POWER IN MIND

News, Innovation,
& Breakthroughs

Volume 7
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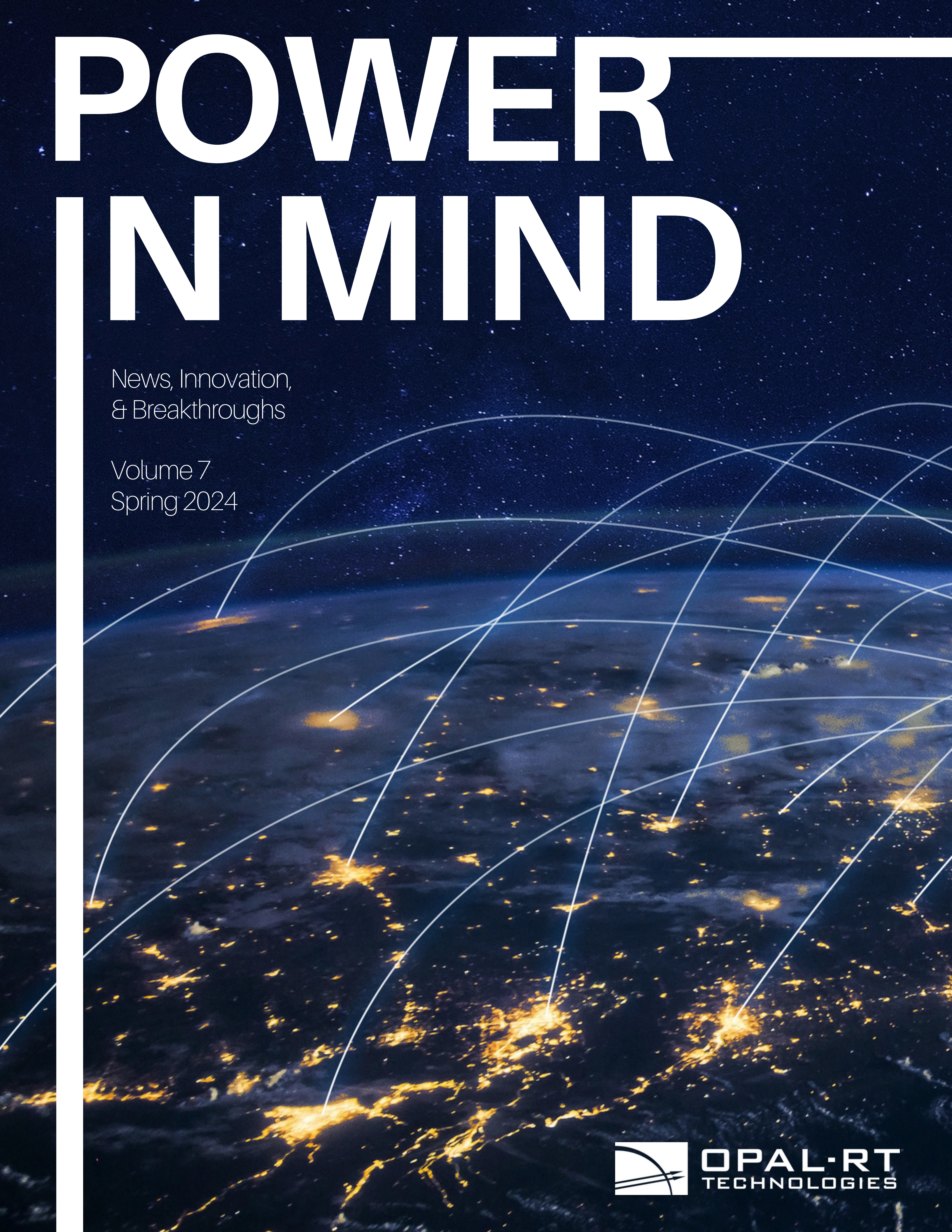


OPAL-RT
TECHNOLOGIES

A Word from the Editor

Welcome, dear readers, to another captivating edition of OPAL-RT's Power in Mind Magazine. In our last edition, we explored the transformative capabilities of Field-Programmable Gate Arrays (FPGAs) and their indispensable role in powering the evolution of real-time simulation in power systems and power electronics. Today, we embark on a journey into the dynamic realm of power system digitalization—a transformative journey that promises to redefine the very fabric of our energy landscape.

As we transition from traditional analog grids to the advanced, interconnected networks of smart grids, we find ourselves at a pivotal moment in the evolution of power engineering. The integration of advanced digital technologies into our grid infrastructure marks a paradigm shift—one that promises to revolutionize the way electricity is generated, transmitted, and distributed.

Power grid digitalization encompasses a myriad of innovations, from the deployment of smart meters and sensors to the implementation of sophisticated communication networks and automation systems. Through real-time monitoring, control, and optimization, these technologies empower utilities to enhance grid resilience, integrate renewable energy sources, and improve overall efficiency—all while providing better services to customers.

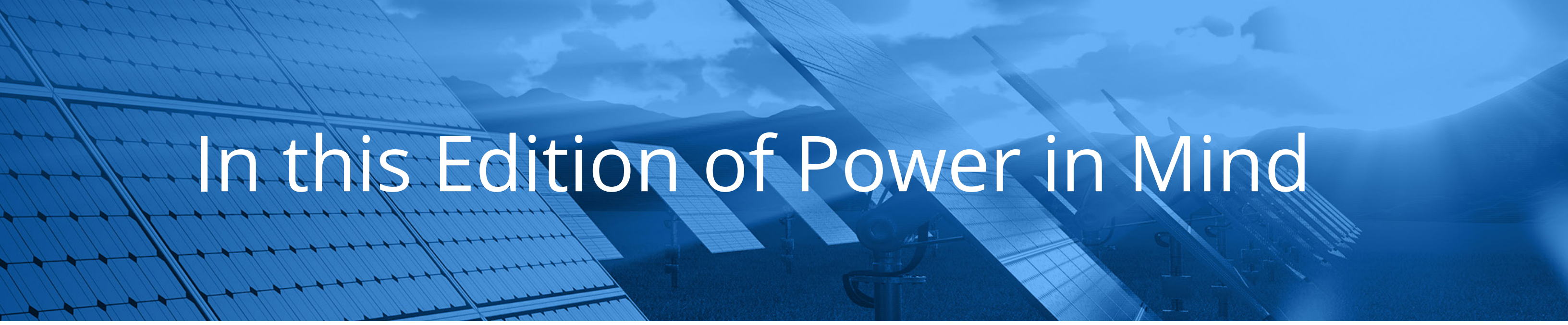
Central to this digital transformation is the communication network—the lifeline of the smart grid. From wired network over coper or fiber optics to wireless networks using 5G or satellite communication, these networks facilitate seamless data exchange and control commands across the grid, enabling utilities to monitor operations and respond to disturbances with unprecedented agility. However, ensuring the reliability and resilience of these networks presents its own set of challenges, from interoperability to infrastructure vulnerabilities or even cybersecurity threats. As we navigate these challenges, the need for robust testing solutions becomes increasingly apparent, ensuring the cybersecurity, reliability, and efficiency of our critical infrastructure.

As we delve into the articles and insights presented in this edition, I invite you to join us in exploring the boundless possibilities of power system digitalization. Together, let us embark on a journey of discovery and innovation, as we shape a brighter, more sustainable future for generations to come.

Happy reading! ■

Etienne Leduc,
Head of Energy Market

Etienne Leduc is a highly accomplished professional in electrical engineering and power systems at OPAL-RT TECHNOLOGIES. With expertise in real-time simulation and hardware-in-the-loop testing, Etienne has made significant contributions to power system simulation and control technologies. He is dedicated to promoting green energy solutions, particularly in renewable energy integration and grid modernization.



In this Edition of Power in Mind

Behind the Cover

This edition's cover showcases the interconnected world of modern power systems: The illuminated lines represent continuous global innovation and progress, highlighting advancements in sustainable energy, from cutting-edge renewable technologies to smart grid developments.

Front page design: Maija Baroni

Featured article by: Louis Raymond
Editors: Etienne Leduc, Brad Armstrong, Geneviève Deschamps, and Sofía Escalera Eguíluz
Design and layout: Sofía Escalera Eguíluz, Maija Baroni and Tania Gray

Navigating the Challenges of Power Grid Digitalization

Reading time: 4 minutes

By: Louis Raymond, Go-to-Market Manager, Protection, Cybersecurity, Digitalization

The transition from traditional power grids to digitalized ones represents a significant paradigm shift in the way electricity is generated, transmitted, and distributed.

Traditional power grids, considered as "analog" grids, were characterized by centralized generation, one-way power flow, and limited communication and control capabilities. In contrast, digitalized power grids, also known as "smart grids," leverage advanced digital technologies to enable real-time monitoring, automation, and optimization of grid operations.

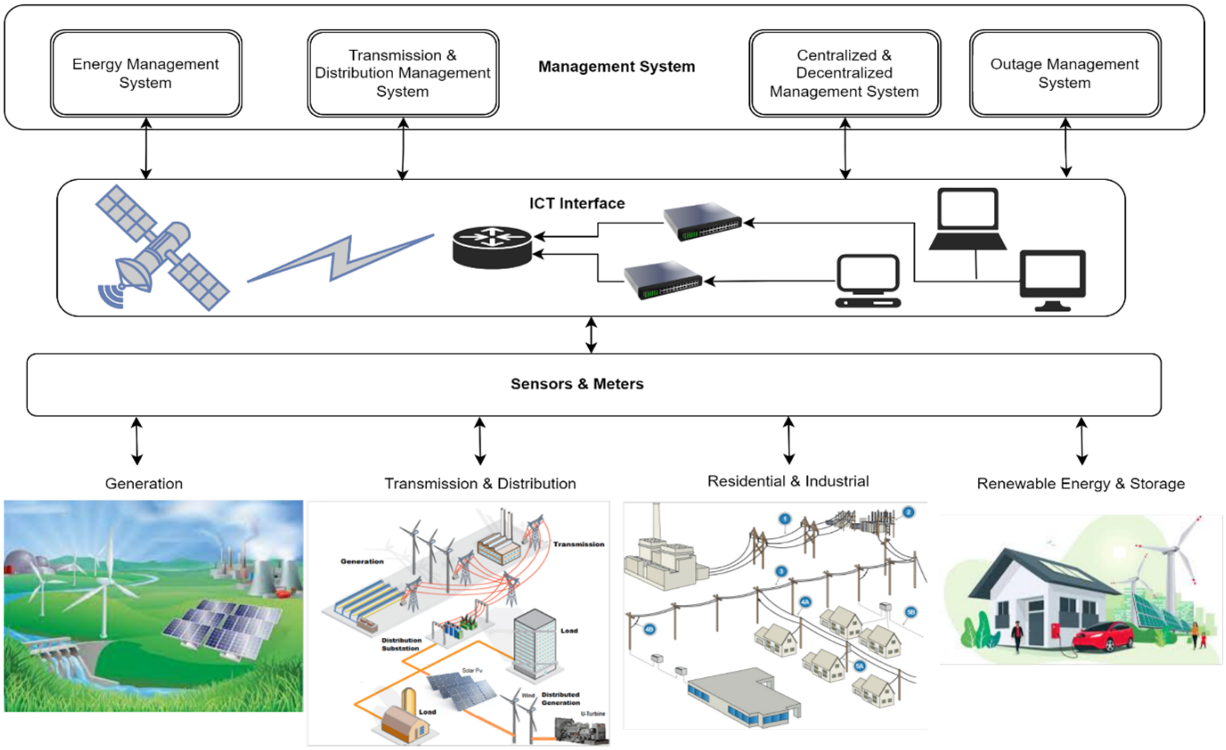
This transition is driven by several factors, including the increasing integration of renewable energy sources, growing energy demand, and the need to enhance grid reliability, efficiency, and sustainability.

