

Energy

Power Grids

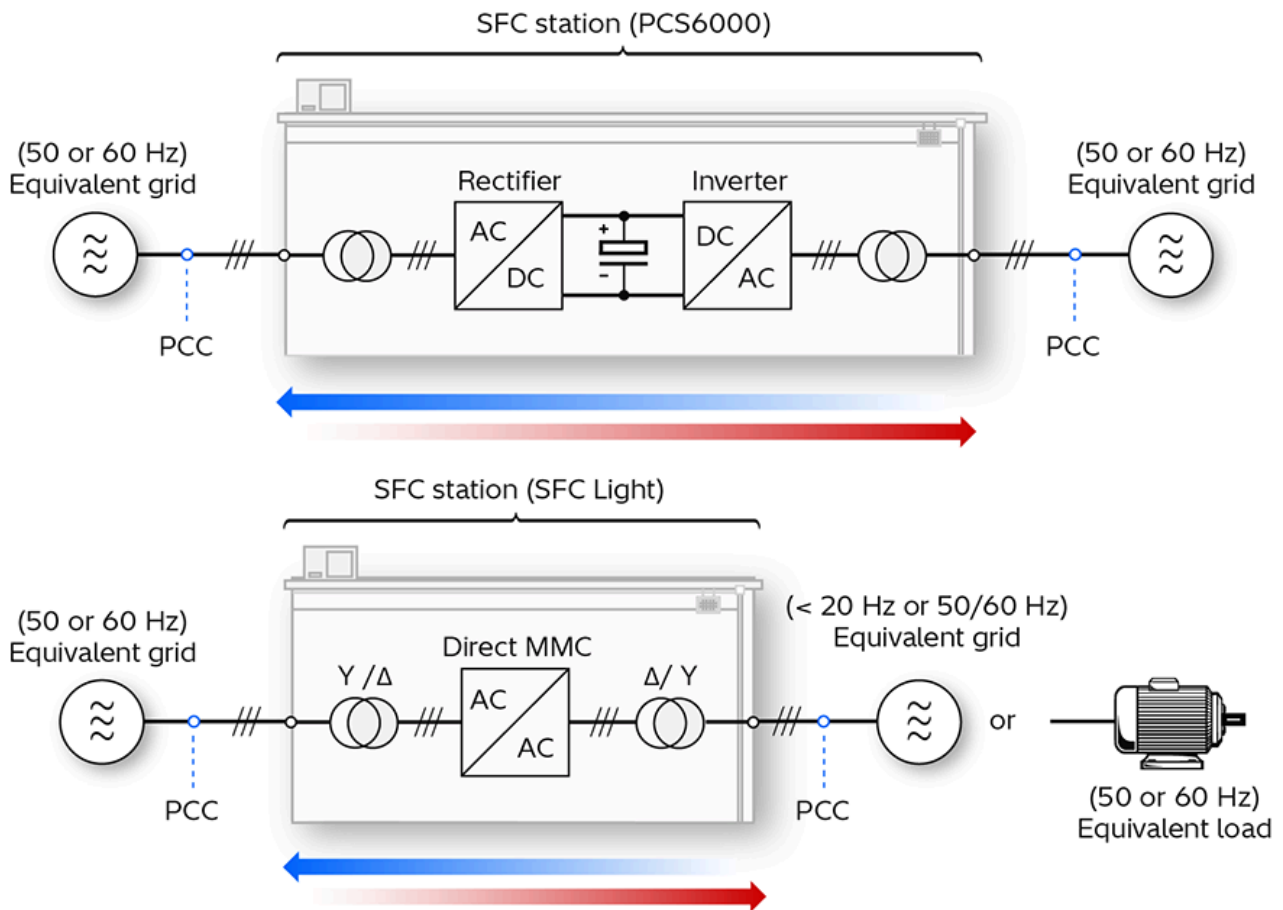
May 28, 2026

Energy

1. Towards More Sustainable and Interconnected Power Systems by Establishing Reliable Grid Intertie with Static Frequency Converters

The paper showcases different static frequency converter (SFC)-based grid intertie solutions to facilitate the realization of a highly interconnected and flexible—thus, versatile—electrical infrastructure, able to address the challenges of today's power systems. Such solutions assure a seamless connection between sources and loads operating at different frequency and voltage levels. The presented SFC topologies, along with the provided control capabilities and ancillary services, are technology enablers to integrate decentralized equipment, maximize the interoperability within a large infrastructure, and realize loss-optimized energy links. This will pave the way to more cost-effective and environmentally friendly electrification for modern power systems.

(Hitachi Energy Ltd.)



[1] Simplified Block Schemes of SFC-based Grid Intertie between Different Grids for Indirect (PCS6000) and Direct (SFC Light) Converter Configuration, Respectively

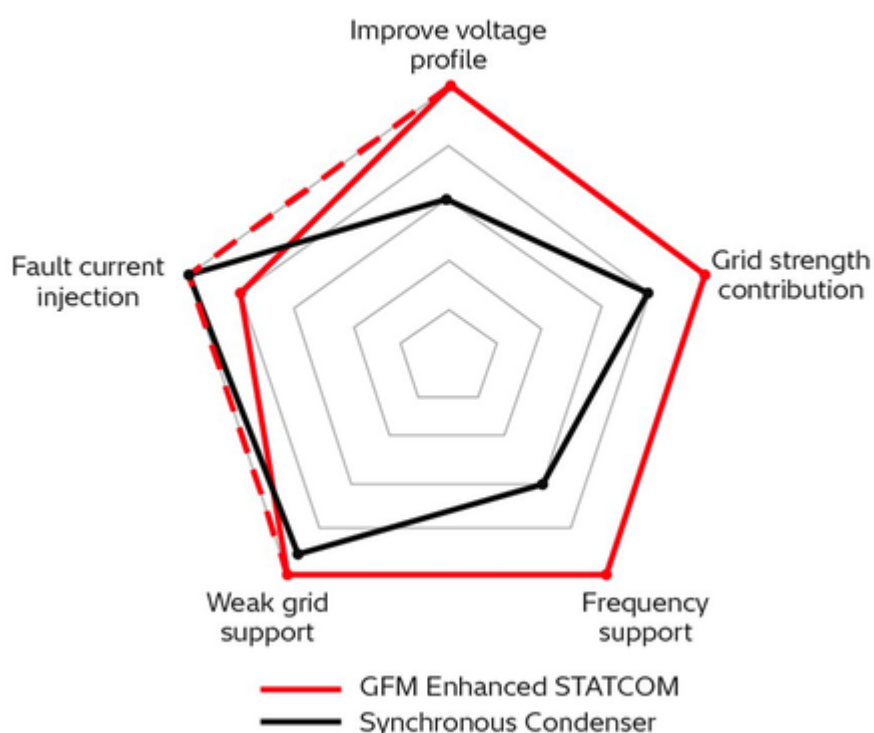
PCC (Point of Common Coupling)

2. Stability Enhancement in Weak Grids with High Renewable Penetration: Synchronous Condenser vs. Converter-based Technologies

Integrating renewable energy sources into weak grids presents significant challenges for maintaining grid stability. Several essential services are required to ensure a stable and secure grid, including voltage support, fault current injection, system strength support, frequency control, and inertia support. Synchronous condensers, with their inherent inertia and fault current capabilities, have been traditional solutions for grid stability. Recent advancements in power electronics and control structures have led to the development of various technologies aimed at enhancing power grid stability.

