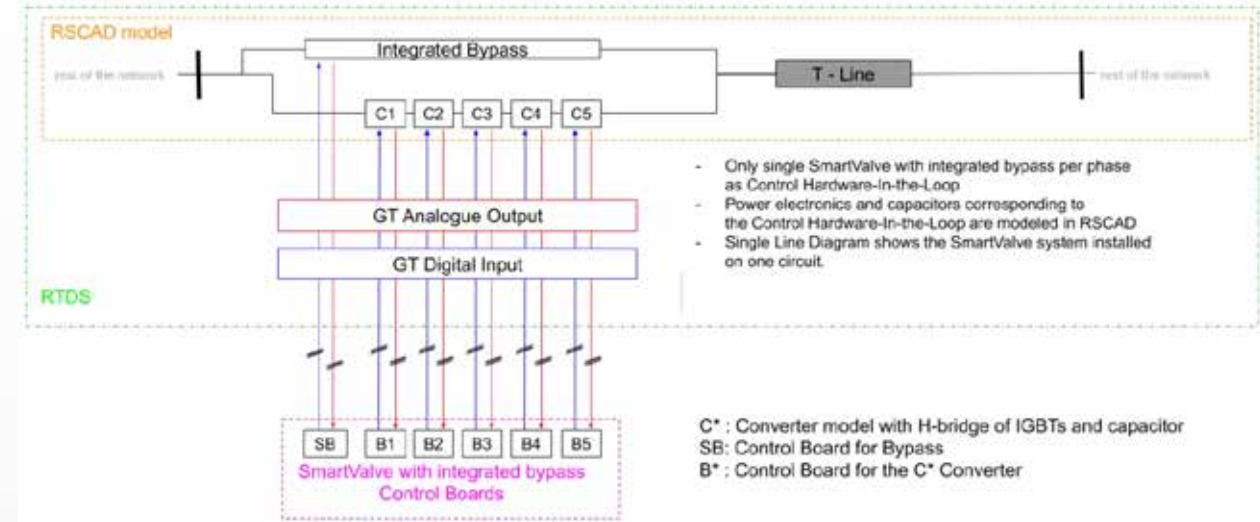
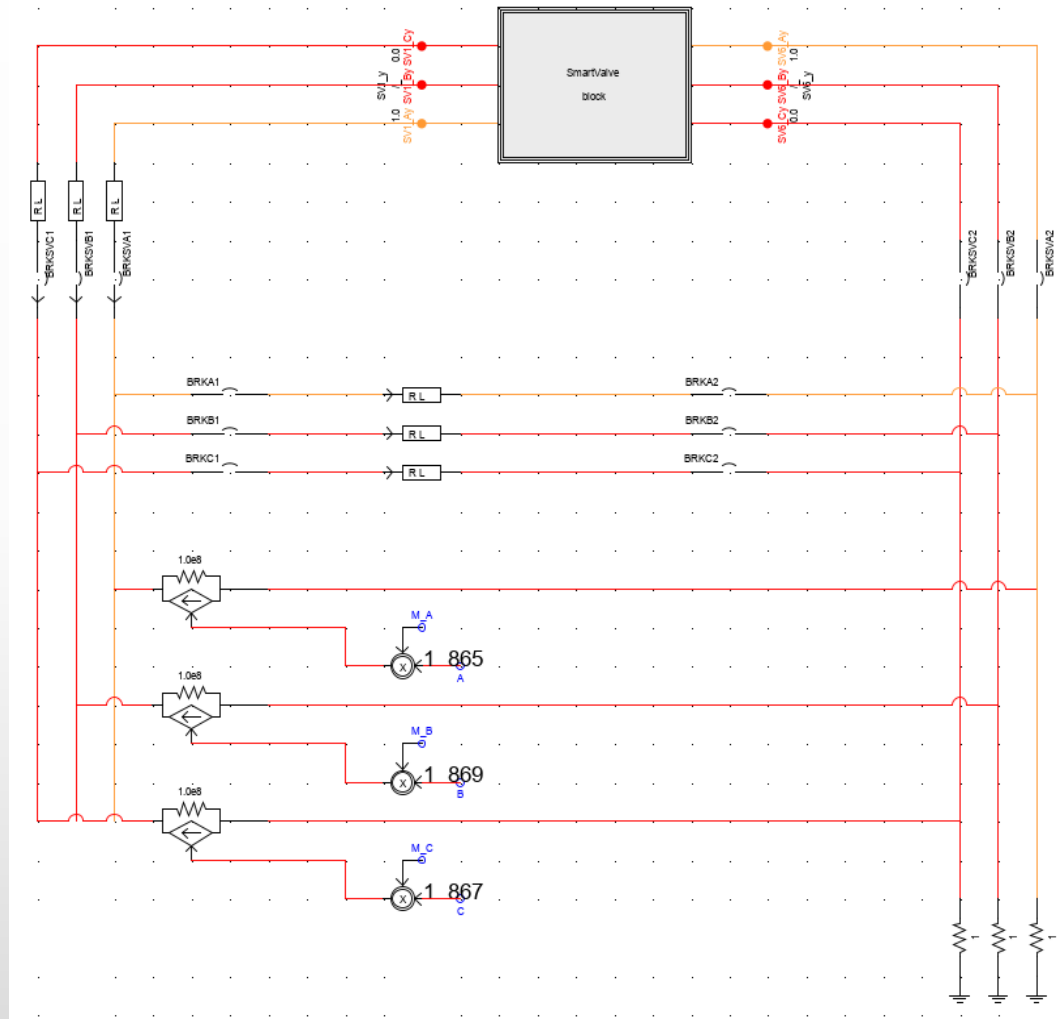
Hardware-in-the-loop



