Hitachi Review

May 2025 Technical Information

Power Grids

Green Energy & Mobility

#Co-creation and Open Innovation #Sustainability #Generative AI #IoT/Data Utilization #Digital Solutions

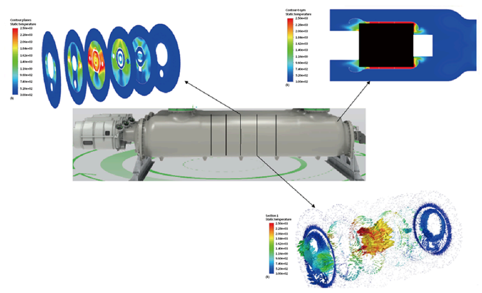
1. Development and Type Testing of a 420 kV 63 kA, 50 and 60 Hz SF_6-free High Voltage Circuit Breaker

Circuit-breakers are key elements of any electrical installation, and the availability of SF_6-free circuit-breakers is crucial for reducing the CO_2 footprint of electrical installations, transmission systems and power grids.

The world's first SF_6-free 420 kV 63 kA circuit- breaker was introduced at CIGRE 2022. It offers maximum flexibility for its application in different countries, as its design covers both 50 and 60 Hz frequencies and both gas- insulated switchgear (GIS) and dead-tank breaker (DTB) applications with the same interrupter. The breaker has been fully type tested according to IEC and IEEE standards and has been installed and energized. It is suitable for inductive switching and has successfully demonstrated extended electrical endurance (E2), proving the performance and reliability of the technology. Simulation tools and SF_6-free design strategies adopted are fully mature, enabling the rapid development and extension of the SF_6-free circuit-breaker portfolio to the highest voltage level ever achieved. The world's first SF_6-free EconiQ 550 kV metal-enclosed circuit-breaker for GIS and DTB applications and the world's first SF_6-free EconiQ 420 kV Live Tank Breaker LTA were launched at CIGRE 2024.

(Hitachi Energy Ltd.)

[01] Breaker Development and Optimization Based on Advanced 3D Simulation Tools



2. Retrofill for 420 kV Gas-insulated Lines: Technical Concept and Return of Experience

SF_6 technology has enabled reliable, compact, and scalable high-voltage equipment for the power grid. The high global warming potential of SF_6 has been recognized, along with the impacts of man-made climate change. Reducing equivalent carbon emissions to limit global temperature and achieving net-zero carbon emissions are now recognized as global imperatives.

Substituting the SF_6 in installed equipment aims to dramatically reduce damaging emissions.

A retrofill concept has been developed and fully qualified for a 420 kV gas-insulated line design. The SF_6 is replaced on-site with a gas mixture of nitrogen (N_2), oxygen (O_2) and of fluoronitrile (C4-FN), with the high-voltage equipment staying in place. Key technical points of the retrofill concept are: minor (or no) changes in hardware, very short outage times (retrofill deployment is fast), 99% reduction of CO_2 equivalency compared to SF_6, equivalent dielectric performance with minimal increase of the filling pressure, optimal gas tightness, long-term stability, and chemical compatibility of the gas mixture with the equipment's materials.

The first project has been in operation since December 2021 in the Richborough National Grid Electricity Transmission UK substation. It was commissioned successfully, and since then is optimally operational with no signs of degradation in either the equipment or the gas.

(Hitachi Energy Ltd.)

[02] Richborough National Grid Electricity Transmission UK Substation, EconiQ Retrofill

3. Market Driven Architecture for Remote Monitoring of HV Assets

Remote high-voltage breaker monitoring using cloud systems is key to providing detailed views for operators and original equipment manufacturer (OEM) specialists. This supports maintenance efficiency and cost-effectiveness. However, customers face challenges related to cybersecurity, data privacy, and integration with existing systems. The first two concerns can be addressed with best practices, best-in-class products, and regulations such as the European Union Data Act.