Static synchronous compensators (STATCOM) and Enhanced STATCOM, which can provide active and reactive power support, show considerable promise. These technologies offer grid-forming (GFM) capabilities that can significantly improve the stability of weak grids with high renewable penetration. Advancements in STATCOM and Enhanced STATCOM technologies offer enhanced control tunability, controllable damping, and immediate response to grid perturbations. This paper investigates the comparative performance of synchronous condensers versus STATCOM and Enhanced STATCOM with GFM capability in providing services and enhancing the stability of weak grids with high renewable penetration.

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[2] Summary of Capabilities of Technologies: GFM Enhanced STATCOM, Synchronous Condensers

3. Ultrasonic Testing of Glass Fiber-reinforced Polymer Composites Used in High-voltage Insulating Components

Surge arresters are designed to protect the insulation of gas-insulated switchgear, cables and connected devices from transient overvoltage. The active elements of Hitachi Energy surge arresters, serially connected metal-oxide varistor blocks, are compressed during the manufacturing process with the help of insulation elements (so-called loops)

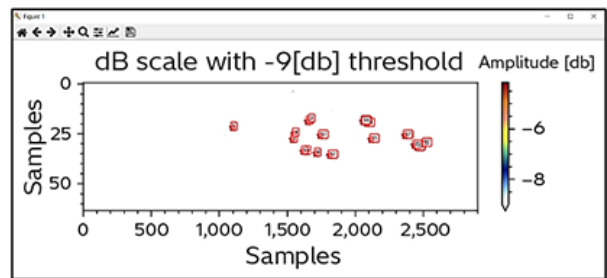
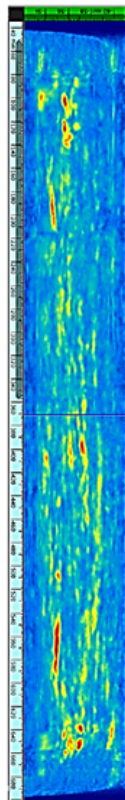
made of glass fiber-reinforced polymer composites. To meet customer demand for products that are “partial discharge-free for life,” insulating materials used, especially composite loops, must be assessed for structural defects (voids, cracks, delamination).

The research conducted has shown that the expensive computed tomography technique, currently used to examine composite loops, can be successfully replaced by a significantly cheaper and faster ultrasonic testing procedure.

The project resulted in the development of a fully functional prototype solution for automated ultrasonic scanning and evaluation of composite products. It integrates a hardware platform for water-immersive total focusing method and a software package designed to process scan data and classify components, distinguishing good-quality parts from faulty ones.*1

(Hitachi Energy Ltd.)

*1. Ziaja-Sujdak et al. "Ultrasonic Testing of Glass Fiber-Reinforced Polymer Composites Used in High-voltage Insulating Components," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 32, no. 1, pp. 83-91, Feb. 2025.



Number of defects found: 41

Decision: Red (noGO)

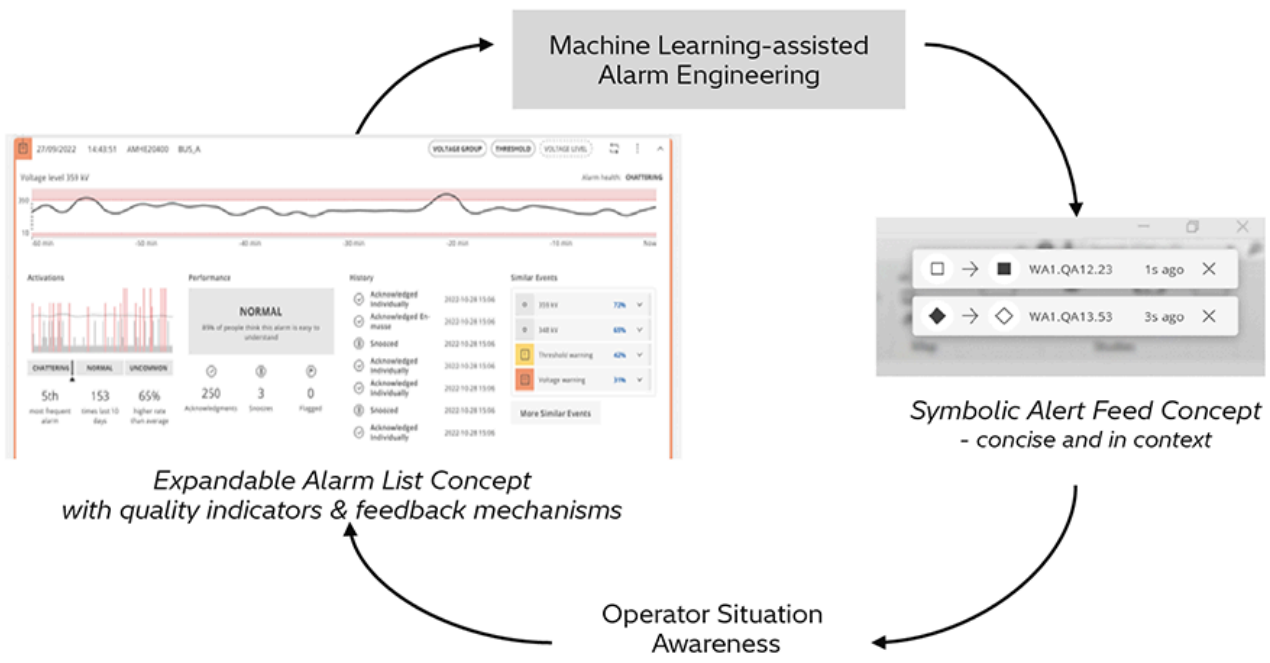
4. Operational and Organizational Alarm Management Support by Integrating Machine Learning, Metrics, and User Interface Design

Alarms in large SCADA systems such as electric networks are not only essential, but also a source of risk and work. The quantity and rate of alarms that grid operators must handle is increasing with network expansion, transmission and distribution system coordination, and adoption of more verbose equipment.

Methods for quantifying alarm system performance as well as managing alarm quantity and quality using machine learning (ML) were presented in recent CIGRE conferences. In the 2025 International Symposium, applications of these methods to support real-time operations and inform organizational alarm management processes were illustrated. Two conceptual user interfaces, a) expandable alarm list and b) symbolic alert feed, embody ways to give useful alarm analytics to real-time operators, provide user feedback mechanisms to report alarms, and enhance the effectiveness of alarm change management processes.

Data-driven ML is a promising approach to managing alarms, especially if implemented to benefit both real-time operators and back-office engineers. Supporting win-win 'virtuous cycles' of knowledge sharing and alarm quality improvement can drive systemic change.

