success story

Implementation of centralized protection schemes using an HIL setup

A success story with the University of Vaasa

University of Vaasa

The University of Vaasa is an international, multidisciplinary research university focused on sustainable business, energy, and society. Guided by its strategic focus areas – energy transition, business renewal, and societal transformation – it works closely with industry and society in the Nordic region's largest energy technology hub to create impactful solutions. Its vision is to be internationally recognised as a high-impact research university that contributes to global scholarship and offers transformative education grounded in excellence, equality, and inclusion. With a mission to generate and share knowledge for a sustainable future, the University advances clean energy, responsible production, and sustainable economic growth through research, innovation, and partnerships. Its core values of courage, community, and responsibility shape a culture of innovation, inclusivity, ethics, and societal impact.

Scalable solutions

As global grids evolve to accommodate higher renewable penetration, ensuring reliability, selectivity, and rapid fault isolation becomes paramount. Grid operators, therefore, seek scalable solutions that not only mitigate these risks but also reduce lifecycle costs and enhance operational efficiency. This narrative draws from pioneering research conducted at the University of Vaasa, Finland, in collaboration with international companies and experts.

Grid resilience and sustainability

By leveraging digitalization, virtualization, and advanced communication standards, this effort transforms theoretical concepts into practical implementations, yielding measurable benefits in grid resilience and sustainability. Supported by initiatives like the CIRP-5G and Smart Grid 2.0 projects funded by Business Finland, the work addresses these imperatives through the development and hardware-in-the-loop validation of centralized protection and control (CPC) systems.

The challenge for IBR integration

In an era defined by the urgent push toward decarbonization and the integration of renewable energy sources, power systems face complexities. Traditional protection schemes, designed for unidirectional power flows in passive grids, struggle with the dynamic behaviors introduced by inverter-based resources (IBRs) such as wind turbines and solar photovoltaic systems. These challenges manifest as reduced short-circuit power, protection blinding, false tripping, and suboptimal coordination under varying topologies, issues exacerbated in networks operating near thermal and voltage limits.

Virtualized CPC (VPC)

The foundation of this success lies in the evolution of computer relaying, a concept tracing back to 1969 when early digital computer-based relaying research demonstrated the potential for consolidated fault detection. Fast-forward to the present: the maturation of IEC 61850 standards, high-speed 5G networks, edge and cloud, and artificial intelligence (AI) has enabled virtualized CPC (VPC), a software-driven paradigm that consolidates bay-level functions into high-performance platforms. Unlike distributed schemes requiring numerous physical relays, VPC centralizes data acquisition, processing, and decision-making within a substation, using time-synchronized measurements.