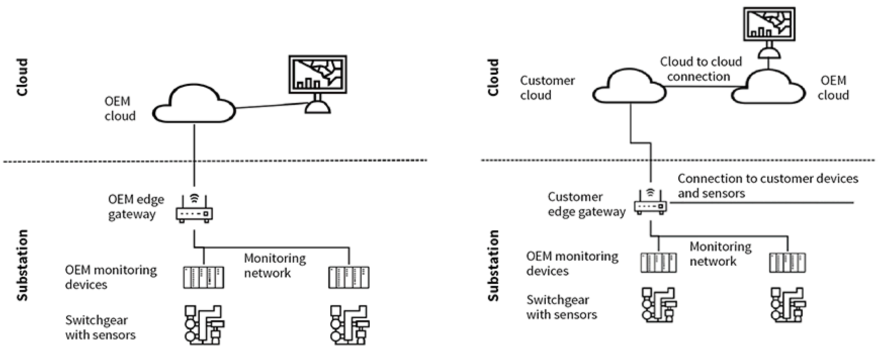
The third concern is addressed by a flexible remote monitoring architecture* covering customers' different conditions and requirements. The architecture supports the use cases, "green field" installation where an end-to-end solution covers sensors, monitoring systems, and cloud applications, as well as "(partial) brownfield" for customers who already invested in (remote) monitoring capabilities and want to add our products or services.

The architecture is broadly based on open interfaces (e.g., MQTT) and defined points of integration to enable flexible yet standardized solutions. This enables our customers to leverage their existing digital investments and yet easily expand the capabilities of their monitoring solution.

(Hitachi Energy Ltd.)

* S. Scarpaci, J.-E. Frey, S. Sehestedt, L. Merkert "Market driven architecture for remote monitoring of HV assets", Cigre 2024 Paris Session, Paper ID 10399

[03] "Green Field" and "Brown Field" Solutions for Remote Monitoring



4. Large Scale Grid-forming BESS Replaces Synchronous Generation, Enabling High Renewable Penetration & Low System Load in Australia’s Major Northern Grid

Hitachi Energy is delivering the Darwin-Katherine grid forming BESS (DKBESS) at the Channel Island Power Station. The primary aim of the project is to replace the retiring, gas-fired generation with advanced battery energy storage. The DKBESS supplies the critical power system stability services - inertia, system strength and voltage and frequency control, to stably transition away from fossil fuel-based- generation and underpin the stable operation of a grid with very high levels of renewable energy (RE).

The Darwin-Katherine network load varies from 60 MW to 300 MW and the relative size of the DKBESS, with a peak output of 70 MW, magnifies the challenges and benefits of integrating modern grid-forming technology as an enabler of high RE power systems. The project highlights the complexities of the connection process, as well as innovative control system approaches to not only replace stability services from thermal generation, but in most cases provides a superior performance.

This project provides a real-world example for how interconnected grids around the world can successfully progress toward high RE-based power systems.

(Hitachi Energy Ltd.)

[04] The 35MVA Darwin-Katherine BESS (DKBESS) in the Foreground, Located at the Channel Island Power Station in the Background

5. Solar PV, EV Charger, and Grid Integration to Enable Australia's First Fully Electric Public Road Transport System

Building upon Brisbane's existing rail, bus, and ferry networks, and in preparation for the 2032 Olympic Games, the city is creating an ambitious new transport system: an electric, high capacity, turn-up-and-go, fully accessible system of metro vehicles connecting the city to the suburbs.

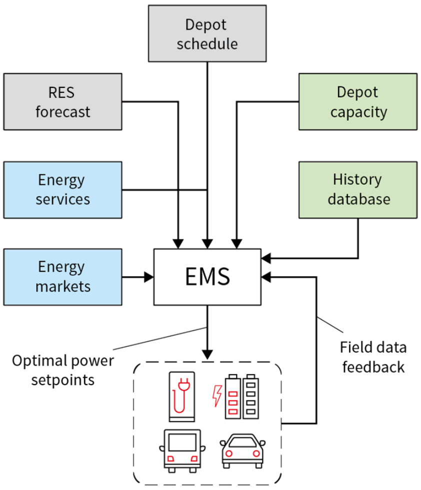
Brisbane is using the e-mesh energy management system (EMS) at their metro depot to optimize charging of the metros. The depot hosts a range of distributed energy resources (DER) including one megawatt of distributed solar photovoltaic (PV), and Grid-eMotion Flash and Grid-eMotion Fleet metro vehicle chargers.

The EMS leverages both day-ahead and intra-day optimizations that minimize site energy and demand costs while delivering required charging performance. The optimization is refined throughout the day with live field measurements and accounts for site energy and demand tariffs, available energy sources, forecast asset performance, and metro timetables.