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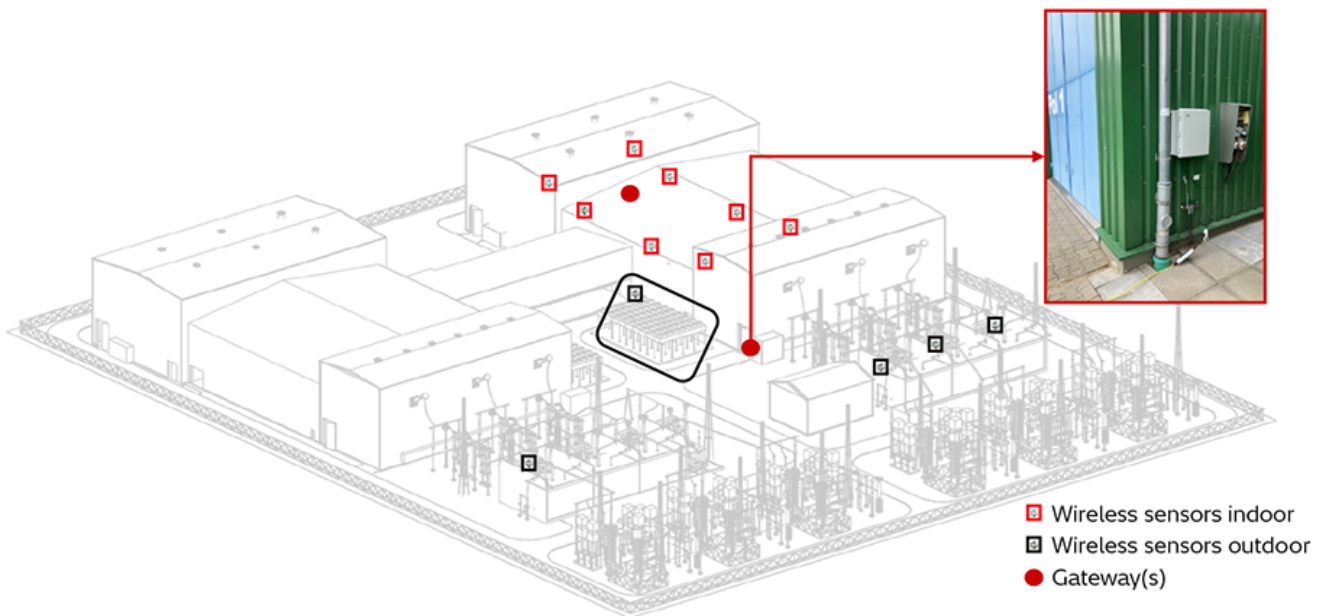
[4] Conceptual User Interfaces Enabling Interaction between Engineering and Operations Alarm Management Processes

5. Enhanced Condition Monitoring with Wireless Sensor Networks in HVDC Stations

Modern critical infrastructure, such as high-voltage direct current (HVDC) stations, demand advanced digital condition monitoring, reliable operation and rapid troubleshooting capabilities to keep reliable operational uptimes. HVDC stations are usually uncrewed, there is restricted access to service personnel, and components are exposed to harsh environments, such as high electromagnetic fields. Deployment of additional wired sensors for temporary measurement campaigns is cumbersome and costly.

With the progress of wireless technologies in the last decades, wireless sensor networks have been positioned as a valuable alternative for temporary deployments in multiple domains. Hitachi Energy Research has designed a wireless sensor network proof of concept for an HVDC station in Germany. The pilot aims to demonstrate the feasibility of wireless sensor monitoring in different environments of the station, both indoors and outdoors. In both environments, the pilot has shown promising performance and has proven technical feasibility of wireless sensor networks in HVDC stations. The work was first presented at ETG Kongress and will be published at CIGRE 2026 in Paris.

(Hitachi Energy Ltd.)



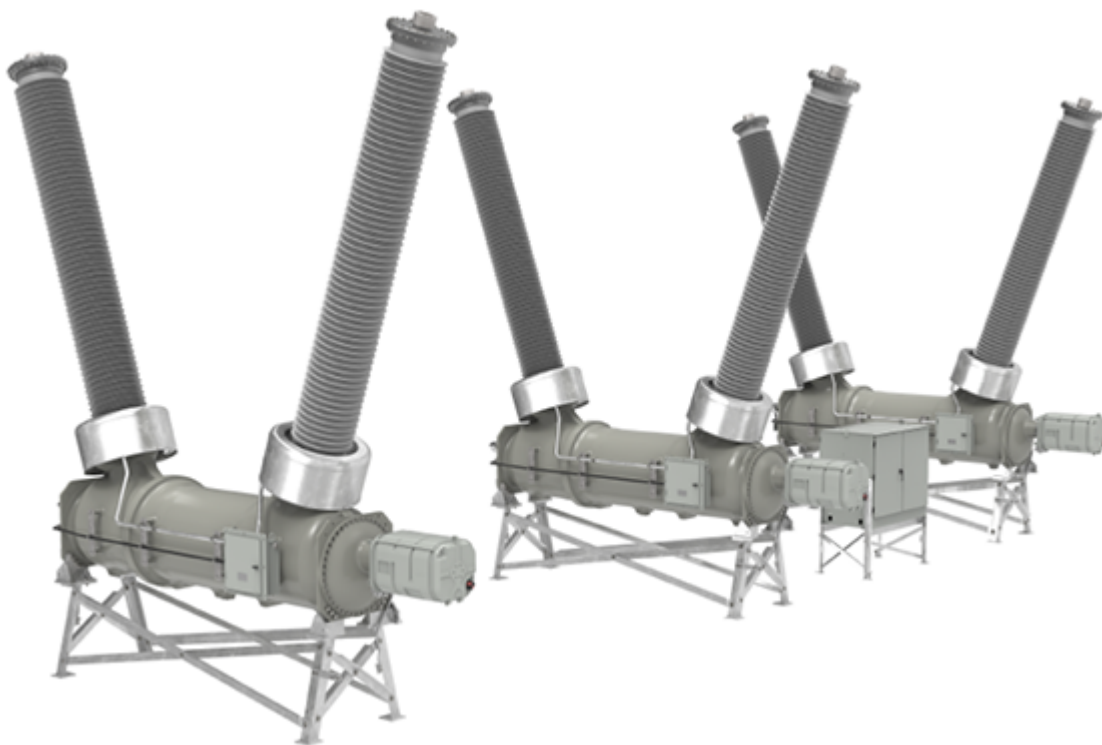
[5] HVDC Wireless Sensor Network (WSN), Outdoor Setup

6. Development of a 550 kV 63 kA SF₆-free High-voltage Metal-enclosed Circuit Breaker

To address climate change, the power industry is moving toward SF₆-free switchgear, replacing a strong greenhouse gas with a global warming potential (GWP) of around 23,400. At CIGRE 2024, the first 550 kV, 63 kA SF₆-free circuit breaker was introduced and tested for dead-tank breaker (DTB) and gas-insulated switchgear (GIS) applications. It uses a CO₂/O₂/C₄-FN gas mixture with electrical properties similar to SF₆, allowing comparable dimensions, and is provided with optional pre-insertion resistors (PIR). Each pole features two arcing chambers in series and a proven spring-hydraulic mechanism. A platform design maximizes common parts between DTB and GIS, improving efficiency and reliability. The breaker passed rigorous type tests, including chopped-wave impulse tests according to IEEE standards, confirming strong insulation margins against severe transients. Independent labs validated performance and compliance with industry standards.

This achievement demonstrates scalability of the CO₂/O₂/C₄-FN gas mixture technology up to 550 kV, following earlier applications at 145–420 kV. Utilities now have interchangeable solutions with existing SF₆ equipment, accelerating the transition to sustainable high-voltage switchgear.