Abilities

- Ø Functional Performance Studies
- Ø Firmware Validation

Functional Performance Test (FPT)

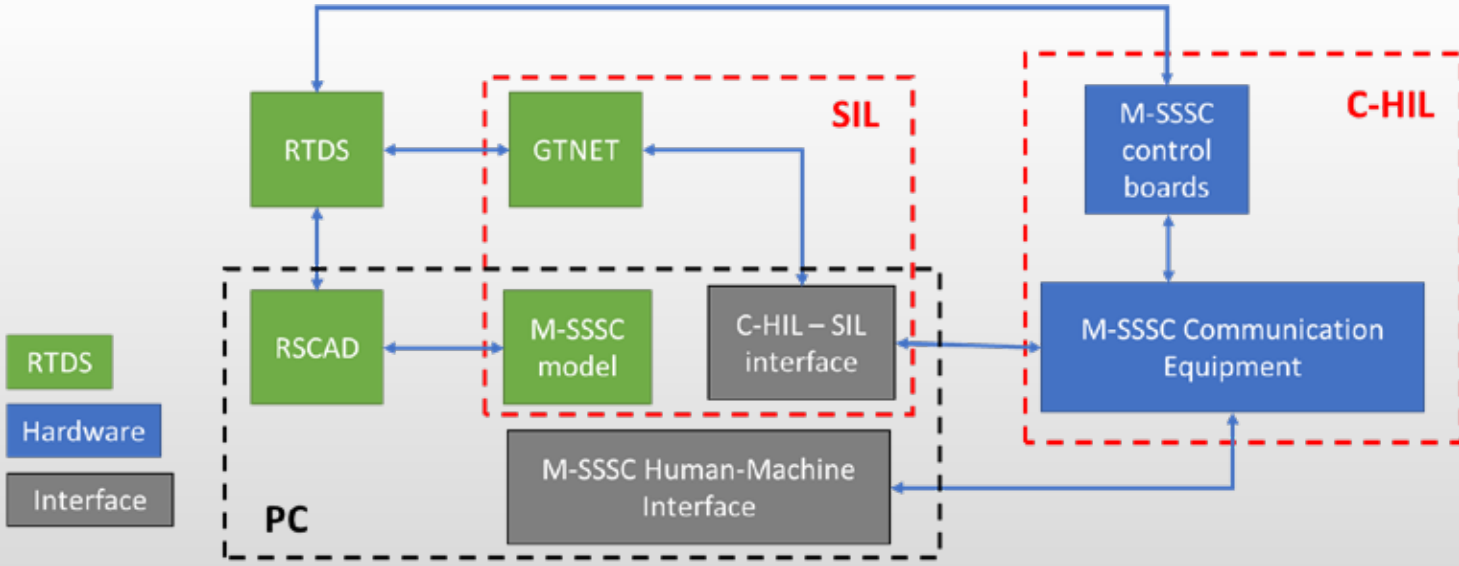
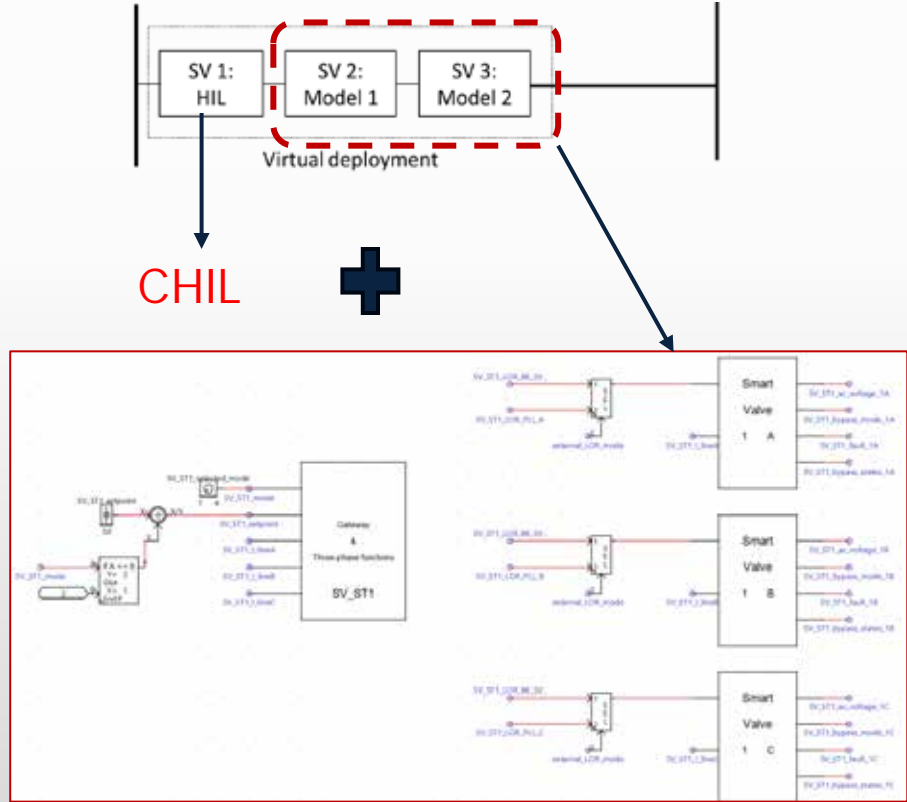