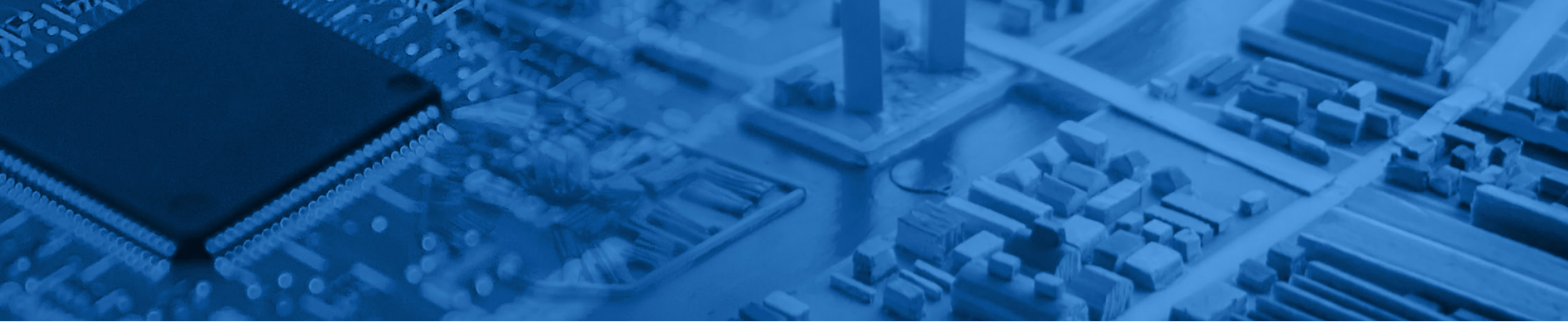
What Does Power Grid Digitalization Entail?

Power grid digitalization involves the integration of advanced digital technologies into the electrical grid infrastructure.

This includes deploying smart meters, sensors, automation systems, and **communication networks** to enable real-time monitoring, control, and optimization of grid operations. Digitalization also encompasses the adoption of data analytics, artificial intelligence, and predictive algorithms to analyze grid data, optimize energy flows, and detect anomalies or potential issues proactively.

By digitizing grid infrastructure, utilities can enhance grid resilience, integrate renewable energy sources, implement demand response programs, and improve customer services.





Communication Network

The communication network attached to a smart grid is a crucial infrastructure that enables real-time data exchange, control commands, and monitoring across the grid. It encompasses various technologies such as fiber optics, radio, cellular, satellite networks. These networks facilitate seamless communication between smart meters, sensors, substations, and utility control centers, enabling utilities to monitor grid operations, optimize energy flows, and respond to grid disturbances efficiently.

In this way, advanced communication protocols like IEC 61850 aim to ensure interoperability among smart grid devices, but challenges such as varying interpretations and implementations can lead to compatibility issues, that need to be tested. Likewise, emerging technologies like 5G promise low-latency, high-bandwidth connectivity, further enhancing the capabilities of smart grid communication networks, but the reliability of these technologies also needs to be tested.

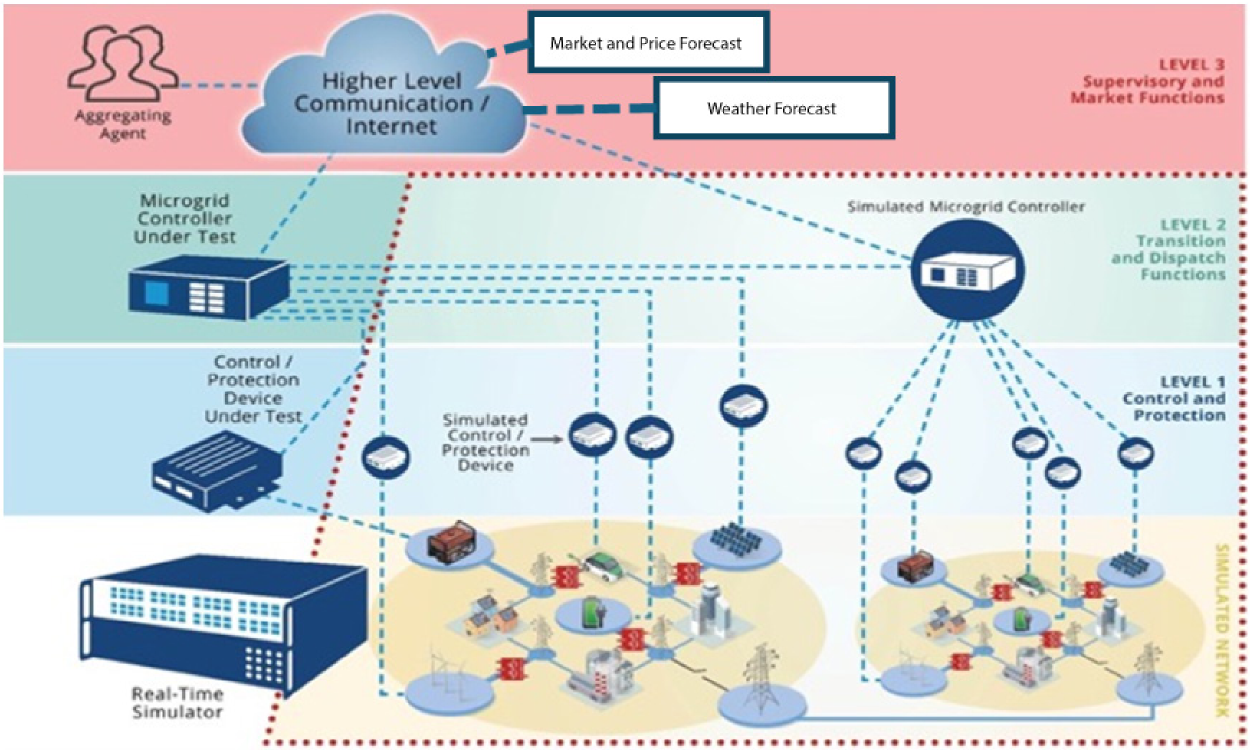
COMMUNICATION MEDIA

Different types of communication media are used:

- **Terrestrial communication such as fiber optics for high-speed and reliable data transmission.**
- **5G networks with low-latency, high-bandwidth communication for real-time monitoring and control.**
- **Satellite communication for remote connectivity, enabling grid monitoring and control in remote or inaccessible areas where terrestrial networks are unavailable.**

COMMUNICATION PROTOCOLS

Smart grids rely on various communication protocols to facilitate data exchange and control commands between grid components



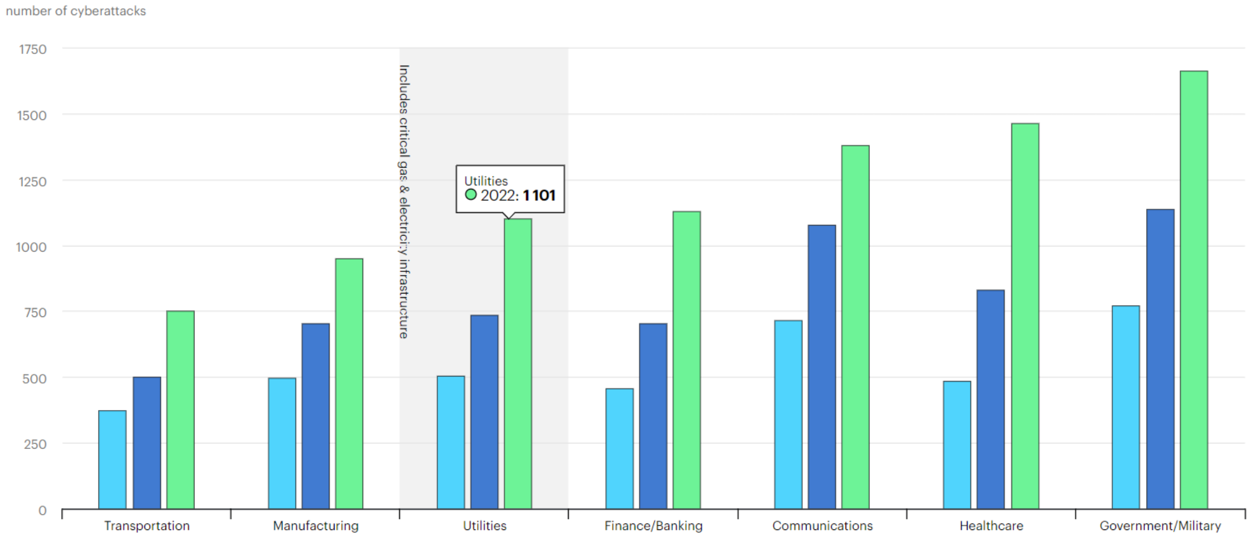
and utility control centers. IEEE 1547 specifies technical requirements for the interconnection of distributed energy resources (DERs) with electric power systems. Communication protocols such as those listed below may be used for data exchange and control between DERs and grid infrastructure, depending on specific implementation requirements and industry standards.