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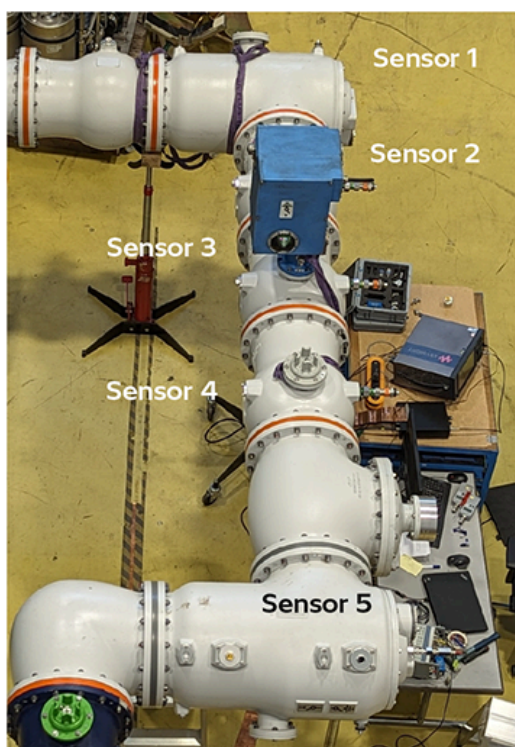
[6] 3D Rendering of 550 kV 63 kA SF₆-free Dead Tank Breakers

7. Partial Discharge Diagnosis of Eco-efficient Gas-insulated Switchgear

To perform diagnostics of gas-insulated switchgear (GIS) regarding partial discharges (PD), the ultra-high frequency (UHF) method is generally applied. Users and manufacturers have ambitious goals to reduce the carbon footprint, and SF₆ alternatives are developed and deployed with this goal in mind. This is a strong motivation to establish similar placement rules for PD sensors and qualification procedures. Compared to SF₆ GIS, the gas pressures are moderately higher in the eco GIS and physical properties of the CO₂/O₂/C₄-FN mixture are somewhat different. This motivated the authors to do a comparative investigation.

The measurement results of detailed investigations prove that it is in principle possible to transfer the results collected from years of experience in the use of UHF diagnosis to eco-gases. This ensures that the results of the laboratory tests on SF₆ systems can also be transferred to equipment of similar geometry using eco-gases. The placement rules established for PD sensors on SF₆ equipment can therefore also be transferred to SF₆-free equipment based on eco-efficient CO₂/O₂/C₄-FN and N₂/O₂/C₄-FN gas mixtures.

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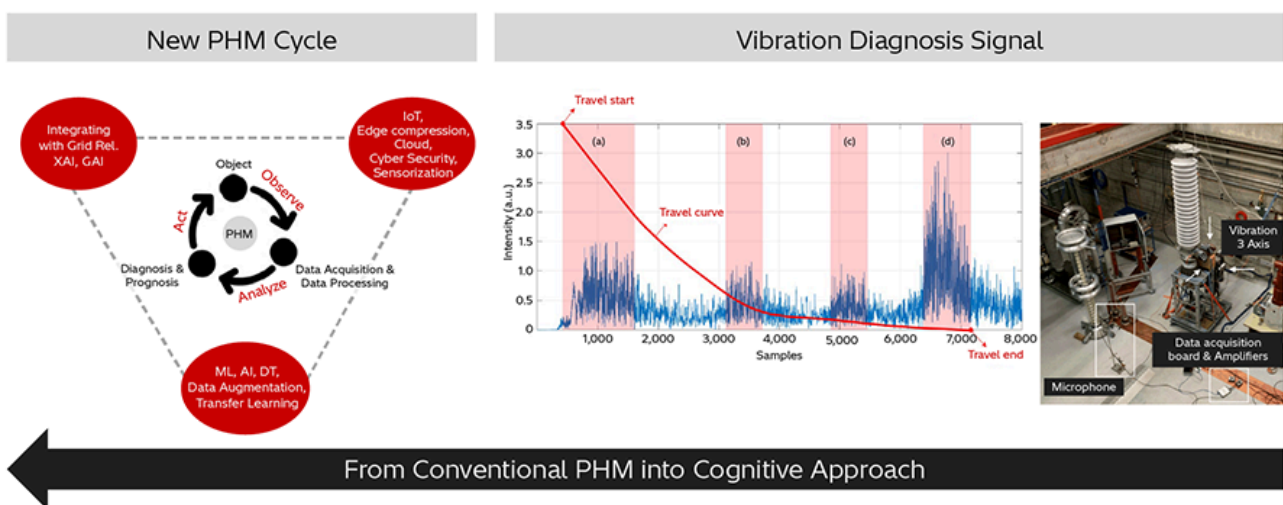
[7] Internal UHF Sensor and Compact Test Set-up for Sensitivity Measurements

8. Digitalization Revolutionizes Asset Management for Smarter, more Efficient Operations for High-voltage Circuit Breakers

High-voltage circuit breakers (HVCB) are vital for maintaining power system stability and continuity. Conventionally, diagnosis and monitoring of HVCBs covering key diagnostic signals – including electrical (such as coil current and contact resistance), mechanical (including vibration and motion), and gas analysis (for gas breakers) – is used to assess breaker condition. Recently, advanced modeling techniques, including artificial intelligence (AI) and machine learning (ML), are being explored to interpret these signals and forecasting failures. The integration of monitoring data into asset management strategies as well as operation can be considered as a new mindset, highlighting its role in optimizing maintenance schedules, extending equipment lifespan, and enhancing grid reliability and resiliency. Recognizing emerging trends such as the role of digital twins in enabling prognostics and health management (PHM) for HVCBs has become increasingly important. It is clear that proactive maintenance supported by continuous monitoring and timely diagnostics is essential to prevent costly outages.

(Hitachi Energy, Ltd.)

Citation: Ali Razi-Kazemi, “Diagnosis and monitoring of high-voltage circuit breakers,” Webinar for IEEE Trans. Dielectric and Insulation (IEEE-DEIS)-Young Professionals, Oct. 2025.



[8] From Past Towards Future on Asset Performance Management of HVCBs

DT (Double Throw), 5D (Five Dimensions), XAI (Explainable AI), GAI (Generative AI), IoT (Internet of Things)

9. Advances in Data-driven Models for Digital Twins of Power Transformers

Digital twins for power transformers integrate sensor data, design parameters, maintenance records, and online monitoring into a real-time virtual representation. Converting this heterogeneous data into usable information relies on physics-based models (thermal equations, aging laws), data-driven approaches (statistical methods, machine learning (ML), deep learning), knowledge-based systems (fuzzy logic, expert rules), or hybrid combinations.

Hybrid models are particularly promising: For instance, physics-informed neural networks (PINN) embed governing partial differential equations (PDE) / ordinary differential equations (ODE) directly into the loss function, achieving higher accuracy with reduced training data for applications like dynamic thermal behavior or cellulose degradation.