1. Demonstrate basic functional behavior
2. Validate firmware and settings
3. Validate steady state operation, changes in operating setpoints and transient conditions
4. Validate end-to-end connectivity with SCADA/EMS

Hardware-in-the-loop + Software-in-the-loop

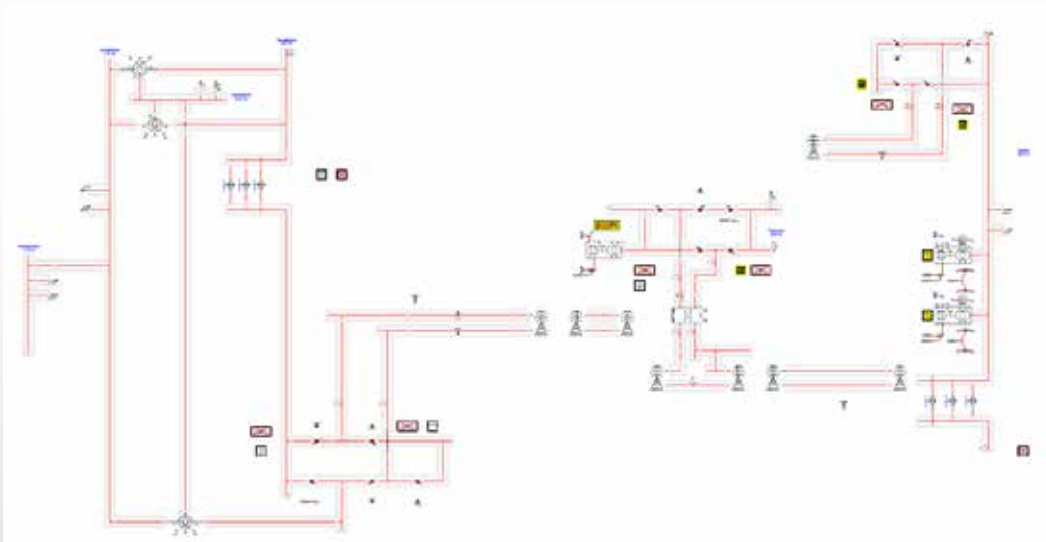
To represent an M-SSSC system with multiple devices connected in series, one M-SSSC is studied with C-HIL, and the remaining M-SSSCs are represented as RSCAD models in a Software-In-Loop (SIL) array.