- **DNP3 for SCADA systems, substation automation and control.**
- **IEC 61850 GOOSE, Sampled Values, MMS for communication in smart grid systems.**
- **Modbus for simpler device-level communication.**
- **IEEE C37.118 for Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDCs) for wide area monitoring and control.**
- **IEEE 2030.5 for data exchanges between smart grid devices, energy management systems, and utility control centers.**

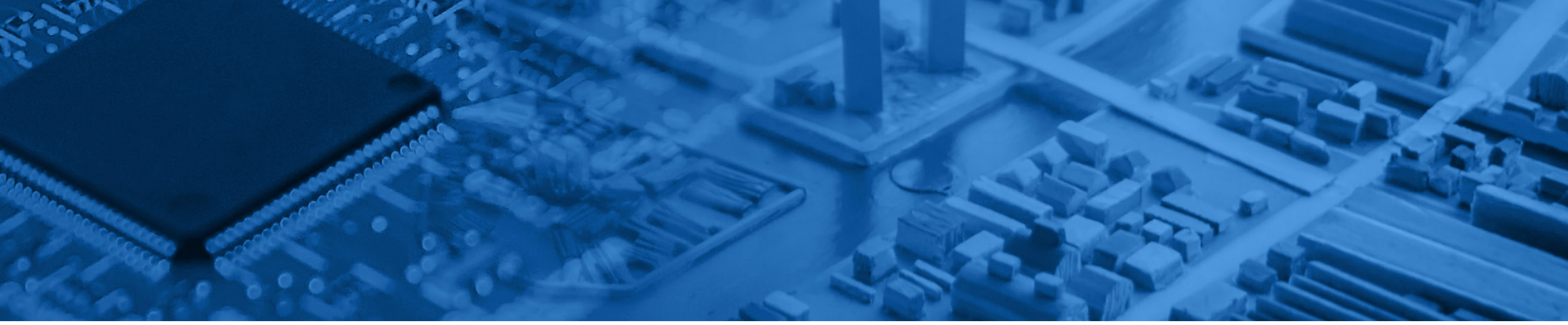
OPAL-RT simulators emulate industry-standard communication protocols, enabling users to perform the most realistic real-time simulations possible.

Reliability as a Watchword

In the intricate realm of smart grids, communication networks serve as the backbone, orchestrating the exchange of data and commands among diverse grid elements. However, ensuring their reliability presents multifaceted challenges. External interference, congestion, and cybersecurity threats jeopardize data transmission integrity. Physical infrastructure vulnerabilities, susceptibility to natural disasters, and compatibility issues further compound reliability concerns. Striking a balance between stringent Quality of Service requirements, scalability, and capacity demands poses additional hurdles. Overcoming these challenges necessitates robust cybersecurity measures, redundancy, fault tolerance, and collaborative efforts among manufacturers, DSOs and TSOs to fortify network reliability and resilience in the ever-evolving landscape of smart grid technology.



Average number of weekly cyberattacks per organization in selected industries, 2020-2022
https://www.iea.org/commentaries/cybersecurity-is-the-power-system-lagging-behind



The Challenges of Cybersecurity

More specifically, the transition to digitalized power grids, which means a very strong link between Power Grid and Communication Network, is not without new challenges, such as the intrinsic risks of cybersecurity and therefore finding testing solutions, to face it in the development phase.

CYBER-ATTACKS

Cyber-attacks targeting grid control systems, communication networks, or critical infrastructure can disrupt grid operations, causing power outages, grid instability, and service interruptions, with severe economic and societal impacts.

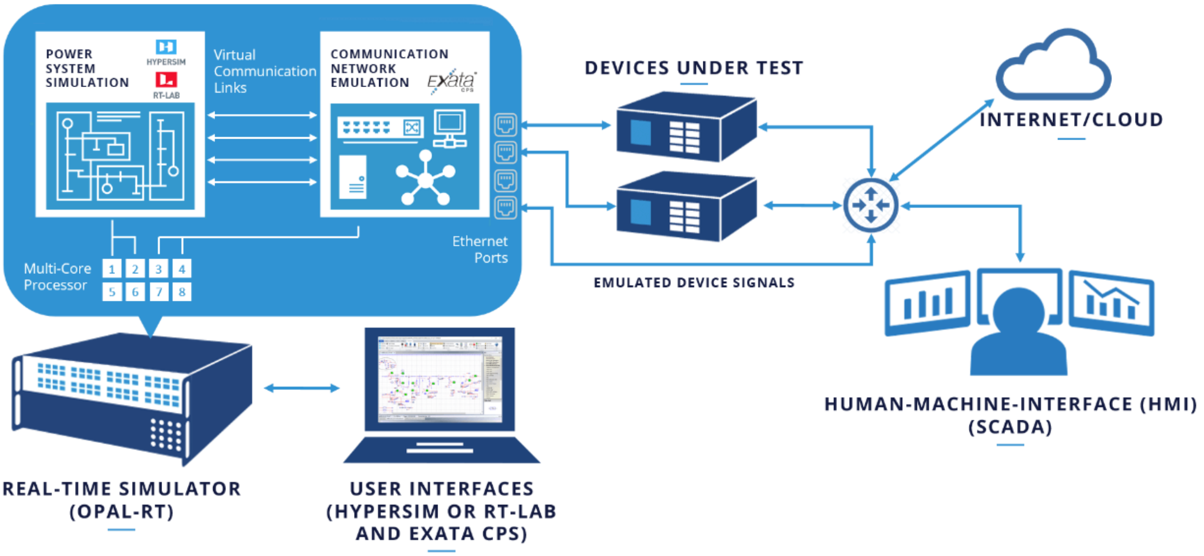
Amongst notable cyberattacks on power system infrastructure, we can list:

- **Ukraine Power Grid Cyberattack (2015 and 2016): cyberattacks targeted the power grid in Ukraine, causing widespread power outages. The hacker accessed the SCADA information, disrupted the normal operation, and caused the disconnection of 30 substations in total, affecting 225,000 customers for approximately 3 hours.**
- **Dragonfly "Energetic Bear" Attacks (in operation since 2011): cyber espionage campaign, targeted power utilities, to gain access to critical infrastructure systems, potentially compromising grid operations and control.**

Smart grids are vulnerable to numerous cyber-attacks, including malware, ransomware, phishing, DoS, MitM, GNSS Spoofing/Meaconing attacks.

Cyber-Physical Power System Testing Platform for Cybersecurity

While the SIL (Software-in-the-Loop) testing approach focuses on cybersecurity assessments and integrity evaluations, an HIL (Hardware-in-the-Loop) testing platform assesses the reliability, functionality, and performance of smart grid systems. Integrating both SIL and HIL testing methodologies can provide a holistic approach to evaluating the cybersecurity and reliability of smart grid infrastructure, ensuring that critical security



CYBER-PHYSICAL SYSTEM (CPS) CO-SIMULATION

controls and mechanisms are effective under various operating conditions and cyber threat scenarios.

HIL testing is essential for smart grids and cybersecurity as it enables the validation of grid control algorithms, communication protocols, and cybersecurity measures in a realistic environment. By simulating cyber-attacks, network vulnerabilities, and grid disturbances, HIL testing allows engineers to assess the effectiveness of cybersecurity defenses, identify weaknesses, and refine response strategies. Additionally, HIL testing enables utilities to validate grid control algorithms and optimize grid performance while ensuring interoperability and compatibility of grid devices and systems.

OPAL-RT supports co-simulation of cyber-physical systems, enabling the integration of physical and cyber components in a unified simulation environment, as described below.

Perspective

As smart grids become more and more complex, the need for a cyber-physical solution for the development, testing and assessment of power grids and communication networks becomes absolutely necessary, to ensure the cybersecurity, reliability, and efficiency of critical infrastructure.

While Artificial Intelligence (AI) for assisted decision is already there, as mentioned in the “Digital Twin: Ensuring the Stability and Reliability of Tomorrow’s Power Grid” webinar delivered at previous OPAL-RT Learning Journey, in the future, AI techniques/algorithms will likely get into the game more largely.

Indeed, to cope with the complexity of smart grids, AI may help not only to optimize grid operations by analyzing data, but also help to predict equipment failures, and eventually also enhance grid security by detecting and responding to cyber threats in real-time, ensuring a resilient and sustainable energy infrastructure.

Let’s see how your HIL users will integrate this into their development in the future! ■

A Brief Chat About Network Digitalization

We sat down with Jean-Nicolas and asked him a few brief questions about network digitalization.

Jean-Nicolas oversees North American R&D collaborations with universities, national labs, and industry partners, shaping OPAL-RT's roadmap with its international excellence centers & CTO office.

Question: What is network digitalization?

Network digitalization encompasses a multifaceted transformation. It involves communication for smart energy systems, integrating the Internet of Things, and addressing crucial cybersecurity concerns. But in broad terms, it's about enabling the energy transition and managing the influx of renewable energy sources and decentralized production. This requires robust control mechanisms over distributed energies through digital communication. Additionally, artificial intelligence will play a pivotal role in the energy transition, enabling algorithms to support decision-making in the control rooms and power system automation. Utilizing modeling and simulation technologies further enhances grid resilience and security, especially with the integration of inverter-based renewable energy technologies which brings a whole set of new challenges to maintain grid stability.

Question: What are some of the biggest obstacles to achieving the necessary level of network digitalization?

Some of the most significant challenges lie in workforce training and technology validation. The industry needs to adapt by diversifying their talents not only in electrical engineering, but also in software and communication systems engineering. The power system engineers we see entering the industry now need to understand many facets of the digitized power system, which also makes it very exciting. To accelerate the adoption of the new technologies, it is crucial to have engineers trained on understanding the technology as well as the different tools available to test it.

Question: How does simulation and HIL accelerate this process or overcome any obstacles?

Simulation plays a crucial role in training artificial intelligence algorithms by generating synthetic data for better decision-making. Additionally, it is crucial in testing controls and protections of the new technologies before they are installed in the field. Simulation technologies will play a big role in developing digital twins of the grid, enabling contingency analysis and support decision-making in the control room.