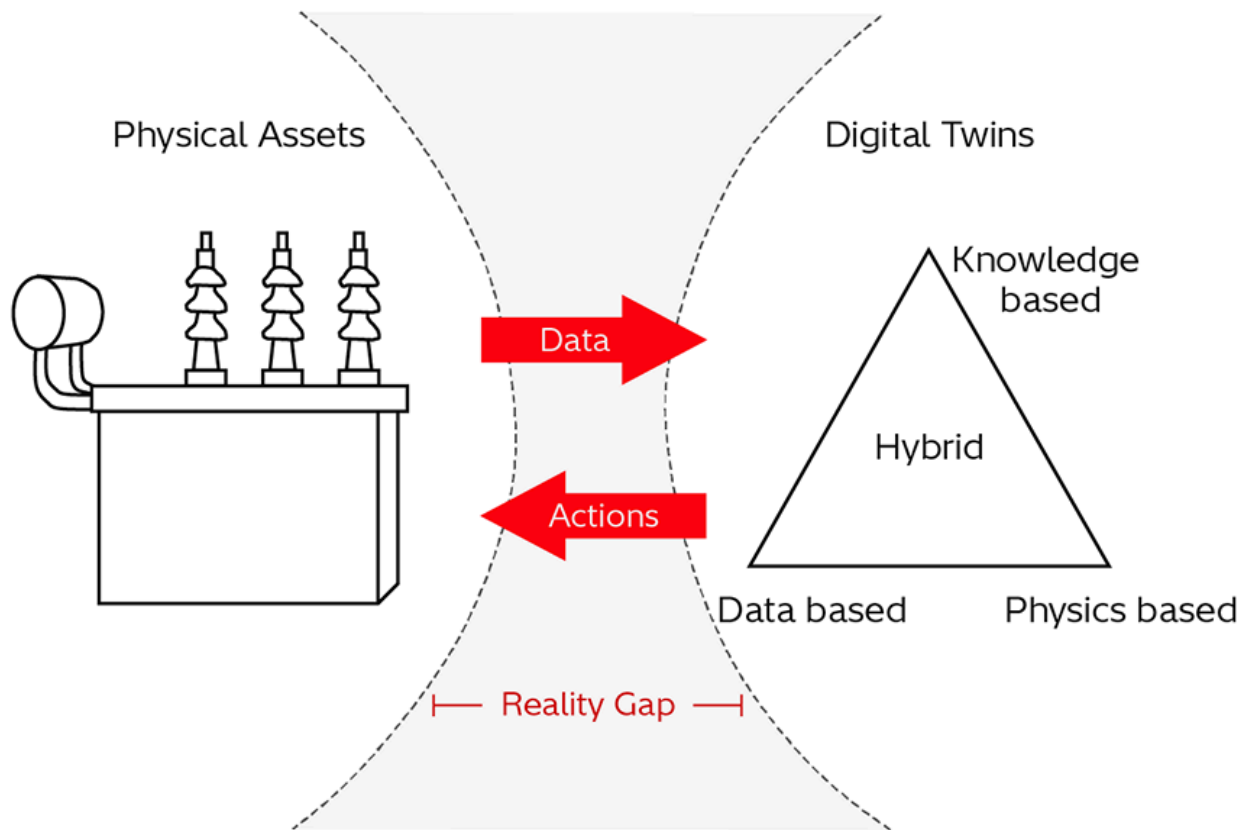
Key application domains for transformer digital twins include:

- (1) dissolved gas analysis (DGA) - based fault diagnosis, where ML overcomes limitations of classical ratio methods
- (2) condition assessment via health indices combining multiple diagnostic parameters
- (3) thermal load management, where combining IEC and IEEE loading guides with continuous parameter adaptation outperforms factory test calibration

Challenges include cybersecurity vulnerabilities, limited failure data for training, and the trade-off between cloud-based and edge deployments.

(Hitachi Energy Ltd.)

Citation: Sruti Chakraborty, Patrick Picher, Alexander Alber, Mauricio Soto, Frederica Bragone, Brian Sparling, "Advances in Data-Driven Models for Digital Twins of Power Transformers," CIGRE Canada, Oct. 2025.



[9] The Digital Twin Concept

10. HVDC GridStar – Digital Platform for HVDC Engineering

High-voltage direct current (HVDC) GridStar is a cloud-based digital engineering platform designed to streamline system study calculations, enabling scalability, faster iterations and consistent data quality. Traditional approaches rely on running calculations on local machines, making reviews and approvals cumbersome, processes unclear and version management challenging, with low reusability and onboarding difficulties. The overall engineering tasks involve several manual transactions and synchronization among engineers requiring senior experts to analyze the results carefully.

GridStar addresses these limitations by integrating projects, studies, and calculations in a collaborative cloud environment with built-in version control, where the user can bind data and reuse workflows as templates. To scale development, study management has been introduced, where expert engineers can upload and manage their own tools to finetune the process. GridStar is already in use by the organization with seven active delivery projects, with more than six additional projects planned.

Future enhancements include an ongoing proof-of-concept initiative for running executables of the electrical simulation tool, power systems computer aided design (PSCAD), and integration support for product lifecycle management (PLM) to validate capabilities, refine configurations, and optimize features for evolving requirements, such as faster tender response and proactive marketing effort. In the future, the GridStar platform could also be used to house machine learning tools and AI agents to explore anomalies, automated iterations, and earlier customer feedback to shorten engineering cycle.

(Hitachi Energy Ltd.)



[10] GridStar Study Canvas with Calculation Control Panel

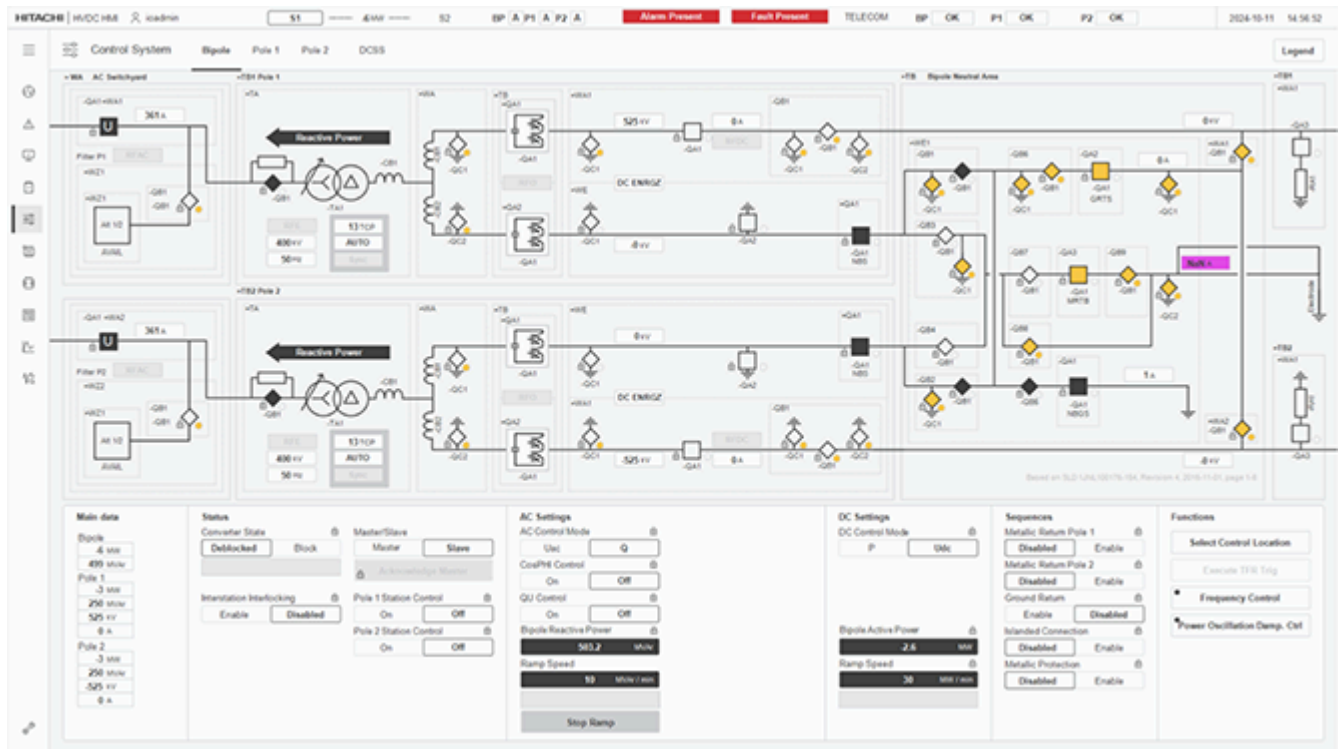
11. InterOPERA – Enabling Multi-vendor HVDC Grids