- Python scripts and the GTNET care enable the same coordinator to:
- Ø Send setpoints to real and virtual devices
 - Ø Coordinate multiple devices using the same protocols



Hardware-in-the-loop + Software-in-the-loop

Harmonic Performance Tests (HPT)



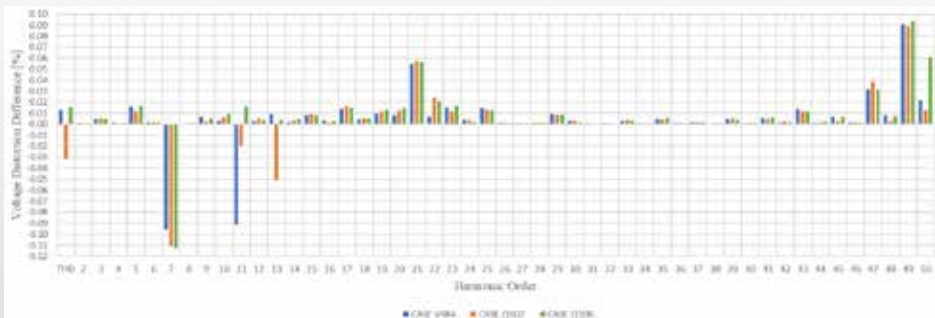
- **Configuration:** C-HIL + SIL
- **Description:** The HPT system includes a scaled-down representation of the customer network ring with frequency-dependent transmission line models and equivalent Foster-Cauer analog circuits from the surrounding network.
- **Goal:** HPT validates the harmonic emissions of the M-SSSC and its response to the background harmonics of the system. The tests use the C-HIL+SIL configuration and monitor the system behavior for a certain range of harmonics measured in the real system.

Hardware-in-the-loop + Software-in-the-loop

Harmonic Performance Tests (HPT) - Results



Comparison of C-HIL vs SIL voltage waveforms

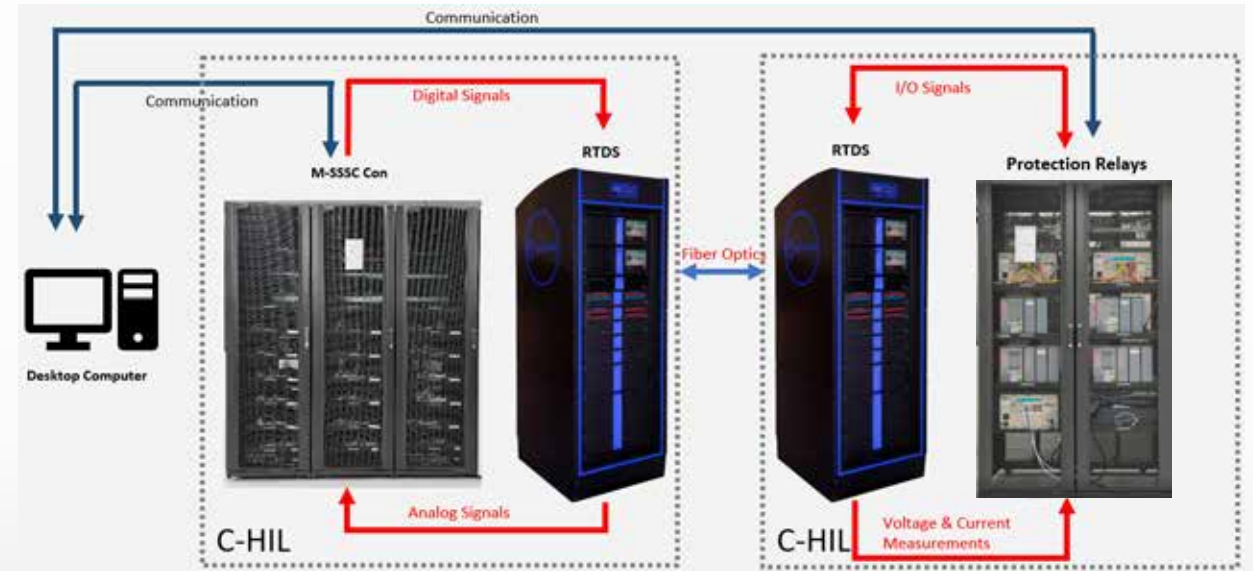
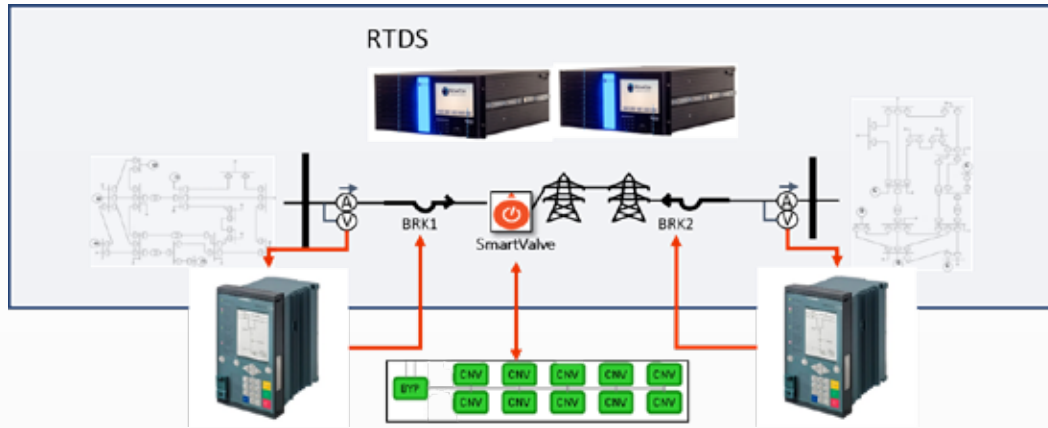