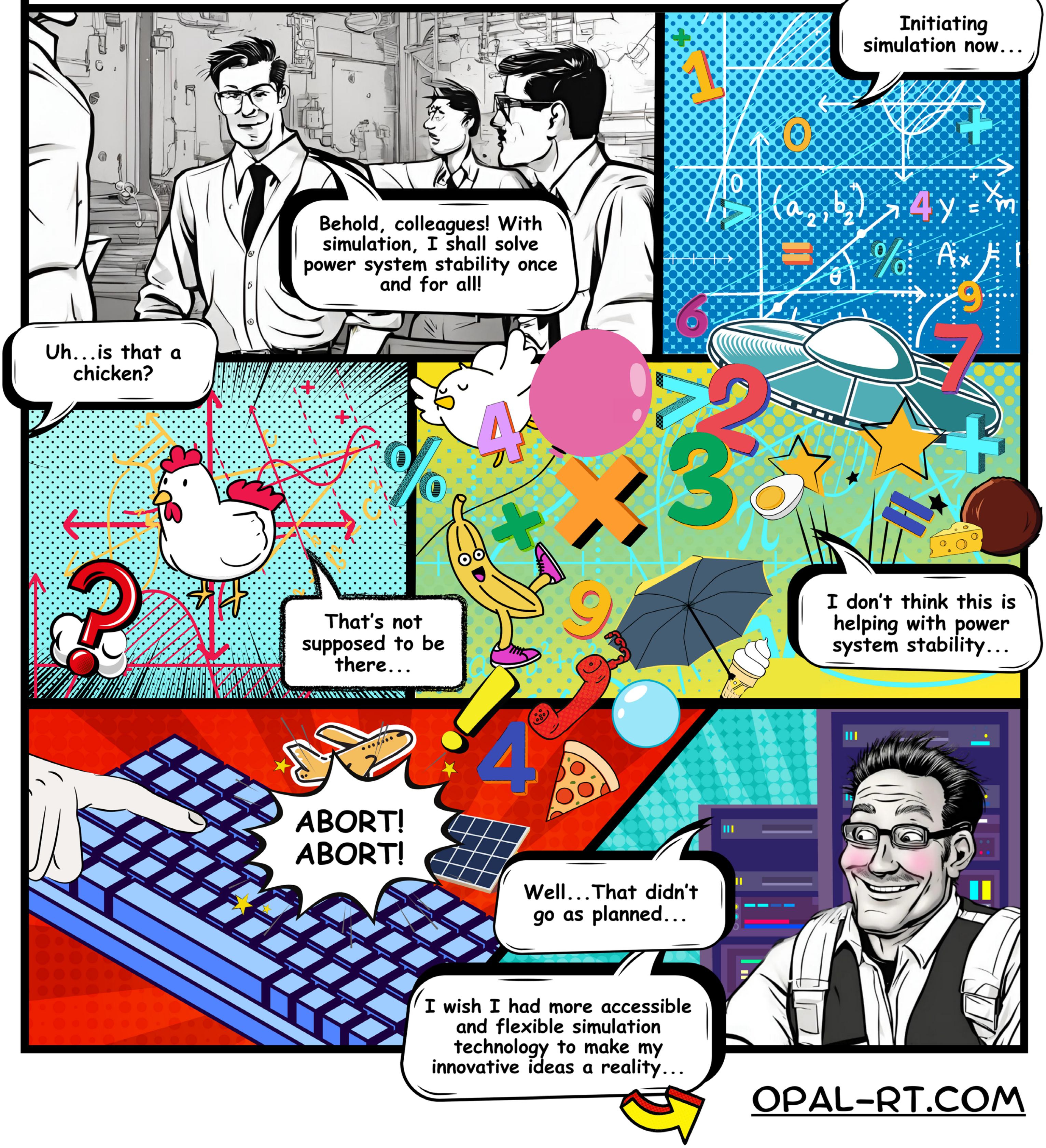
Question: How is OPAL-RT contributing to this effort?

For over 20 years, OPAL-RT has played a vital role in advancing power system capabilities and we continue to do so. Our real-time simulators remain at the forefront of advancements in power systems. Our simulators allow for grid and communication interconnection simulations, preparing our customers for future challenges. We make it a mission to assist utilities, manufacturers, and system operators in conducting specialized studies and tests to ensure safe operation of the new technologies integrated in the cyber-physical power system, by offering fast simulation tools and real-time testing platforms tailored to this industry.■

Jean-Nicolas Paquin
Vice President Engineering and Electrical Expertise

SIMUL-WOES

A Tech Odyssey Without OPAL-RT



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ELECTRIFYING THE WORLD BEYOND REAL TIME

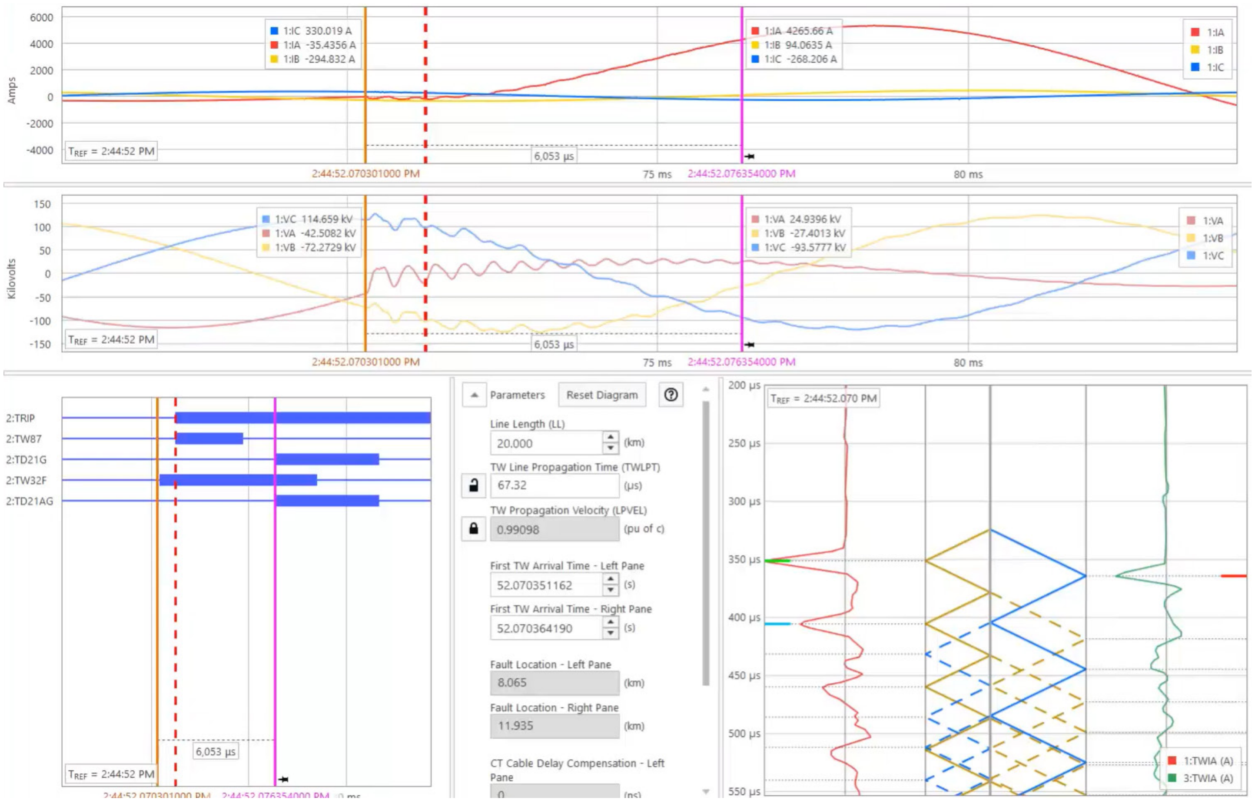
Innovations in Traveling Wave Relay: Testing for a Sustainable Energy Future

The evolving landscape of power systems, marked by the rapid proliferation of Inverter-based Resources (IBRs), is swiftly reducing the overall grid inertia. This paradigm shift necessitates a reevaluation of protection strategies, driving the growth of the traveling wave protection market. Moreover, this technology holds promise for mitigating arc flashes and preempting wildfires.

Testing traveling wave (TW) relays poses formidable challenges, compounded by the complexities of high-frequency phenomena and increasingly complex network topologies. The stringent demands of TW fault location algorithms, requiring data acquisition rates up to 5 MHz for precise capture of transient events, underscore the need for precision in the testing process.

In collaboration with industrial partners, OPAL-RT is at the forefront of addressing these challenges. Through advancements in its FPGA-based power system and power electronics simulation toolbox, the eHS solver offers the capability to simulate highly precise frequency-dependent (FD) lines at timesteps as low as 500 ns across diverse network topologies. With the ability to simulate up to 15 FD line segments together with CP and PI lines on a single FPGA, and the scalability to combine multiple FPGAs for virtually any network size, OPAL-RT provides a comprehensive solution.

Our approach integrates cutting-edge simulation techniques with HIL testing methodologies to navigate the complexities of TW relay testing. By ensuring the fidelity and efficacy of TW relay systems in safeguarding power transmission networks against transient disturbances and emergent threats, we contribute to forging a robust and sustainable energy future through innovation and collaboration. ■



Line Length (LL): 20.000 (km)

TW Line Propagation Time (TWLPT): 67.32 (µs)

TW Propagation Velocity (LPVEL): 0.99098 (pu of c)

First TW Arrival Time - Left Pane: 52.070351162 (s)

First TW Arrival Time - Right Pane: 52.070364190 (s)

Fault Location - Left Pane: 8.065 (km)

Fault Location - Right Pane: 11.935 (km)

CT Cable Delay Compensation - Left Pane: 0 (ns)

OPAL-RT
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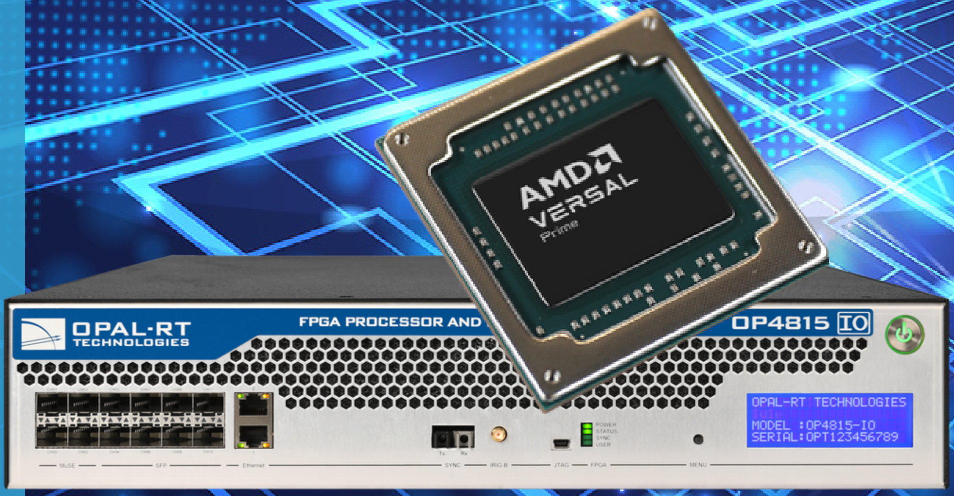
Series

Unleash Traveling Wave Relay Testing with VersalTM FPGA Technology



Embrace **complex power systems** and **power electronics** circuits without the constraints of yesterday's decoupling techniques. **Double your simulation capacity** for agile development and innovative control strategies with **unparalleled precision** and near-zero latency.

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POWER SYSTEM ON FPGA

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OP4800 Series

Testing Cyber-Physical Resiliency on a Microgrid

Introduction

SAFEGUARDING SMART GRID SYSTEMS

Microgrids, small-scale power networks, operate independently or with the main grid but face security risks due to online connectivity. Attacks on communication and control systems managing Distributed Energy Resources (DERs) like solar panels and batteries are increasing, posing threats like power outages and equipment damage. Enhanced security measures, including specialized software and simulation of cyberattacks, are vital for protection.