The EU-funded InterOPERA consortium aims to establish technical standards that enable future multi-terminal, multi-vendor high-voltage direct current (HVDC) systems, addressing not only technical specifications and validation, but also commercial, legal and regulatory frameworks. In collaboration with Transmission System Operators (TSOs), other HVDC vendors, wind turbine manufacturers, project developers and academia, Hitachi Energy contributes to defining interoperability standards.

The project is structured in two phases: Phase 1, completed in 2025, focused on collaboration frameworks and functional specifications; Phase 2 will validate interoperability through software simulations and physical hardware demonstrators.

As part of this effort, Hitachi Energy has delivered both software in loop and hardware in loop (demonstrator) control and protection systems to Réseau de Transport d'Électricité (RTE) and Delft University of Technology (TU Delft) laboratories for multi-terminal multi-vendor simulations. Scheduled for completion in 2027, InterOPERA project is expected to pave the way for multi-terminal HVDC as a cornerstone of sustainable power grids offering a significant opportunity to scale the HVDC market.

(Hitachi Energy Ltd.)



[11] Screenshot of Deblocked Converter Station Setup in RTE Laboratory’s Real-time Simulator in Lyon

12. Hybrid Transformer – Powering the Future of Distribution Grids

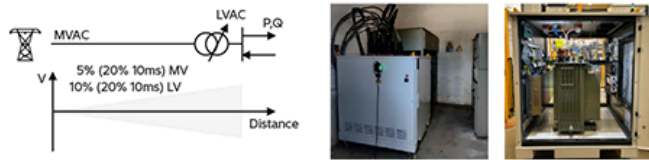
The hybrid transformer (HT) project, a collaboration between Ente Nazionale per l'Energia Elettrica (ENEL) and Hitachi Energy, marks a significant step toward smarter, more adaptive distribution grids. Successfully commissioned this summer at a 250 kW pilot site near Brindisi, Italy, the HT integrates conventional transformer technology with advanced power electronics to address modern grid challenges posed by renewable energy and fluctuating demand. Key features include dynamic voltage regulation, power factor correction, phase load balancing, and harmonic filtering—enhancing stability, efficiency, and power quality. Field tests confirmed its ability to unlock 10–30% additional capacity from existing infrastructure, reducing the need for costly upgrades.

Positioned as a strategic asset, the HT offers a multifunctional, cost-effective alternative to traditional solutions like on-load tap changers and STATCOMs. This innovation represents a cornerstone for resilient, flexible grids, accelerating the energy transition toward cleaner and more efficient systems.

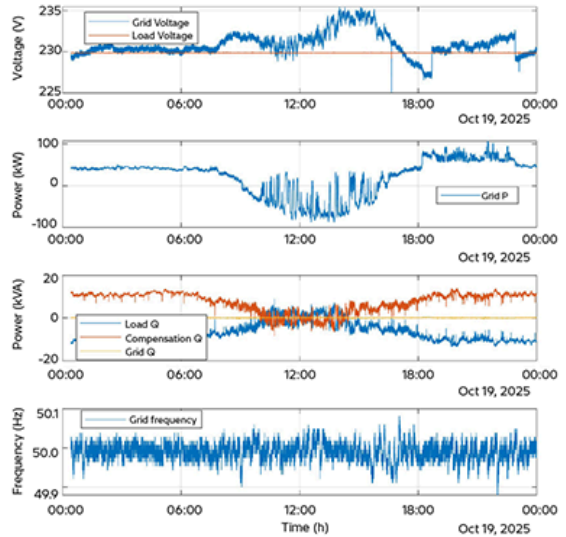
(Hitachi Energy, Ltd.)

Substation:

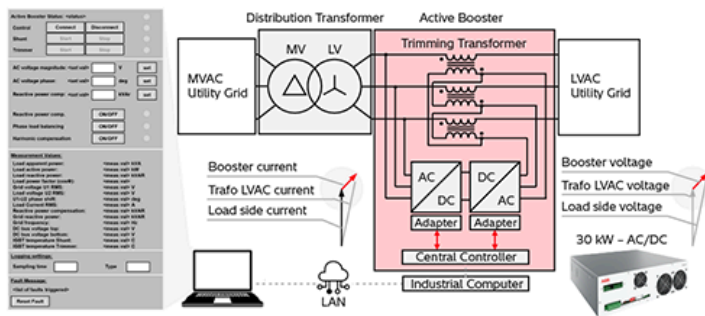
End of MV line with high penetration of solar (100% of DT power)



Sample measurement data plot from HT logger feature



Hybrid Transformer Concept – From User Interface to Power Hardware



[12] Hybrid Transformer: From Concept to Fully Functional 250-kW Field Pilot and Logged Operation Data Showing Control and Monitoring Features

MV (Middle Voltage), MVAC (MV Alternating Current), LVAC (Low Voltage AC), LAN (Local Area Network)

13. Leading the Development of New Solutions for Offshore – Power Transformers Enabling the World’s Largest Floating Offshore Substation (800 MW)