Voltage Distortion Percent Change After M-SSSC

Analysis and discussion:

- The HPT tests confirmed that the algorithms implemented to optimize the converters' duty cycles helped keep the incremental harmonics within the limits allowed for the design.
- The results also showed a good performance of the M-SSSC control system facing real background harmonic conditions. The M-SSSC injects quadrature voltage to its fundamental component for all considered cases.

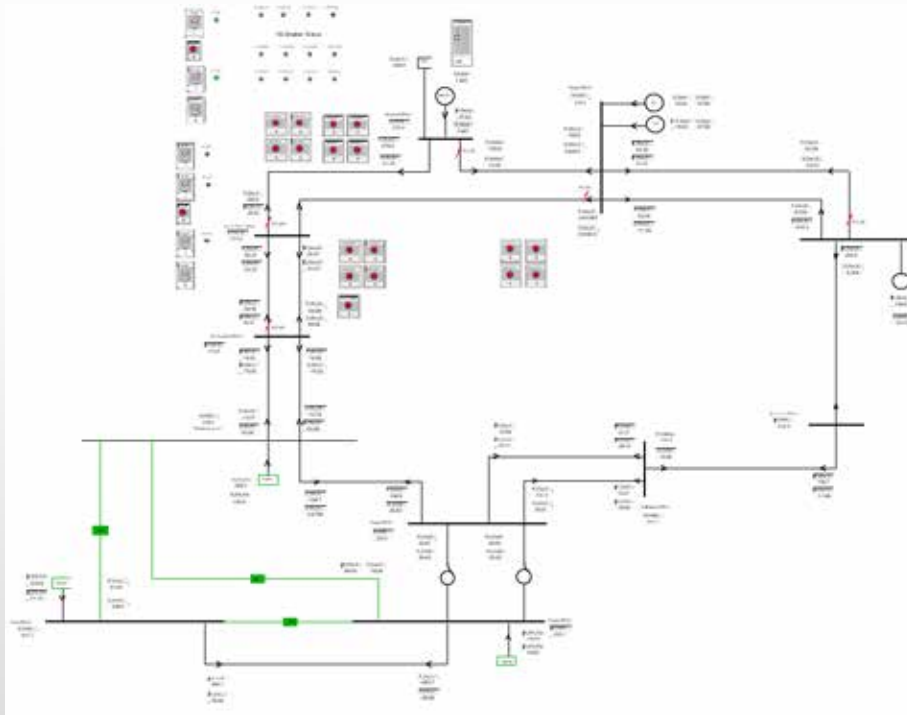
Hardware-in-the-loop + Software-in-the-loop + Protection-in-the-loop



- The RTDS on the right connects to the relays and amplifiers that interact with the RSCAD simulation.
- RTDS on the left connects to the C-HIL configuration and transmits the analog signals from the ongoing simulation to the M-SSSC control boards, which feed the device's digital outputs back to the simulation in the RSCAD.