Meet the Team

VEBIC (Vaasa Energy Business Innovation Center) and FREESI lab at the University of Vaasa focus on Smart Grid research. They utilize cutting-edge facilities like the Smart Grid Laboratory for testing and innovation in grid integration and power system protection.

The Problem

MICROGRID CONTROLLERS UNDER ATTACK

HIL simulation expertise aids in fortifying microgrid controllers against cyber threats. The lab's upgraded facilities enable real-time simulations essential for testing relay protection systems and inverter-based DER control.

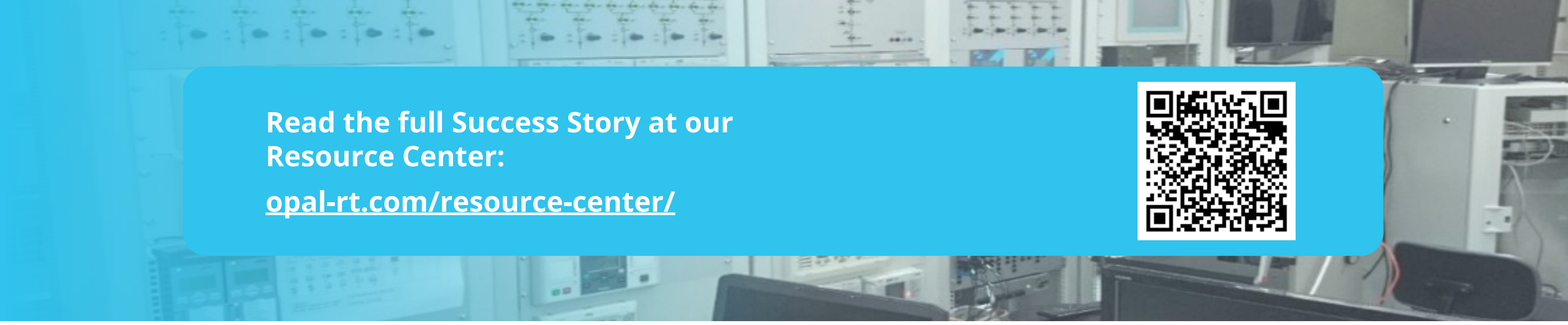
Configuration

The lab's multi-vendor environment, centered on IEC 61850, facilitates the integration of devices for controller development and validation. Ongoing research focuses on AI-enabled algorithms for microgrid controllers.

Simulation of Cyberattacks

Two scenarios highlight the impact of cyberattacks on microgrid operation: delay-type and packet modification attacks. These simulations aid in understanding vulnerabilities and developing defense strategies.

> *"The results show effective use of emerging multi-agent hardware controllers, AI algorithms, and OPAL-RT modeling."*
>
> Mike Mekkanen, Researcher - University of Vaasa



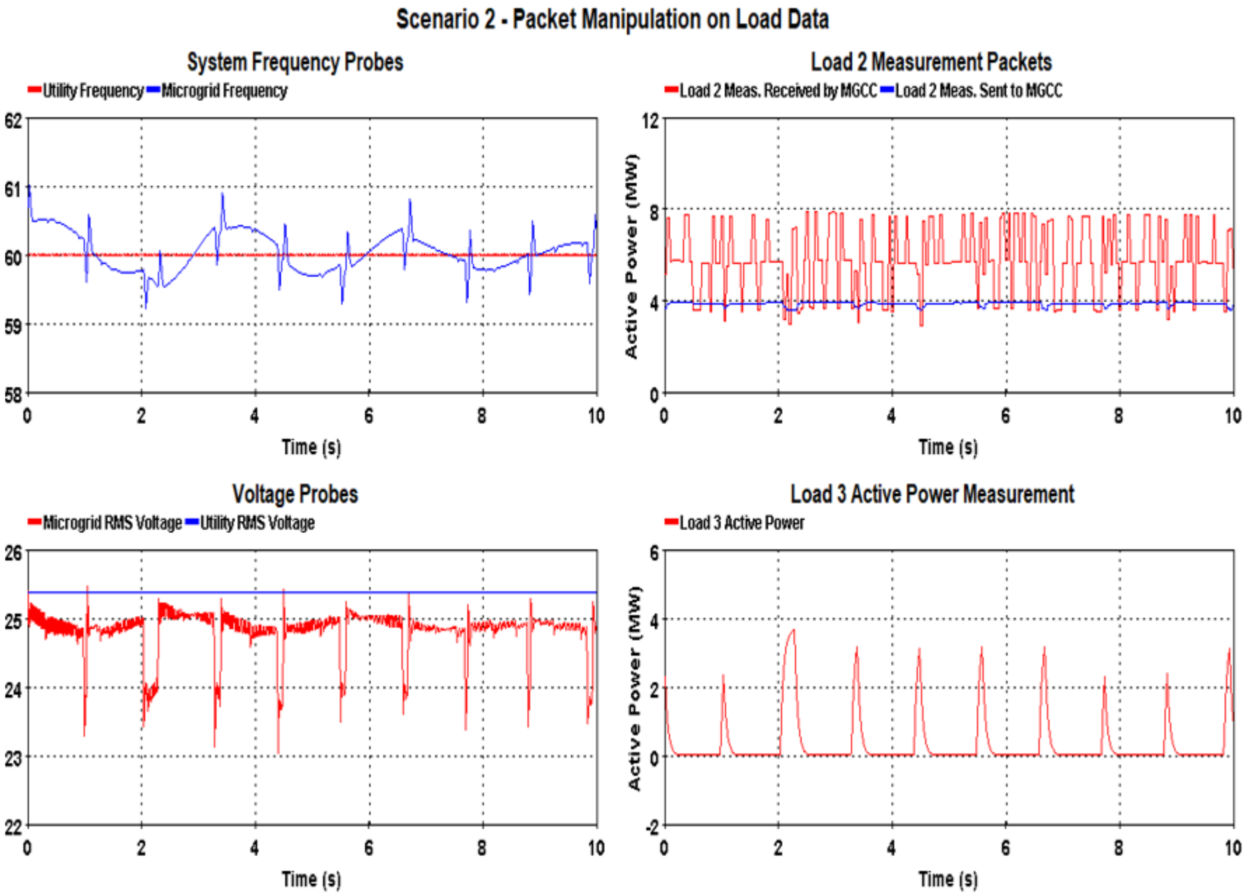
Read the full Success Story at our Resource Center:

opal-rt.com/resource-center/

Scenario #2: The So-Called "Man In The Middle" Attack

With Scenario #2, we experience islanded microgrid subject to "packet modification"- type cyber-attack:

- **Load 2 measurements are manipulated before they are received by the MGCC.**
- **MGCC periodically trips and reconnects Load 3 since it is programmed to shed the priority Load 3 if the mismatch between generation and load exceeds 3 MW.**
- **Figure shows the microgrid suffering from a decline in power quality, including high frequency and voltage oscillations.**



Cyber-Physical Systems Lab

A collaborative project between University of Vaasa and Lule University aims to enhance CPS security in the energy sector. Leveraging expertise from both universities, the project creates a simulation-based environment for testing cybersecurity measures.

Conclusion

Thorough testing of microgrid controllers is essential for ensuring network security and reliability. Testing should cover functionality, interoperability, and resilience against cyber threats, ultimately maximizing the benefits of microgrids while minimizing risks. ■

Research Collaboration: Université Laval

Read the full article here.

Enhancing Overcurrent Protection in DC Microgrids through Data-Driven Schemes

by Saeed Sanati

INTRODUCTION

Over-current (OC) protection is vital for DC microgrid reliability, demanding advanced tools like OPAL-RT simulators. This study introduces an adaptive directional OC method for DC microgrids, utilizing the robustness of the IEC 61850 protocol. Integrating K-means clustering for relay setting groups, it enhances protection reliability and speed with seamless coordination. Leveraging communication networks, it adapts effectively across fault scenarios and grid topologies, validated by the OP4512 OPAL-RT simulator. Rigorous simulation and experimental testing evaluate communication-assisted OC protection, promising heightened grid resilience and operational efficiency.

METHODOLOGY AND EXPERIMENTAL SETUP

The approach integrates real-time simulations, advanced algorithms, and communication-based coordination. Utilizing an OP4512 OPAL-RT simulator, RT-LAB, and MATLAB, the setup involves IEDexplorer software simulating GOOSE message exchange for nearby OC relays in diverse scenarios.

IMPLEMENTATION DETAILS AND SIMULATION PROCESS

A standard 14-bus IEEE grid is simulated using Simulink. While the focus was on the main protective relay for the experimental tests, the proposed algorithm is designed for application across all OC relays within the DC microgrid. Measurements were sampled at a frequency of 5 kHz. By altering microgrid conditions, various scenarios were explored, including pole-ground and pole-pole short circuits with fault impedance of 0.5 ohms on a power line, both with and without individual power generation sources in the microgrid.

EXPERIMENTAL RESULTS

Figure 1 presents the current waveform observed by the main relay, both demonstrating the effectiveness and superior speed of the proposed method compared to traditional schemes.

CONCLUSION

The method offers substantial improvements in fault protection for DC microgrids, enhancing speed, selectivity, and communication-based coordination. These findings suggest minimized disruptions and accelerated adoption of DC microgrid technologies. OP4512 OPAL-RT's role in advancing research at Laval University is pivotal. ■

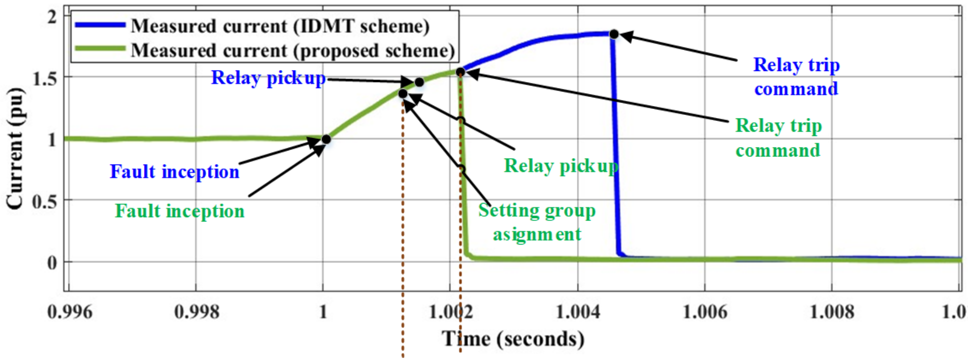


Figure 1. The current waveform and the OC operation sequences in the case of correct adjacent relay operation while pole-pole fault occurs at the power line without any power source outage.

Research Collaboration: Concordia University

Read the full article here.