In a grid facing increasing constraints, the EMS plays a critical role optimizing limited grid resources to ensure that the electric metros are ready to leave the depot on time and with adequate charge.

(Hitachi Energy Ltd.)

[05] EMS Uses a Range of Forecast, Vehicle Schedule, and Field Data to Optimize Vehicle Charging



RES: renewable energy resources

6. Controlled Switching of Coupled Power Transformers Based on Residual Flux Estimation

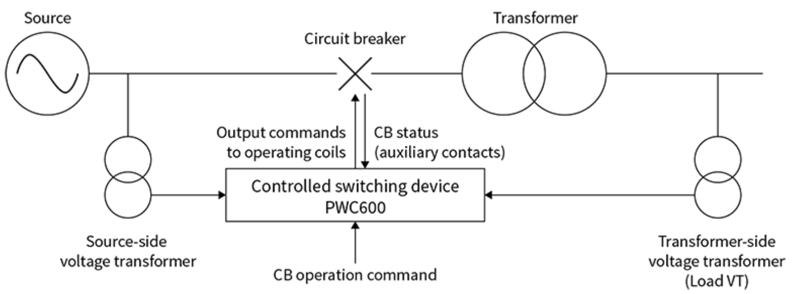
Traditionally, pre-insertion resistors (PIR) on circuit breakers (CBs) have been used for controlling the transformer inrush currents and to mitigate the voltage drops during energizing of power transformers. More recently, controlled switching (CS) has also been successfully employed for the same purpose.

Hitachi Energy has released a new CS device for transformers, that will minimize inrush currents and reduce voltage drops. Novel algorithms are designed to calculate the limb voltages and therefore, estimate the residual flux in limbs to ensure successful energization with less inrush currents. Field results from different installations validated and proved that controlled switching can minimize the inrush currents to the lowest extent and lower than the no load current of the transformer, leading to results like those obtained with PIR, as shown in the table (results obtained from various transformer configurations).

The field results on different (size, configuration) transformers evidence that controlled switching is the most effective and efficient way for reducing the transformer inrush current and increase the life of transformer & circuit breakers.

(Hitachi Energy Ltd.)

[06] Controlled Switching of Power Transformer Using Residual Flux Estimation Based on Voltage Measurement at Secondary Voltage of Transformer



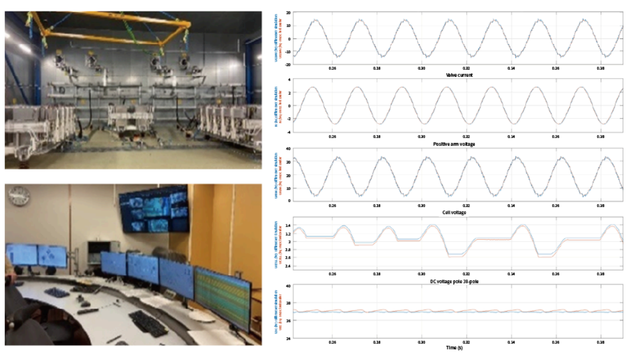
7. The Vectorized Approach: An Efficient Method to Model VSC Converters and its Verification Against Tests

The green transition requires enabling interoperability of multi-vendor HVDC grids with fast, reliable and accurate converter models. This article presents an efficient method to model modular multi-level converters (MMC) solely with software, utilizing the virtual MACH platform in an offline software- in-the-loop environment.

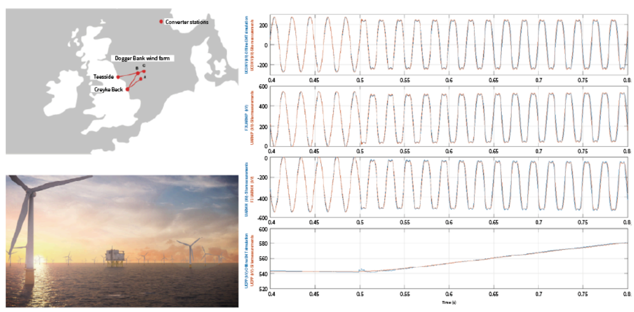
Our virtual control and protection (C&P) platform enables the capture of dynamic behavior of the real system and enhances the capacity to integrate HVDC systems into complex AC and DC networks in a flexible, scalable, and efficient manner, without the need for additional equipment. This helps to reduce the amount of time needed to design, validate, and integrate C&P systems without compromising on accuracy. The methodology permits not only to achieve accurate results through the engineering, execution and installation phases, but through the complete life cycle of the project, including after-sales support. The simulation results obtained using this approach are compared to real measurements from full-scale tests (Figure 1), and commissioning measurements from the DC cable energization of the Dogger Bank A offshore wind project (Figure 2).