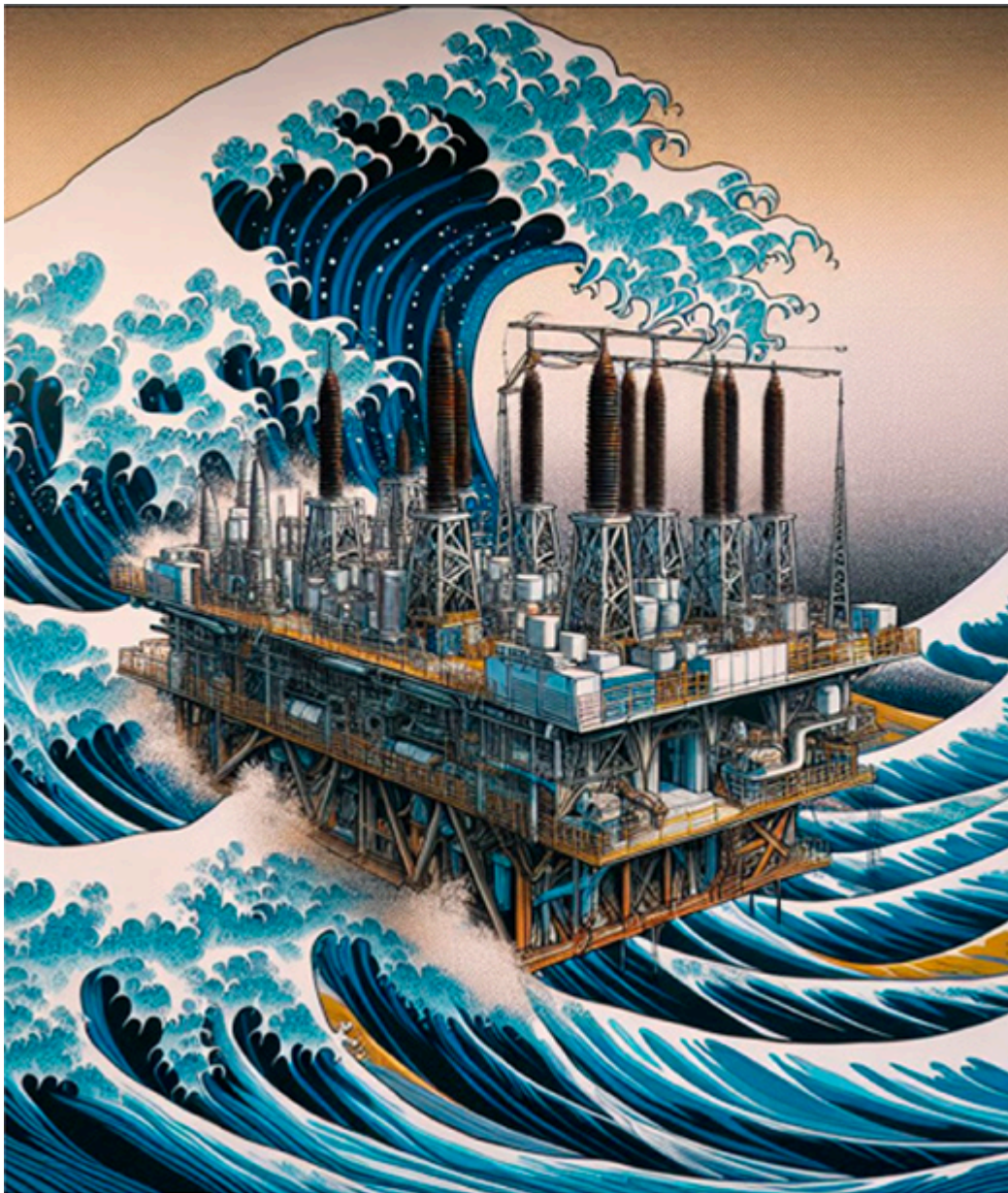
This project addresses the design and validation of power transformers on floating offshore substations (FOSS), focusing on mechanical resilience and operational reliability under extreme marine conditions. It supports Hitachi Group’s clean energy strategy with innovative, reliable transformer solutions that address sustainability and enable offshore integration.

As part of the scope, a combination of advanced simulation and experimental methodologies to evaluate fatigue performance, structural stability, and long-term behavior of anisotropic materials in transformers and on-load tap changers (OLTCs) has been carried out. Additionally, customized servo-driven rigs were built to replicate wave-induced accelerations and high-cycle fatigue.

The application of Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) analyses have helped to better understand the structural stability of the solution, including sloshing phenomena in liquid-filled components.

This project establishes a benchmark for robust FOSS design and positions Hitachi Energy at the forefront of offshore grid innovation.

(Hitachi Energy Ltd.)



[13] Floating Offshore Substation under Extreme Environmental Conditions

14. Taking Sustainability to Next Level – The World’s Largest 765-kV Ester Transformer

Continued growth in electrical energy consumption comes with strong global demand and devotion to more sustainable solutions in power grids. The 765 kV transmission system offers more than three times higher power transfer capacity and more than 50% less power loss compared to the 400 kV system, making it very efficient and sustainable.

Power transformers, as a key element of any transmission grid, traditionally use mineral oil, well known for its excellent properties, as an insulation and cooling medium. More recently, transformer technology innovation has advanced the use of alternative fluids, such as natural ester, with additional fire safety and environmental performance features. Ester-filled power transformers have been operating in transmission networks up to 400 kV for more than ten years.

The outcome of this project is a 250 MVA, 765/400/33 kV, ester-natural cooling, air-natural cooling (KNAN), ester-directed cooling, air-forced cooling (KDAF) single-phase auto transformer, which makes it the world’s largest ester-filled power transformer. Resilient dielectric (Basic Insulation Level -BIL 2100 kV) and thermal design have been developed by several calculation and simulation tools, applying the best know-how which has been verified by extensive tests.

(Hitachi Energy Ltd.)



[14] World's Largest 765-kV Ester-filled Transformer

15. One Size Does Not Fit All – New Compact Optimized Design for On-Load Tap Changers

Designed to Fit. Engineered to Perform. As grids become more dynamic and energy generation plus demand become more distributed than before, the role of on-load tap-changers (OLTCs) has expanded — unforeseen voltage fluctuations drive compact transformer applications that demand high performance in smaller footprints.

The tap-changer type VUBB Compact, an integral part of Hitachi Energy’s proven T-Sync OLTC family, is a new-generation tap-changer engineered to meet this need. It brings the reliability and rugged design of the widely trusted VUBB platform into a smaller, smarter, and more space-conscious solution — ideal for transformer original equipment manufacturers (OEMs) and end-users navigating modern design constraints without compromising operational excellence. A sustainable, future-ready design, including reduced material usage, improved efficiency and reduced carbon footprint, the VUBB Compact supports the sustainability goals of transformer OEMs and grid operators alike. Its design is optimized for long life cycle operation and minimal environmental impact.

(Hitachi Energy Ltd.)



[15] Tap-changer Type VUBB Models

16. Green Insulation Gases Driving Bushing Innovation

Sulfur hexafluoride (SF_6) has for many decades dominated in high-voltage equipment. Initiatives to replace SF_6 with “eco-gases” that can achieve similar performance have been established. These eco-gases allow us to build state-of-the-art high-voltage

equipment on the same principles as SF₆ technology, occupational health-and-safety standards, and gas handling procedures. The most common transformer bushing is resin impregnated paper (RIP), while the technology excels in mechanical robustness due to its solid construction, it is important to select the right compatible material for its application.

With the increasing demand for HVDC applications along with the requirement of net zero carbon emissions, eco-gases have great potential to replace the SF₆ in current state of the art HVDC bushings and GIS. As a result, interfacing components are adapted to fit thanks to extensive qualification processes where understanding of potential material degrading is the key. The solution itself is qualified in such a way that it shall neither impact the performance of the gas nor the surrounding materials.

(Hitachi Energy Ltd.)