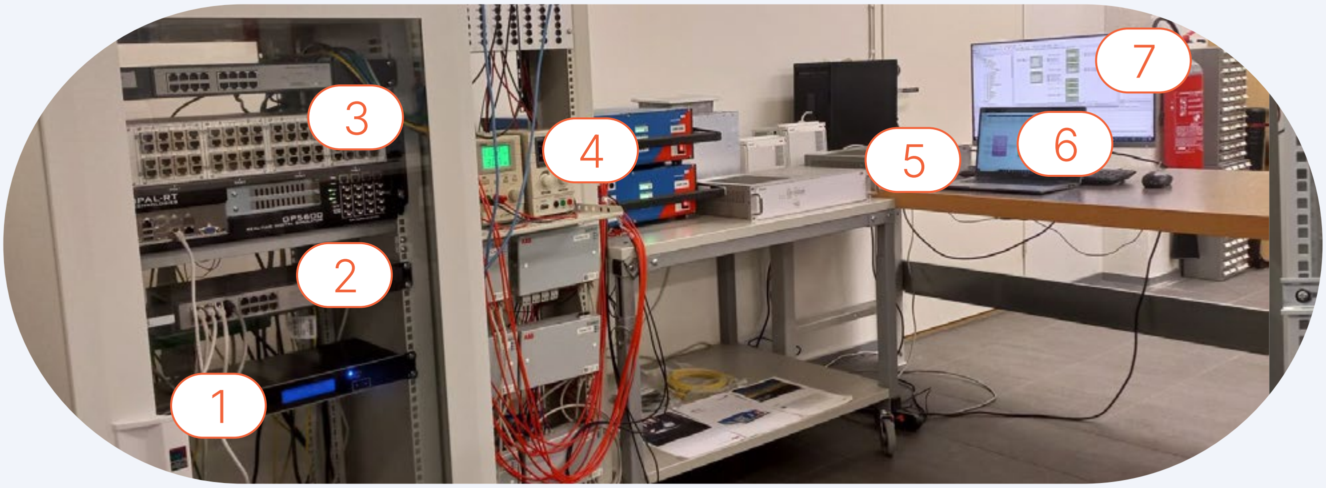
FREESI-lab

The FREESI (Future Reliable Electricity and Energy Systems Integration) laboratory serves as a pivotal component of the University of Vaasa's VEBIC (Vaasa Energy Business Innovation Center) research platform, focusing on energy and sustainable development. FREESI is a smart grid laboratory that facilitates advanced research into flexible energy systems, grid integration of inverter-based distributed energy resources (DER), and power system protection. Equipped with state-of-the-art facilities, including the OPAL-RT OP5600 real-time simulator, CHIL (Control Hardware in the Loop) capabilities, and a unique setup for IEC 61850-based protection, automation, and communication (PAC) systems, the laboratory supports cutting-edge studies in relay protection and microgrid modeling. As a member of DERlab, an international network of leading research laboratories, FREESI underscores its global relevance.

Centralized protection and control

Centralized Protection and Control (CPC) is defined by IEEE WG 15 as ‘a system comprised of a high-performance computing platform capable of providing protection, control, monitoring, communication and asset management functions by collecting the data those functions require using high-speed, time synchronized measurements within a substation’. CPC is not a novel concept, but the arrival of affordable and high-speed servers, improved communication links, and the maturation of standards such as IEC 61850 have paved the way for more effective power system protection. As a result, centralized protection can now play a key role in the future active distribution networks that will operate closer to their voltage and thermal limits. Like the adoption of prior innovations in power system protection, virtualization and centralization are likely to encounter resistance, necessitating time for widespread acceptance. Nevertheless, established commercial off-the-shelf technologies and standards have laid a robust foundation for this evolution.

HIL innovations

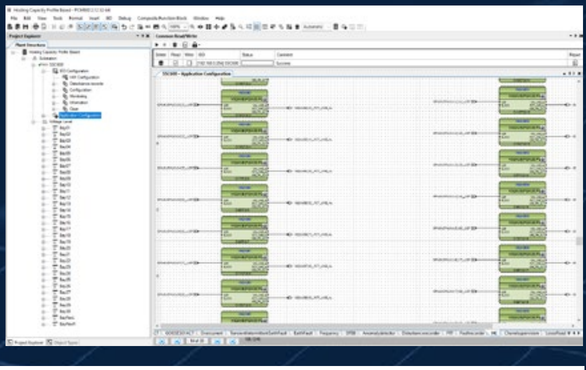


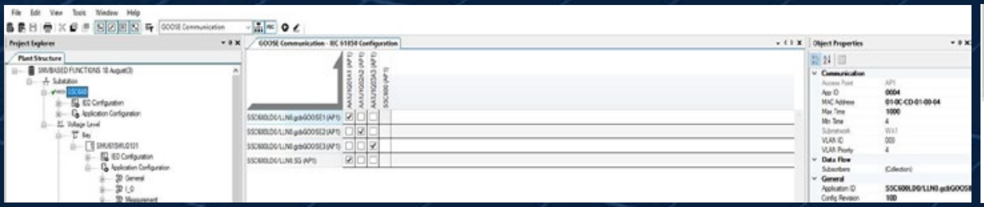
1. Reason RT430 GNSS Precision-time clock (GE)
2. Ethernet Switch
3. OPAL-RT (OP5600)
4. SMU615 (Merging Unit)
5. SSC600 (Centralized protection and control device)
6. System for Modeling in MATLAB and RT-LAB
7. System for IED Configuration (PCM600)