(Hitachi Energy Ltd.)

[07-1] Submodule Level Validation: Comparison between the Model and Measurements from IEC 62501 Test



[07-2] Arm Level Validation: Comparison between the Model and Measurement from Dogger Bank A Offshore Wind Farm

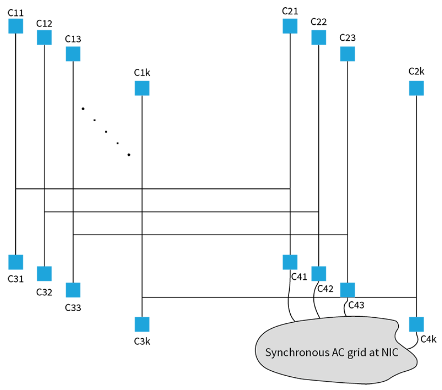


8. Less Connection for More Security – Novel Transmission and Power Grid Design in NEOM Grid with 100% Renewable

A novel backbone transmission architecture for operating a grid with 100% renewable is presented in this article. The clear advantages of this grid configuration are shown, that is, the overall grid is connected allowing for resource sharing which gives high resiliency. The deliberate separations prevent fault propagation and interaction which solves the problem related to large integration of renewables and weak AC system by design. The transmission architecture based on a modular multiterminal DC (MTDC) transmission backbone refer to Figure 1. Each of these MTDC modular building blocks are based on 4 terminal bipolar MTDC with voltage source converter (VSC) high-voltage DC technology, which offer key functions for the realization and operation of ENOWA future grid through enhanced controllability and a number of services, such as grid forming control, black start capability, voltage stabilization of connected AC grids, etc. The overall systems are interconnected via DC links and an AC power pool so that power exchange among different islanded AC grids is possible and under control. The new backbone transmission in many ways is more robust, more flexible in control, and easy in operating since power flow congestion, fault propagation, potential interactions are avoided by design. This new grid configuration sets a new paradigm for future power grid dominated with renewable sources.

(Hitachi Energy Ltd.)

[08] NEOM Backbone Transmission and Power Grid Architecture



9. Bi-mode Insulated Gate Transistor – An Outstanding Key Component in Present and Future HVDC Systems

The challenge of designing cost efficient and technically competitive application for renewable energy integration requires simultaneous development of many components such as high voltage direct current transmission (HVDC), static synchronous compensator (STATCOM) and HVDC DC breaker together with the most suitable power semiconductor device.

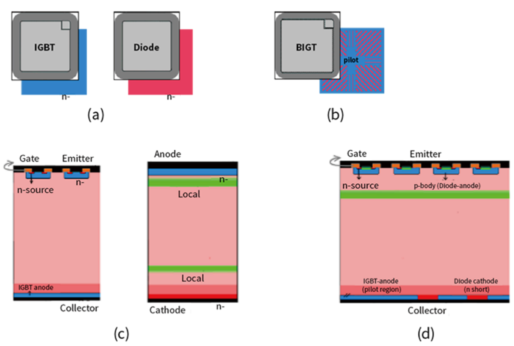
BIGT is an optimal semiconductor component which is well suited for present and future HVDC systems. The BIGT integrates both IGBT and diode into a single chip. This provides a major advantage to the usable module footprint (Figure 1). This directly benefits current handling capability and diode surge capability.

In HVDC applications, the state-of-art converter topology is a half-bridge (HB) cell based modular multi-level converter as shown in (Figure 2).