Dynamic Performance Study (DPS)

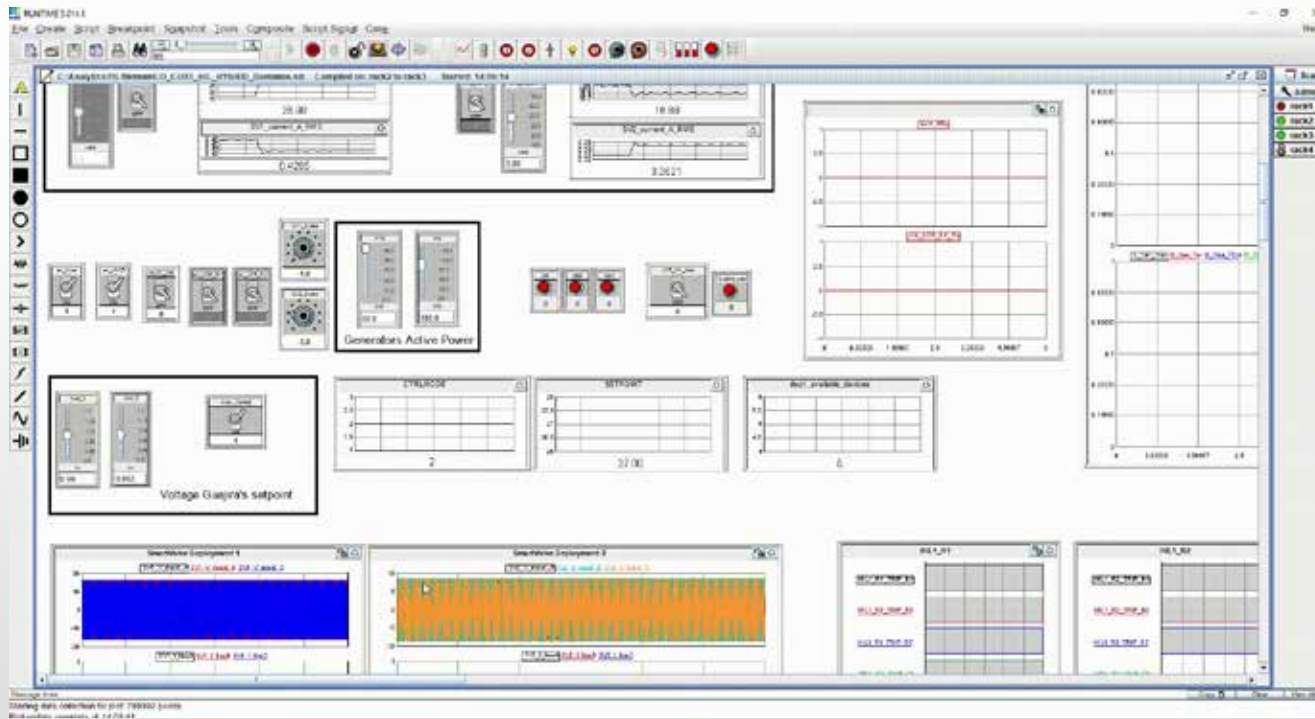
Dynamic Performance Study (DPS)



- Configuration: C-HIL + SIL + PIL
- **Description:** The project's area of influence is modeled within the RTDS. The accuracy of the network model was tested against load flow results and dynamic simulations using the National Interconnected System database.
- **Goal:** DPT tests use the C-HIL+SIL+PIL configuration to validate the M-SSSC and protection scheme response to realistic and critical system failures.