Power Hardware-in-the-Loop Emulation of Stator Winding Fault in PMSM

by Neetusha Kalarikkal

Permanent Magnet Synchronous Machines (PMSMs), being compact, highly efficient, and having good dynamic performance, are popularly used in electric vehicles, wherein high reliability and fault tolerance are essential. Inter-turn short-circuit (ITSC) fault in the stator winding of a PMSM is one of the common catastrophic faults; the behaviors and effects of which on a yet-to-be-prototyped motor can be studied using a Power-Hardware-In-the-Loop (PHIL) Emulation of the same. The PHIL emulation of a prototype motor with ITSC fault has been done by Prof. Pragasen Pillay's research team at Concordia University, Montreal, in collaboration with the OPAL-RT team.

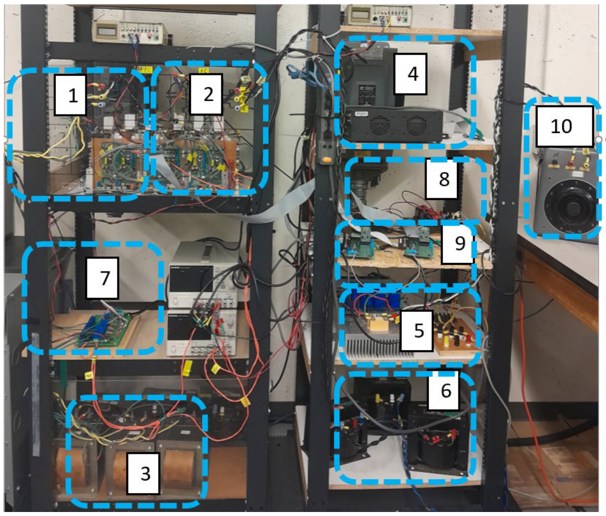


Figure 1: Experimental Setup for the Emulator setup for PMSM. (1) Active Front-end Converter (AFEC) (2) Emulating Converter (3) Coupling inductors for AFEC (4) OPAL-RT (5) Test Inverter (6) Coupling inductors for Emulating Converter (7) Sensor board for AFEC (8) Sensor Board for TI (9) Protection Boards (10) Auto Transformer

Using the analytical model of faulted PMSM as the reference, a MATLAB model of the same is developed, which is then implemented in the Emulator Setup using real-time simulation tools and hardware test-benches. A hardware setup consisting of a Test-inverter (TI), coupling inductors, the Emulating converter (EC), and a Front-end converter (FEC) has been built for this purpose. Figure 1 depicts the hardware setup used for the purpose. OPAL-RT's real-time simulator, OP4510, was used for implementing the machine model and the control logic for the FEC, TI, and EC.

The emulation of the ITSC fault of a machine with 15% shorted turns in phase A was accomplished. Figure 2 represents the experimental waveforms for the Emulation of faulted PMSM. When a fault occurs, the current waveforms become asymmetric, and ripple gets introduced in the electromagnetic torque. The research provides an alternative solution using the emulator setup, for studying ITSC faults in PMSM machines in the laboratory environment when the actual machine is yet to be prototyped. ■

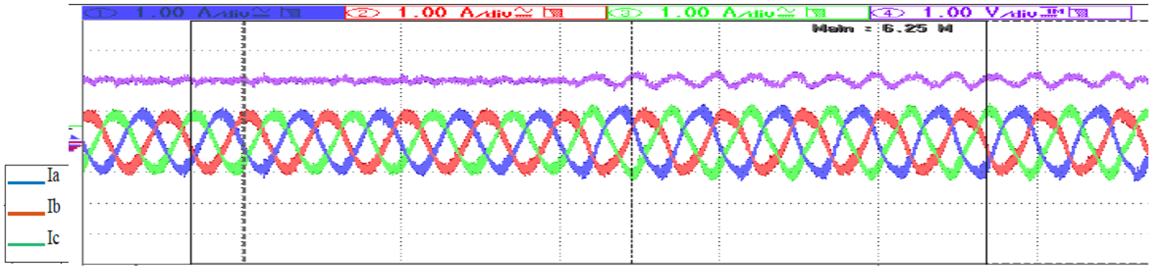


Figure 2: Experimental Results for Emulation of faulted PMSM. CH1 to CH3 (blue, red, green): current waveforms 1A/div; CH4(violet): electromagnetic torque waveform 1 Nm/div

Research Collaboration: Concordia University

Emulation of Electrical Machines with Mechanical Faults

by Solihah Sharief Shiekh, PhD Student and Prof. Pragasen Pillay

Mechanical faults, particularly air gap eccentricity, account for nearly 12 – 16% of the total motor faults. Uneven air gaps between the rotor and stator bore are referred to as eccentricity in motors. Axially non-uniform, or inclined eccentricity (IE), is most commonly observed in real-world situations. It involves a non-uniform displacement of the motor's axes, leading to an uneven air gap along the length of the motor. Despite being the most frequent, however, this has received very little attention from researchers. Ignoring these problems can result in unbalanced magnetic pull, stator winding problems, and, in severe cases, friction between the rotor and the stator, which can cause a motor to fail. Thus, the primary objective is to create an analytical method to diagnose such faults early using a technique known as motor current signature analysis (MCSA). For analytical modeling, a 2-D modified winding function approach (MWFA) is employed. A numerical model using 2-D finite element analysis is implemented. Both models' effectiveness is validated through experimental tests. Using this accurate model to investigate the faulted motor's behavior, the expensive test benches and equipment is replaced with a virtual machine that can be tested for different fault conditions using power hardware-in-loop (PHIL) based emulation. PHIL is increasingly used as an economical test bench for testing the drive system. The electrical machine is emulated in a laboratory environment with real-time power flow. With the emulation, the risk, time and cost associated with a physical machine subjected to faults can be saved. This concept of emulation has been realized through collaboration with our industrial partner, OPAL-RT. A real-time simulator, OP4510, is utilized to perform the MCSA and thus, detect such faults. The emulating currents drawn are shown in Fig.2 ■

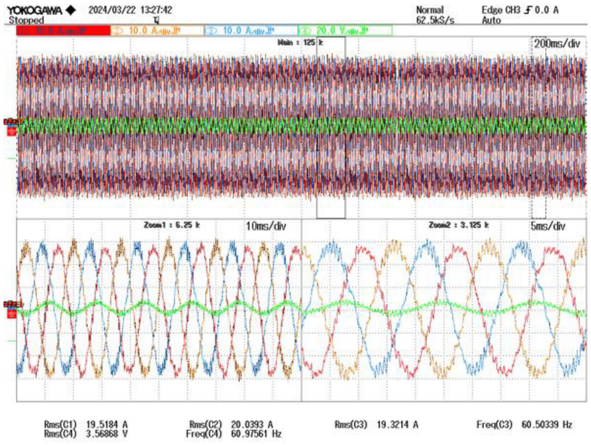


Fig. 2. Faulted currents with 57% eccentricity from one end of the rotor.

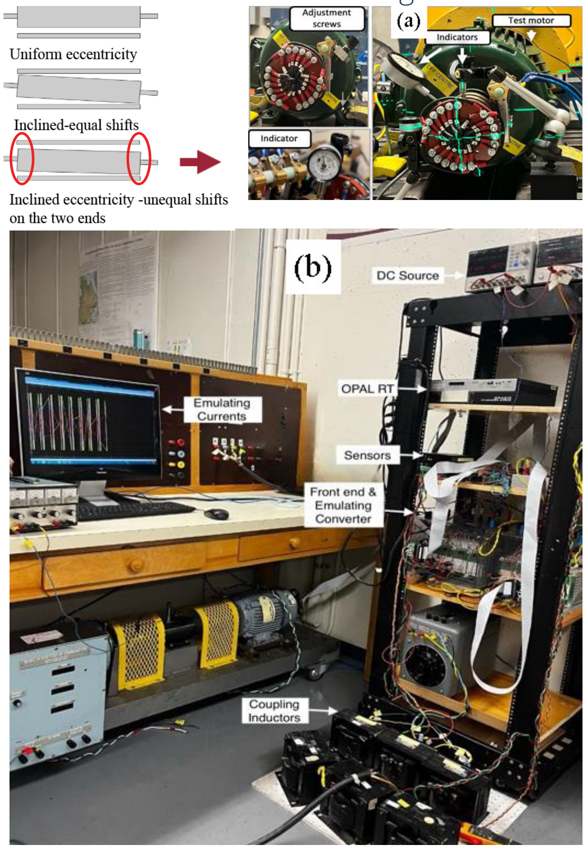


Fig. 1. (a) Experimental test setup for 780 W, 36V Wound rotor Induction Motor (WRIM). (b) Emulator setup for WRIM.

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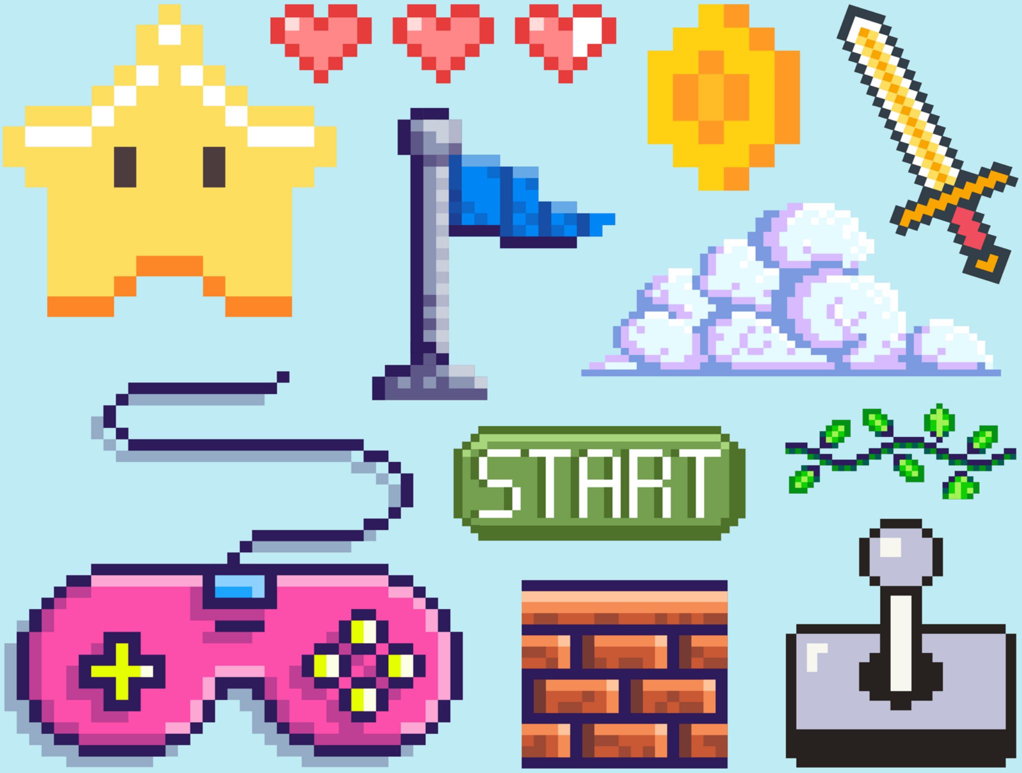