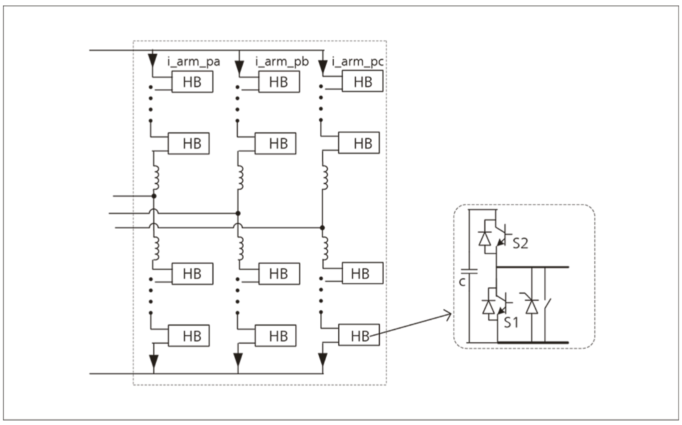
The BIGT allows reducing conducting losses and increasing transient current capability at the same time.

(Hitachi Energy Ltd.)

[09-1] IGBT & Diode (a), BIGT Chip and Backside Doping (b), Schematic Cross-section IGBT, Diode and BIGT (c), (d)



[09-2] Modular Multi-level Converter



10. Experimental Analysis of Transient Overvoltage Protections in Distribution Transformers

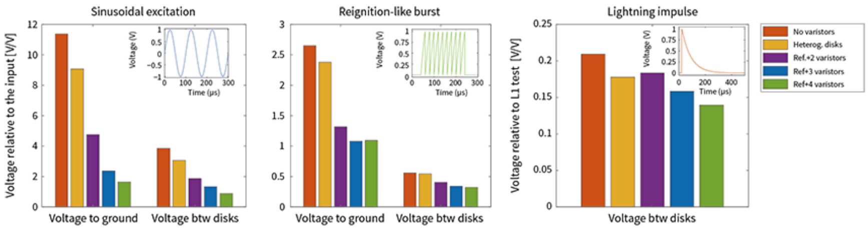
Fast transients occur in electrical networks because of events like switching operations or lightning strikes. These phenomena may degrade the insulation of the exposed transformers and result in catastrophic failures. Although classical solutions like RC snubbers or surge arresters provide a reasonable degree of protection, they are not able to limit over-voltages occurring into the windings because of their natural frequencies. In this context, Hitachi Energy proposes the connection of varistors to intermediate coil nodes.

The performance of this technology has been evaluated in a disk-foil transformer including two, three or four varistors, in comparison with an unprotected unit and a unit with alternating conductor widths. Different test signals were introduced into the windings while the internal voltages at each disk were measured.

The unprotected unit and the unit with unequal disks exhibit strong internal resonances that can result in significant over-voltages. The samples equipped with varistors suppress the main resonances, while the remaining ones have amplitudes low enough to not represent a risk. The improvements are achieved in terms of voltages to ground and between disks for oscillatory and impulsive impinging signals.

(Hitachi Energy Ltd.)

[10] Maximum Voltages to Ground and between Disks for Different Input Signals: Sinusoidal, VCB Reignition Burst and 1.2/50 μs Impulse



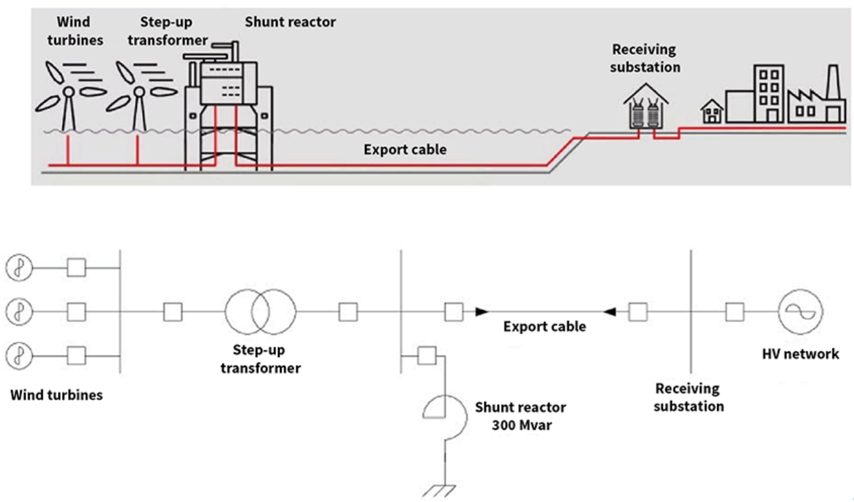
11. Challenges regarding Factory Acceptance Test of Large Offshore Shunt Reactor