Dynamic Performance Study (Validation)

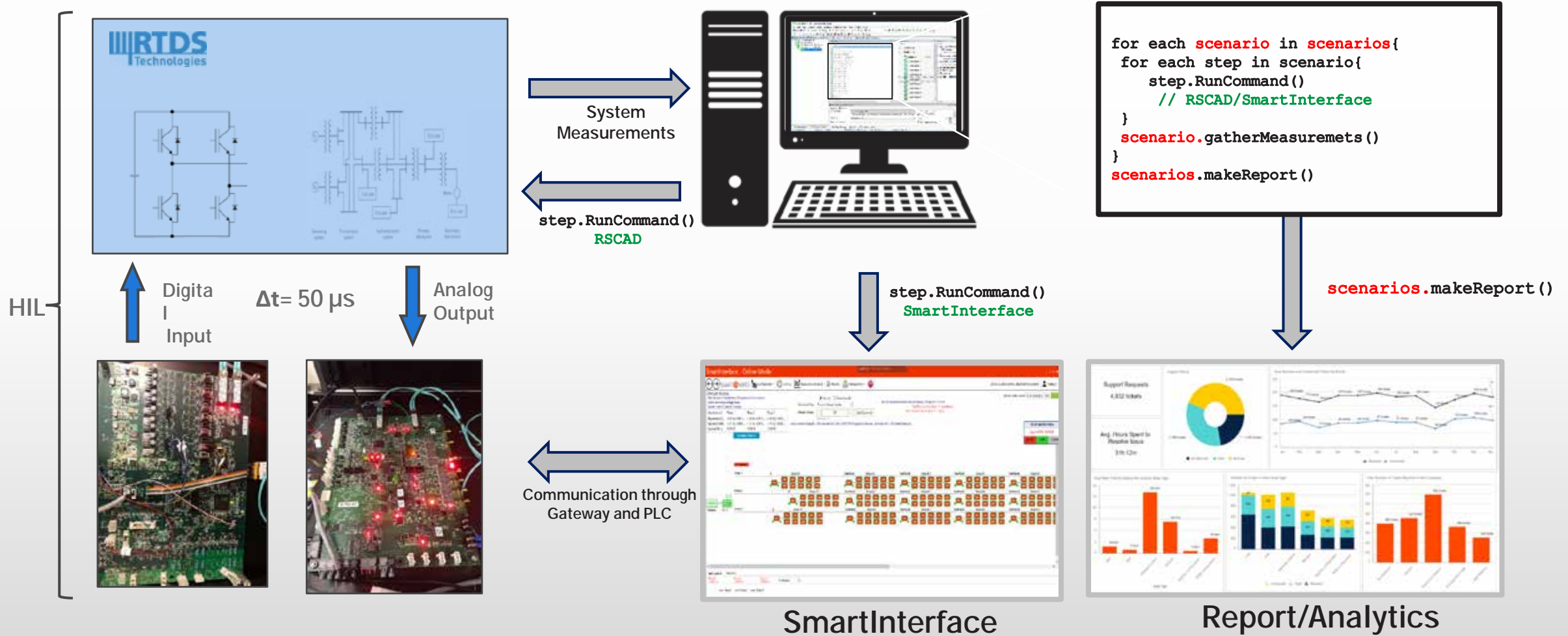
Dynamic Performance Study (DPS) - Results



Analysis and discussion:

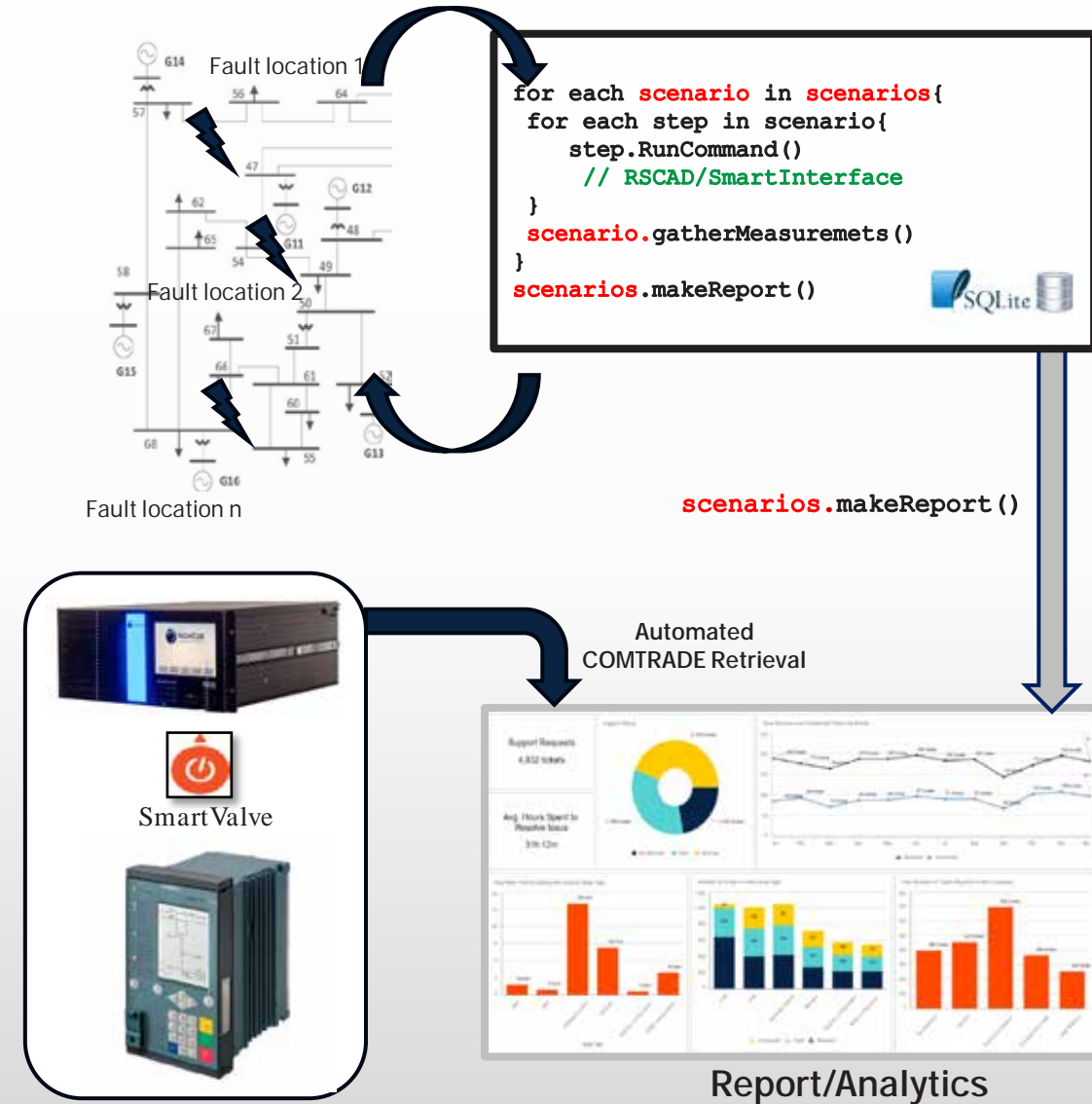
- The DPT cases were fundamental to finalizing the configurable adjustments of the M-SSSC solutions at the Santa Marta substation.
- The tests captured ISA best practices in protection coordination. They focused on ensuring proper coordination between the M-SSSC bypass actions and components' protection schemes near the M-SSSC installations.

Python Automation – Scenario Orchestration



Python Automation – Orhestration and Data Collection

- Integration with an SQL database is conducted to adjust each HIL run
- Allows multiple fault locations to be tested to validate M-SSSC bypass as well as validating the lack of impact on protection coordination.
- Allows the relays to be put into numerous configurations (2-terminal, 3-terminal) in an automated way to test the effect of different relay configurations for the same fault location.
- Automated report collection ensures that for each scenario:
 - Data recorded in RSCAD is collected
 - Event data records and COMTRADE files are collected from each M-SSSC control board
 - COMTRADE files are retrieved from each relay in the protection-in-the-loop configuration
- A complete report can be generated for each scenario to allow post analysis.
- Allows 50+ scenarios to be generated in a completely automated fashion.



APFC projects completed with 25+ utilities across the world

CHIL validations have been a critical component in validating a majority of our deployed devices

North America



- Central Hudson (NY) deploying APFC at 345 kV to unlock 185 MW firm capacity.
- Bulk of Gen and data center interconnection projects approved in GA, NY, VT, CA, ID, WA



Europe



- NGET using APFC across seven 275 kV and 400 kV circuits, delivering 2 GW transfer capacity increase



Colombia and Brazil



- Over 1.1 GW firm capacity unlocked to support demand increase & generation interconnection



Australia



- Over 185 MW firm capacity unlocked, improving reliability and transfer of electricity between states.



Tech Hub & HQ: RTP, North Carolina, USA
Manufacturing: St. Petersburg, Florida, USA



Global Presence: Additional offices in Ireland, Colombia, and a global workforce
Major Partners: Mitsubishi, Infineon, Jabil



Operational Record: 3,200+ device-years of operation
Intellectual Property: 100+ patents, know-how and technology stack

More info: www.smartwires.com