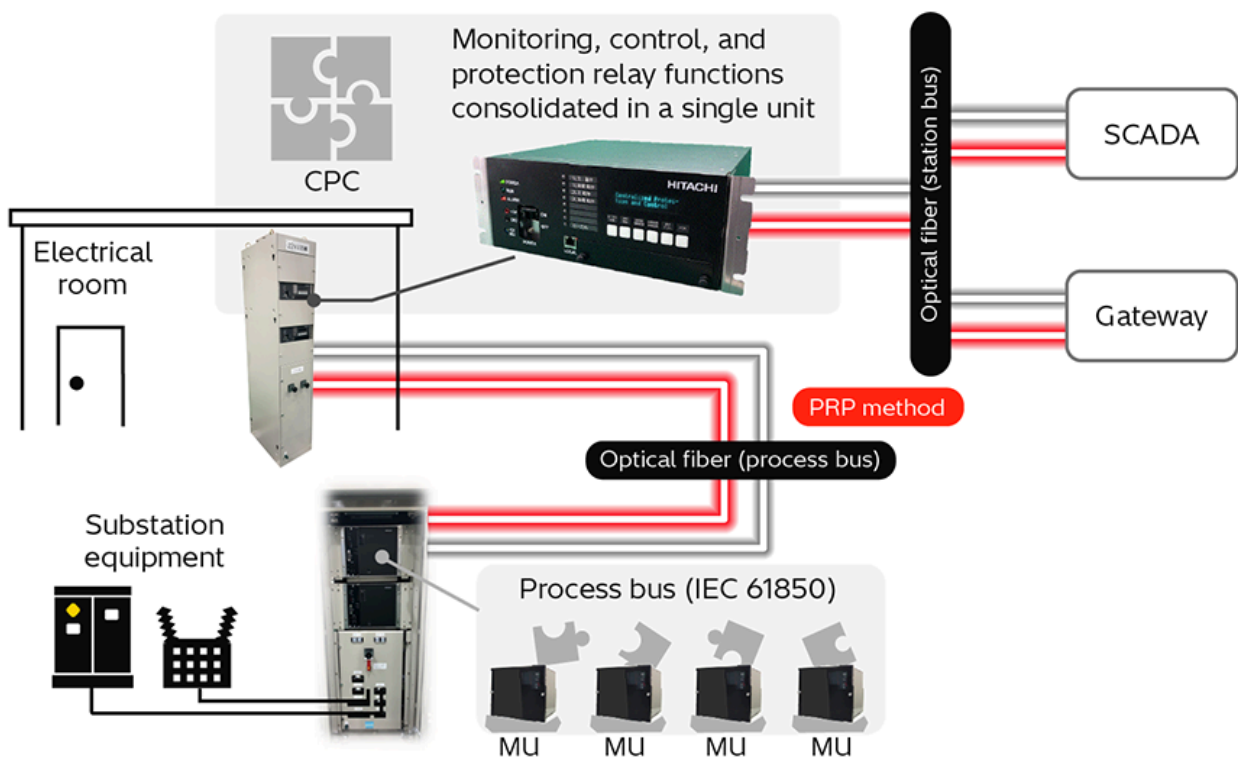
[16] Hitachi Energy Transformer – GIS bushing: GARIP Eco

17. Fully Digital Substation System for East Japan Railway Company Feeder Substations

In November 2025, Hitachi supplied a fully digital IEC 61850-compliant system to railway feeder substations of East Japan Railway Company. The system applies a process bus incorporating sampled values (SV). Moreover, use of centralized protection and control (CPC) enables optimization of the number of units, which include merging units (MUs)

installed adjacent to substation equipment. This use of CPC to consolidate monitoring, control, and protection relay functions also allows for unit redundancy. Likewise, in communications, the parallel redundancy protocol (PRP) allows for a redundant configuration, further enhancing system reliability. In addition to more efficient use of space in indoor electrical rooms, shorter installation time due to fewer metal cables, and enhanced safety, adoption of the system also contributes to the sustainability of substations by improving operation and maintenance and by reducing the overall workload required for future upgrades.

In the future, Hitachi intends to draw on its experience from this project to expand the use of digital substations by electric power utilities and railway operators.



[17] Block Diagram of Fully Digital Substation System

18. Protection and Control System with Resampling

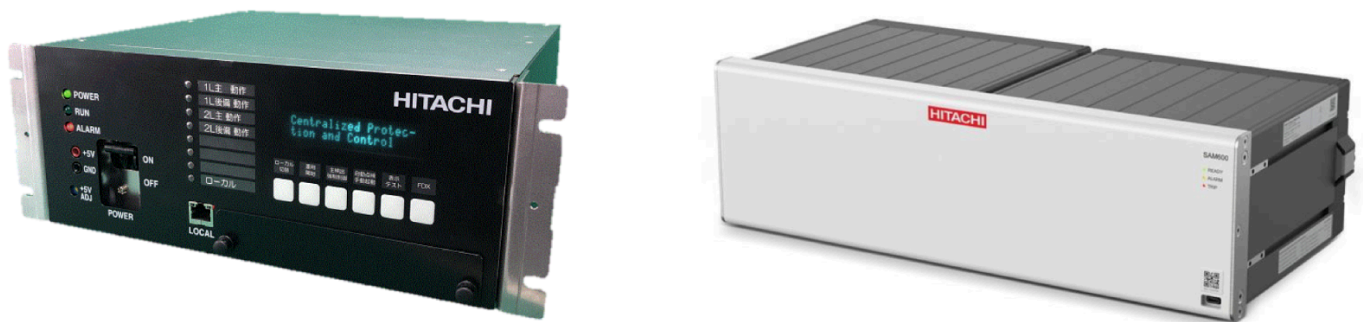
The market for protection and control systems in Japan is seeing rising demand for digital substation systems that comply with the IEC61850 standard. Hitachi has taken a proactive approach to development and has commercialized intelligent electronic devices (IEDs) that are fully digital and equipped with advanced functions. This included

the supply in 2025 of the first system in Japan to provide fully digital protection and control for the entire substation.

Whereas protection and control systems in Japan perform sampling at a 3.75° phase interval, the IEC 61869-9 international standard recommends 4.5°. Accordingly, Hitachi developed the new protection and control system with IEDs that are equipped for resampling to overcome this difference in sampling rate and incorporated an algorithm that works with overseas MUs as well as the existing highly reliable Japanese protection relays.

Testing with MUs made by Hitachi Energy Ltd. demonstrated that the system satisfied the performance requirements for things like relay arithmetic error and operating time, indicating that it has the flexibility for use in multi-vendor installations.

In the future, Hitachi intends to exploit its synergies with Hitachi Energy and increase digital substation sales that draw on its past experience.



[18] Hitachi IED (WTD-STD-C) (left) and Hitachi Energy MU (SAM600 Version 3.0) (right)

19. Multi-terminal Line Current Differential Protection Relay Featuring Selective Judgement

Highly reliable protection relay systems are built by using utility communication networks and by having protection relays communicate via their own transmission formats. However, existing protection relays are not well-equipped to adapt to the trend toward greater use of multi-terminal transmission lines.

Now, Hitachi has commercialized a multi-terminal current differential protection relay Master Terminal Judgement Scheme that uses the IEEE C37.94 communication standard, which is suitable for microwave communications. The new protection relay is suitable for multi-terminal transmission lines, increasing the maximum number of line ends from four

to eight. This system configuration using IEEE C37.94 communications also improves reliability, with benefits that include reducing the total system cost, improving resilience to natural disasters, and mitigating the impact of power system faults. In development testing based on the B-402 electrical standard, the protection relay achieved good results on all tests.

(First installation: April 2025)



[19] Multi-terminal Current Differential Protection Relay