Offshore wind farms are rapidly expanding to meet the growing demand for renewable energy. The power generated must be transferred to onshore power system with cables. By increasing the voltage of the AC installations, higher power can be transferred over longer distances. However, increasing length and voltage of AC cables adds more reactive power which must be compensated by shunt reactors, which tends to become very large in rated power. These reactors can widely exceed the three- phase capacity of most reactor manufacturers test facilities. International standards (IEC, IEEE) allow some compromises in the testing of large shunt reactors, but sometimes alternative methods need to be used, which must be agreed between customer and reactor manufacturer already at tender stage.

While alternative testing methods, such as single-phase testing or testing with reduced power, can be used when full three-phase testing is not possible due to limited test facility capacity, fully testing a shunt reactor with a three-phase energization and at full power remains the preferred and most accurate approach.

(Hitachi Energy Ltd.)

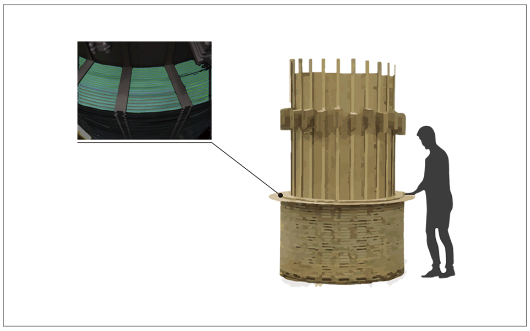
[11] Typical Wind Farm Setup



12. Artificial Intelligence in Transformer Manufacturing

The manufacturing of windings for high-voltage power transformers is highly complex, requiring precise design and skilled manual labor. Mistakes, though rare, can be costly, making quality control essential.

[12] **Physical Setup**



This research explores the integration of AI and machine learning into winding disc manufacturing to enhance efficiency, reduce errors, and support operators. The AI system combines advanced image processing, component classification, and quality control modules to assist rather than replace human workers, automating routine checks and improving production quality.

Focusing on the complex winding process of UHVDC converter transformers, the research aims to expand AI to other parts of manufacturing. AI's adoption promises to reduce production costs, failure rates, and training time while improving safety and productivity.

The system is also designed to ensure continuity in production even if the AI fails, striking a balance between technological advancement and operational practicality, with positive economic and social implications.

Socially, the system has the potential to significantly improve working conditions by reducing repetitive, dangerous, or physically demanding tasks, leading to a safer and more satisfying work environment.

(Hitachi Energy Ltd.)

13. Probabilistic Framework for Resilience Enhancement of Distribution Grids

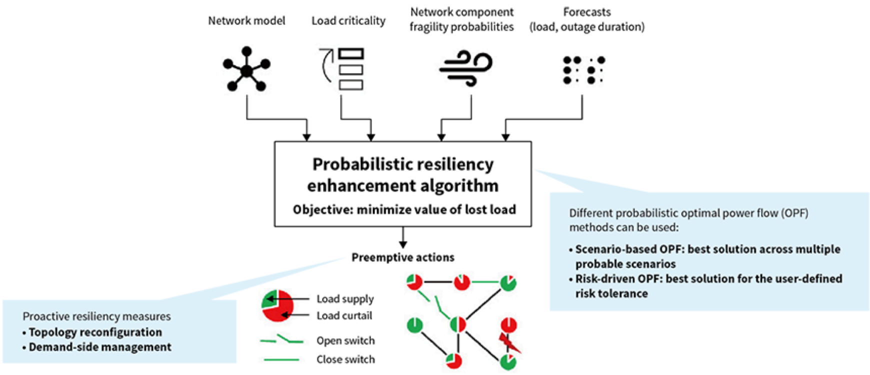
Extreme weather events can severely disrupt electricity grids, causing outages and high economic losses. Electric utilities aim to minimize these impacts and ensure quick restoration. Proactive grid hardening strategies, such as topology reconfiguration (see Figure 2) and demand-side management, help reduce outage duration. However, the unpredictable nature of extreme weather poses significant challenges for implementing resilience measures.