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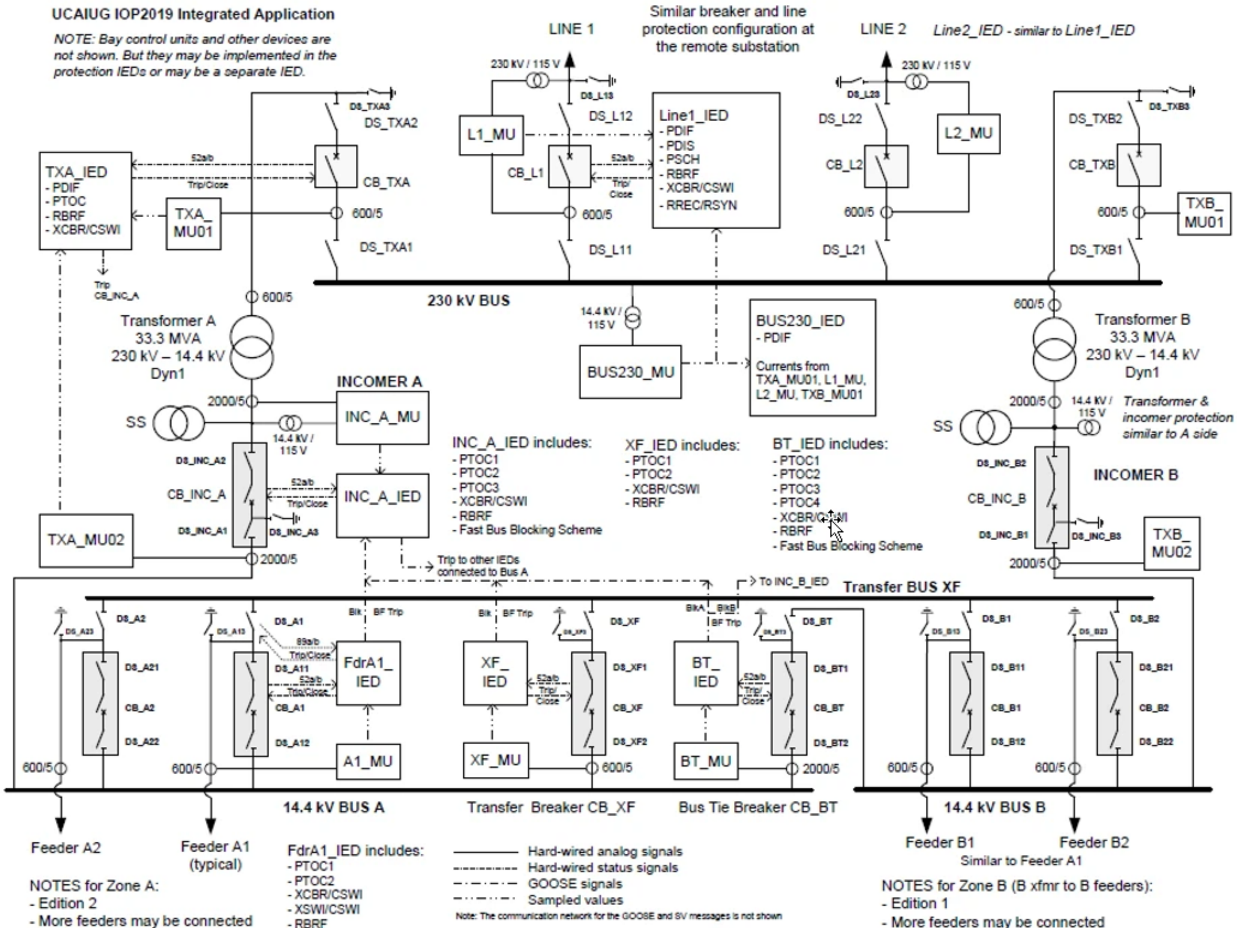
IEC 61850 Substation Automation System design in HYPERSIM

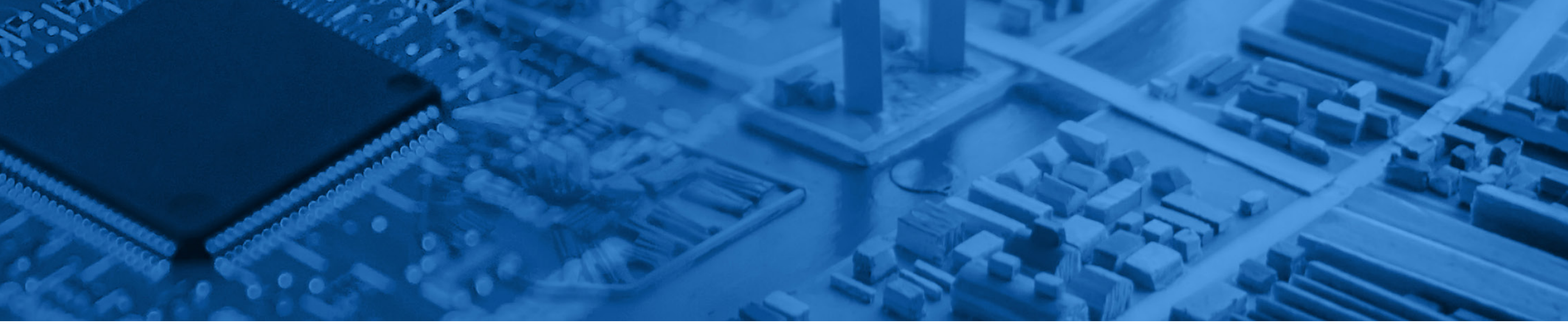
The IEC 61850 standard for substation automation has seen significant adoption since its inception almost a quarter of a century ago. Today, thousands of substations worldwide rely on this technology, reflecting its widespread use and importance in the power sector. Its emphasis on interoperability across all substation components has made it a cornerstone of digital substations, driving investment and modernization efforts.

An example model implemented in HYPERSIM is based on a design that was developed during the Interoperability conference (IOP) by the IEC 61850 User Group under the UCA International User Group (UCAIUG) in 2017 and 2019. It illustrates a digital substation divided into two major voltage levels, each comprising multiple bays. Each bay is equipped with protective IEDs and merging units, facilitating the transformation of analog values into digital samples for efficient relay operation. The coordination among these devices is facilitated by the publication of GOOSE messages and reports, ensuring swift and precise responses to substation events.

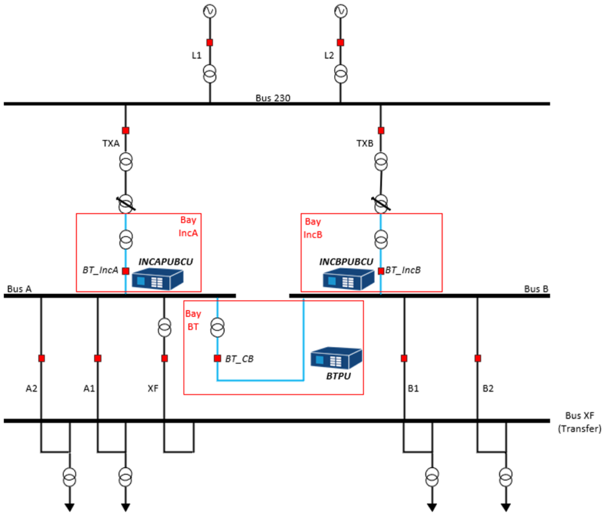
To bring this conceptual framework to life, a systematic approach is adopted:

- **Scenario specification: Time definite overcurrent function which is simple to implement and only requires a time delay to be configured and current threshold is chosen as the main protection function.**

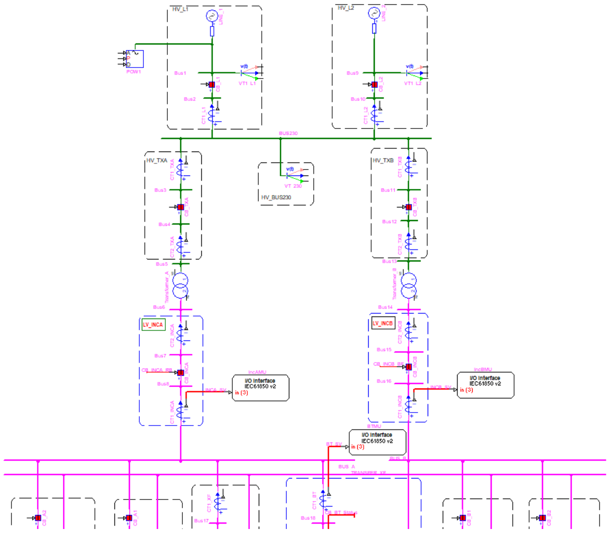




- **A Reverse IEC 61850 Substation Automation System design in HYPERSIM specifies the Blocking GOOSE application for the tie breaker bay (BT) and incomer bay A (IncA), the Breaker Failure GOOSE application between BT and incomer bay B (IncB), and MMS control over the overcurrent function parameters of the IED at the IncB bay.**