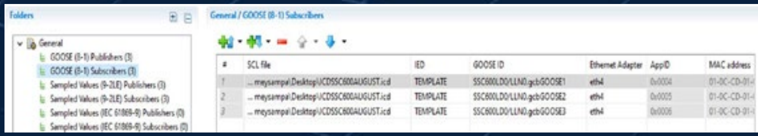
The true measure of success emerged in the laboratory, where a comprehensive HIL setup as shown below brought these innovations to life. The HIL setup developed during Business-Finland funded CIRP-5G project. Using OPAL-RT real-time simulations, ABB's SSC600 centralized protection device, capable of protection up to 30 feeders, and REX640 relays, we configured an IEC 61850-compliant architecture. Merging units (SMU615) digitized analog voltage and current signals from feeders, transmitting Sampled Values (SVs) at 4 kHz rates and GOOSE messages for commands and control, all devices synchronized via Precision Time Protocol (PTP) Version 2. The testbed replicated a realistic distribution network as well as inclusion of real-time simulator and centralized relay. OPAL-RT simulators can generate SVs directly, emulating real-time dynamics. Most protection functions including directional overcurrent (67), line differential (87L), and non-directional overcurrent (51P), intermittent earth fault, LVRT, and frequency functions have been studied during the project. Rigorous case studies validated the operation of the whole system.

Configurations

After implementation of setup extensive configuration conducted to test different use cases and functionalities. And the technical and engineering manual of SSC600 and SMU 615 have equipped us with required knowledge. Most of the required settings are mentioned in references [1] and [2]. Some of the required steps are also shown below figures.





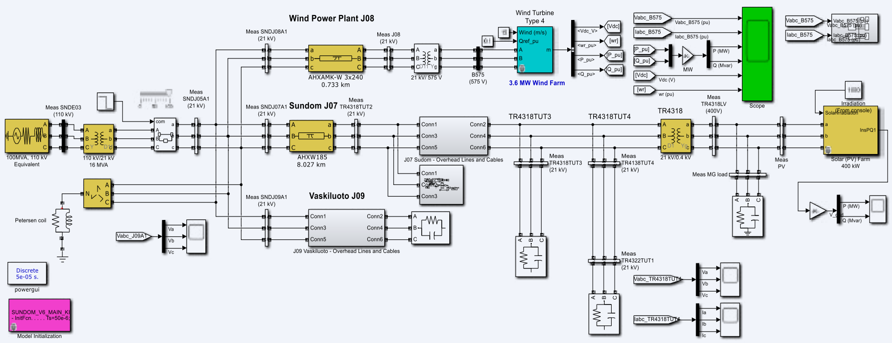


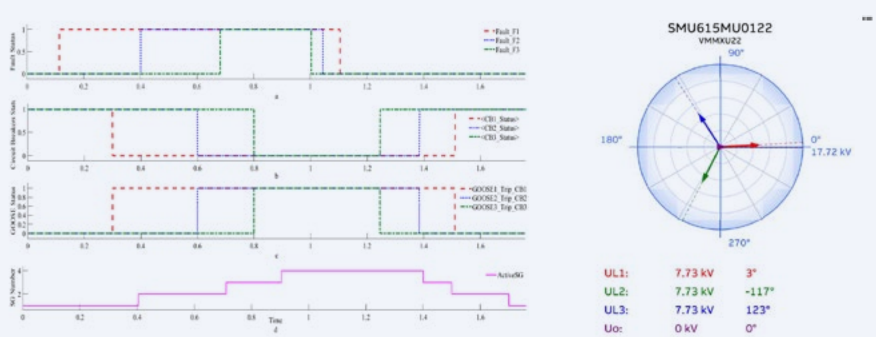
1. M. Pashaei, K. Kauhaniemi and H. Laaksonen, «Implementation of Adaptive Centralized Protection Scheme in Active Networks with a HIL Setup,» 2024 International Conference on Smart Energy Systems and Technologies (SEST), Torino, Italy, 2024, pp. 1-6, doi: 10.1109/SEST61601.2024.10694251.