Hitachi Energy Research has developed a new probabilistic optimal power flow-based framework to proactively enhance resilience (see Figure 1). This framework assesses and implements proactive resilience strategies aimed at rerouting power flow away from vulnerable network components and ensuring secure operation. Inputs to the framework include network model, load criticality, load forecast, outage duration forecast, and network component fragility probabilities.

The framework can help operators implement effective operational strategies in real-time, thus improving network resilience against extreme weather. The effectiveness is measured by metrics including value of lost load. The framework is adaptable to various weather events and network types, and its application is demonstrated on a reference distribution grid with real-world data, showing improved values for the metrics.

(Hitachi Energy Ltd.)

[13] **Overview of the Proposed Probabilistic Proactive Resilience Enhancement Framework.**



PPF: optimal power flow

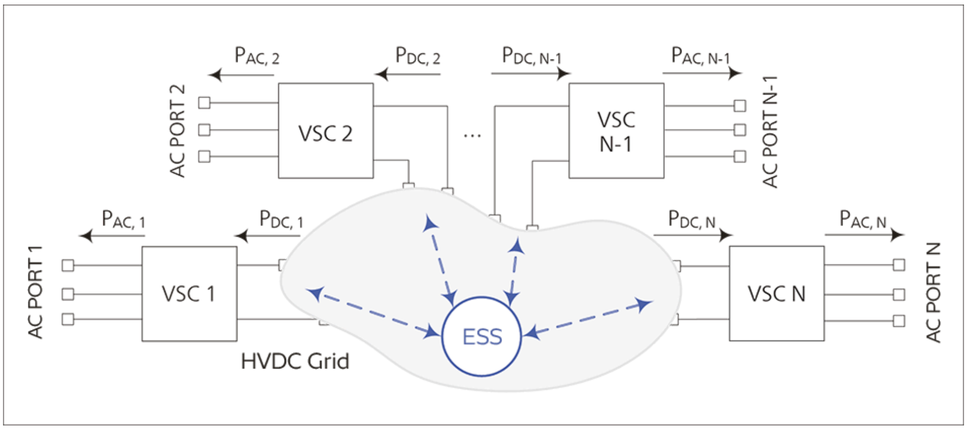
14. The Role of Energy Storage and Grid Forming Control in the Future HVDC System

Energy storage in HVDC systems can play an important role in the future. Firstly, for grid resilience that requires fast responses, it broadens the modus operandi of VSC-HVDC grid-forming operation to address frequency and voltage stability. Secondly, in the long run, it is one step ahead towards a 100% renewable source. Storage into HVDC systems creates several new features, beyond synchronous generators or condensers. These are the capability of HVDC systems to withstand frequency events with large rate of change of frequency.

For example, an exemplary case study on the Nordic 32 benchmark system already shows that a three second energy storage system in a point-to-point HVDC wind park connection, is enough to achieve a significant improvement in frequency nadir performance following a severe generator outage. Other features are, for instance, the support of black-start events, power modulation and power ramping control. Integrated storage into DC grids scenarios, centralized or distributed storage, will first support the connected converter stations and improve the DC voltage stability, towards the vision of a 100% renewable source having storage of various kinds.

(Hitachi Energy Ltd.)

[14] Conceptualization of Energy Storage Systems Integration in Multi-terminal HVDC Configuration

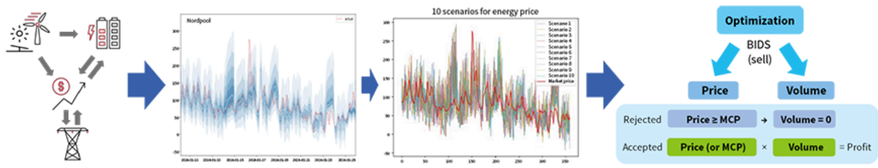


15. Automated Market Bidding for Battery Energy Storage Systems

Due to the growing number of renewable energy source (RES) generation units, the volatility of power supply is increasing, and this may have unwanted effects both on reliability of the power grid, as well as on electricity pricing. Battery energy storage systems (BESS) can be used to quickly balance the fluctuations, both in terms of under- and overproduction of electricity. This is done through electricity markets. Participating in electricity trading is not trivial due to the fluctuations in prices of energy and ancillary services, which may result in lost opportunities or even financial losses. A simplified stochastic optimization approach has been applied to deal with the price uncertainties, improving both the solution robustness (not violating the battery limits), and profit (ensuring better return-on-investment for BESS). Consideration of different price forecast scenarios along with their probabilities and utilization of the developed solution shows comparatively higher profits for the BESS owners. This provides a certain robustness against price changes, especially when using high-quality forecasts covering the true variations.