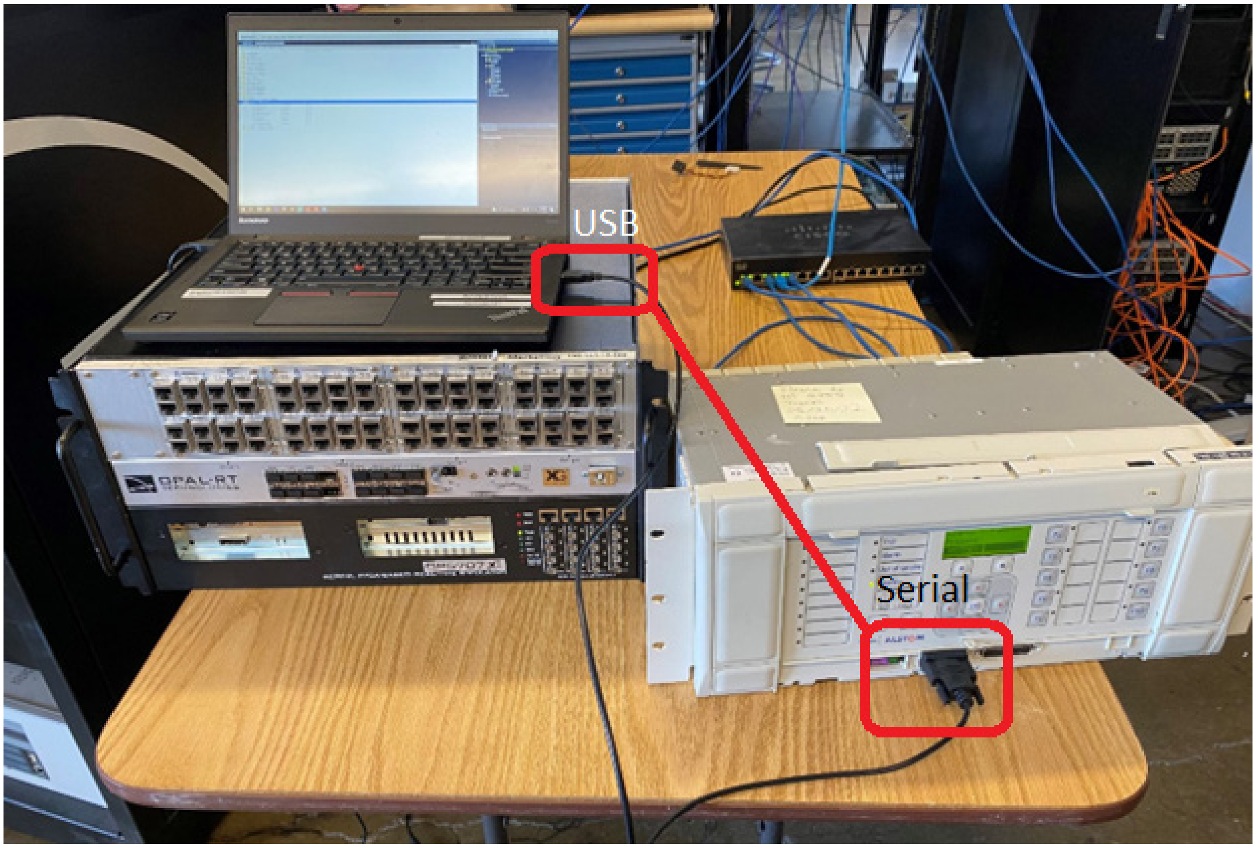


- **SCD file creation: GOOSE applications are configured along with report control blocks.**
- **Implementation of single line design in HYPERSIM: By leveraging HYPERSIM's capabilities for configuration and protection logic design and using data points from control blocks from an SCD file in the model itself, the single line diagram and protection logic containing protective relay components, instrument transformers, and breaker mechanisms are integrated in the model. Therefore, the substation automation system including the three chosen bays, GOOSE applications, MMS Reports, and Sampled Value streams is fully implemented in HYPERSIM and ready for real time simulation and with great attention to detail the design ensures robust performance under various fault scenarios.**



- **The culmination of this design process enables rigorous testing of substation scenarios, such as reverse blocking, breaker failure, or MMS control scenarios. Through both software-in-the-loop and hardware-in-the-loop testing, which includes a P444 Alstom IED as replacement for the virtual IED at the bay BT, the system's efficacy is validated for each scenario and performance is reviewed to ensure reliability in real work applications.**

The integration of the IEC 61850 standard and simulation tools like HYPERSIM represents a significant step toward efficiency and reliability in substation automation system design. With a focus on interoperability and performance, this approach supports the evolution of smarter and more resilient power systems, contributing to sustainable progress in the



electric power industry.

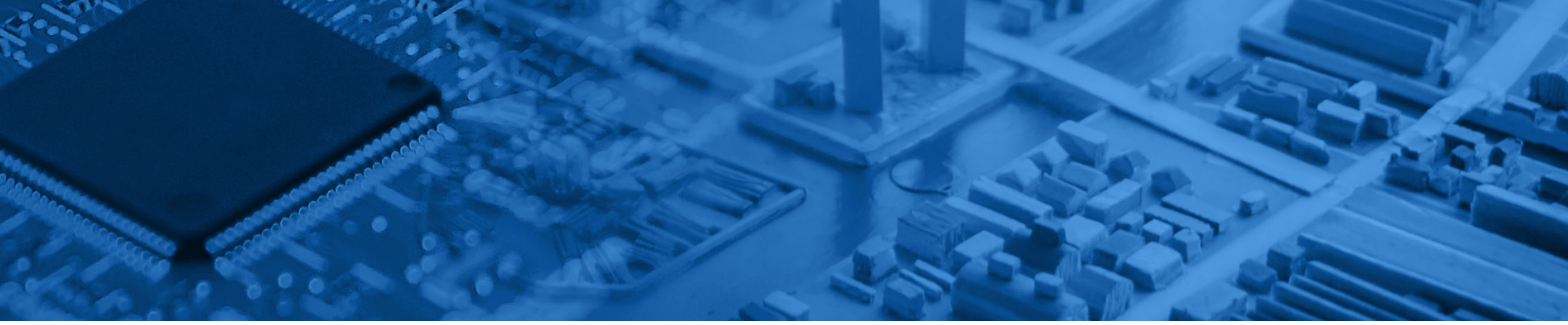
Hardware-in-the-Loop

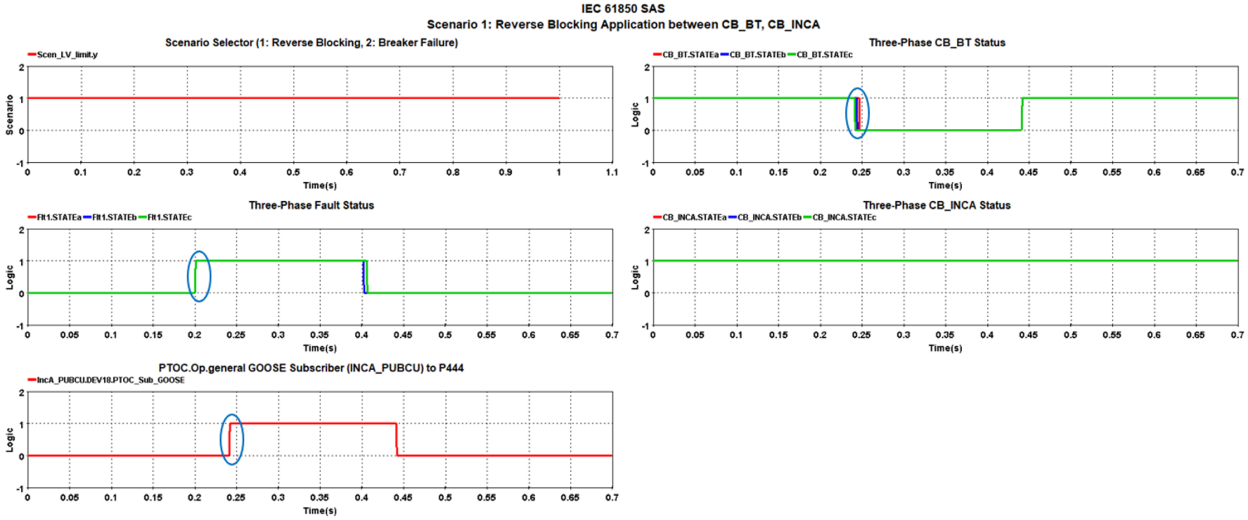
Alstom relay P444 is used to replace the virtual IED at the bay BT. By configuring the IED with its own IED configuration tool, which is Agile S1, we have made GOOSE applications which fit the scenarios for reverse blocking and breaker failure. By communication with the IED through Sampled Values and GOOSE applications, the IED can receive measurements from its assigned bay in the model and transmit status of overcurrent function back to the simulator which will enable different scenarios. The picture shows the connection between the simulator, Alstom IED and a laptop.

The following results are from the different protective scenarios. Since this relay does not have an impact on the IED from bay IncB, scenario 3 results are not shared.

REVERSE BLOCKING:

- **Scenario 1 is selected.**
- **Fault occurs at 0.2 s.**
- **Overcurrent function at the IED at bay BT (Alstom P444) operates close to 0.24s.**
- **GOOSE message is being published to IED at bay IncA. It is the overcurrent function output.**
- **Breaker opens at bay BT at approximately 0.24s.**
- **IED at IncA cannot send a trip signal to open breaker at IncA. The overcurrent output is blocked.**



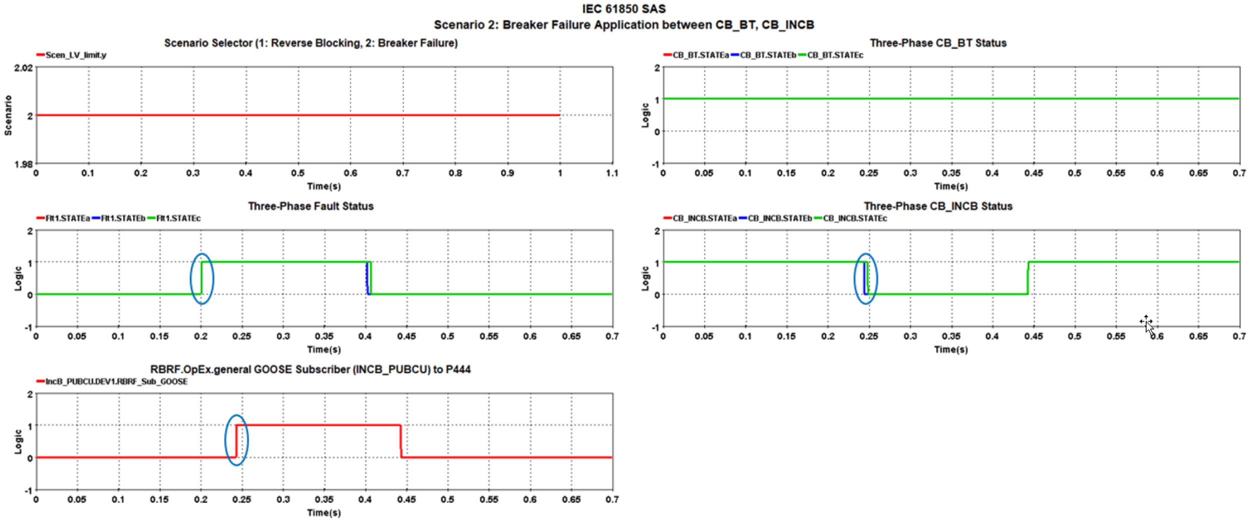


IEC 61850 SAS

Scenario 1: Reverse Blocking Application between CB_BT, CB_INCA

BREAKER FAILURE:

- Scenario 2 is selected.
- Fault occurs at bay BT at 0.2 seconds.
- Overcurrent function at the IED at bay BT operates at 0.25s which is the Alstom P444 IED.
- GOOSE message is being published to IED at bay IncB. It is the breaker failure function.
- Breaker at BT fails to open despite the overcurrent function operating as intended.
- IED at IncB sends a trip signal to the breaker and opens it at 0.25s. ■



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Scenario 2: Breaker Failure Application between CB_BT, CB_INCB

Check out the full example here:

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