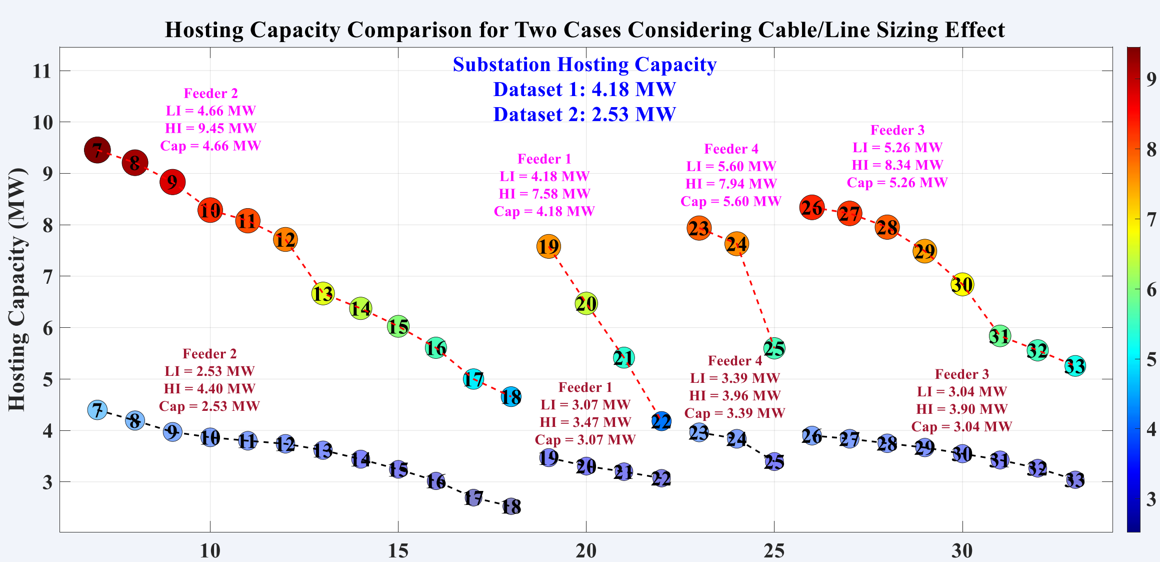
2. Meysam Pashaei, et.al, "Real-time hardware-in-the-loop approach for adaptive centralized protection schemes using clustering algorithms,Expert Systems with Applications, 2024.

Objective and result

The main objective of developing this setup was to research system-wide approaches and to develop new functionalities that traditional protection schemes are incapable of providing. The goals include implementing adaptive protection schemes and introducing new wide-area monitoring and control features, such as blocking local ROCOF during system-wide disturbances, as well as exploring the use of 5G communication and R-GOOSE. Feasibility study of hosting capacity analysis using sampled values was also conducted in one of the projects. Some of the results related to adaptive protection for the following test system and the IEEE 33-bus test system are shown in the figures below.







Conclusion

The University of Vaasa's implementation of centralized protection schemes using a Hardware-in-the-Loop (HIL) setup demonstrates its leading role in advancing future-oriented, sustainable energy systems. By combining digitalization, IEC 61850-based communication, real-time simulation, and collaboration with industry partners, the University has successfully transformed theoretical protection concepts into validated, practical solutions. The FREESI laboratory, as part of the VEBIC research platform, has been a cornerstone in enabling this progress, providing a world-class environment for testing adaptive protection, wide-area monitoring, and hosting capacity analysis. This work proves that centralized protection systems are not only feasible but also capable of addressing the emerging challenges brought by inverter-based distributed energy resources and evolving grid requirements. The results achieved through Business Finland-funded projects (such as CIRP-5G and Smart Grid 2.0) highlight the University's ability to contribute impactful research to industry, enhance power system resilience, and support the global transition towards cleaner and smarter energy networks.

> We used the OPAL-RT system to simulate up to 30 sampled value streams, demonstrating its suitability for large and complex substation environments. The platform's built-in IEC 61850 example projects are particularly helpful as starting points for those new to the topic, providing practical guidance for implementing GOOSE and Sampled Values communication. Overall, OPAL-RT's flexibility, scalability, and supportive ecosystem make it an excellent tool for developing and testing centralized protection schemes.

Meysam Pashaei
University of Vaasa
meysam.pashaei@uwasa.fi

MEYSAM PASHAEI

KIMMO KAUHANIEMI

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