(Hitachi Energy Ltd.)

［15］ Workflow from Forecasting to Bids Resulting into a Market Decision



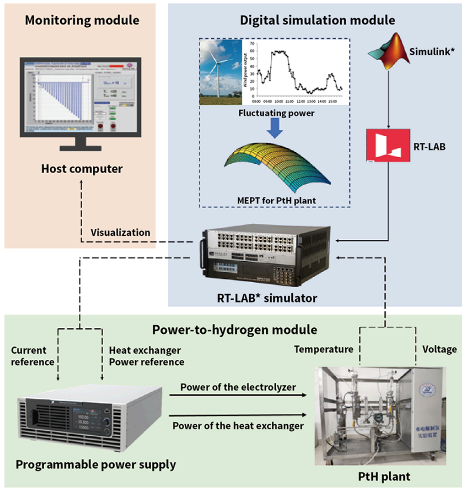
16. Maximum Efficiency Point Tracking Control for the Water Electrolysis System Based on Power Hardware in the Loop

Hydrogen is vital for supporting renewable energy utilization in high renewable penetration power systems, yet the fluctuating nature of renewable inputs demands enhanced operational flexibility in power-to-hydrogen (PtH) plants.

Hitachi Energy developed a coupled multiphysics model that integrates electrical and thermal systems and represents energy flows and processes in the industrial scale PtH plant. The model highlights trade-offs in controlling electrolyzer voltage and temperature. A maximum efficiency point tracking (MEPT) strategy to optimize energy allocation between the electrolyzer and heat exchanger was also introduced, considering temperature effects on electrochemical reactions. To address the challenge of accurately modeling multi-energy coupling in PtH processes, a power-hardware-in-the-loop (PHIL) platform is developed, combining a digital power system model with an industrial PtH plant. Experimental validation demonstrates that the MEPT strategy can improve hydrogen production efficiency by up to 3.18% compared to conventional methods under different load conditions. The PHIL platform significantly contributes to the study and optimization of renewable power systems, offering a real-time simulation basis for flexible hydrogen production control strategies.

(Huazhong University of Science and Technology; Hitachi Energy Ltd.)

［16］ Power-hardware-in-the-loop Platform for Experimental Validation



*See the list of “trademarks”.

17. Impact of Climate and Weather Variability on Energy System Planning

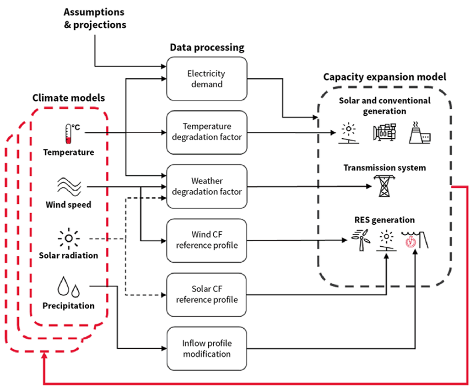
Various locations around the world have been experiencing new environmental conditions and an increased frequency and intensity of extreme weather events. As a result, the power grid is stressed both from the demand and supply-side, foreseeing an increase in electricity demand and an effect in generation availability and efficiency.

An approach to integrate the impact of climate and weather variations in a capacity expansion planning model, used for long-term energy systems planning, was developed. The most relevant climate parameters are air temperature, wind speed and solar irradiance, which affect the entire energy system in different areas. Long-term projections for each climate variable are filtered, processed and used to determine the climate's impact on the electricity demand and supply side.

It is established that the variability of climate and weather parameters has an impact on different components of the energy system, including also the transmission network. Different capacity factors for some renewable resources will decrease the annual yield, leading to investment in alternative sources.

(Hitachi Energy Ltd. and ETH Zürich)

[17] Extended Framework of the Capacity Expansion Model to Account for Climate Impact



CF: climate forecast

Hitachi Review

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